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Service International de la Rotation Terrestre et des Systèmes de Référence

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Proceedings of the IERS Workshop on Combination Research and Global Geophysical Fluids

Bavarian Academy of Sciences, Munich, Germany,
18 – 21 November 2002

Edited by
Bernd Richter, Wolfgang Schwegmann,
and Wolfgang R. Dick

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Preface

The IERS Workshop on Combination Research and Global Geophysical Fluids taking place in Munich, November 18–21, 2002, focused on two major themes, namely the combination of the space geodetic techniques at various levels and the steps required to proceed towards a rigorous combination of the IERS products and the status and future activities within the Global Geophysical Fluid Centres.

The first and second day of the workshop was devoted to the three primary IERS products, namely the International Terrestrial Reference Frame (ITRF), the International Celestial Reference Frame (ICRF), and the Earth Orientation Parameters (EOP; including the new IAU recommendations) and the rigorous combination of these three components into a consistent set of high-accuracy products. To reach such a goal also the IERS conventions and standards for modelling, parameterisation and analysis strategies had been considered. In view of the requirements of the new satellite missions, the demanding questions concerning global change and the interaction between components of the Earth's system to be studied, these products and their accuracy and consistency become of more and more importance.

Reports on the progress made in analysing the IERS EOP Alignment Campaign and the IERS SINEX Combination Campaign, major research activities of the Combination Research Centres (CRCs), Products Centres (PCs) and other interested parties, had been of special importance for this workshop. Based on these experiences the primary set of IERS products will be considerably improved and well aligned in the future.

Approaching the 5th anniversary of the establishment of IERS´ Global Geophysical Fluids Centres (GGFC), the second part of the workshop was devoted to an insightful review of what has been reached, what is planned for the future, and how to better define the roles and responsibilities in serving the community. It is a quickly evolving field of research with ever-increasing requirements on physical reference frames that demand understanding, modelling, and prediction of the global geophysical fluids and their effects on Earth rotation, time-variable gravity, geo-centre motion, and surface deformations. During a two-day portion of the workshop (days 3 and 4) technical reports and plans from each of the eight Special Bureaus (Atmosphere, Oceans, Hydrology, Tides, Mantle, Core, Gravity/Geo-centre, Loading) were presented.

The IERS workshop on Combination Research and Global Geophysical Fluids was a technical forum consisting of 95 IERS representatives and scientific individuals from 21 countries, that discussed the scientific contributions, different viewpoints as well as concerns about the future of the IERS products. The main goal of the workshop clearly was to start with the improvement of all the various IERS products in accuracy, consistency, stability, timeliness, user-friendly access, and documentation, to make first steps towards a rigorous combination of the various products and thus to contribute significantly to the realization of an "International Global Geodetic Observation System" (IGGOS).

Markus Rothacher, Bernd Richter

Towards a Rigorous Combination of Space Geodetic Techniques

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Abstract: The IERS with all its different components and products, ranging from the definition and realization of the reference frames (ITRF and ICRF), over EOPs and global geophysical fluid data all the way to conventions, is in a unique position to contribute in an essential way to the integration and combination efforts that are necessary to cope with the next generation of scientific missions and challenges. Concentrating on its core products first, the IERS should strive for a rigorous combination of ITRF, EOPs, and ICRF. A scheme for such a combination to obtain a much more consistent and accurate set of IERS products is presented and discussed. The vision of a rigorous combination goes, however, far beyond the combination of ITRF, EOPs, and ICRF, and includes all three pillars of space geodesy, i.e. geometry, Earth rotation, and the gravity field. The interaction of the two pillars "geometry" and "Earth rotation", where the IERS is playing a major role, with the third pillar "gravity" and with the global geophysical fluids is therefore discussed as well. It shows that, on the long run, a rigorous combination of all common parameter types and all three pillars of space geodesy has to be achieved. The project of an Integrated Global Geodetic Observing System (IGGOS) proposed by the IAG might be the framework for such an ambitious undertaking.

1 Introduction

Space geodesy may be seen to consist of three major pillars: the geometry of the Earth surface (continents and oceans) and its displacements, the orientation of the Earth axis and its rotation speed, and the Earth's gravity field and its time variations (see Figure 1). For all three pillars, well-defined, highly accurate and stable global Earth-fixed and celestial reference frames are of primary importance (see central box in Figure 1), especially in order to measure, detect and monitor changes in time (as, e.g., sea level change).

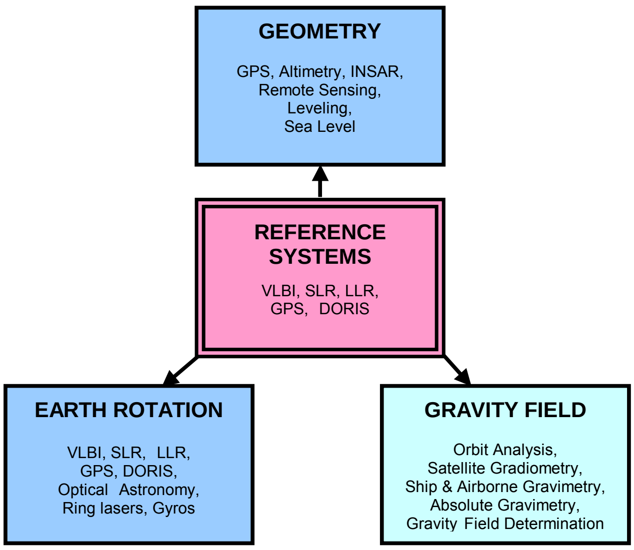

Fig. 1 The three major pillars of space geodesy. The IERS is heavily involved in three of the four boxes, namely geometry, Earth rotation, and reference frames.

According to the Terms of Reference (http://www.iers.org/iers/about/tor/) the core products of the IERS comprise the International Terrestrial Reference Frame (ITRF), the International Celestial Reference Frame (ICRF), the Earth Orientation Parameters (EOPs), the global geophysical fluid data, and the processing standards and constants given in the IERS Conventions. The IERS is thus directly involved in two of the pillars (geometry and Earth rotation) and responsible for the definition and maintenance of the reference frames. In addition, it is quite clear that also the interactions with and links to the third pillar, the gravity field, have to be carefully considered when generating the IERS products. The geocenter location to define the origin of the ITRF may serve as an example of such links.

Over the last decade considerable changes took place in space geodesy: the accuracy of the space geodetic techniques has improved dramatically reaching now 10^{-9} for geometry and Earth rotation and, with the new satellite missions CHAMP, GRACE and GOCE, also the gravity field part may approach this accuracy level. Many new missions (the gravity missions mentioned above; the altimetry missions JASON-1, ENIVSAT, ICESAT; astrometry missions) are being prepared, planned, or operational already. All these developments pose new and demanding challenges concerning the consistency and accuracy of the three pillars and thus the IERS products in particular and show that a rigorous combination of the different IERS products is crucial to meet these challenges.

2 Present status of IERS product generation

Let us have a short look at how the core products of the IERS are presently generated by the IERS Product Centers (PCs). First of all, we should mention that the individual products are combined almost independently of each other, although we know that according to the simple formula

$$x_{inertial}(t) = R(t) \cdot x_{earth-fixed}(t), \qquad (1)$$

the ITRF, given by the Earth-fixed coordinates $x_{earth-fixed}(t)$ of the stations, the rotation matrix $R(t)$, defined by the EOPs, and the ICRF, realized through the quasar coordinates symbolized by $x_{inertial}(t)$, should be combined together in order to maintain the consistency between these three IERS products (ITRF, EOPs, and ICRF). An example of the connection between ITRF and EOPs can be seen in Figures 2a and 2b, where the use of different ITRF realizations over time (e.g. ITRF91, ITRF92, ITRF93, etc.) led to jumps in the polar motion time series compared to a series based on one reference frame only (ITRF94). The impact of the change in the reference frame definition for the ITRF93 realization is particularly pronounced.

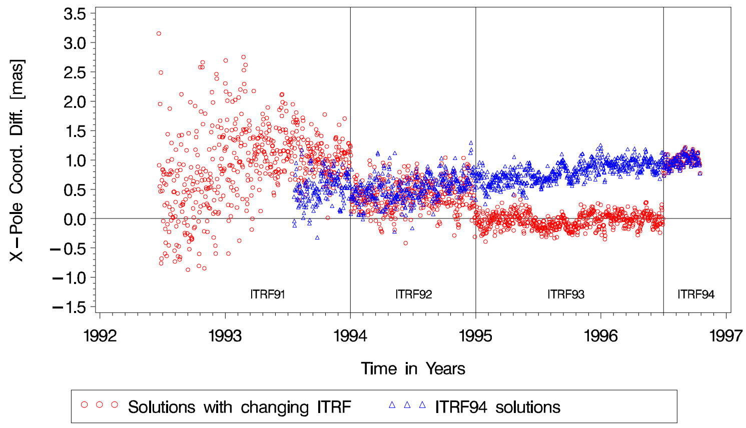

Fig. 2a Different ITRF realizations used to estimate polar motion (X-component) from GPS data. Jumps are evident in the time series where the ITRF realization was changed.

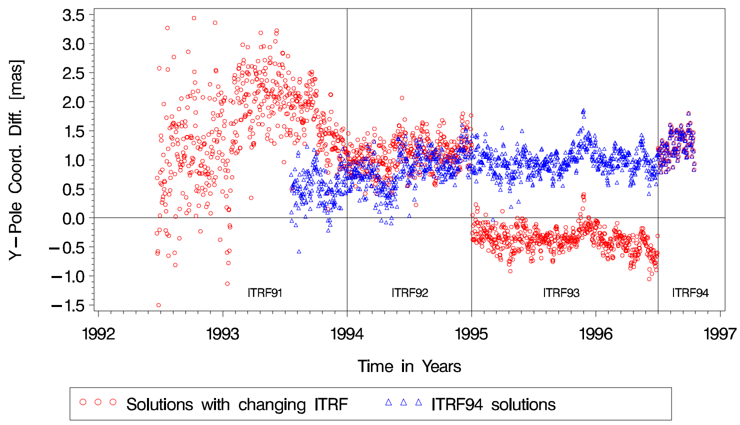

Fig. 2b Different ITRF realizations used to estimate polar motion (Y-component) from GPS data. Jumps are evident in the time series where the ITRF realization was changed.

Of the individual IERS products mentioned above, the ITRF is the most advanced product considering how it is combined from the various space geodetic techniques. Site coordinates and velocities are rigorously combined using the full variance-covariance information of the individual solutions (Altamimi et al., 2002). The IGS already delivers a multi-year solution correctly generated from the solutions of the individual IGS Analysis Centers (ACs) (see Ferland, 2002). The other technique services contribute just solutions of individual analysis centers at present.

IERS time series of EOPs are combined without taking into account correlations. Offsets and drifts are removed from the individual series, although such offsets and drifts should not be present, in principle. Only the IGS submits a rigorously combined series of EOPs to the IERS. For the status of VLBI see also (Nothnagel et al., 2002), for ILRS see (Noomen et al., 2002; http://ilrs.gsfc.nasa.gov/working_groups/awg/awg_activities/awg_nice_200_minutes.html).

The presently adopted ICRF has been computed by only one AC of the IVS (Ma et al., 1998; IERS 1998 Annual Report, 1999). No combination of different analysis center solutions has been attempted so far nor a more demanding combination together with EOPs and ITRF.

Finally, the various global geophysical fluid products are neither compared nor combined and many of the products to be expected from the sub-bureaus of the Global Geophysical Fluids Center (GGFC) are not routinely available.

We may therefore identify some clear deficiencies in the present status:

- Except for GPS, no intra-technique combination is performed yet. This means that neither systematic errors between the ACs nor the variability between the results of the individual ACs are known.
- Except for the ITRF, no rigorous inter-technique combination is performed. This means that the IERS products (ITRF, EOPs, ICRF) are not consistent, that systematic biases between the technique solutions are not known in detail and are not dealt with, and that the strengths of the individual techniques are not exploited at all.
- The interaction between the GGFC and the IERS PCs or ACs is very small.
- Apart from a few geocenter studies the gravity field is neither considered and nor combined with other products, even if it may be important for the consistency between the three pillars.

From this summary of the present status we immediately see, that considerable improvements in the correctness of the IERS product generation are possible. These improvements should at least lead to a better consistency if not to a general improvement of the products.

An overview of the present status of combining ITRF, EOPs, and ICRF may also be found in (Angermann et al., “IERS SINEX Combination Campaign“, this volume).

3 Vision of a Rigorous Combination

The concept of a rigorous combination of the space geodetic technique is not a new idea. The Commission on International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG), especially with its Subcommission on “Coordination and Combination of Space Geodetic Analysis”, has been a forum for such activities since a long time and an Integrated Global Geodetic Observing System (IGGOS) was already the theme of the IAG Symposium in 1998 in Munich (see e.g. Rummel et al., 2000; Rothacher, 2000). Due to the establishment of the technique services IGS, IVS, and ILRS and in the near future IDS, a much better coordination of the individual techniques has become possible and we are in a much better position today to really realize such a combination.

The vision of a rigorous combination in this context includes the following three points:

- All parameter types common to more than one space geodetic observation technique are rigorously combined including the full variance-covariance information of all these parameters.
- All observing instruments co-located at the same site are linked based on reliable and extremely accurate local ties.
- All observation instruments co-located on the same satellite are linked based on reliable and extremely accurate eccentricity vectors between the instruments.

The parameter space for such a combination is given in Table 1. The parameter types that are important for the IERS products are shaded. Whereas the vision of a rigorous combination comprises all common parameters including the combination of gravity field coefficients, satellite orbit and atmosphere parameters, and possibly even common clock corrections for, e.g., co-located VLBI and GPS (assuming both measurement types being based on the same ultra-stable oscillator), we will only consider the parameter types belonging to the ITRF, EOPs, and ICRF in more details here. A rigorous combination of all three pillars, i.e. of geometry, Earth rotation, and gravity, is still a task that is too demanding to be considered a realistic near-term goal.

A rigorous combination will automatically guarantee, that the resulting products are really consistent, that the complementarity of the techniques is fully exploited, and that technique-specific systematic biases may be distinguished from genuine geodetic or geophysical signals.

If such a rigorous combination can be achieved, it will certainly be one of the major contributions to an IGGOS project. A schematic representation of the relations between the space geodetic observation techniques, the three pillars of space geodesy, and the interactions with the Earth's system is given in Figure 3. It illustrates (arrows toward the right) that a combination of the space geodetic techniques should result in better information about the three pillars, and a better knowledge of geometry, Earth rotation, and the gravity field will help to better understand the processes in the Earth system (global geophysical fluids). A more accurate modeling of the Earth processes and interactions and independent information about the global geophysical fluids (e.g., from meteorology, oceanography, geophysics, etc.) on the other hand (arrows toward the left) will allow for better correction models in the processing of the space geodetic data. It should also be mentioned that each of the various components of the Earth's system has an impact on all three pillars and models should be developed that consistently account for the effects on all three pillars. Some of these ideas go far beyond the scope of the IERS and should be addressed within IGGOS. The sub-bureaus of the IERS GGFC already started to gather information about the different components of the Earth's system and to study the relations to the other IERS products.

Table 1 Parameter space for a rigorous combination of the space geodetic techniques. The IERS is involved with the shaded areas.

Parameter type	**VLBI**	**GPS/ GLON.**	**DORIS/ PRARE**	**SLR**	**LLR**	**Alti-metry**
Quasar Coord. (ICRF)	X					
Nutation	X	(X)			X	
Pole Coord. X, Y	X	X	X	X	X	
UT1	X					
Length of day (LOD)		X	X	X	X	
Sub-daily ERPs	X	X				
ERP Amplitudes of ocean tides	X	X		X		X
Station Coord.+ Velocities (ITRF)	X	X	X	X	X	(X)
Geocenter		X	X	X		X
Gravity field		X	X	X	(X)	X
Satellite orbits		X	X	X	X	X
LEO orbit determination		X	X	X		X
Ionosphere	X	X	X			X
Troposphere	X	X	X			X
Time/Frequency transfer	(X)	X	X			

In the next section we are focussing on the correct combination of ITRF, EOPs, and ICRF solutions, in Sections 5 we will consider the interaction of the IERS products with the gravity field, and in Section 6 the interaction with the global geophysical fluids.

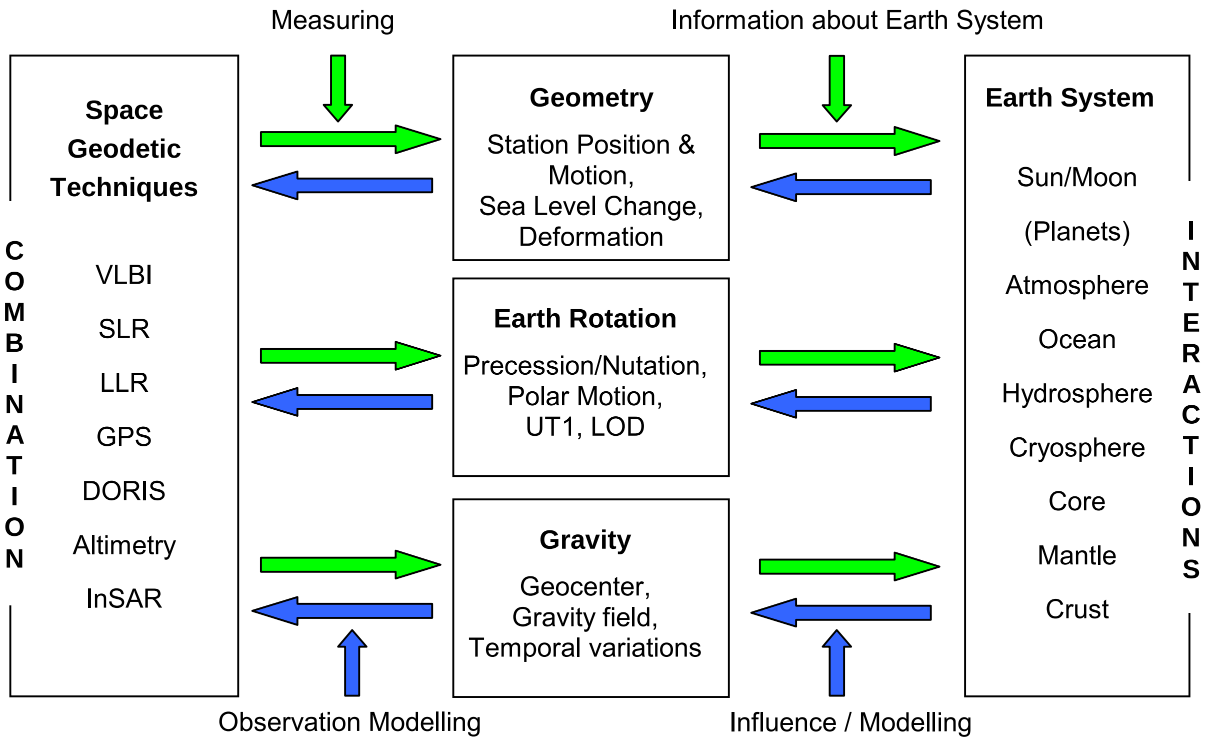

Fig. 3 Combination of the space geodetic techniques, the three pillars of space geodesy, and the interaction with the components of the Earth's system (e.g., global geophysical fluids)

4 Combination of ITRF, EOPs, and ICRF

The rigorous combination of the ITRF, the EOP time series, and the ICRF is the most evident way to improve the consistency and accuracy of the major IERS products and a first crucial and concrete step towards the vision outlined above. In this section we will discuss the primary issues of such a combination.

The scheme that seems appropriate for a rigorous combination of ITRF, EOPs, and ICRF can be divided into two parts, namely (1) the generation of weekly solutions using a correct inter-technique combination, and (2) the generation of multi-year solutions based on the weekly combined inter-technique solutions. These two parts of the procedure are shown schematically in Figures 4 and 5. For any exchange of solutions the SINEX format is used as a standard for all techniques (see <[1]>).

The weekly inter-technique combination is based on the "weekly" (i.e. weekly solutions for GPS, SLR, and DORIS; 24-hour sessions for VLBI) SINEX files, that should be the result of an intra-technique combination done by the corresponding technique service, i.e., by the IGS, IVS, ILRS, and IDS,

[1] ftp://alpha.fesg.tu-muenchen.de/iers/sinex/format/

because the services have the best knowledge of their own technique and technique-specific problems. The “weekly” SINEX files should contain site coordinates – site velocities are not necessary for a one-week interval; that is why one week seems very appropriate –, EOPs for each day (offsets and rates), and quasar coordinates (VLBI only) to allow a rigorous combination of ITRF, EOPs, and ICRF. The inter-technique solution is performed by IERS combination centers yet to be defined (Call for Participation). In this combination step, much care will have to be taken to understand and remove systematic biases between the individual techniques and to make best use of the local tie information. After some time we will end up with a time series of weekly combined SINEX files allowing us to proceed to the second step of the procedure, the multi-year solutions.

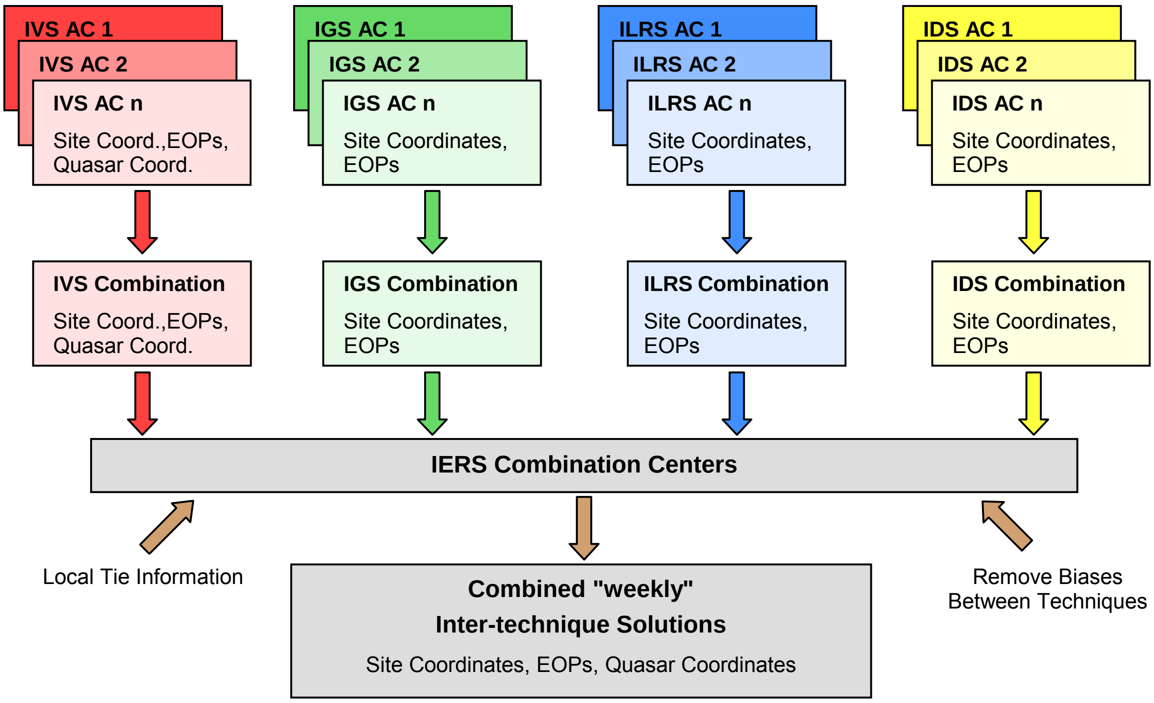

Fig. 4 Scheme for a rigorous combination of weekly inter-technique solutions

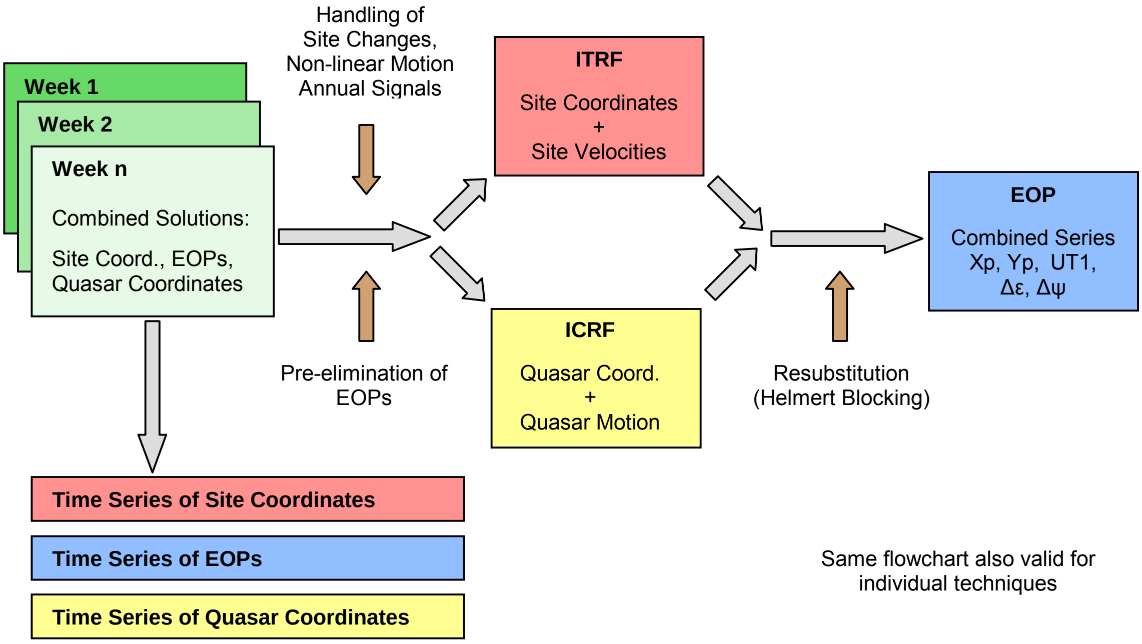

Fig. 5 Scheme for a rigorous combination of multi-year inter-technique solutions from weekly solutions

The series of weekly SINEX files resulting from the inter-technique combination will be the basis for the multi-year solutions (see Figure 5). By combining all the weekly SINEX files into one large solution and by setting up velocity parameters, it will be feasible to obtain a new set of ITRF site coordinates and velocities, a series of EOPs fully consistent with this ITRF realization, and a new set of corresponding quasar coordinates (ICRF). Because of the large number of EOPs – about 36,500 EOPs will result from twenty years of data – it may be necessary to treat the EOPs with a pre-elimination/re-substitution scheme (also called Helmert blocking) as outlined in Figure 5. As an extremely important by-product we will obtain time series of all three parameter types involved (i.e., site coordinates, EOPs, and quasar coordinates) to study their temporal variations. It is the goal that such a consistent set of IERS products for ITRF, EOPs, and ICRF will eventually replace the present set of products.

The advantages of such a rigorous combination procedure are quite evident:

- The final products will fully benefit from all techniques and their strengths.
- A fully consistent set of ITRF/EOP/ICRF products will be obtained.
- Fully consistent time series of weekly site coordinates, EOPs, (and quasar coordinates) can be produced.
- Flexibility to handle equipment changes, non-linear site motion, annual signals, earthquakes, etc. is given.
- Systematic biases will become more visible and a better understanding of these biases will eventually lead to improved solutions.

Very accurate co-location information (fundamental stations and satellites) are required to really benefit from the combination and to allow the assessment of systematic biases. There will also be no way around studying and understanding all systematic biases. In addition, it will be of utmost importance, that the solutions of the individual techniques (and even the individual analysis centers) are based on common standards concerning three different categories, namely modeling, parameterization, and processing. The modeling standards (i.e., IERS Conventions) include the treatment of solid Earth tides, loading effects, pole tides, tropospheric refraction, relativistic corrections, etc. In order to be able to rigorously combine the SINEX files from different techniques also the parameterization has to be standardized (e.g., consistent representation of EOPs with offsets and drifts, as identical time intervals as possible, etc.). Finally, standards concerning the processing have to be adopted to ensure, e.g., timeliness and reliability.

Probably the most critical part of the combination procedure will be the treatment of systematic biases. Quite a considerable number of problematic issues is already known, and we may expect that during the development of combination algorithms and comparisons made, additional inconsistencies will emerge. Let us point out just a few of the difficulties to be overcome:

- Systematic effects in the time series of station coordinates (e.g., annual signals, non-linear motion, and equipment changes)
- Differences in the ITRF global scale (e.g., from antenna phase center variations, troposphere mapping functions, relativistic corrections, GM, etc.)
- Systematic biases in Length of Day (LOD) and nutation rates for satellite techniques
- Biases in geocenter coordinates between techniques
- Systematic orbit biases (e.g., 5 cm offset between IGS orbits and SLR measurements)
- Systematic differences in the reference frame realization by the different techniques resulting in offsets and drifts in the individual EOP series

As an illustration, an example of such systematic biases is given in Figure 6, where the high-frequency prograde polar motion spectrum obtained from long GPS and VLBI sub-daily EOP time series are compared.

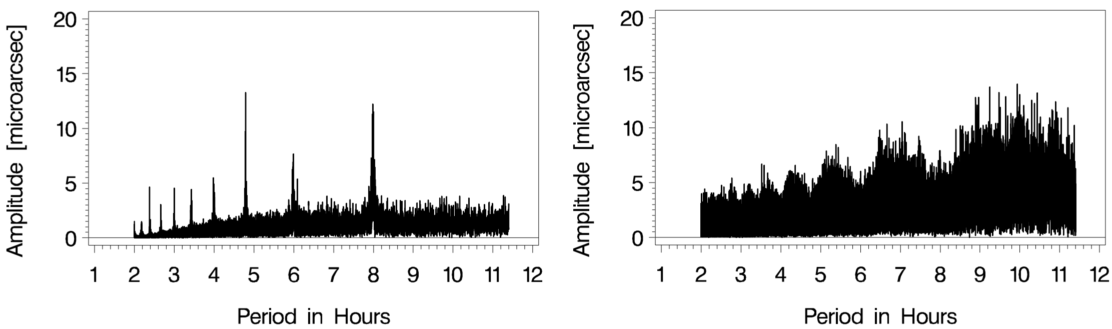

Fig. 6 Comparison of the prograde polar motion spectrum below periods of 11 hours derived from sub-daily GPS and VLBI EOP estimates, respectively

Whereas significant amplitudes are visible in the GPS spectrum at frequencies of 2, 3, 4, ... cycles per day, no such signals can be detected in the corresponding VLBI spectrum. There is even a decrease in the VLBI amplitudes at these frequencies. A closer inspection of the GPS EOP time series suggests, that a very small systematic bias in the daily polar motion rates of only a few ten microarcseconds is sufficient to produce such a spectrum. Due to the fact that the GPS results can be compared to those of VLBI, we are able to conclude that most (if not all) of the signals seen at periods below 11 hours should be considered artifacts resulting from the GPS processing strategies (e.g., small systematic biases in the orbit modeling over each daily solution). This example should indicate how important the comparison and combination of the space geodetic techniques is.

5 Interaction with the Gravity Field

Although the IERS is not directly involved in the generation and combination of global gravity field models – the new International Gravity Field Service (IGFS) has been established for this task – there are some crucial links between the gravity field and the two other pillars, namely geometry (ITRF) and Earth rotation:

- The spherical harmonic coefficients C_{10}, C_{11}, and S_{11} of a global gravity field are directly related to the location of the geocenter, which is a central part in the definition of the origin of the ITRS.
- The coefficients C_{21}, S_{21}, and S_{22} are coupled with the Earth‘s figure axis and the Greenwich meridian and thus with Earth rotation.
- The gravity field is also very important for high-precision orbit determination and thus for all parameters (site coordinates, EOPs, etc.) estimated with satellite observation techniques.
- In view of the big improvement in spatial and temporal resolution of the Earth’s gravity field due to the new satellite missions (CHAMP, GRACE, and GOCE), the reference frame, in which the gravity field information is given, will become more and more crucial (e.g. orientation of the gravity field with respect to ITRF).
- Finally, let us mention that gravity field variations take place due to exactly the same Earth processes (e.g., mass redistribution by global geophysical fluids) that are responsible for variations in Earth rotation and geometry.

In the near future, there will be many Low Earth Orbiting (LEO) satellites carrying GPS receivers (approximately 30 by the year 2008). This means that we will have a four-layer scenario: (1) the quasars constellation, (2) the GNSS constellation (GPS, GLONASS, GALILEO), (3) the LEO constellation, and (4) the tracking networks at the Earth’s surface. It is quite evident, that the combination of all four layers, from the quasar layer defining the ICRF down to the station layer defining the ITRF, will give an optimum solution concerning the ensemble of global geodetic parameter types. Some of the reasons to include the LEO layer are, that no tropospheric delays have to be considered for GNSS receivers on LEO satellites, that the LEO data should help to improve the geocenter estimates, that there is a totally different geometry between GNSS satellites and LEOs than between GNSS satellites and ground stations, and that the LEOs represent the ideal link to connect the gravity field parameters with the geometrical parameters and the EOPs.

This shows that in the long run only a rigorous combination of all three pillars will ensure the consistency of the corresponding geodetic products. Some institutions are already getting prepared for this challenging effort.

6 Interaction with the Global Geophysical Fluids

When looking at Figure 3 we see that the global geophysical fluids (components of the Earth’s system) play an essential role for the three pillars and thus for the IERS products. Again, there are two directions of information flow to be considered: in one direction, the parameters estimated in the solutions of the space geodetic techniques give information about the global geophysical fluids; in the other direction, the global geophysical fluids give information necessary to interpret time variations in the three pillars and to model the influences on the space geodetic observations.

Examples of the wealth of information about global geophysical fluids contained in the global geodetic parameters are:

- Site coordinates are changing due to ocean and atmospheric loading, plate tectonics, etc.
- Earth orientation is heavily influenced by the global geophysical fluids (from the Earth's core to the ocean and atmosphere).
- Orbital parameters depend on the direct atmospheric effects (air drag) and, indirectly, on all gravity field changes due to mass redistributions.
- The geocenter location varies due to mass redistributions.
- The atmosphere has a direct effect (delay) on the space geodetic signals.

Examples of the importance of global geophysical fluid data for the processing and interpretation of the space geodetic observations are:

- Corrections for sub-daily EOP variations using models derived from ocean tide models.
- Corrections for loading effects derived from ocean and atmosphere models.
- Derivation of information about the atmosphere (troposphere mapping functions, dry delay and gradients) from meteorological models.
- Modeling of the center of mass variations using information about mass redistribution in the atmosphere and oceans.

When thinking of a rigorous combination of all techniques and data, we will have the problem how to assess the quality of these combined solutions. Independent data and models concerning global geophysical fluids may be an important tool to evaluate these combined solutions.

All this eventually calls for an integrated and consistent modeling of all geophysical fluid signals seen in geometry, Earth rotation, and gravity field, an obvious topic for the IGGOS project.

7 Conclusions

We have seen that an integration and combination of all space geodetic techniques is vital to improve the consistency of the results, to realize optimum reference frames (ITRF and ICRF) and EOP series for future missions and challenges (e.g., global change), and to be in a position to distinguish between genuine geophysical signals and technique-specific biases. For a rigorous combination, all links between the techniques (at fundamental stations as well as on the satellites) have to be made available with high accuracy and reliability (local ties, satellite antenna offsets, etc.), and all common parameter types between the techniques should be compared and combined to the extent possible. This will eventually include the gravity field parameters. Concentrating on its core products, the IERS should strive to play an essential role in these integration and combination efforts and thus contribute with its various components (ITRF, EOPs, ICRF, global geophysical fluids, and standards and conventions) to the planned IGGOS project and, more generally speaking, to a more detailed view and understanding of the complexity of the "System Earth" and its geophysical processes.

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Combination of Station Positions and Velocities

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Summary: The main focus of this position paper is to review the current status of the combination of station positions and velocities with an emphasis on the modelling, strategies and datum definition. A particular attention will be given to the current achievement, underlying accuracy level, weaknesses and limitation factors inherent to individual techniques as well as the distribution and quality of collocation sites. Goals and recommendations for future improvements are proposed.

1 Background

Although this paper deals with combination of station positions and velocities in a broad sense, it should be inscribed in the context of the IERS activities. Therefore, in order to illustrate the discussion of this paper, some examples will be taken from ITRF results and particularly the most recent version, namely ITRF2000 (Altamimi et al., 2002).

On the other hand, it is important to delimit the scope of this paper by assuming the following:

- Combination of time series of stations positions is outside the scope of this paper. However, some suggestions are proposed at the end of this paper for future IERS products and improvement of the consistency between IERS products.
- Although it would be a promising approach, multi-technique processing at the observation level is not discussed here.
- Station velocities are assumed here constant and linear.
- Station non-linear motion should be treated at the level of individual techniques or time series analysis and not at the combination level. However, since non-linear motions of some observing stations of space geodesy could be important, some recommendations are suggested hereafter.

In this paper we try to summarize the current status of this activity and draw some recommendations for improvements. These recommendations are presented in a broad sense of the IERS combination activities and they apply to the ITRF in particular. They (and other possible specific ITRF recommendations) should be discussed/adopted by the Working Group on ITRF Datum (WGID), the ITRS Center as well as the IERS Directing Board.

2 Combination model

The basic model currently used for combination of different sets of station coordinates is the one based on the formula of 7 transformation parameters. Given the context of this paper, we assume that the 7 parameters are valid at a given epoch and have linear time variations.

The input data are:

- individual solutions (station positions at given epochs and velocities) provided by analysis centers of the different techniques, expressed in various reference frames
- local ties (expressed as values at given epochs and linear variations), connecting stations of different techniques in collocation sites

The unknowns are:

- 14 transformation parameters between each individual frame and the combined one
- positions and velocities of all stations available in individual solutions, expressed in the combined frame

There are currently two combination approaches:

Type A:

One step combination: simultaneous estimation of transformation parameters of each individual solution w.r.t. the combined frame as well as combined station positions and velocities. In this case the datum definition of the combined frame could be achieved either by:

- fixing the 14 degrees of freedom
- using minimum constraint equations relating the combined frame to an external frame

Type B:

Two step procedure: in the first step, individual solutions are transformed in a selected given frame and in the second step, all the transformed individual solutions are combined together by stacking their normal matrices, assuming that they are all expressed in the same frame. In this case the datum definition is implicitly realized through the selected frame.

Note that in Type A approach, all common stations between at least two individual solutions interact in the estimation of the transformation parameters, whereas in Type B, stations which are common to two individual solutions and are not available in the selected frame may bias the combined frame.

We intentionally concentrate on the basic combination model only, excluding all other analysis strategies, such as stochastic modelling, weighting, minimum constraint equations, etc.

Current status

- IGN ITRF CC is using the Type A approach
- DGFI ITRF CC is using the Type A approach
- NRC ITRF CC is using the Type B approach and software upgrade is in progress
- Other combination groups: unknown

Recommendation 1:

The combination centers (groups) are asked to evaluate the consistency/impact of the above two approaches on the combined TRF.

3 Datum definition

The concept of reference systems is in fact a purely mathematical convention (or model) introduced to describe the physical Earth and the temporal variation of its shape. Therefore, all the parameters (origin, scale, orientation) needed to define a Terrestrial Reference System (TRS) or its physical materialization by a Terrestrial Reference Frame (TRF) could be selected arbitrarily or by convention. Meanwhile, space geodesy observations allow access to some of the TRF parameters. Satellite techniques sense the Earth Center of Mass, which could be used as a natural TRF origin, the scale depends on the modelling of some physical parameters and the orientation (unobservable by any technique) is still arbitrarily (or conventionally) defined.

In the context of IERS, the ITRS definition fulfills the following conditions:

- it is geocentric, the center of mass being defined for the whole Earth, including oceans and atmosphere.
- the unit of length is the meter (SI). This scale is consistent with the TCG time coordinate for a geocentric local frame, in agreement with IAU and IUGG (1991) resolutions. This is obtained by appropriate relativistic modelling.
- its orientation was initially given by the Bureau International de l'Heure (BIH) orientation at 1984.0.
- the time evolution of the orientation is ensured by using a no-net-rotation condition with regards to horizontal tectonic motions over the whole Earth.

The meaning of datum definition to be retained here is to specify the frame origin, scale and orientation parameters and their time evolution.

Delimiting the scope of this paper to combination of station positions and linear velocities, it is therefore assumed that the corresponding TRF time evolution is linear.

Any geodesy based TRF, used by a variety of users and in particular geophysicists, should preserve the physical properties embedded in space geodesy observations. Consequently, datum definition parameters accessed by the observations (such as the scale and the origin) should be selected as part of the TRF datum definition.

Unlike the TRF origin and scale, there is no physical property (or geodetic technique) known to allow the TRF orientation determination or its time evolution. To conventionally define the later (called also "rotational datum"), the current approach is to use the No-Net-Rotation (NNRC). Note that this choice is the one specified in the ITRS definition. On the other hand, one of the justifications for NNRC is that the Tisserand frame (the basis of NNRC) is used in the theory of Earth rotation, having the property to minimize the Earth's crust motion and deformation that would affect the Earth Orientation Parameters. Moreover, the TRF long-term stability is certainly more easy to maintain using NNRC than using other conditions, such as the hot-spot hypothesis.

Given the nature of this activity (assuming linear station velocities), a reasonable approach for the TRF orientation time evolution, is the selection of TRF core sites for which linear motion is assumed. The long-term stability of the TRF rotational datum should then be ensured over the selected core sites. However, non-linear motions of the TRF core sites should be clearly investigated (see recommendation 5 below).

Note: It should be emphasized that the strict ITRF datum definition issue constitutes the main mission of the WGID. Therefore, TRF datum definition recommendations formulated below should be discussed and possibly adopted by the WGID.

Current status

TRF origin: In the ITRF experience, SLR is currently providing the best determination of the Earth Center of Mass. However, the translation rate differences between satellite TRFs are heavily dependent on the network configuration, the orbit and the used observations. Moreover, the geocenter motion, affecting the TRF origin stability, is not clearly handled by the ACs.

The ITRF2000 origin is defined by fixing to zero the translation and translation rate parameters between ITRF2000 and the weighted mean of most consistent SLR solutions. As result from ITRF2000 solution, the origin accuracy of ITRF2000 (over 10 years) is estimated to be about 1.5 mm in X and Y and about 4 mm in Z translation components.

Recommendation 2 on TRF origin:
The ILRS is urged to investigate refinement of the SLR origin to reduce small, but still existing, discrepancies between the ILRS ACs and in particular in the Z component and its correlation with the SLR TRF scale. The IGS is urged to investigate methods to properly handle all GPS-antenna and transmitter related effects to improve GPS TRF origin. The capability of satellite techniques to accurately determine geocenter motion has to be clarified within a joint effort by the Technique Centers, together with the WGID. IGS should study the inclusion of LEO satellites into their global solutions in order to help improve the geocenter estimates.

TRF scale: the current analysis also showed that the best scale inter-technique agreement is between VLBI and SLR solutions. However, TRF scale and scale rate are affected by station vertical motions and other modelling such as the troposphere, as well as technique-specific effects, such as VLBI, GPS and DORIS antenna-related effects, and SLR station-dependent ranging biases.

The ITRF2000 scale is defined by fixing to zero the scale and scale rate parameters between ITRF2000 and the weighted mean of 5 SLR and 3 VLBI solutions. The ITRF2000 global scale accuracy (over 10 years) is estimated to be at 0.5 ppb (3mm) level. While the largest scale discrepancy between the 3 VLBI solutions (using the same software) does not exceed 0.3 ppb, it may reach 1 ppb in case of SLR and exceed 5 ppb in case of DORIS solutions.

Recommendation 3 on TRF scale:
IVS, IGS and IDS are urged to refine / investigate their various modelling, such as the troposphere and antenna-related effects in order to improve the TRF scale consistency. ILRS is asked to clarify the range bias impact on the SLR TRF scale. The effect of IGS equipment changes on station height determinations needs to be minimized. A joint effort by all Technique Centers is needed to monitor station height variations in order to minimize effect on the TRF scale.

TRF orientation: the definition of the TRF orientation at a given epoch is not an issue, while the current approach used to define its time evolution is the one satisfying the NNRC. The current accuracy of the NNRC realization is not yet clear and needs more investigation. Only a few models satisfying this condition are available at the present time, and their agreement is around 2 mm/y as described below. The realization of a NNR model using entirely (and uniquely) space geodesy observations is not possible currently for mainly the following two reasons:

- Space geodesy observing sites (and in particular those of high quality) are far from optimally distributed to allow an accurate discretization of the whole Earth surface.
- The rigorous realization of the NNRC is a complete integral of the Earth surface, including zones of deformation, while geodesy observations are not yet at this level of refinement.

On the other hand, we should distinguish between a NNR model realization and the TRF rotational datum definition. In the former, geophysical deformation information should be accounted for, while for the TRF long-term stability, the later should rely on core sites, whose motions could be accurately monitored.

The ITRF2000 orientation is defined by adding to the combination model a TRF minimum constraint equation (restricted to the orientation and its rate), allowing the alignment of ITRF2000 orientation to ITRF97 at epoch 1997.0 and its orientation time evolution to the geophysical model NNR-NUVEL-1A. This alignment is operated over 50 sites of high geodetic quality having the following properties: (1) continuously observed during at least 3 years; (2) located on rigid parts of tectonic plates and far away from deforming zones; (3) velocity formal error (as result of the ITRF2000 combination) less than 3 mm/y; and (4) velocity residuals less than 3 mm/y for at least 3 different solutions. The 50 sites used in the alignment are located on rigid parts of tectonic plates according to (Argus and Gordon, 1996).

In a recent GRL publication (Altamimi et al., 2003), it is demonstrated that the ITRF2000 alignment to NNR-NUVEL-1A model (satisfying the NNRC) is achieved at (or better than) the 1 mm/y level. This publication also presents comparative analysis between ITRF2000 and two other NNR models: the one published by Kreemer and Holt (2001) and APKIM2000.0 derived following procedure published in (Drewes, 1998). The agreement between these two models, ITRF2000 and NNR-NUVEL-1A, in terms of NNRC realization, range between 1–2.3 mm/y at the equator of the Earth surface.

<u>Recommandation 4 on TRF orientation</u>:
The WGID and ITRS Center are asked to set up criteria selection and to establish a list of TRF core sites. These sites should be of high geodetic quality so that they can be used in the definition of TRF datum orientation and its time evolution. They are also asked to adopt an optimal method to ensure the best accuracy and stability of the TRF NNRC realization. Some suggestions would be:

- Given the conventional nature of the orientation/rate definition, ITRF2000 could be adopted as a standard/conventional frame for TRF orientation rate definition.
- NNR-NUVEL-1A is being inadequate, another conventional NNR model could be adopted. More models need to be tested and evaluated.

4 Non-linear Site Motions

There are mainly two types of combinations for the TRF:

<u>Case A</u>:

An ITRF style of station positions (at a given epoch) and constant or linear velocities which correspond to the main focus of this paper. In this case, the combiner has no choice other than combining positions and velocities as they are submitted by the ACs. This means that if a particular modelling should be applied to stations having non-linear motions, this should be done at the AC's level and not at the combination level. For instance, modelling discontinuities of station positions (break-wise modelling) requires that all AC's (within each TC) need to adopt the same time breaks, and in a coordinated way between all the TCs for collocation sites.

<u>Case B</u>:

Time series combination of station positions. In this case, the combiner may have different choices in how the non-linear motions are handled, such as stochastic estimation of station positions.

The notion of "non-linear motion" to be retained here is that related to geophysical phenomena, e.g. Earthquakes. All other kinds of discontinuities in station positions originating from, e.g., equipment and processing changes should be addressed within each Technique Center.

Meanwhile in terms of TRF datum definition, considering the Case A approach, assuming linear TRF time evolution, it is recommended to investigate non-linear motions of TRF core sites.

Current status

Break-wise modelling is considered by some ACs (in particular within IVS and IGS) with no coordination between ACs or for time breaks consistency in the collocation sites.

Recommendation 5:
Technique Centers (IVS, ILRS, IGS, IDS) through their respective Analysis Centers, CRCs, ITRF CCs and other groups dealing with time series combination or research groups in geophysics are encouraged to investigate non-linear motions of space geodesy observing sites starting with TRF core sites. Sites with obvious non-linear motion should not be listed in the TRF core sites.

Recommendation 6:
Technique Centers (IVS, ILRS, IGS, IDS) are urged to ask their respective Analysis Centers to adopt a unique list of time breaks, as a consequence of geophysical phenomena. The ITRS Center and Technique Centers are also asked to ensure consistency of time breaks in the collocation sites.

5 Collocation Sites and Local Ties

Collocated geodetic sites are key element of combination research. Without collocations an inter-technique combined TRF would not exist. A global distribution of collocations is desired and the quality of local ties must be high.

Current status

The currently available local ties used in ITRF combinations were collected by the ITRS Center starting in the 1980's. They are from diverse sources and of various qualities, sometimes without variances. In ITRF2000, the local ties were used as observations, with proper variances, see (Altamimi et al., 2002) for more details.

The ITRF Report 4 on local ties (March 22, 2001) summarizes local tie problems in collocation sites as result from ITRF2000 Analysis:

- ITRF2000 contains 101 sites having 2 (72 sites), 3 (25 sites) or 4 (6 sites) collocated techniques.
- The number, distribution and quality of the ITRF2000 collocations were insufficient and old SLR-VLBI mobile collocations are now obsolete.
- 200 local tie vectors were included in the combination.
- 38 local tie vectors were missing, 25 of which are highly important.
- 20 vectors were declared as dubious: post fit residuals ≥1 cm.

Since the publication of ITRF2000, some progress has been made on the collocation site issue:

- A working group has been formed within IAG/CSTG to follow up local tie problems.
- Some local tie problems were identified, confirming ITRF2000 analysis, e.g. Fairbanks.
- A new survey of the entire Hartebeestoek 4-technique site is in preparation.
- New surveys of sites in Italy (Noto and Medicina) have been finished and a new survey for Matera is in preparation.

The situation of collocation sites of the currently active stations is now more dramatic, in particular for "time series combination approach", see the appended per pair-technique maps (based on the information currently available at the ITRS Center):

- SLR and VLBI observing stations are poorly distributed.
- VLBI 24-hour session observing networks are very sparse and not all connectable in terms of common stations. The consequence of this situation is that the number of VLBI collocations with other techniques is not always the same at weekly or monthly time interval.
- The current number of SLR-VLBI collocation sites does not exceed 6.
- Almost all active VLBI and SLR stations are collocated with GPS, but there are still 6 SLR sites not collocated with GPS.
- Only 8 VLBI-DORIS collocations exist and they are not well distributed.
- Only 7 SLR-DORIS collocations exist and they are not well distributed: 5 in the southern hemisphere and 2 in the northern hemisphere.
- There are 28 well distributed GPS-DORIS collocations.

The current available local ties are values at different (mostly unknown) epochs and they are thus considered as static, i.e. without time variation. For future improvement of the combination results, it is important to consider time variations of the local ties. This implies organizing repeated (yearly!) surveys in the collocation sites.

Recommendation 7:
In order to improve collocation sites distribution and observing networks:

- International effort is needed to improve VLBI-SLR collocations by installing new SLR systems (e.g. SLR2000) at all VLBI sites. These are very critical for the long term TRF scale maintenance.
- IVS is urged to schedule repeated Global-TRF observing sessions.
- IDS is asked to consider installing DORIS beacons at all SLR and VLBI sites, starting with sites collocated with GPS in order to augment the number/distribution of the 4-technique "primary" sites.

Recommendation 8:
The Working Group on Local Ties should be recognized by the IERS DB and integrated in the IERS structure. It should involve all the Technique Centers and representatives from potential agencies willing to contribute to this issue.

Recommendation 9:
The Working Group on Local Ties is asked to organize repeated local surveys in the collocation sites. Per-site local tie components (at the survey epoch) and their time variations should be provided in SINEX format with full variance-covariance matrix.

6 General remarks for future products/improvement

As soon as progress is made on the recommendations listed above, the IERS should think about future products, and the improvement and consistency between products. Concerning new products, we suggest the following:

- multi-technique time series solutions of "station positions + EOP", at weekly or monthly interval
- 3-years interval of multi-technique solutions of "station positions & velocities + EOP".

However, these suggested new products still need investigation and in particular the first one. While we can clearly define a frame for type-2 suggested product, similarly to ITRF-style, the problem of type-1 product is much more complicated on how to maintain exactly the SAME frame definition in time, in particular if we want (we should) assume a non-linear motion. One option for type-1 product is to select TRF core sites (to be used for the datum definition), for which we assume linear motions as suggested above. However, the other non-core stations having real non-linear motion may affect the time series combination. Moreover, while in case of IGS and IDS we "can" maintain the same number/distribution of core stations, it is not the case for SLR and worse in case of VLBI. And the problem becomes more complicated for IERS given the uneven distribution/quality of the collocation sites at each time interval. Consequently, type-1 product still need much work within each Technique Center (and of course IERS), from the theoretical/mathematical as well as the numerical/stability points of view.

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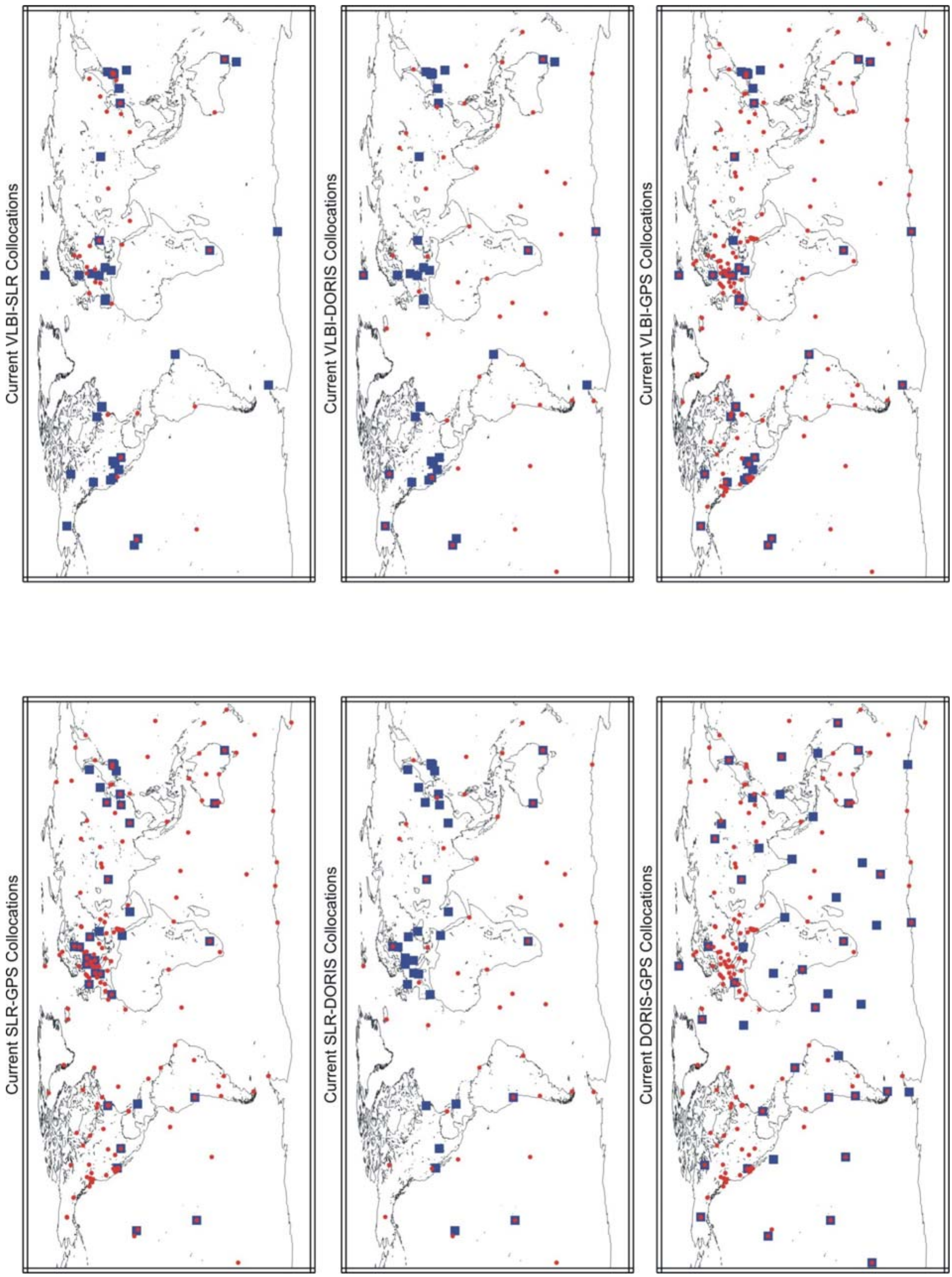

Fig. 1 Combination of co-location site for the geodetic space techniques.

ITRS Center Views on Combination Issues

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Abstract: This is a short memo presenting our views on the topic: "Introduction and motivation".

1 The ITRS Center mission and organization

The ITRS Center is a component of IERS. Its Mission is to produce ITRF products consistent with IERS standards, under the supervision of the IERS Analysis Coordinator.

The ITRS Center is presently supported by various groups for its work:

- the ITRF Combination Centers (IGN, DGFI, NRC)
- the Working Group on ITRF datum, presently chaired by Kristine Larson
- the CSTG WG on local ties, chaired by Jim Long

2 Combination issues

The general methodology applied up to now in the ITRS Center activities uses a combination of results provided by individual Analysis Centers (ACs). In the current situation, ACs process data from a single technique, in the frame of a Technique Center. In the future, we can consider multi-technique processings (some Combination Research Centers (CRCs) are already investigating this approach).

Three categories of models can be considered for these combinations:

- Position-velocity model
  - Current operational model in ITRS Center
  - See Altamimi et al., this volume, for details
- Extended model including additional parameters such as EOP, tropo factor,
  - Under investigation, ITRS Center has contributed in these researches (see Altamimi and Boucher, this volume)
  - See Ray and Zhu, this volume
- Time series model
  - Also under investigation (Pilot experiments)

3 Additional comments

- About stochastic model for combination

  Need to reflect various aspects:
  - Modelling errors in ACs
  - Measurements processed by several ACs
  - Constraints
  - Helmert scaling, correlation factors
  - Critical for time series approach

- About Multiplicity of ACs in one technique
  - Two step processing versus global combination
  - Needed for Quality check
  - Needed for Detection of modeling discrepancies
- Need of a strong cooperation in IERS and with Technique services (IGS, …)
  - To be solved by IAG? IGGOS?
  - Specific task of co-location (instrument setting, local surveys…)
- Need of reference documents for better combinations
  - We must increase the role of IERS Conventions
  - We need additional documents for each AC describing in detail its processing strategy

Remarks on Some Problems in the Combination of Station Coordinate and Velocity Solutions

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1 Introduction

The present realizations of the IERS Terrestrial Reference Frame (ITRF) are based on the combination of individual technique specific solutions for station coordinates and velocities provided by several analysis centers. There are some problems in the combination procedure which shall briefly be discussed in the following.

2 Datum characteristics of individual solutions

The individual solutions may be unconstrained, partly constrained, minimum constrained, loosely constrained, or over-constrained with respect to the realization of the datum parameters, i.e., the definition of the necessary 7 parameters in case of stationary three-dimensional coordinates (3 translations, 3 rotations, 1 scale) or 14 parameters for kinematic coordinates (the same for the velocities).

- If the solutions are unconstrained, then the normal equation matrix (N) has to be singular with a rank defect of 7 or 14, respectively.
- If they are partly constrained, then some of the datum parameters are introduced into the adjustment procedure, e.g., the scale by fixing the speed of light. The rank defect is then reduced by these given datum parameters (e.g., from 7 to 6).
- If they are minimum constrained only a maximum of 7 or 14 datum parameters may be introduced into the processing (e.g., fixed).
- If they are loosely constrained, then the solution (adjustment) of coordinates (and velocities, respectively) must result in very large r.m.s. errors.
- If they are over-constrained, then they may deform the total network by contradictions or tensions in the constraints, and it will be very difficult (or impossible) to combine them with other solutions.

The problem in these classifications is that the constraints are often not clear.

- Solutions may be directly constrained by fixing a number of parameters (e.g., station coordinates or velocities). This will normally be known to the provider of the solution.
- They may also implicitly be constrained without the perception of the provider. This may happen by the applied models in the processing, e.g., by the used gravity field that fixes the origin of the coordinates by means of the lower harmonic coefficients (C_{10}, C_{11}, S_{11}).
- There are also hidden constraints by the uncontrolled introduction of conditions, e.g., by fixing velocities to zero in case of short time observations or to a certain model, e.g., NNR NUVEL-1A, or even by setting velocities identical for different stations.

A conclusion of these statements is, that individual solutions may **only** be combined by 7 (or 14) parameter similarity (Helmert) transformation, if they are **not** deformed by introducing any constraints. If some constraints are introduced, the transformation has to be reduced to the remaining free parameters. If more than 7 (or 14) constraints are introduced, the solution cannot be used at all. The proof of such constraints can preferably be done by analyzing the **normal equations** (N) of the individual solutions.

3 Combination of individual solutions

The individual solutions of the same or different techniques may be combined on the level of observation equations, normal equations or solutions. The most appropriate approach is the combination of observation equations. This requires, however, sophisticated software packages and does not allow the distributed processing as it is done by the services.

The combination of normal equations is equivalent to the observation equation approach if all the used models and required parameters are identically introduced. Even parameters not estimable from individual techniques (e.g., geocentre variations from VLBI) may be included.

The combination of solutions with their variance-covariance matrix does not allow the analysis of constraints or the inclusion of additional parameters (e.g., atmospheric delay).

When combining individual technique specific solutions or normal equations one has to consider that the standards, models, or solved parameters may **not** be identical (e.g., time scale TDT or TCG, gravity field model, identical site velocities) or not consistent. Several services are performing benchmark projects for comparing different software of the Analysis Centers for this purpose.

3.1 Intra-technique combination (solutions using technique specific data)

Individual solutions of one technique are **not** independent of each other because

- they all use the identical observation data,
- some combined solutions include already other individual solutions (e.g., IGS solutions),
- regional solutions include parts of the global solutions.

The consequence is that the weighting (estimation of variance-covariance components) of individual solutions is problematic. If various solutions of the same technique are combined with other techniques' solutions they may not be introduced as independent. A conclusion is that the IERS technique centers should provide a unique combined solution for the ITRF.

3.2 Inter-technique combination (different techniques' solutions)

In the combination of solutions of different techniques co-location sites and the eccentricities (local ties) play the most important role. Are they sufficiently well determined to introduce them as a constraint?

Some estimated parameters of the different solutions should or have to be identical, e.g., the atmospheric parameters. Were identical models and standards used? Other parameters are supposed to be identical but they aren't, e.g., station velocities at co-location sites are not necessarily identical.

The weighting of individual solutions has to be done by a sophisticated a posteriori variance-covariance estimation including all the correlations between them. Individual solutions of the same technique are highly correlated. Identical observations may only enter once into the adjustment.

The conclusion of these statements is that inter-technique combination should be based on the unique solutions provided by the Technique Centers (Services) instead of individual solutions.

4 Estimated parameters in the combined solution

Identical effects in different observation techniques must be modeled or estimated by identical parameters (e.g., atmospheric refraction, atmospheric/oceanic loading, ...). The variation (time dependency) of parameters has to be analyzed (e.g., is the variation of coordinates linear, i.e., are there constant velocities?) The identity of parameters has to be proven, e.g., in case of identical site velocities the local ties have to be time independent. Repeated surveys are necessary to prove that, or local ties may be adjusted in the combination procedure.

The consistency of parameters of different reference systems has to be guaranteed, e.g., between the ICRF, EOP and ITRF. This leads to the requirement of a common adjustment of all components of the reference frames.

5 Effects of the ITRF network design on combination results

The network design may affect the results of the ITRF combination. Deformations or tensions may be caused by using

- too old observations in abandoned stations (e.g., mobile SLR and VLBI stations of the 80’s).
- too young stations (e.g., newly installed stations with observations less than one year).
- too bad observations (e.g., observations with inaccurate instruments).

The quality and reliability of stations and observations is more important than the quantity. One should do a combination in hierarchic levels (e.g., reliable global network and densification by additional stations). Co-location conditions (identical parameters) should only be introduced for parallel (simultaneous) observations.

6 Recommendations

As a conclusion of the above discussion we give the following main recommendations:

- Techniques’ combined solutions should be provided by the Technique Centers as unconstrained normal equations. The ITRF combination should be based on these normal equations.
- Parameters common to different techniques (affecting the observations, e.g., atmosphere **or** affecting the reference frame, e.g., EOPs) must be included in the normal equations.
- The combined station coordinates and velocities network should include only reliable sites and observations (emphasis to be given to quality rather than to quantity).

TRF Combination at NRCan: Status Report

Remi Ferland

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This is a contribution to the International Terrestrial Reference Frame (ITRF) activities by NRCan as an ITRS Combination Center for the International Earth Rotation Service (IERS). The current objective is to develop and apply the capability to combine solutions containing station coordinates and velocity determined with the DORIS, GPS, SLR and VLBI techniques, available using the Software INdependent EXchange (SINEX) format. Two other centers are currently involved in similar activities (IGS & DGFI) with the objective being to have redundancy in the TRF solution. Since the late 1980's IGN has been the sole responsible for determining the ITRF realizations. The recent work at NRCan related to the ITRF combination activities was almost exclusively dedicated to the combination/analysis software upgrades and data analysis. In principle all the contributing solutions are combined simultaneously to generate the final solution. At NRCan, the data combination is currently done using a two-step procedure. In the first step, the solutions within each technique (intra-technique) are combined separately. In the second step, all the intra-technique solutions obtained in the first step are combined to generate the final solution. This approach has been chosen because it is less demanding on the available resources. With the two-step approach, it is also easier to detect and isolate some problems. This approach introduces some approximations. As is most often the case in this type of analysis, iterations are required.

In the intra-technique combination, the following activities are performed: 1) standardize the solutions to a consistent "flavor" of SINEX; 2) remove constraints & rescale covariance; 3) Remove outliers (previous iteration); 4) align all solutions to a reference using 14 or less transformation parameters as appropriate; 5) combine; 6) analyze results. Techniques with only one solution available (e.g.: LLR) can obviously bypass this step. For techniques with only 2 solutions, the isolation of outliers is problematic. At this time, the problematic stations are noted and rejected from both solutions. For a few solutions, the removal of the constraints caused a significant degradation of the relative station coordinates/velocities. Several attempts were made to keep all the techniques solutions, but to avoid unduly slowing down the process at this time; some solutions have been excluded from the analysis. There may be some numerical problems/inconsistencies in the apriori/estimated matrices of those solutions and further investigation is required. Some intra-technique combinations are almost ready, e.g.: 3D-RMS of the position residuals is about 6 mm for the GPS combination.

During the second step, combinations were also made with the results from the first step and the local ties. At this time, only the stations that have ties are included in the combination. The other stations will be added subsequently in an extended adjustment or by using back substitution. The ties at each site are allowed to translate (TX, TY, TZ) in the adjustment. The combined solution currently includes the DORIS, GPS, SLR and VLBI. The 3-D RMS of the residuals varies from 8 mm to 29 mm in position, and from 2 to 9 mm/y in velocity. The origin (SLR), scale and rate (VLBI & SLR), orientation and rates (ITRF97 & NNR) will also need further attention as the adjustment progresses. Table 1 summarizes the 3-D RMS statistics for each technique after the latest intra-/inter-technique combinations. In the intra-technique columns, the RMS residuals are between each relevant solution and the combined intra-technique solution. Similarly, the inter-techniques RMS are between the technique combination and the inter-technique combination. Positions RMS are determined from the position residuals at the minimal position variance. In the table, the GPS-D technique refers to the GPS densification solutions. Since in this case, there is little or often no overlap between the solutions, they were compared to the IGS combined solutions to extract meaningful statistics; those solutions haven't yet been included in the inter-technique combination. There were also two (GRIM5, CSR) multi-techniques solutions. Those haven't been included yet.

Table 1 3-D RMS position and velocity statistics for the intra-technique and inter-technique combinations

	Intra-technique		**Inter-technique**	
Techniques	**Position 3-D RMS (mm)**	**Velocity 3-D RMS (mm/y)**	**Position 3-D RMS (mm)**	**Velocity 3-D RMS (mm/y)**
DORIS	35	11	33	10
GPS-D	8	6	–	–
GPS	13	6	4	2
Multi	–	–	–	–
SLR	26	10	24	5
VLBI	16	2	6	3

A few more iterations of the combination process are needed to produce the final solution. Analyses of the quality of the determination of the origin and scale consistency also need to be done. Comparisons with the official ITRF 2000 will also be performed.

Celestial Reference Frame Issues

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1 IERS responsibilities with respect to the ICRF

According to the recommendations of the IAU (International Astronomical Union) the IERS has the responsibility of monitoring the ICRS (International Celestial Reference System), and maintaining its current realization, the ICRF (International Celestial Reference Frame). These activities are run jointly by :

- the ICRS Center of the IERS
- the IVS (International VLBI Service for Geodesy and Astrometry)
- the IAU Working Group on the International Celestial Reference System

1.1 Maintenance of the ICRF (IVS / ICRS Center)

- Since January 1, 1988 the Celestial Reference Frame recommended by the IAU is based on a set of extragalactic directions, replacing the FK5 (Fifth Fundamental Catalogue). While the FK5 gave coordinates of galactic objects (stars) in a reference system based primarily on the dynamics of the solar system (the so-called equator and equinox of J2000.0), the definition of the ICRS is based on a kinematical concept, according to which the axes of the system remain fixed with respect to the most distant matter of the universe.
- According to the rules adopted in the 1991 IAU Recommendations, the fundamental directions of the celestial reference system will remain fixed in space, as long as the directions of the distant sources can be globally considered as fixed directions. The adopted positions of the defining sources may be re-estimated when improved information is available, but the direction of the coordinate axes will be maintained by implementing the statistical condition that the new coordinates of selected sources show no global rotation with respect to the old set (no-rotation condition). It is also foreseen that some sources may be deleted or new ones could be added in the future. This is the purpose of the maintenance of the ICRF.
- The initial ICRF realization consisted of equatorial coordinates of 608 extragalactic radio sources derived from about 1.6 million observations accumulated by a worldwide network over 1979–1995. It was derived by a sub-group of the WGRF that agreed on an optimal data analysis strategy (Ma et al., 1998, AJ 116, 516). It included three categories of objects, with
  - the most compact and best observed 212 defining sources, with a median uncertainty of 0.4 mas on individual positions,
  - compact sources (294) whose positions were likely to be improved when more observations would be accumulated in the future, and
  - sources less appropriate for astrometric purposes (102), but which were provided for possible ties of reference frames at other wavelengths or for other objectives.

The ICRF was obtained by a global single analysis of all VLBI observations available at the time of computation. The source selection and analysis strategies applied were discussed by the team of co-authors of the ICRF.

- In the following are the rejection criteria which were adopted for the selection of extragalactic sources for the ICRF:
  - Arclength formal error > 1 mas
  - < 20 observations
  - < 2-year span of data
  - 3 σ or > 0.5 mas discrepancy between catalogues
  - Excessive structure
  - Large, significant "apparent motions"
  - Arc source, i.e., position adjusted for each session.
- Several sources have been rejected since 1998.

1.2 ICRF-Ext.1 (1999): results of a 5 years maintenance (1994–1999)

The ICRF-Ext.1 was constructed on the basis of five years of additional observational data spanning December 1994 through April 1999 (600 000 observations, 461 sessions). The list and coordinates of the defining sources were not changed (although it was found that some of them showed discrepant positions). The coordinates of the candidates and other sources were refined. 59 new sources were added to the frame, bringing the total number to 677. In addition to the consideration of new observations, some improvements were brought in the analysis models, including :

- Tropospheric mapping function
- Troposphere linear interval
- Subdiurnal EOP
- Fixed station axis offsets
- Added noise for each session

1.3 Comparisons of catalogues via ICRF

The relative orientations between individual celestial reference frames established by individual teams (BKGI, GSFC, IAA, SHA), and the ICRF are regularly determined through the rotation angles which transform coordinates from the individual VLBI frames to ICRF. They are calculated on the basis of the defining sources only.

- Rotations : three rotation angles around each of the rectangular axes of the ICRF are estimated. They are typically of the order of a few μas or a few tens of μas.
- Slopes and bias: slopes defined in function of the right ascension and the declination, biases in function of the declination are estimated for checking purposes. They are usually statistically insignificant.

1.4 Link with the dynamical frame (LLR)

- Aim: position of the inertial dynamical ecliptic at a given epoch (J2000.0)
- This link requires the combination of various components
  - Moon's libration ephemerides (Celestial Mechanics)
  - Moon's orbital ephemerides (Celestial Mechanics)
  - Earth's nutation (VLBI)
  - ITRF (VLBI, GPS, SLR, DORIS)
  - Selenocentric coordinates of lunar stations.

1.5 Check of the celestial pole offsets (VLBI)

- **Combination** of VLBI data with precession-nutation theory (IERS1996, MHB2000)
- Aim: periodical check (Annual Report) of the offset between the mean pole at J2000.0 and the ICRS pole.

- Involves
  - An up-to-date theory of the precession-nutation of the Earth (MHB 2000 replacing IERS, 1996)
  - VLBI time series of the celestial pole offsets dψ, dε.
- Results :
  - Sensitivity to the nutation model used (1–2 mas difference between the estimations of the pole offsets in dψ, and dε, when using one or the other theory above.
  - Sensitivity to the catalogue used, IERS-Ext.1 or individual solutions (BKGI, GSFC, IAA, SHA etc…)

1.6 Link to Hipparcos and other frames

This link is maintained through programs of densification at optical wavelengths (UCAC project of the USNO, Carlsberg Meridian Circle Program etc…). 2MASS (2 Micron All Sky Survey) recent release is available in order to make the link with Hipparcos Catalogue.

2 Present status in the field

2.1 ICRF catalogue

- Condition of no rotation of the ICRF well verified
- Confirmation of possible improvements by taking into account the stability of source coordinates

2.2 Links

- Densification programs very active (2MASS, UCAC etc…)

3 Problems and deficiencies encountered

3.1 Rationale for a revised ICRF

- In 2002 over 3.2 millions observations of over 700 sources are available. This is twice the number of observations used for the initial ICRF. It was shown (Gontier et al., 2001, A&A 375, 661) that, as results of the steady improvement of the observing conditions by the world astro-geodetic VLBI network, the radio source coordinates become much more stable and reliable towards the end of the 1980s. The 15 years of observations used for the initial ICRF can therefore be expected to be of much lower value than those accumulated during the most recent 12–15 years.
- The influence of time stability of the radio-source directions on nutation determinations was investigated in parallel to the study of atmospheric perturbations to the astronomically driven precession and nutations (Dehant et al., 2003, JGR 108, B5). The effect was found to become negligible at the seasonal and free nutation periods after 1990. For the precession correction and the obliquity rate, the 9.3 year nutations and the 18.6 year nutations, the effect reaches 10–30 microarcseconds, a level that is not negligible when compared to the observed discrepancies between VLBI results and the IAU2000 precession-nutation model, that may reach nearly 100 microarcseconds. This result shows that the role of the celestial reference frame stability is worth analysing in a rigorous way if further progress is sought in the measurement of the Earth's precession and nutation.
- Another study presented at the 2002 IERS Analysis Workshop and later published (Feissel-Vernier, 2003, AA 403, 105) concludes that a selection process based on the time stability of directions of individual radio-sources strengthens the no-net rotation, condition and improves the internal consistency of the frame.

3.2 Other points:

- The VLBA Calibrator Survey (VCS1) added ~1200 new sources to the astrometric catalogue north of –30 deg, but the observing schedule was unlike the usual astrometric/geodetic mode. (Beaseley et al., 2002, ApJ Sup 141, 13)
- Requirement for a clear explanation of the rotations between individual celestial catalogues, and of their discrepancies concerning the coordinates of the extragalactic sources, in order to optimise in the future the extension of the ICRF.
- Proposition to make a combined catalogue in parallel to the ICRF or possibly replacing it in the future. This proposition might be discussed.
- Although the true pole of any observed date is now measured with a precision better than 0.1 mas, the celestial pole offset (direction of the mean pole at J2000.0 in the ICRS) is highly dependent on the observational data and of the precession-nutation model used. Its determination could be ameliorated by a specific weighting of the estimations.
- Proper motions of quasars (or motion of their photocenter) are supposed to be null or negligible (one of the postulates in the construction of the ICRF). Simulations based on relativistic formulas show how tangential displacement can be enhanced in the case of high-speed velocities.

3.3 Possible discussions

- New discussion of the parameter selection and modelling in the analysis
- Selection of the observation span and of the sources to be considered for applying the no-net rotation condition to the initial ICRF
- Considering the global character of the CRF-EOP-TRF products
- Method of computation, e.g. unique global analysis vs comparison/combination of several global analyses
- Reassessment of the tie of celestial frames available in the optical wavelength (Hipparcos etc…)

4 Goal and future steps for improvement

- The IVS is designing the future CRF observing program to improve the astrometric data set, particularly by increasing astrometric observations in the southern hemisphere and by targeting sources to fill gaps and to provide more information about the prospective defining sources. In addition observations using the VLBA have begun to create a frame at higher frequencies.
- An **overwhelming change** in the definition of the ICRF is expected with the future Space missions; a new ICRF defined optically may be constructed in the future on the basis of very promising results through space observations programs:
  - FAME (Full-sky Astrometric Mapping Explorer), but NASA has withdrawn funding
  - SIM (Space Interferometry Mission), finishing Phase A
  - GAIA, confirmed and scheduled for not later than 2012
- Concepts for the future ICRF
  - **problem of the continuity**: will all the quasars included in the present ICRF be observed by the future astrometric space missions?
  - will the « ICRF of the future » be a dual catalogue (cross-identifications radio-optical) or a pure optical one?

5 Schedule of the next steps and concrete recommendations

- **Experimentation** of a combined catalogue to be compared with the ICRF (as BKGI)
- **Construction of a « rigorous combination »**
  - simultaneous adjustment of the ITRF, the EOPs, and the ICRF, producing a fully consistent set of ITRF site coordinates and velocities, EOP series, and ICRF coordinates.
- **Preparation** of the future space missions

General Combination of EOP Series

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Summary: The objective of the session was twofold: first to present the impacts of the IAU Resolutions on IERS products, and in particular those concerning the Earth Orientation Parameters (EOP); and secondly to review the variety of current methods used for combining Earth Orientation Parameters time series (Polar motion, Universal Time, and precession-nutation).

The impact of IAU 2000 Resolutions on all IERS Products was thoroughly discussed at the previous IERS Workshop (Paris, April 2002). The problem has been addressed from many points of view, and described in detail in the presented papers contained in the Proceedings of the Workshop (Capitaine et al. 2002). Future products of the IERS will be affected by the changes that have been adopted by the IERS Directing Board at its 35th Meeting that immediately followed the Workshop; the description of all these changes is covered by Position paper by Rothacher (2002). This topic is transferred to another chapter of the present publication.

1 Background

Until 1972, astrometry based on a network of optical instruments was the only technique able to monitor the Earth Orientation (polar motion coordinates, Universal Time UT1, and nutation). Since, various techniques have shown their capability to give all or a part of these parameters: Doppler observations of navigation satellites, laser ranging to the Moon and to dedicated artificial satellites, Very Large Baseline Interferometry (VLBI) and more recently GPS and DORIS. Other techniques, like inertial one (optical and cold atoms gyroscopes) might give contributions in the future. The life time of observational techniques is limited (technology evolution, agencies funding priority, etc…). It is fundamental that new techniques be introduced to replace those that are disappearing. At least 3 independent techniques are necessary for complementarities (none of the techniques being able to derive all EOP) and redundancy aspects linked in particular to systematic errors determination. The Earth's orientation needs to be monitored over the long-term for reference frames metrology. Whereas, space geodesy for geophysical researches and operational requirements (e.g. Space probes orbits, GPS orbits and reference frames monitoring) require higher sample rates. This is for EOP predictions as well as solutions.

The different Earth Orientation Parameters (EOP) series currently derived from the individual techniques are inhomogeneous in their temporal length, quality, and temporal resolution. This fact supports the concept of long-term equally spaced combined solutions benefiting from the individual contributions at the various time scales. In the process of EOP time series combination, various points should be considered. A non-exhaustive list of these points would include: individual time series characteristics (temporal resolution, internal precision, internal stability at various time scales as well as the corrections for bias, rate, and seasonal variability); statistical analysis (proper scaling of individual series, weighting, smoothing, and interpolation); comparisons; and checks of the final combined solution: with respect to individuals series and between combined series derived by independent centres.

2 What does "combinations" mean?

The word "combinations" can have different meanings:

- Intra-technique combinations refers to the production of a single time series using results from different analysis centres of a same technique, like GPS, made available at identical dates. We are faced with a weighted averaging. The critical points are the real error estimation of data, stability, and systematic error evaluation.
- Multi-technique combination refers to the production of a single time series using various time resolutions, various internal precision, systematic errors / deviations, weighting, interpolation, smoothing as well as the use of different procedures to produce the combination.
- "Rigorous" Global Combinations at different levels refers to the examination of observations processing, covariance matrices analysis, or simultaneous combination of terrestrial frame and EOP.

In the present session we will restrict to the 2 first items. "Rigorous" combinations will be discussed in another session.

Characteristics of ideal combined EOP solutions

An ideal combined EOP solution should have the following characteristics: be continuous, given at equidistant intervals without any gap, homogeneous, stable at the various time scales (reference system maintenance) with negligible systematic errors. It can be slightly smoothed to remove the high-frequency noise and able to handle the introduction of new series while maintaining the stability of the system.

Statistical analysis

In the process of combination, different critical steps should be considered. Formal errors are an internal value derived by each analysis centre. These errors may not be realistic and should be rescaled by an external procedure. This leads to a value used for weighting the various series in the course of combinations. The different approaches are used for interpolation and smoothing. These approaches include: Vondrak algorithm, Fourier, and spline. An alternative method uses a Kalman filter to produce a single time series. The Kalman filter approach requires accurate modelling of the errors for each of the techniques used in the combination.

Current characteristics of EOP estimates, precision, accuracy

Precision gives an estimation of the agreement of various individual solutions with respect to combined solutions (Earth Orientation Center, Rapid Service/Prediction Center, and JPL). This agreement is 50–100 μas for Polar motion, 4–10 μs for Universal Time, and 200 μas for nutation offsets. Accuracy reflects the real uncertainties of a solution taking into account the inconsistency and systematic errors of the EOP system with respect to the terrestrial and celestial frames. These inconsistencies and systematic errors are more critical than precision. It appears that so far the accuracy level is above the precision, for Polar motion (150–200 μas), Universal Time (15–20 μs), and nutation offsets (200 μas).

Check and comparisons of the EOP combined solutions

Different approaches are used for assessing the quality of the EOP combined solutions: its internal consistency, their differences with individual solutions, differences between series derived by the same centre using different routines, and differences between independent solutions (Earth Orientation Center, NEOS, and JPL).

The different current methodologies for EOP combinations

We present thereafter the procedure approaches of the current groups which are currently deriving combined temporal series of earth orientation parameters, i.e. the Earth Orientation Center at Paris Observatory, France; the Rapid Service/Prediction Center at USNO, Washington, USA; JPL, Pasadena, USA; and Astronomical Institute, Prague, Czech Republic.

Improvements and prospects

The increasing precision reached by the various techniques in the determination of EOPs allows better combination series. Improvements have been currently developed in different statistical processed involved: weighting, interpolation, smoothing, and outliers detection. New approaches for instance based on combined smoothing (Vondrak) or non-linear algorithms are under investigation. Other products of interest are or will be also introduced, i.e. se of GPS LOD for near-real time UT1 extrapolation, AAM estimates for near-real time UT estimation, pole rates for interpolation, and GPS nutation rates for densification. In order to better assess the systematic corrections, pre-intra-technique combination solutions are computed. New predictions algorithms based on non-linear processes (chaotic, SSA, neuronal network) are under investigation. Deriving more consistent and accurate products is a permanent challenge in the EOPs monitoring. This can be done by consistency studies of the EOP system with respect to both terrestrial and celestial frames, or using the rigorous approach based on a simultaneous determination of EOPs and the terrestrial frame.

3 The various EOP combinations currently performed

3.1 Combination of EOP series at the IERS Earth Orientation Center

General presentation of the IERS Earth Orientation Parameters (EOP), operational activities and yearly analyses are presented in the web site <[1]>. Determination of EOP is in the form of combined solutions derived from the individual series. Various solutions are computed: long-term solution (IERS C01), normal values at five- and one-day intervals (IERS C02 and C03) and the operational smoothed solutions at one-day intervals in Bulletin B published with a delay of thirty days between the date of publication and the last date of the standard solution. Bulletin B is updated in the IERS C04 computed twice weekly.

The Earth Orientation Center is collecting on two modes operationally and yearly for long-term analyses, EOP time series derived by analysis centers of the various techniques (VLBI, SLR, GPS, DORIS).

We present the state of the art and future prospects concerning the multi-technique EOP combined solution made at IERS Earth Orientation Center.

Procedure for IERS C04 computation

The first step in the general procedure for deriving the IERS multi-technique combined solution is the evaluation for each solution of the correction of systematic errors, bias and drift in order to translate it into the IERS system. The formal uncertainties estimated by the analysis centers being an internal consistency value, an external calibration has usually to be made in order to reflect the real uncertainty of the estimates. This is done using the Allan variance analysis (Gray and Allan, 1974; Gambis, 2000) of the differences between series without any reference to a combined series. When three or more series of similar quality and time resolution can be differenced, the pair vari-

[1] http://hpiers.obspm.fr/eop-pc

ance of the noise of each series can be evaluated, provided that their errors are assumed to be statistically independent. The pair variance thus obtained is used as an estimate of the uncertainty of a single determination in a given series; its ratio with the rms formal uncertainty over the same period provides a scaling factor, on which the weighting of the combined individual results is based. In order to work on small quantities, a reference series is used. Currently the reference is the C04 slightly smoothed. This reference is interpolated for the dates of the individual series using for instance Lagrange's polynomials and then removed from these individual series. Since the reference is in fact added back at the end of the combination process, its choice is arbitrary and does not pollute the final solution. After a chronological merging of the data, all data within an predefined interval are averaged, this interval is [-0.5d, 0.5d]. The series is slightly smoothed (the frequency cutoff is about 2 days). This smoothing allows the elimination of erroneous data using the 2.57 sigma criteria. This series is added back to the reference in order to give the final combined solution. For universal time, zonal tides with periods smaller than 35 days are previously removed. For nutation, terms between 3 and 20 days (MHB 2000) are in a first step removed.

Regular improvements were implemented in the combination procedures or for predictions, for example:

- Use of Atmospheric Angular Momentum for UT1 short-term predictions (Gambis, 1988),
- Intra-technique pre-combined solutions for a better estimation of systematic errors,
- Use of GPS LOD estimates for near-real time UT1 determination (the improvement of the solution is a factor 8 for 1 week and respectively 16 and 24 for 2 and 3 weeks compared to usual predictions based on VLBI data) (Gambis, 1998), and
- Use of Ultra rapid EOPs for real-time estimations.

New developments under investigation include:

- Use of pole rates for the interpolation of GPS series,
- Method of combined smoothing (Vondrák & Gambis, 2000; Vondrák & Čepek, 2000), and
- Analysis of high-frequency EOP variations.

Predictions

Different approaches are used for prediction of the Earth rotation parameters.

Polar Motion:
The formalism uses at first a floating period fit (Bevington, 1969) for both the Chandler and annual components estimation over a past time interval of several years. An autoregressive filter is then applied on the short-term residuals series and used for the prediction. For the nutation offsets $d\psi$ and $d\varepsilon$, the predictions are based on an empirical model (Conventions 1996).

Universal Time:
The present formalism used is based on the assumption that the long-term fluctuations (annual and semi-annual) of the preceding year are valid over the next few months. For the prediction, of short-term variations, an autoregressive process is used. New procedures for this prediction that are linked to Singular Spectrum Analysis (SSA) (Bougeard et al., 2002) and neuronal networks are under investigation.

Long-term series: C 01 (1846–2002)

EOP(IERS) C 01 is a series of the Earth Orientation Parameters given at 0.1 year interval from 1846 to 1889 (polar motion only) and 0.05 year interval from 1890 until now (polar motion, celestial pole offsets; UT1–UTC since 1962). For many decades, the observations were made using mostly visual and photographic zenith telescopes. Since the advent of the space era in the 1960's, new geodetic techniques were used for geodynamics. Now, the global observing activity involves Very Long Baseline Radio Interferometry (VLBI), Lunar (LLR) and Satellite Laser Ranging (SLR), Global Positioning System (GPS), and more recently DORIS.

The C 01 series was recomputed in the course of 2001 to take into account, from 1900 to 1961, the series recomputed by J. Vondrak (1995) is based on the processing of optical data using Hipparcos catalogue as the celestial frame. The C01 series is a composite series based on the following solutions:

1846–1899: Fedorov et al. (1972) polar motion solution derived from three series of absolute declination programs (Pulkovo, Greenwich, Washington).

1900–1961: Vondrak et al. (1995) solution derived from optical astrometry analyses based on the Hipparcos reference frame The series gives polar motion, celestial pole offsets and Universal Time (since 1956).

1962–2001: BIH and IERS solutions (BIH and IERS annual reports).

Normal point solution: C 02 (1962–2002), C 03 (1993–2001)

Other series, based on normal points solutions given at various time intervals, are also proposed to users, i.e. C 02 (5-day intervals, polar motion, UT1–UTC, $d\psi$, $d\varepsilon$), C 03 (one-day intervals, polar motion, UT1–UTC) (Gambis, 1996; Eisop and Gambis, 1997). These series use the full correlation matrix when available. The initial processes of weighting using Allan's variance and systematic errors to refer to the IERS systems are similar to C04. In this solution the data are transported to the central date of an interval of 5 or 1 day (respectively for C02 and C03). The projection is made according to the reference (i.e. C04). A linear equation system is solved using a least-square process. Alternative methods based on robust estimators like M-Huber can be used. These estimators are a generalization of both the L1 and L2 class. They have been implemented in our analyses and are now currently used (Bougeard et al., 2000; Gambis et al., 2002). A better detection of outliers is gained.

Consistency of IERS EOP series with ITRF and ICRF

Individual EOP series determined from the analyses of the various techniques present mutually systematic errors, generally limited to biases and drifts which can be attributed to the adoption of different references frames CRF and TRF. Consequently, the determination and the maintenance of a reference EOP solution is essential. Monitoring of the consistency is currently performed at the Earth Orientation Center in the IERS Annual Reports since 1991. The mean consistency is regularly improving for the different techniques. So far the mean estimated values are about 0.1 mas for polar motion and 20 microseconds for UT1 (IERS Annual Reports). There are different approaches to estimate the consistency of the IERS EOP system with respect to both terrestrial and celestial reference frames (Bizouard et al., 2002, Gambis et al., 2002). The topic of consistency monitoring is more directly concerned in session 4.

3.2 Combination of EOP series at the Rapid Service / Prediction Center at USNO

IERS Rapid Service Techniques

The algorithm used by the IERS Rapid Service / Prediction Center for the determination of the quick-look Earth orientation parameters is based on a weighted cubic spline with adjustable smoothing fit to contributed observational data (McCarthy & Luzum, 1991a). Contributed data are corrected for possible systematic differences. Biases and rates are determined with respect to the C04 system of the IERS Earth Orientation Center (EOC). Statistical weighting used in the spline is proportional to the inverse square of the estimated accuracy of the individual techniques. Minimal smoothing is applied, consistent with the estimated accuracy of the observational data. Weights in the algorithm may be either an a priori values estimated by the standard deviation of the residual of the techniques or based on the internal precision reported by contributors.

Operationally, the weighted spline uses as input the epoch of observation, the observed value, and the weight of each individual data point. The software computes the spline coefficients for every data point which are then used to interpolate the Earth orientation time series so that x, y, UT1–UTC, $d\psi$, and $d\varepsilon$ values are computed at the epoch of zero hours UTC for each day. The only data points that are excluded from this process are points whose errors, as reported by the contributors, are greater than three times their average reported precision or those points that have a residual that is more than four times the associated a priori error estimate. Since all of the observations are reported with the effects of sub-daily variations removed, no processing is done to account for these effects (see IERS Gazette No. 13, 30 January 1997).

The daily values errors listed in Bulletin A are derived from the quality of the spline fit in the neighborhood of the day in question. Comparisons of the accuracies of three different Rapid Service / Prediction Center products compared to the C04 series maintained by the IERS EOC at the Paris Observatory show mean differences of less than 0.07 mas for polar motion and less than 0.005 ms for UT1–UTC. The standard deviations of these differences were less than or equal to 0.017 mas and less than 0.080 ms for polar motion and UT1–UTC, respectively. The agreement between the weekly Bulletin A Rapid solution and the Bulletin Daily solution with the IERS EOC solutions are quite good.

USNO's Prediction Techniques

Polar motion predictions are based on the extrapolation of an annual and semiannual ellipse and a Chandler circle fit to the previous 400 days of observed values of x and y (McCarthy and Luzum, 1991b). The differences between the last observed pole position and rate and those of the curve are computed. These differences are then used to adjust the extrapolated curve by an amount that decreases with the length of the forecast. In February 1998, the near-term polar motion predictions (less than about 30 days) were improved significantly by modifying the transition process from the last observed polar motion result to the long-term predictions. Continuity in the first derivatives was enforced placing great weight on the observed polar motion rate reported by the IGS in their Rapid series. The improvement was most pronounced for the shortest prediction intervals. The procedure for UT1–UTC involves a simple technique of differencing (McCarthy and Luzum, 1991b).

The very near-term UT1–UTC prediction is strongly influenced by the observed daily Universal Time estimates derived at USNO from the motions of the GPS orbit planes reported by the IGS Rapid service. The IGS estimates for LOD are combined with the GPS-based UT estimates to constrain the UT1 rate of change for the most recent observational day. For the 5 days after the latest observed day, AAM-based predictions of LOD excitation are combined smoothly with the longer-term UT1 predictions described above.

Errors of the estimates are derived from analyses of the past differences between observations and the published predictions. Formulas published in Bulletin A to extend the tabular data. The prediction of dψ and dε is based on the KSV_1996_3 model (McCarthy, 1996). Recent prediction performance in UT1–UTC has been improved by 42% at 10 days into the future by the addition of a UT1-like data product derived from NCEP AAM (UTAAM) to the combination and prediction routine (Johnson et al., 2002). This estimate of improvement was determined by examining one year of daily solutions that used UTAAM in the combination and prediction solutions.

Rapid Service Research and Improvements

The Center is continuously evaluating its products and researching possible improvements. The Center is currently working on meeting the resolutions passed at the 24th General Assembly of the International Astronomical Union recommend the implementation of a number of new procedures concerning the transformation between the celestial and terrestrial reference systems. Information regarding these changes is available in Chapter 5 of the IERS Conventions 2000. The Center is also working to include VLBI data from USNO and the IVS combination series. These modifications and additions to the Rapid service and prediction products should be completed by January 1, 2003. The Center is also working on an improvement to the bias and rate estimation techniques by April of 2003.

Current research efforts are focused in a few areas. These include: improving the UT1-like data products estimated from GPS and AAM, the usefulness of other global geophysical fluid models, improved error estimates, and the automation of more Bulletin processes.

Availability of Rapid Service

The data described above are available from the Center in a number of forms. You may request a weekly machine-readable version of the IERS Bulletin A containing the current ninety days worth of predictions via electronic mail form at <[1]> or <[2]>. Internet users can also direct an anonymous FTP to <[3]> and change to the ser7 directory where they can access the IERS Bulletin A or more complete databases. World Wide Web access is available at <[2]>.

3.3 Combination of EOP series at the JPL (CRC)

In support of tracking and navigation of interplanetary spacecraft, a Kalman filter has been used at the Jet Propulsion Laboratory (JPL) for more than a decade to combine independent measurements of the Earth's orientation. A Kalman filter has a number of properties that make it an attractive technique for combining Earth orientation measurements (Gross et al., 1998). Changes in the Earth's orientation can be described as a randomly excited stochastic process. Consequently, between successive measurements of the Earth orientation parameters, the uncertainty in the knowledge of their values grows and rapidly becomes much larger than the uncertainty in the measurements. Thus, it is important to analyse each measurement at its measurement epoch, rather than at some "nearby", regularized epoch as is commonly done in normal-point methods of combining data sets. Kalman filters are an effective means of dealing with irregularly spaced data sets since the state vector and state

[1] ser7@maia.usno.navy.mil
[2] http://maia.usno.navy.mil/
[3] ftp://maia.usno.navy.mil

covariance matrix can be propagated to the measurement epoch regardless of whether or not the measurements are equi-spaced.

Due to this growth in the uncertainty of the Earth Orientation Parameters between measurements, when intercomparing data sets in order to evaluate their relative accuracies (and hence to set relative weighting factors), it is important to compare independent measurements whose epochs are as close as possible to each other. This argues for comparing an individual data set against a combination of all other independent data sets (rather than against some other individual series) so that the difference in the epochs of the measurements being compared is minimized. Since it is unlikely that independent measurements will be given at exactly the same epoch, it is important that the interpolation procedure used in generating the combined series accounts for the growth in the uncertainty of the Earth orientation parameters between measurements. The JPL Kalman Earth Orientation Filter does this in an objective manner by employing realistic stochastic models of the uncertainty growth between measurements.

Finally, the degree of smoothing applied to the measurements should vary with both the precision and the sampling interval of the measurements. As improvements have been made to the measurement systems, the precision with which the measurements have been made has dramatically improved, and the sampling interval has gotten dramatically smaller. With a Kalman filter, the degree of smoothing applied is a function of both the precision of the measurements and the time span over which the state vector and covariance matrix must be propagated, that is, of the sampling interval of the measurements. Thus, with a Kalman filter, the degree of smoothing is automatically adjusted as the precision and sampling interval of the measurements change.

For these, and other reasons, a Kalman filter was chosen to combine Earth orientation measurements at JPL. Reference series of Earth orientation parameters obtained by combining the most accurate available measurements of the Earth's orientation are generated annually at JPL. These series, the most recent of which are SPACE2001, COMB2001, and POLE2001 (Gross, 2002), can be obtained by anonymous ftp to <[1]>. In addition, updates to these reference series, including short term predictions, are generated twice-per-week in a rapid service mode. These rapidly combined and predicted Earth orientation series can be obtained by anonymous ftp to <[2]>. As part of an operational program, it is anticipated that such annual reference combinations and rapid service-style updates will continue to be generated indefinitely.

3.4 Combination of EOP series at the Prague CRC

Some of the Earth Orientation Parameters (namely those that are referred to celestial reference system, i.e., Universal Time and celestial pole offsets) are observed by VLBI, while their time derivatives (length-of-day, celestial pole offset rates) are observed by satellite techniques (GPS, SLR).

Satellite methods, unlike the VLBI, measure the orientation of the Earth with respect to satellite orbits, and therefore are not capable of measuring directly the Earth's orientation with respect to the International Celestial Reference System (ICRS). Because the modeling of satellite orbits in space is a complicated task (their motion is subject to many influences, both gravitational and non-gravitational) and some of the orbital elements are correlated with some EOP, the exact and stable tie to ICRS is very difficult. Therefore, the satellite methods can provide only the time derivatives of those Earth Orientation Parameters that are sensitive to ICRS (i.e., Universal Time and precession-

[1] ftp://euler.jpl.nasa.gov/keof/combinations/2001
[2] ftp://euler.jpl.nasa.gov/keof/predictions

nutation). Satellite observations can thus deliver unique contribution to the spectrum in the high frequency range only (up to 14 days).

This is a typical example when the recently proposed method of combined smoothing, introduced shortly by Vondrák & Gambis (2000) and described in detail by Vondrák & Čepek (2000) can be used. The solution is based on two independent series of measurements:

- Series of function values;
- Series of time derivatives;

of the same time function whose analytical expression is unknown. We are looking for a smooth curve that fits both observed series well, by minimizing a weighted sum of three parameters S, F and $\overline{F}$, expressing the smoothness

$$Q = S + \varepsilon F + \overline{\varepsilon}\overline{F} = \min.$$

$$\Rightarrow \quad \frac{\partial Q}{\partial y_i} = 0, \quad i = 1, 2, \ldots N.$$

of the curve and its fidelity to both series, respectively:

The 'coefficients of smoothing' $\varepsilon, \overline{\varepsilon}$ act as weighting factors, expressing the relative importance of the three parameters: the larger these coefficients, the better the fit to observations but the rougher the curve. The choice of the numerical values of coefficients of smoothing, based on numerous experiments with simulated data, led to the following conclusion:

- Provided the minimum period $P_{\min}$ of the signal is known and the resolution of observations is 7 days for function values, 1 day for time derivatives, the optimal choice is

$$\varepsilon = \left(\frac{12.6}{P_{\min}}\right)^6, \quad \overline{\varepsilon} = \left(\frac{16.9}{P_{\min}}\right)^4.$$

This choice assures that the smoothing is sufficiently weak not to suppress the signal contained in both series of the input data, and at the same time sufficiently strong to suppress the high frequency noise of the observations.

However, the straightforward use of the method does not lead to an optimal result; there are large systematic errors in long-period part of the spectrum in GPS data (the dominant period is around 60 days, with amplitude of about 0.1 mas / day). Therefore, it is necessary to 'calibrate' the GPS data with respect to VLBI (that is more stable in long-periodic sense), prior to combination.

The method was used to combine VLBI and GPS observations, both UT1 / LOD and celestial pole offsets / celestial pole offset rates (Vondrák et al., 2002a, b, 2003). Most recently, the following combinations have been worked out:

- Combination of UT1 / LOD in the interval 1997.1 – 2002.1, based on the series of:
  - UT1, given at unequally spaced intervals (from 1 to 7 days) in the most recent IVS combined solution `ivs02002.eops`;
  - LOD, given at strictly 1-day intervals in the IGS combined solution `igs00p02.erp` (these values have already been calibrated against VLBI by the IGS).

The coefficients of smoothing $\varepsilon = 34\,\text{days}^{-6}$, $\overline{\varepsilon} = 34\,\text{days}^{-4}$ (calculated for $P_{\min} = 7\,\text{days}$) were used. The statistics of the combination yields the *a posteriori* average uncertainties (computed from the residuals of both series from the combined curve) that are quite comparable to the *a priori* values (reported by the IVS and IGS), as can be seen from Table 1.

Table 1 Average uncertainties in UT1 and LOD

Average uncertainties in	UT1 [µs]	LOD [µs]
a priori	2.8	10.4
a posteriori	4.0	8.9

- Combination of celestial pole offsets in the interval 1994.3 – 2002.0, based on the series of:
  - Celestial pole offsets, given at unequally spaced intervals (from 1 to 7 days) in the same IVS combined solution as above, i.e. `ivs02002.eops;`
  - Celestial pole offset rates at 1-day intervals, given in the GPS solution made at CODE in Berne. These values had to be first calibrated to VLBI in order to remove the long-periodic (periods longer than about a month) large systematic errors due to GPS orbit mismodeling. This was assured by computing the offset of the integrated GPS rate (over three consecutive VLBI intervals, i.e., 3 – 20 days) from the difference of VLBI data at the two endpoints, and removing the offset from GPS data.

The same coefficients of smoothing as above were used. The comparison of average *a posteriori* and *a priori* uncertainties is given in Table 2.

Table 2 Comparison of average *a posteriori* and *a priori* uncertainties

Average Uncertainties in	VLBI $\Delta\psi$ [mas]	GPS $\Delta\dot{\psi}$ [mas/day]	VLBI $\Delta\varepsilon$ [mas]	GPS $\Delta\dot{\varepsilon}$ [mas/day]
a priori	0.101	0.079	0.041	0.033
a posteriori	0.125	0.151	0.042	0.056

The *a priori* and *a posteriori* uncertainties are more or less equal in case of VLBI observations, but substantially different for GPS rates – the latter are about two times larger than the former. It seems that the formal GPS uncertainties are highly underestimated in this case.

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EOP Alignment Campaign, IDS/IGS/ILRS/IVS EOP Combinations, Systematic Errors

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1 Introduction

The combination of independent estimates of Earth Orientation Parameters (EOP), derived from global space geodetic observations, can be considered an ideal tool for investigating characteristics of the individual estimates (i.e. systematic and random errors) as well as stabilizing the results. As an attempt of a joint investigation into various aspects of combinations, the IERS has initiated a campaign of data analysis, combination and comparison of such EOP. In order to reduce the level of inflicting effects, these EOP had to be estimated on the basis of ITRF2000 station positions and velocities.

In parallel to the investigations of the IERS, the space geodetic services, IGS, IVS and ILRS, as well as the DORIS group have started their own analysis of (combined) EOP series. Special considerations taken into account by the different groups are summarized below.

2 International DORIS Service (IDS)

The recent launch of three new satellites (NASA-CNES's Jason 1 in late 2001, CNES's Spot 5 and ESA's Envisat in the first half of 2002) doubles the number of satellites carrying the DORIS navigation payload. The enhanced technology of the embarked new generation receivers, as well as the checking and upgrading of the network of terrestrial beacons that is well under way, will contribute to an increased interest in combinations.

Present status

The IDS products may be prepared under several forms, depending on their further use. The standard global geodetic solutions with variance-covariance information (SINEX files) are complete except for the orbits, which are available separately. In addition, it may be convenient to prepare time series of the parameters that vary in time.

In November 2001 the IDS Central Bureau initiated an analysis campaign that originally focused only on sets of station coordinates derived from the June 2001 observations of the Spot2, Spot4 and Topex/Poseidon satellites. The campaign objectives were set as follows:

- Check the level of consistency of results obtained using different software packages.
- Identify and analyze possible systematic discrepancies.
- Study the possibility of defining time series of sets of station coordinates as an IDS product.

- Initiate the process of combining DORIS results into unified IDS products.
- Check the consistency of the estimated time varying parameters (Geocenter, EOP) with the estimated reference frames (sets of station coordinates, ephemerides).

Responses were received from six Analysis Centers (IGN-JPL, INASAN, CSR, LEGOS-CLS, CNES/SOD, CNES-CLS/SSALTO), while others (IAA, St Petersburg; Geod. Obs. Pecny, Czech Rep.) expressed interest to participate at a later time. The content of the responses was larger than expected, in several ways: the data span covers several years, as compared to the single month originally requested, and the products span not only sets of stations coordinates, but also times series of the Earth's orientation parameters and of the geocenter location and orbits. The Central Bureau has started the analysis of the submitted solutions, with the technical support of the IERS ITRS Center. Results are presented at the 2002 IERS Combination Workshop.

Problems and deficiencies encountered

While the DORIS orbit computation activities are quite developed in the framework of the space oceanography missions, the activities devoted to the Earth's motions and to reference frames are still in a warming up phase. The latter topics are not central to the space altimetry groups. Therefore, new analysis centers are required. This evolution is taking place, in particular with new groups in Europe, but it is still too slow. As an example, only one DORIS solution could be provided for the IERS EOP alignment campaign (IGN-JPL). In addition, the open distribution of the observed data is not yet very smooth.

Goals and future steps for improvements

The future steps for improvement are both organisational and technical:

- Settle the organization of the data flow and the access to information on the DORIS system.
- Develop the Central Bureau combination capabilities, e.g. time series of SINEX-TRFs and corresponding EOPs and TRF origin motion ("geocenter").
- Encourage the development of new analysis centers and develop discussions and interactions.
- Check/update the local ties in the co-location sites involving DORIS.

Schedule of these next steps and recommendations

- The progressive upgrade of the stations and the checking of local ties is under way (IGN action).
- The data flow and information circulation system is under way and should be completed by the end of 2002. See http://lareg.ensg.ign.fr/IDS.
- An Analysis Workshop is planned in early 2003 in Paris to further discuss the combination results and prepare the definition of the future IDS products.

3 International GPS Service (GPS)

Within IGS, the combined station coordinates, EOP and apparent geocenter coordinates are generated using the Analysis Centers (AC) (COD, EMR, ESA, GFZ, JPL, NGS, and SIO) weekly SINEX solutions. This short report focuses on the pole position estimates. All the available covariance information provided by the ACs is used during the combination. A cumulative solution of station coordinates/velocities is also updated weekly. The AC coordinator combines and aligns the orbit products to the weekly SINEX solution to ensure consistency of the IGS products. As part of the orbit combination process an independent combination of the EOP is also produced (igs95p02.erp) and used to quality control the SINEX EOP (accumulated in "igs00p02.erp"). All EOP estimates are provided for the middle of each day. All the solutions are aligned by an unweighted 7/14 parameters Helmert transformation using the current IGS realization of ITRF. More details about the IGS analysis procedure can be found in the annual and technical reports available at <[1]>.

Since February 28, 2000 (MJD 51602,GPS Wk 1051), the difference between the daily igs00p02.erp and igs95p02.erp X and Y pole estimates are –0.02 ± 0.05 mas and –0.01± 0.05 mas. The MIT Global Network Associate Analysis Center (GNAAC) has also computed independent weekly combinations of the AC SINEX solutions including EOP. The X and Y pole differences between "igs00p02.erp" and the MIT estimates since November 21, 1999 (MJD 51503, GPS Wk 1037) are –0.01± 0.04 mas and –0.01± 0.04 mas. More recently, since April 21, 2002 (MJD 52385, GPS Wk 1163), the GNAAC "NCL" also includes the AC daily EOP as part of its weekly SINEX combination; the results of the pole comparison with igs00p02.erp are –0.01± 0.02 mas and +0.02± 0.02 mas. These internal comparisons are on average consistent at the 0.02 mas level, with a noise level at or better than 0.05 mas. Routine external comparisons between igs00p02.erp and IERS Bulletin A show pole differences of 0.01±0.06 mas and 0.18±0.06 mas, suggesting a significant bias between the IGS pole position and the IERS Bulletin A.

The objective of the IERS Analysis Campaign was to better understand the stability, consistency and limitations of EOP alignment when using ITRF2000, with an accuracy goal of 0.1 mas. The test included all the IGS weekly solutions between February 27, 2000 and February 23, 2002. Those solutions contain weekly station coordinate estimates as well as daily EOP. The weekly solutions were constrained using the ITRF2000 as well as its IGS realization (IGS00). In both cases, the set of 54 reference frame stations currently used to realize ITRF2000 was used. The tests were also repeated using the most reliable stations available (154 for ITRF and 132 for IGS). The tests also included minimal and formal constraints on the network and heavy position weights. Heavy weights are 100 times the formal weights. In the case of minimal constraints, the weekly solutions were aligned to the reference frame realization of the epoch using a weighted 7-parameter Helmert transformation. Inner constraints were also applied in this instance to produce meaningful statistics. Note that in this procedure, the application of the inner constraints had no effect on the estimated parameters. In all cases, the noise level of the X & Y pole position differences with respect to the official IGS EOP time series "igs00p02.erp" always remained below 0.03 mas.

The effect of the alignment strategy on the EOP was also tested for the ACs. For all the network and weighting strategies, the average differences with respect to "igs00p02.erp" was at or below the 0.01 mas level for both pole axis when considering all the AC simultaneously. When considering the ACs separately, the average differences with respect to igs00p02.erp were generally below 0.04 mas, with occasional exceptions. For some ACs the Y pole component is more affected by network configuration and constraining strategy. Note that the AC network configuration varies and the number of stations processed vary between ACs.

There are still a few minor problems to resolve with some AC solutions, but those are not expected to significantly affect the results currently available. Those are dealt with, as they occur and as time permits.

[1] http://igscb.jpl.nasa.gov/overview/pubs.html

4 International VLBI Service

The VLBI technique has the great advantage that all observing sessions, even the oldest ones, can be re-analyzed in a single run using the same reference frames and models available at that time. It is, therefore, no big effort to re-analyze all geodetic VLBI sessions since the advent of the high precision Mark III system in late 1979. From January 1, 2002 onwards all submissions of EOP series from IVS Analysis Centers have been based on the ITRF2000 reference frame either fixed or constrained to it. The IVS EOP series are, thus, ideally linked to ITRF2000 in a consistent way from the first data points onwards. The accuracy of the combined EOP series as deduced from the post-fit residuals and verified by comparisons with the IGS pole series is in the range of 100 microarcseconds in the x and y pole components and 15 microseconds in UT1.

On the research side the IVS Analysis Coordinator has issued a call for the Second IVS Analysis Research Project soliciting submissions of special EOP series from IVS Analysis Centers in the summer of 2001. The data was limited to all VLBI sessions of the so-called NEOS series in the period January 1, 1999 to December 31, 2000. This series was observed once per week with a 5-station network thus providing 104 EOP data points. The EOP had to be estimated on the basis of ICRF radio source positions (International Celestial Reference Frame) and ITRF2000 station coordinates and velocities. Ten submissions have been received in addition to the six regular contributions in late 2001 providing ample material for a detailed investigation.

The EOP series resulting from the routine IVS combination has an accuracy of about 100 microarcseconds and can, thus, be used as an accurate and reliable reference series. Weighted RMS differences of seven of the series submitted for the Second IVS Analysis Research Project with respect to this reference series range from 37 to 108 microarcseconds in the x and y pole components and from 2.3 to 7.4 microseconds in UT1. Biases between 11 and 157 microarcseconds in x and y pole and between 0.5 and 7.6 microseconds in UT1 have been taken into account.

Although these results have demonstrated the good agreement of the different analyses it has to be noted that the EOP are based on observations of almost identical networks throughout the series. As further investigations have shown, the effects of different network configurations are quite severe. VLBI EOP results of series of two separate networks observing on the same day do show systematic differences of up to 130 microarcseconds (MacMillan and Ma 2000). The origin of these have been investigated extensively but convincing explanations are still missing.

From the beginning of 2002 IVS has added a second session of routine EOP observations per week with the same rapid turn around policy as the old NEOS session. Now networks with varying configurations regularly observe on Mondays and Thursdays. The impact of the variations in the network configurations are still being studied in view of the problems incurred at the time when different networks observed in parallel.

In the future, the impact of VLBI network configurations on the EOP determinations will receive high priority within the IVS' investigations. All IVS Analysis Centers are asked to concentrate their efforts on this topic and actively participate in the investigations. The cause or the causes of the discrepancies between different networks will certainly permit a deeper insight into systematic errors inherent in the VLBI technique and will eventually lead to higher accuracy of the results.

5 International Laser Ranging Service (ILRS)

In October 2002, the ILRS has organized one of their bi-annual Analysis Working Group (AWG) meetings. The AWG has a number of so-called pilot projects in development, each aimed at specific results.

In the ILRS Pilot Project called "benchmarking", the ILRS AWG has defined a reference set of observations and computation model elements, with the aim of producing analysis results that should be 100% compatible. The goal is not to reach the best possible fit to the observations (indeed, that does not happen) but to determine errors in the various software programs and in handling procedures. During the October AWG meeting the first results were reported (it was the first meeting after the definition of this pilot project), and a number of items have been identified where the analysts can fine-tune the results and come up with better agreements (depending on the product that is looked at, the internal consistency may range from dm to sub-mm). This project is considered an essential stepping-stone towards individual and combination solutions with the best possible quality.

Another pilot project, that has been in development for quite some time now, is on "positioning and Earth orientation". The AWG has gone through a long process here, involving issues like formats, definition problems and such. Also the question on a representative (good) analysis product for Earth orientation has been on the table for some time. A conclusion has been reached now and as a result a Call for Participation for contributions to an official ILRS analysis product on station coordinates and EOPs (with the IERS Bulletin A as a customer for the latter) has been released in November 2002. A good number of reactions to this invitation has been received, and a full-scale test phase has been scheduled for the first months of 2003. If everything goes OK, the analysis system can be operational around the time of the 2003 EGS meeting (or shortly thereafter). This will produce daily solutions for x- and y-pole and LOD, and a full set of global station coordinates. Before submitting the EOP solutions, they will be converted to the ITRF2000 reference frame first.

6 IERS Alignment Campaign

In September 2001 the IERS Analysis Coordinator presented the 'IERS Analysis Campaign to align EOPs to ICRF / ITRF2000' as proposed by J. Ray. The intention of the IERS Alignment Campaign is to create EOP series with the highest possible consistency with ICRF and ITRF2000. The aim of this project is to achieve an overall accuracy of 0.1 mas. This will lead to an intermediate solution until a rigorous combination of EOP together with ITRF / ICRF is possible. Therefore we have to analyse and understand the origin of systematic errors belonging to the reference frame.

At the end of September 2001 the IERS Alignment Campaign was started with an initial call for participation. The Campaign is subdivided into two parts. In a first step the Technical Centers were asked to produce EOP series with a reference frame fixed to the ITRF2000 / ICRF at the level of uncertainty. In addition they were asked to produce solutions with different constraints on ITRF2000 (ICRF). The second step consists of the analysis of the submitted EOP series by comparison with the official annual solutions 2000 and by study the consistency against each other. The final results should be recommendations for future realizations of reference frames.

Until May 2002 21 proposals were presented, see also the web pages <[1]>. 12 of them contributed to the first step and produced more than 40 EOP series from all techniques with various constraints to realize the ITRF2000 reference frame. The series are stored and are publicly available from ftp archive <[2]>. In addition to each series a description file about the constraints, the reference frame, the reference sites and the combination approach used is available. In the second step 12 participants are now analysing the submitted EOP series.

The analyses have to deal with many special problems coming from the pooling of EOP series from different techniques. In order to compare the series they need to be reformatted and resampled in one common format. Problems occur with data gaps, different interpolation schemes and different signs. In a first comparison of the EOP series against each other, three EOP parameters (X_{pol}, Y_{pol}, UT1–UTC) were studied by a simultaneous estimation of offset, drift and a scale factor. Additionally possible time lags (shift in time) were detected. In polar motion (X_{pol}, Y_{pol}) most series agree within ±0.5 mas in offset and almost no drift, except IGN 01 (DORIS) and ASI 01 (≈ 1.5 mas/a). Drifts are mainly observed between the long VLBI series (IAA, GAUS, GSFC) where the ITRF2000 velocities are used over long time intervals. The VLBI series show also a good accordance in UT1–UTC, < ± 1 ms. The comparison with the satellite techniques is a known problem. Until now there is no significant indication that fixed constraints are better than loose constraints, only the ASI 01 series differs from the other series, maybe due to the loose constraints conditions used. After identifying the great differences and removing all error sources like interpolation and sampling errors, further investigations will concentrate on the smaller differences between the EOP series. The analysis of the remaining residuals should help to detect systematic errors. Final results are expected until the end of the year 2002.

Recommendations:

- Solve problems occurring from reformatting, resampling and interpolation
- Create a new database with comparable EOP series until end of the year 2002
- Analyse offsets and drifts in X_{pol}, Y_{pol}; find relations to the ITRF-realization
- Develop strategies to combine / compare UT1 and LOD of satellite techniques and VLBI
- Call analysis groups finish their studies until February 2003
- Conclusion and presentation of final results during the EGS General Assembly, April 2003

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[1] http://alpha.fesg.tu-muenchen.de/iers/
[2] ftp://alpha.fesg.tu-muenchen.de/iers/eop/

Consistency Analysis Between EOP Series and Reference Frames

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1 Background: Consistency of IERS EOP series with ITRF and ICRF

Earth Orientation Parameters (EOP) provide the transformation between the International Terrestrial Reference Frame (ITRF) and the International Celestial Reference Frame (ICRF). The IERS reference series, labelled IERS C04 is obtained from the combination of individual EOP series derived from the various astro-geodetic techniques, mostly VLBI, GPS and SLR. These individual EOP series present mutually systematic errors, generally limited to biases and drifts which can be attributed to the adoption of different reference frames CRF and TRF in the analyses of observations. It is also essential that the reference series C04 be not affected by these individual systematic errors to ensure a long-term stability. However, as the C04 is independently maintained, it is expected that small inconsistencies could appear after some time. This fact already lead in the past to a small adjustment of polar motion (biases and drifts) in 1997. In order to assess whether a correction should again be applied to C04, various consistency studies were carried on, using the IVS pilot project 2001 and the IERS alignment campaign in 2002. It appears that the C04 is for pole components, inconsistent with ITRF2000 at a level of 0.1 to 0.2 milliarcseconds. However, it is premature to apply any correction to it since the level of inconsistency between the different techniques, mostly GPS and VLBI is at the same level. More investigations are needed to identify the reasons of the discrepancies within identical techniques with the same or different packages used and also between the different techniques.

2 Monitoring inconsistency at the Earth Orientation Center: current method

There are different approaches to estimate the consistency of the IERS EOP system with respect to both terrestrial and celestial reference frames. The usual method performed at the IERS since 1991 consists in comparing the individual EOP solutions to the IERS C04 after estimation of the rotation angles between on one hand the individual CRF with respect to ICRF and on the other hand the individual TRF with respect to ITRF. The formalism is described in Zhu and Mueller (1983). Figures 1 to 3 represent, since 1991, the evolution of the inconsistency for the different techniques VLBI, GPS and SLR (Gambis et al., 2002; Bizouard and Gambis, 2002). Note that the mean inconsistency is for the various techniques at the level of 100 μas for polar motion and 20 microseconds for UT1 since the year 2000 (IERS Annual Reports).

This approach using the comparisons of rotation angles from individual frames to ITRF is now not straightforward because of constraints introduced in the determination of the terrestrial and celestial frames; angles between the individual TRF and the ITRF cannot be now easily computed.

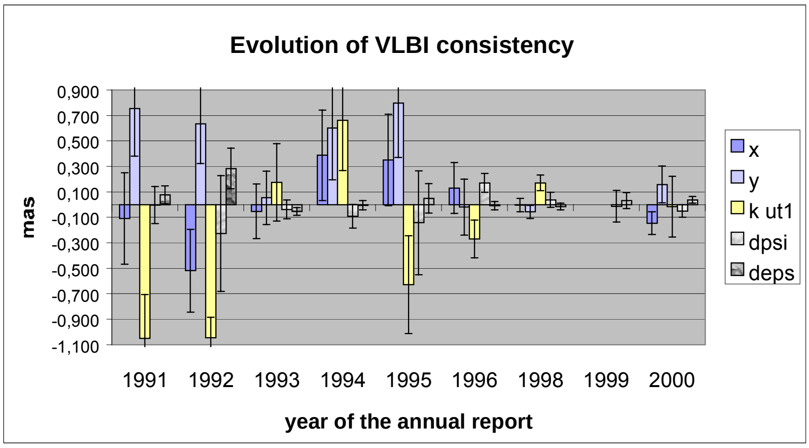

Fig. 1 Evolution of the consistency of VLBI solutions since 1991

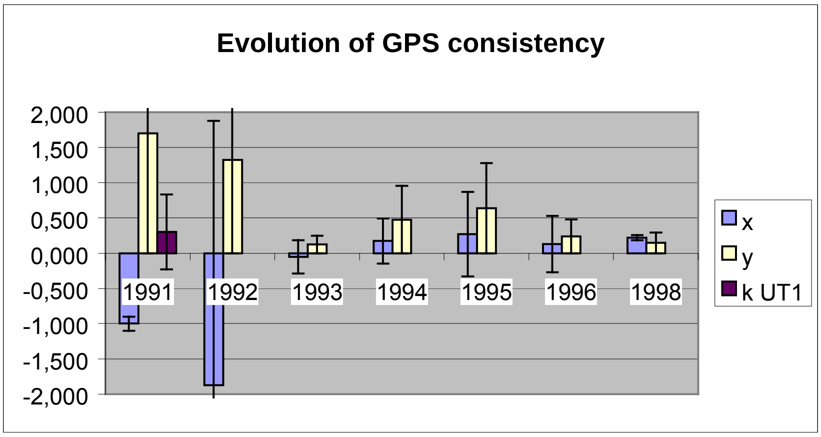

Fig. 2 Evolution of the consistency of GPS solutions since 1991

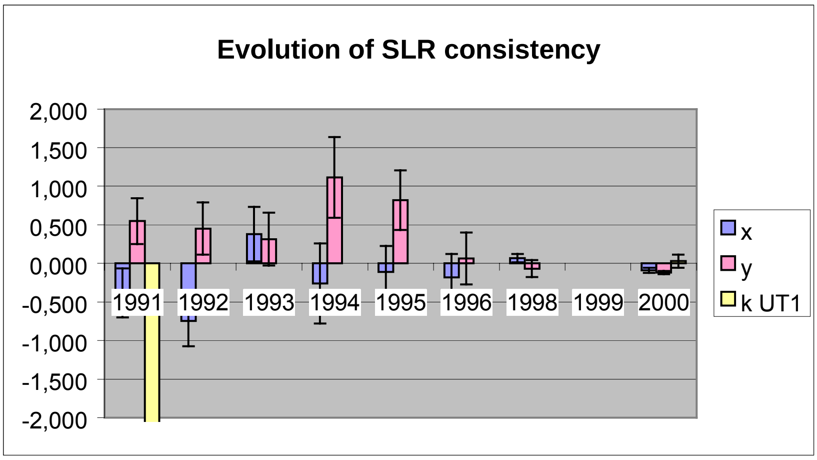

Fig. 3 Evolution of the consistency of SLR solutions since 1991

A more satisfying method to monitor the consistency, so far not realized within the IERS is based on a rigorous computation of both frames, CRF, TFR and EOP parameters. This approach, beyond the scope of the present paper is carried on progressively at the IERS. So far only preliminary results were obtained.

An intermediate approach for a better understanding of the origin of inconsistencies is based on 2 analysis campaigns: the second IVS pilot campaign (Nothnagel, 2001) and the IERS alignment campaign (Rothacher, 2002). In the frame of these campaigns, analysis centers were asked to derive EOP series with high constraints concerning both terrestrial and celestial reference frames. For the IERS alignment campaign, we limited our analyses to series for which terrestrial and celestial reference frames were held fixed to respectively ICRF-Ext.1 and ITRF2000.

3 IVS Pilot 2001

Eleven Analysis Centers submitted EOP series for the second IVS pilot project. These series were derived from all available NEOS-A 24hr VLBI sessions over 1999 and 2000. In these solutions, the celestial and the terrestrial reference were fixed respectively to ICRF-Ext.1 and to ITRF2000 with the associated velocity field.Estimated parameters include the pole components X-Pole, Y-Pole, UT1–UTC and the nutation offsets dPsi, dEps with respect to IAU 1980 model.The individual VLBI series are compared to IERS C04 together with the operational GPS series also referred to ITRF2000 through the IGS realization.

Tables 1 and 2 give the statistics concerning the systematic biases the mean values of which were computed. Units are µas for polar motion and nutation µs for UT1.

Table 1 Systematic biases between VLBI EOP series and the reference IERS C04

VLBI	AUS	BKG	CAN	DGFI	GSFC	IAA	IGG	JPL	OSO	OSO2	SPBU	Mean*	rms
xpole (µas)	–58	–16	–94	–114	–55	–143	–161	–220	62	55	–86	**–60**	76
ypole (µas)	367	330	–403	312	328	286	319	696	330	311	347	**326**	24
UT1 (µs)	6	8	7	8	8	6	10	13	14	16	7	9	3.4
dψ (µas)	28	–90	36	–17	9	15	90	851	96	108	31	–12	58
dε (µas)	49	43	0	3	21	86	–19	–2764	96	116	38	48	34

* CAN and JPL are excluded for polar motion; JPL for nutation

It appears from these tables that for X-Pole, biases are not homogeneous ranging from –16 µas (BKG) to –220 µas (JPL), the standard deviation being in the range of 100 to 200 µas. The mean bias, CAN and JPL excluded, is -60 ± 76 µas. For Y-pole biases are much more homogeneous than for X-pole with a mean value of 326 ± 24 µas. For UT1 biases are ranging between 5 and 25 microseconds. Again JPL presents anomalous rms. For nutation offsets, biases and rms are much less homogenous than for the other parameters. Mean values are respectively –12 ± 58 µas and 48 ± 34 µas for dψ and dε.

4 Biases of GPS operational EOP series

For comparison, the same analyses were conducted for the 7 GPS operational series, over 1999–2000. Biases and rms are reported in Table 2.

Table 2 Systematic biases between GPS EOP series and the reference IERS C04

GPS	CODE	JPL	GFZ	ESOC	NOAA	SIO	EMR	Mean *	rms*
xpole (µas)	20	–47	–70	–29	–85	–39	–23	**–45**	24
ypole (µas)	186	180	184	257	158	207	148	**188**	36
LOD (µs)	8	–7	–5	–33	–29	0	–19	–12	15

It appears that these series are mutually more consistent than for the IVS Pilot series (mean values are –45 ± 24 µas and 188 ± 36 µas respectively for X-and Y-pole. However significant inconsistency of about 150 µas exist in Y-pole when compared to VLBI series. This could be expected from the fact that GPS series are referred to a realization of the ITRF2000 which present significant small rotation with respect to the frame.

In conclusion, it appears that there is a slight inconsistency in the IERS C04 y-pole solution of about 100 – 150 µas with respect to ICRF-Ext.1 and ITRF2000. However its values are of the same order as the discrepancy between VLBI and GPS solutions (150 µas).

5 IERS alignment campaign

The idea of the campaign was to compute EOP series with highest possible consistency with ITRF2000 / ICRF and investigate what the ultimate achievement of the overall accuracy. The main objectives were to study systematic discrepancies within techniques due to softwares difference, between techniques due to sub-network effects and understand their origin. The analyses we performed concerned more specifically long-term consistency, trends and biases, between techniques and the reference IERS C04. We have limited our analyses to long-term EOP series derived by analysis centers in which both references frames were fixed to ICRF and ITRF2000 in the course of the calculations (i.e. 5 VLBI, 3 SLR one GPS, one DORIS series). In fact for GPS and DORIS, the terrestrial reference frame is materialized by a realization of the ITRF2000. Tables 3 and 4 present systematic errors, respectively biases and drifts, between individual solutions obtained within same techniques, identical or different softwares, and IERS C04 for all parameters. The initial date for which biases and rates are computed is MJD=50448.0. Table 5 gives the overall weighted rms of these solutions compared to the C04 over the whole data span of each series. For polar motion, the rms agreement ranges from about 100 µas (GPS) to 2 mas (DORIS). For UT1, the mean rms is about 15 µs.

Table 3 Bias between individual solutions and IERS C04 for all EOP parameters. CSR solution, computed in a different reference frame than ITRF2000 was transformed using the correction given for the 1997 correction (IERS Gazette 8).

	Institute	Software	Data span	X µas	sX µas	Y µas	sY µas	UT1 µs	sUT1 µs	dPsi µas	sdPsi µas	dEps µas	sEps µas
VLBI	BKG	CALC	1984–2002	–114	6	143	5	–1	1	–27	8	6	4
	GSFC	CALC	1979–2001	–103	5	148	4	–1	1	–63	7	5	4
	SHA	CALC	1979–2002	–201	10	194	8	14	1	–15	8	8	4
	DGFI	OCCAM	1984–2002	–135	5	134	5	1	1				
	GAUS	OCCAM	1983–2002	–200	10	133	6	1	1				
	IAA	OCCAM	1980–2002	–138	6	116	5	–3	1	–39	9	27	4
SLR	ASI	GEODYN	1984–2002	–235	15	110	14						
	IAA	GROSS	1983–2002	–59	3	58	3						
	CSR	UTOPIA	1976–2002	–366	8	50	8						
GPS	CODE	BERNESE	1995–2002	44	4	–35	4						
DORIS	IGN/JPL	GIPSY	1992–2001	1042	57	377	33						

Table 4 Drift between individual solutions and IERS C04 for all EOP parameters. CSR solution, computed in a different reference frame than ITRF2000 was transformed using the correction given for the 1997 correction (IERS Gazette 8).

	Institute	Software	$\dot{X}$ µas/yr	s $\dot{X}$ µas/yr	$\dot{Y}$ µas/yr	s $\dot{Y}$ µas/yr	$\frac{dUT1}{dt}$ µs/yr	s $\frac{dUT1}{dt}$ µs/yr	d $\dot{\psi}$ µas/yr	sd $\dot{\psi}$ µas/yr	d $\dot{\varepsilon}$ µas/yr	s d $\dot{\varepsilon}$ µas/yr
VLBI	BKG	CALC	20	2	37	2	2	.1	–5	2	–1	1
	GSFC	CALC	16	1	31	1	2	.1	–14	2	–3	1
	SHA	CALC	–5	3	56	2	6	.2	0	3	–2	1
	DGFI	OCCAM	12	2	41	2	2	.2				
	GAUS	OCCAM	37	3	36	2	2	.1				
	IAA	OCCAM	3	2	38	2	3	.1	–10	2	–1	1
SLR	ASI	GEODYN	3	3	8	3						
	IAA	GROSS	11	1	–3	1						
	CSR	UTOPIA	–103	2	33	1						
GPS	CODE	BERNESE	–17	1	49	1						
DORIS	IGN/JPL	GIPSY	–203	23	–53	13						

A slight but significant systematic error appears in Y-pole rate component of the IERS C04 (about 20 µas/yr), a few µs in UT1. However within VLBI technique, the comparisons show significant inconsistencies of solutions using same or different softwares (100 µas for pole biases and 30 µas/yr for pole rates). In addition, there are inconsistencies between the different techniques, DORIS excluded (300 µas for pole biases and 50 µas/yr for pole rates). In conclusion, within the inconsistencies level between different techniques, it appears that IERS C04 has a long-term consistency with the different solutions at the level of 100/300 µas in polar motion, and a few µs in UT1.

Table 5 Weighted RMS between individual solutions and the reference IERS C04

	Institute	Software	Data span	X µas	Y µas	UT1 µs	dPsi µas	dEps µas
VLBI	BKG	CALC	1984–2002	307	266	20	405	172
	GSFC	CALC	1979–2001	265	230	19	403	194
	SHA	CALC	1979–2002	532	453	47	420	188
	DGFI	OCCAM	1984–2002	212	199	16		
	GAUS	OCCAM	1983–2002	320	206	12		
	IAA	OCCAM	1980–2002	266	246	17	408	177
SLR	ASI	GEODYN	1984–2002	611	606			
	IAA	GROSS	1983–2002	249	239			
	CSR	UTOPIA	1976–2002	301	292			
GPS	CODE	BERNESE	1995–2002	125	116			
DORIS	IGN/JPL	GIPSY OASIS 2	1992–2001	3258	1860			

6 Conclusion

Individual EOP series determined from the analyses of the various techniques present mutually systematic errors, generally limited to biases and drifts which can be attributed to the adoption of different reference frames CRF and TRF. There are different approaches to estimate the consistency of the IERS EOP system with respect to both terrestrial and celestial reference frames. The current method performed at the IERS since 1991 consists in comparing the individual EOP solutions to the IERS C04 after estimation of the rotation angles between on one hand the individual CRF with respect to ICRF and on the other hand the individual TRF with respect to ITRF. It appears that the mean inconsistency for the various techniques has gradually improved from a couple of milliarcseconds for polar motion in 1991 to about 100 µas for polar motion and 20 microseconds for UT1 after 2000. Another approach to estimate the consistency is to directly inter-compare individual EOP solutions derived with fixed ITRF and ICRF (for VLBI) through an intermediate common solution, here the IERS C04. The analyses performed in the frame of the IVS Pilot Project and the IERS alignment campaign lead to the conclusions that small inconsistencies exist in the reference solution C04, however these inconsistencies are within the inconsistencies between the various technique solutions and in addition within the same technique VLBI, using identical or different software packages.

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Conventions and Combinations

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Abstract: In the future improvement of the IERS combination solutions it will be necessary to address the role of the adopted conventions on the precision and accuracy of the product. It is suggested that the first step be the establishment of clear conventions within each technique followed by a joint effort of the Conventions Center and the Analysis Coordinator to determine the relative importance of the component conventions to the final IERS combined solution.

1 Concepts

In general, the combination of data describing the same phenomenon but derived using different techniques will be compromised unless all of the data contributed to the combination are referred to a common "system." To accomplish this, we use our knowledge of the systematic differences among the results of the different observational and analysis processes. These results are derived through procedures that may involve many sub-procedures. The procedures and sub-procedures rely, to differing degrees, on information regarding phenomena that may, or may not be, related directly to the derived data that are the objects of the analysis procedures. This information may range from observed *ad hoc* assumptions through sophisticated physical models.

In the IERS experience, much of the information that enables the analysis procedures is contained in the *IERS Conventions*. For this reason, and to provide the consumer of IERS products the background necessary to make proper use of those products, the *IERS Conventions* attempts to provide those constants, models, and software that have the most significance to IERS products. Less significant, technique-dependent conventions are left to the technique coordinators.

It is not straightforward, however, to understand the effect of the *IERS Conventions* on the final combination solutions without having a clear understanding of their effect on the contributed data. To accomplish that, it is important that technique analysts first establish clear conventions within their technique. Starting at this level allows each technique to establish the relative importance of numerous conventions to their analysis. Comparing the results of different analysts within the technique to determine the effect of possibly different conventions on their respective solutions can do this most efficiently.

Following the establishment of the importance of various conventions to each technique, it is possible to determine those conventions that affect more than one technique and, in addition, to determine the relative importance to the final combination solution. The Analysis Coordinator in conjunction with the IERS Conventions Center is the best suited to provide this contribution.

It is important to understand that we use the term "conventions" to describe generally the agreed upon constants, concepts, models, procedures, *etc.* that are used in the analyses and, therefore, become part of the reference system of the final product. We can list the conventions in the following basic categories from the most basic to the most technique specific.

Units

Common units are used to enable the products to be used in context with other scientific and technical representations. The SI system is used throughout the Conventions.

Coordinate System Conventions

These are the conventional concepts regarding the definition of the coordinate systems that permit the interpretation of the IERS products. Generally the choice of coordinate system conventions does not affect the precision of the results, but it is more likely to affect the accuracy.

Models

Models refer to the various mathematical descriptions of physical phenomena that affect the IERS products. This category can, in turn, be subdivided into general models and technique-specific models. They generally affect the precision of the products but might have only a minimal affect on the accuracy. An important consequence of the set of models is the accompanying set of Constants, the numerical values of parameters of common interest.

Software

This category refers to the consensus implementation of the categories above through computer software code.

Procedures

This category refers to the actual application of all of the above categories of conventions to produce the final products. This includes conventions regarding the parameters to be constrained, the parameters to be determined, the data span to be used, *etc*. In general, choices here affect the precision of the results with little affect on accuracy.

The *IERS Conventions* makes contributions to each of the categories except for item (6). This item can be the role of the Analysis Coordinator but it is important that (1) the effect of the various conventions on the analysis products be understood within the context of improving observational and analysis techniques and (2) the IERS Conventions work in conjunction with the Analysis Coordinator to ensure an improved combination solution.

2 Product

The Conventions Center is provided jointly by the U.S. Naval Observatory (USNO) and the Bureau International des Poids et Mesures (BIPM), who are working on the new edition of the *IERS Conventions*. The new edition of the conventions has been re-organized with respect to *IERS Conventions 1996*, and numerous updates have been introduced. The work accomplished or in progress is the following:

Chapter 1 General Definitions and Numerical Standards

The chapter has been updated for consistency of notation and concepts with other sections according to IAG and IAU working groups and expanded to provide definitions for concepts used throughout the document.

Chapter 2 Conventional Celestial Reference System and Frame

The chapter has been updated to incorporate the effects of the IAU 2000 24th General Assembly.

Chapter 3 Conventional Dynamical Realization of ICRF

The chapter has been updated to be consistent with notation and concepts of other sections.

Chapter 4 Conventional Terrestrial Reference System

The Chapter has been updated for ITRF2000.

Chapter 5 Transformation Between the Celestial and Terrestrial Systems

The chapter is being modified to be consistent with resolutions adopted at the 24^{th} IAU General Assembly and the 2002 IERS Workshop.

Chapter 6 Geopotential

The chapter has been updated to include the EGM96 conventional geopotential model and for the treatment of tides.

Chapter 7 Site Displacement

The chapter has been updated to account for models used in IERS analysis centers and to ensure consistency with chapters 4 and 6.

Chapter 8 Tidal Variations in the Earth's Rotation

The chapter has been updated to be consistent with resolutions adopted at the 24^{th} IAU General Assembly.

Chapter 9 Tropospheric Model

The chapter has been updated.

Chapter 10 General Relativistic Models for Time, Coordinates and Equations of Motion

The chapter has been updated for consistency of notation and concepts with other sections.

Chapter 11 General Relativistic Models for Propagation

The chapter has been updated for consistency of notation and concepts with other sections.

Appendix Resolutions of the 24th IAU General Assembly

New versions of chapters and accompanying software are posted on the web as they become available, see http://maia.usno.navy.mil/conv2000.html.

The Conventions are now ready for possible last-minute additions, final approval by the contributors, and for final format organization.

3 Future

The BIPM will provide funding for a "Visiting scientist" position to address the issues regarding the relative effects of the conventions on the official products of the IERS. Details have been provided through an IERS Message.

Impact of IAU Resolutions on Earth Rotation Parameters

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1 Introduction

The implementation of the IAU 2000 Resolutions for all the applications related to Earth's rotation is described in Chapter 5 of the IERS Conventions entitled "Transformation between the celestial and terrestrial reference systems". Successive revisions of this Chapter have been made to include the models, expressions and numerical tables as soon as they became available for the implementation of the resolutions and to introduce the most recent developments and improvements. A major revision was made recently in order (i) to follow the actions recommended by the IERS Directing Board after the IERS Workshop in Paris (April 2002), (ii) to take into account the latest comments and remarks from various colleagues, (iii) to introduce the definitive and full forms of the numerical expressions and tables, and (iv) to provide a software package for the practical implementation. This has benefited from specific contributions from several experts for the following sections: "Motion of the Celestial Intermediate Pole (CIP) in the International Terrestrial Reference System (ITRS)" (A. Brzezinski, S. Mathews, Ch. Bizouard), "Prograde and Retrograde Nutation Amplitudes" (P. Defraigne, S. Mathews, Ch. Bizouard, A. Brzezinski), "Procedures and IERS Routines for Transformations between GCRS (Geocentric Celestial Reference System) and ITRS" (P. Wallace) and from general comments (Burghard Richter). Numerical Tables and Fortran subroutines have been added to those already available and now allow the users to implement the resolutions in several ways according to their choice and needs.

The updated version was posted on November 2002 on the webpage of the IERS Conventions Center together with the corresponding numerical tables and software. This version is supposed to be the final version, except for slight corrections which can still be applied before the Conventions are published as an IERS Technical Note in order to take into account the remarks that will be received on the posted version. This paper reports on the latest improvements that have been applied in this Chapter since the previous version that was presented at the IERS Workshop in Paris.

2 Update of Chapter 5 of the IERS Conventions

The major revisions in the text of Chapter 5 of the IERS Conventions 2000 presented here concern the sections on the motion of the CIP in the ITRS and GCRS, the expressions for precession and Greenwich Sidereal Time compatible with the IAU2000 model and the procedures and IERS routines for the Fortran subroutines implementing the IAU 2000 celestial-to-terrestrial transformations.

2.1 Progress in the implementation of the IAU Resolutions

The implementation of the IAU Resolutions in the transformation between the celestial and terrestrial reference systems concerns (see McCarthy & Capitaine, 2002) IAU Resolution B1.3 (*Definition of BCRS and GCRS*), IAU

Resolution B1.6 (*IAU 2000 Precession-Nutation Model*), IAU Resolution B1.7 (*Definition of Celestial Intermediate Pole*) and IAU Resolution B1.8 (*Definition and use of Celestial and Terrestrial Ephemeris Origins*). This introduces a “new paradigm” for the transformation between the celestial and terrestrial reference systems based on the use of the CEO, TEO, Earth Rotation Angle (ERA) and the x, y coordinates of the CIP unit vector in the GCRS, instead of the “classical paradigm” which refers to the equinox.

The implementation of Resolution B1.3 is realized in Chapter 5 using the correct time scales and the correct realization of the GCRS with the IAU 2000 precession-nutation (Mathews et al., 2002) including both the geodesic precession and nutation so that the GCRS and BCRS are without any time-dependent rotations. The implementation of Resolution B1.6 is realized by providing expressions for the model of the motion of the CIP in the GCRS which are consistent with the IAU 2000 precession-nutation model, either for the new or classical paradigms.

The implementation of Resolution B1.7 (which sharpens the definition of the current CEP in the high frequency domain) and B1.8 requires the use of the IAU 2000A expressions for the position of the CIP and the CEO in the GCRS, of the TEO in the ITRS and models for improving the realization of the pole in the high frequency domain.

2.2 Implementation of IAU Resolution B1.7

The standard pole coordinates to be used for the parameters x_p and y_p, if not estimated from the observations, are those published by the IERS with additional components to account for the effects of ocean tides $(\Delta x, \Delta y)_{tidal}$ and for nutation terms with periods less than two days $(\Delta x, \Delta y)_{nutation}$. Corrections for the diurnal and sub-diurnal variations in polar motion caused by ocean tides can be computed using a routine available on the website of the IERS Conventions (see Chapter 8). Table 8.2 (from Ch. Bizouard), the basis for this routine, provides the amplitudes and arguments of these variations for the 71 tidal constituents considered in the model. These subdaily variations are not part of the polar motion values reported to and distributed by the IERS and have therefore to be added after interpolation.

In order to realize the CIP as recommended by Resolution B1.7, nutations with periods less than two days are to be considered using a model for the corresponding motion of the pole in the ITRS. The prograde diurnal nutations correspond to prograde and retrograde long periodic variations in polar motion and the prograde semidiurnal nutations correspond to prograde diurnal variations in polar motion. A table for operational use of the model for these variations $(\Delta x, \Delta y)_{nutation}$ in polar motion for a nonrigid Earth has been provided by an *ad hoc* Working Group (Brzezinski, 2002) based on nonrigid Earth models and developments of the tidal potential (Brzezinski, 2001; Brzezinski & Capitaine, 2002; Mathews & Bretagnon, 2002). The amplitudes of the diurnal terms are in very good agreement with those estimated by Getino et al. (2001). The diurnal components of these variations should be considered similarly to the diurnal and semidiurnal variations due to ocean tides. They are not part of the polar motion values reported to the IERS and distributed by the IERS and should therefore be added after interpolation. The long-periodic terms, as well as the secular variation, are already contained in the observed polar motion and need not be added to the reported values.

2.3 Implementation of IAU Resolution B1.8

2.3.1 Positioning the CIP and the CEO in the GCRS

Definitive and full forms of the expressions for X, Y and s have been provided (Capitaine et al., 2003a) for the parameters to be used in the new transformation, based on the IAU 2000A precession-nutation model and the IAU2000 definition of UT1. They include the effect of precession, bias, nutation and cross terms between precession and nutation.

2.3.2 Positioning the TEO in the ITRS

The expression for *s′* for use in both new and classical transformations for positioning the TEO in the ITRS, has been derived from the current mean amplitudes for the Chandlerian and annual wobbles (Lambert & Bizouard, 2002).

2.3.3 Classical paradigm a the microarcsecond level

The classical transformation, R, to transform from the ITRS to the GCRS, should be written in its rigorous form as (Wallace, 2002) R = B P N T, where B is the matrix transformation from the CRS to the mean J2000, P, the Precession matrix, N, the Nutation matrix, T, the Earth's rotation matrix using GST.

These matrices are such that:

Bias:	$B = R_3(-d\alpha_0)\cdot R_2(-d\xi_0)\cdot R_2(d\eta_0)$,
Precession:	$P = R_1(-\varepsilon_0)\cdot R_3(\psi_A)\cdot R_1(\omega_A)\cdot R_3(-\chi_A)$,
Nutation:	$N = R_1(-\varepsilon_A)\cdot R_2(\Delta\psi)\cdot R_1(\varepsilon_A+\Delta\varepsilon)$,
Earth Rotation:	$T = R_3\,(-\mathrm{GST})$.

The IAU 2000 expressions for the quantities to be used in the classical transformation have been provided. These include, in addition to the MHB 2000 (Mathews et al., 2002) nutation $\Delta\psi$ and $\Delta\varepsilon$, and precession quantities ψ_A, ω_A, ε_A, (obtained directly by addition of the precession rate corrections to the Lieske et al. (1977) precession), the expressions for:

- the equatorial precession quantities z_A, ζ_A, θ_A, derived from the IAU2000 A expressions for ψ_A, ω_A, so that their use is equivalent to the use of the former, at a microarcsecond level for a century (Capitaine et al., 2003c), and
- the Sidereal Time GST, which is the sum of the Earth Rotation Angle (ERA) as a linear function of UT1 and of the expression for the accumulated precession and nutation in right ascension (*i.e.* the sum of the polynomial part of the expression, denoted GMST_{2000}, and the periodic part, which itself is the sum of the classical equation of the equinoxes and of the *complementary terms in the equation of equinoxes)*. This can be written as

$$\mathrm{GST} = \theta(\mathrm{UT1}) + \int_{t_0}^{t} (\psi_A + \Delta\psi_1)\cos(\omega_A + \Delta\varepsilon_1)\,dt - \chi_A + \Delta\psi\cos\varepsilon_A - \Delta\psi_1\cos\omega_A$$

The definitive expressions for GST and *s* (Capitaine *et al.* 2003b) have been obtained by ensuring that there is equivalence between CEO-based and equinox-based z-rotations, and that there is continuity in UT1 on 1 January 2003 0 h TT with the previous relationship $\mathrm{GMST}_{1982}(\mathrm{UT1})$ and the current UT1 estimate.

2.3.4 Consequences of the frame bias

The effect of the celestial pole offsets ξ_0, η_0 is to introduce a constant offset in X, Y and a specific frame bias rotation, B, in the classical transformation. The effect of the equinox offset $d\alpha_0$ (in µas) between the inertial dynamical mean equinox at J2000 and the x-axis of the GCRS, is to introduce terms of the form: –142 t in Y and +1.6 t^2 in X and similar effects in the classical quantities $\Delta\psi \sin(\varepsilon)$ and $\Delta\varepsilon$ respectively.

Current VLBI procedures use corrections for biases and precession-nutation quantities, and this introduces secular and cubic discrepancies with respect to the rigorous transformation of the order of a few 100 μas/c.

3 Expressions and Tables for the implementation of IAU Resolutions

The motion of the CIP in the ITRS is provided in Chapter 5 by Table 5.1 for the components arising from the nutation terms with periods less than two days, $(\Delta x, \Delta y)_{nutation}$. In addition, the component due to the oceanic tidal effects, $(\Delta x, \Delta y)_{tidal}$ is provided in Chapter 8 (Table 8.b).

The definitive and full expressions for the other quantities are:

Motion of the TEO in the ITRS

$s' = -47$ μas t.

Earth Rotation angle

$$\theta(UT1) = 2\pi(0.7790572732640 + 1.00273781191135448 \times (\text{Julian UT1date} - 2451545.0)).$$

Greenwich Sidereal Time:

Expression (35), the electronic table, and Table 5.4, include the following polynomial and periodic parts:

$$GMST_{2000} = 0''.014506 + \theta + 4612''.15739966\, t + 1''.39667721\, t^2 - 0''.00009344\, t^3 + 0''.0000188\, t^4.$$

$$EE_{2000} = + \Delta\psi \cos \varepsilon_A - \Sigma_k C_k \sin \alpha_k - 0.87\ \mu as\ t \sin \Omega.$$

Note that the two largest terms of the complementary terms in the equation of the equinoxes were already included in the current expression for GST (McCarthy 1996).

Motion of the CIP in the GCRS

$$\begin{aligned} X = & -0.''01661699 + 2004.''19174288\, t - 0.''4272190\, t^2 - 0.''19862054\, t^3 \\ & - 0.''00004605\, t^4 + 0.''00000598\, t^5 \\ & + \Sigma i\, [(a_{s,0})_i \sin(\text{ARGUMENT}) + (a_{c,0})_i \cos(\text{ARGUMENT})] \\ & + \Sigma_i\, [(a_{s,1})_i\, t \sin(\text{ARGUMENT}) + (a_{c,1})_i\, t \cos(\text{ARGUMENT})] \\ & + \Sigma i\, [(a_{s,2})_i\, t^2 \sin(\text{ARGUMENT}) + (a_{c,2})_i\, t^2 \cos(\text{ARGUMENT})] + \ldots \end{aligned}$$

$$\begin{aligned} Y = & -0.''00695078 - 0.''02538199\, t - 22.''40725099\, t^2 \\ & + 0.''00184228\, t^3 + 0.''00111306\, t^4 + 0.''00000099\, t^5 \\ & + \Sigma_i\, [(b_{c,0})_i \cos(\text{ARGUMENT}) + (b_{s,0})_i \sin(\text{ARGUMENT})] \\ & + \Sigma_i\, [(b_{c,1})_i\, t \cos(\text{ARGUMENT}) + (b_{s,1})_i\, t \sin(\text{ARGUMENT})] \\ & + \Sigma_i\, [(b_{c,2})_i\, t^2 \cos(\text{ARGUMENT}) + (b_{s,2})_i\, t^2 \sin(\text{ARGUMENT})] + \ldots \end{aligned}$$

Tables 5.2a (X), 5.2b (Y) and 5.2c (s) provide extracts of the full tables for the periodic components of the coordinates *X* and *Y* and for s, which are provided in an electronic form as tab5.2a and 5.2b and 5.2c. Tables 5.3a (luni-solar) and 5.3b (planetary) provide extracts of the full tables for the IAU2000A nutation, which are provided in an electronic form as tab5.3a and b.

IAU2000 precession developments are given by:

- expressions (27), (30), (31) for the updated expressions of Lieske et al. (1977) based on the MHB 2000 correction to precession rates, and
- expressions (32), (33) for the updated developments consistent with MHB2000.

The IAU 2000 precession quantities are

ψ_A = 5038."47875 t – 1."07259 t^2 – 0."001147 t^3.
ω_A = ε_0 – 0."02524 t + 0."05127 t^2 – 0."007726 t^3.
ε_A = ε_0 – 46."84024 t – 0."00059 t^2 + 0."001813 t^3.
χ_A = 10."5526 t – 2."38064 t^2 – 0."001125 t^3.
ς_A = 2."5976176 + 2306."0809506 t + 0."3019015 t^2 + 0. "0179663 t^3
– 0."0000327 t^4 – 0."00000002 t^5.
z_A = –2."5976176 + 2306."0803226 t + 1."0947790 t^2 + 0. "0182273 t^3
+ 0."0000470 t^4 – 0."00000003 t^5.
θ_A = 2004."1917476t – 0."4269353t^2 – 0."0418251t^3 – 0."0000601t^4
– 0."00000001t^5.

4 IERS Software package for the implementation of the IAU Resolutions

The IERS software package at ftp://maia.usno.navy.mil/conv2000/chapter5/ includes the subroutines corresponding to the different options for implementing the IAU resolutions. The IAU2000A (T. Herring) and IAU2000B (D. D. McCarthy and B. Luzum) subroutines, compute the "total" nutation angles (including nutation, plus precession corrections, plus the constant celestial offsets at J2000) corresponding to the IAU2000A and IAU2000B precession-nutation models, respectively. The other subroutines provided by P. Wallace includes the following Fortran routines for implementing the IAU Resolutions, based on the rigorous method in the transformation between the celestial and terrestrial systems. Other software will in due course be released through the SOFA (Wallace, 2000) website.

Method (1):

- X, Y, s transformation consistent with the IAU2000A precession-nutation model
- ERA_{2000}: Earth Rotation angle at date t
- XYS_{2000A}: provides X, Y (GCRS coordinates of the CIP), s (position of the CEO on the equator of the CIP) at date t, consistent with IAU2000A precession-nutation
- BPN_{2000}: CEO-based precession-nutation matrix (based on the two routines above)

Method (2A): classical transformation using the IAU2000A precession-nutation model

- $GMST_{2000}$: Mean Sidereal Time consistent with IAU 2000 precession-nutation and new definition of UT1.
- $EECT_{2000}$: complementary terms in the equation of the equinoxes
- EE_{2000}: Equation of the equinoxes as the sum of the classical part plus $EECT_{2000}$
- GST_{2000}: Sidereal Time as GMST + EE_{2000}
- NU_{2000A}: IAU2000A nutation model
- $CBPN_{2000}$: classical bias-precession-nutation matrix

Method (2B): classical transformation using IAU2000B

- NU_{2000B}: IAU2000B nutation model

For all the methods :

- T2C2000: Forms the TRS-to-CRS matrix
- SP2000: Produces the position of the TEO on the equator of the CIP
- POM2000: Forms the matrix of polar motion

5 The IERS Products in agreement with the IAU Resolutions

The IERS products for the implementation of the IAU Resolutions are provided both for the CEO-based and equinox-based transformations. The new paradigm requires the use of the expressions for X, Y and s consistent with the IAU2000 precession and nutation model. In this case, the IERS products are the estimates for UT1, and the corrections dX and dY. The numerical values for the GCRS CIP coordinates X and Y at the date t are then provided by $X=X_{IAU2000} + dX$, $Y=Y_{IAU2000} + dY$.

The classical paradigm requires the use of the IAU2000 expressions for the classical quantities for precession, nutation and GST. In this case, the IERS products are the estimates for UT1, and the corrections dψ and dε in longitude and obliquity to the IAU2000 precession-nutation model. The IERS products will also continue to provide the corrections dψ and dε to the previous precession and nutation models.

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Issues of a Rigorous Combination

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Abstract: We survey the current status of product combinations within the IERS, noting some weaknesses and limitations of each. A general feature is that the IERS products are not formed rigorously or self-consistently across the service. This leads to inaccuracies that are in some cases greater than the inherent errors of the observing techniques, unnecessarily limiting the usefulness of the products and obscuring our understanding of important systematic errors which should be addressed. The IGGOS concept of a comprehensive, integrated global geodetic observing system provides an ambitious objective which the IERS should embrace to better serve users. Doing so will require new approaches to combined product formation, not just in terms of methodology but also in terms of cooperation among the observing techniques and IERS components. We offer a roadmap of proposed actions which are intended to provoke discuss and stimulate change towards the IGGOS goals.

1 Current status of IERS combinations

1.1 ITRF

- ITRS Center uses the covariance matrices or reduced normal equations provided in SINEX format by various analysis centers (ACs)
- consists of geocentric coordinates and velocities for ~800 stations at ~500 sites
- IGS is the only Technique Center providing a single-technique combined solution
- there are no combined technique solutions from the ILRS, IVS, or IDS
- all other solutions come directly from IAG technique ACs or from other groups; two use multiple satellite techniques (SLR + DORIS, SLR + DORIS + PRARE)
- ITRF2000 combination was rigorous using linear site motions (with some discontinuities included)
- ITRF2000 accuracy is (over 10 years):
  - ~0.5 ppb (3 mm) in global scale
  - ~1.5 mm in x,y geocenter and ~4 mm in z geocenter (long-term)
  - ~2 mm/yr in realizing global no-net-rotation
  - ~2–5 mm for 3D site coordinates globally
  - ~0.5–2 mm/yr for 3D site velocities globally
- ITRF2000 weaknesses:
  - SLR and VLBI networks are globally sparse and poorly distributed (especially in the southern hemisphere)
  - VLBI network is only observed in subnets that are connected via common stations and the assumption of linear site motions
  - number and distribution of multi-technique collocation sites is insufficient; many collocations involved mobile SLR and VLBI sites that have been discontinued
  - important collocation vector ties are missing or of dubious quality
  - uncompensated systematic errors exist between techniques
  - non-linear site motions can only be handled as discontinuities (e.g., coseismic earthquake shifts but not slow post-seismic motions)
  - non-linear geocenter motion not handled
  - NNR-NUVEL-1A inadequate as rotational reference datum

- reliable metadata for site histories and changes is becoming unwieldy and very difficult to maintain (especially for GPS sites)

1.2 ICRF

- formed from a single VLBI AC solution (using a consensus analysis strategy) for radio sources observed through July 1995
- consists of right ascension and declination coordinates in a barycentric inertial frame for 212 defining, 294 candidate, 102 other, and 59 new sources (added in ICRF-Ext.1)
- ICRF-Ext.1 provides improved positions for the candidate and other sources, with 59 new sources, by adding data from December 1994 thru April 1999
- ICRF weaknesses:
  - formal errors were derived by quadratic addition of an empirical error floor (0.25 mas)
  - correlations only available between coordinates of individual radio sources, not rigorously for the entire frame
  - maintenance with extension catalogues using an updated VLBI solution does not ensure rigorous consistency
  - systematic errors not fully evaluated
  - motions of brightness centers not handled, although auxiliary information is available for most sources
  - exists only for X-band (~8.4 GHz) frequency; Hipparcos catalogue is a realization for optical, but is degrading with time
  - extensions to other frequencies under consideration

1.3 EOPs

- Product Centers use time series of values and errors provided by various ACs (complete correlations not used)
- consist of polar motion (x,y), UT1–UTC, and nutation offset values at daily intervals
- IGS is the only Technique Center providing a single-technique, rigorously combined solution
- new combined time series solution issued by the IVS, but is not rigorous, does not use cross-correlations, and is not fully consistent with ITRF
- combined SINEX solution under development by the ILRS
- other solutions come directly from IAG technique ACs or from other groups
- atmosphere angular momentum (AAM) forecast products used for Rapid Service UT1 predictions
- EOP observational accuracies are (with ~1 d delay):
  - ~0.1 mas for daily polar motion (but consistency with ITRF is only about 0.25 mas)
  - ~0.02 ms (0.3 mas) for daily UT1–UTC
  - <0.3 mas for daily nutation offsets (with IERS model)
- IERS EOP weaknesses:
  - EOP combination performed separately from ITRF and not rigorously
  - important VLBI network effects (due to sparse, non-global extent of subnets) cannot be evaluated or handled properly
  - some SLR results seem to rely on implicit smoothing over intervals longer than 1 d and usually use only 1 or 2 satellites in operational solutions
  - uncompensated systematic errors exist between techniques
  - for these reasons, IERS EOP series is not consistent with ITRF at the current level of measurement accuracies

- accuracy of IERS combination apparently not as good as for IGS GPS-only solution [e.g., Ponte and Ali, GRL, 29(15), 2002]

1.4 Global Geophysical Fluids Center (GGFC)

- no combinations or comparisons are performed at this time
- weaknesses:
  - products not fully available for important components
  - often long delays in availability
  - accuracy of available products difficult for users to assess
  - lack of combinations/comparisons hinders some product evaluations by users
  - explicit reference to data sources and explanatory documentation are often not fully clear

1.5 Combination Research Centers (CRCs)

- CRCs pursue independent research objectives
- not directly involved in current IERS product formation
- weaknesses:
  - research efforts not well coordinated and poorly directed to improve IERS products
  - role of CRCs in IERS is not well defined
  - no established mechanism for research gains to be transferred to operational Product Centers
  - results from CRCs not well publicized

1.6 Overall observations

- IERS products currently not sufficiently self-consistent and not always as accurate as possible
- thermal (SNR) measurement noise is rarely significant
- systematic errors seem to dominate in all techniques and products (e.g., antenna effects in VLBI and GPS; station ranging errors in SLR; collocation tie errors)
- current lack of self-consistency makes it more difficult to study and mitigate systematic errors

2 General goals for future improvements

2.1 Idealized IGGOS concept

- aim for a fully Integrated Global Geodetic Observing System (IGGOS)
- to provide users with:
  - highest spatial and temporal resolution
  - global coverage
  - highest accuracy and precision
  - fully and rigorously self-consistent, with complete covariance information
  - robust, reliable, and long-term stable system
  - convey all relevant geodetic parameters in a fully 4D reference system (with time/frequency)
  - must include reliable catalogues and other metadata
  - easily and widely accessible
  - real-time enabled
  - with comprehensive, user-friendly access tools
  - minimize costs by improving efficiencies

2.2 Non-ideal reality

- no single observing technique is adequate
- must use an assemblage of independent techniques, each with its own sensitivities and errors
- combine results optimally to maximize strengths and minimize weaknesses
- mix is dynamic because techniques continue to evolve
- collocated techniques are critical and local ties must be accurately known
- try to achieve IGGOS goals and satisfy most users

2.3 Combination objectives

- handle diverse results derived from independent data types
- systematic and random errors must be evaluated and adequately handled in combination
- must recognize temporally varying characteristics
- appropriate weighting strategies must be developed; they must be dynamic
- develop combination methods that are as rigorous as possible
- recognize possible subtle effects of excluded parameters (e.g., satellite orbits which may convey implicit constraints) – a very difficult but probably important aspect
- consider how to include non-traditional and new observing techniques (altimetry, gravity/geoid, InSAR, ...)
- output homogeneous, regularized user products
- provide reliable error assessments
- combination results should be studied to provide feedback to observing techniques for potential improvements
- service gaps and weaknesses should be identified and filled

3 Expected strengths of contributing techniques

VLBI

- ICRF (only technique)
- celestial pole (only technique)
- UT1–UTC (only technique)
- ITRF scale and scale-rate
- EOP secular rates

SLR

- geocenter motion and ITRF origin (aligned to secular geocenter)
- ITRF scale and scale-rate
- EOP secular rates
- gravity field
- ~LOD (must account for time-varying biases)

GPS

- ITRF densification (best technique)
- polar motion (best technique)
- easy global access to ITRF via IGS orbits (best technique)
- LOD (must account for time-varying biases)
- geocenter motion (may include orbit modelling effects)

DORIS

- highly uniform global ITRF network coverage
- geocenter motion (may include orbit modelling effects)

VLBI + SLR + GPS + DORIS + ties

- ITRF coordinates and velocities

Gravity/geoid

- gravity field, geoid, and their variations
- not yet well integrated with IERS products

InSAR

- high-resolution crustal deformations
- not yet integrated with IERS products

Altimetry

- sea surface height (soon, ice surface too)
- not yet integrated with IERS products

4 Proposed roadmap for future IERS combinations (assumes IGGOS concept)

4.1 Improve VLBI observing network

- most observing sessions use very few stations with sub-global coverage
- global VLBI TRF combination and EOPs depend very sensitively on relatively few common stations and assumption of linear site motions
- causes significant time-varying systematic EOP errors
- can cause systematic errors in TRF scale-rate and EOP secular rates that are very difficult to evaluate
- should try to observe Earth satellites to improve frame ties

ACTION IVS-1:

The IVS is strongly urged to implement regular observing networks with the largest possible number of stations and global extent. It is also highly desirable to develop the capability of observing Earth-orbiting satellites. (ASAP)

4.2 Improve collocations and local ties

- the current IERS reference system is limited in large part by the distribution and quality of inter-technique collocation sites
- many collocations involved mobile SLR and VLBI sites that have been discontinued

- focussed attention is needed to improve the number and distribution of collocation sites and the reliability of collocation ties
- tie problems within technique measurement systems must also be recognized and improved
- greatest effort should be expended on improvements that are likely to yield the greatest improvement in quality and reliability of IERS products
- "satellite collocations", where different techniques observe the same spacecraft, can also improve frame ties if the satellite sensor eccentricities are accurately known

ACTION IERS-1:

The IERS is asked to establish an inter-Service working group to evaluate the number and distribution of inter-technique collocation sites, as well as problems with ties. A new IERS Collocation Coordinator should chair this WG with overall responsibility for global network issues. The WG should make specific recommendations designed to improve the global reference system. (ASAP)

4.3 Improve analysis for station heights/TRF scale

- a wide variety of effects impact the estimation of station heights, more so than horizontal positioning
- these include effects internal to the individual techniques (e.g., antennas) as well as external (e.g., geophysical displacements)
- technique Services should ensure that all significant internal effects are properly modelled in raw data reductions
- consistent treatment of external effects is required across all techniques to ensure meaningful combinations
- the ITRF scale and scale-rate can be sensitively affected
- improvements require coordinated and consistent actions by all the techniques and the IERS

ACTION IERS-2:

The IERS Analysis Coordinator and Conventions Center should clarify which effects should be handled in the internal data reductions of the individual techniques (e.g., tropospheric modeling) and which should be handled a posteriori at the combination level. This is vital to ensure meaningful multi-technique combinations. Ideally, those geophysical effects which deform the Earth around a site with periods less than the combination period should be included in the lowest-level data analysis. As a practical matter, it may not be feasible to include displacements that cannot be accurately predicted apriori using a closed-form analytic expression. Regardless, the SINEX format should permit full documentation of which corrections have been applied. (1 March 2003)

ACTION GGFC-1:

The GGFC should begin to distribute estimates of the time-varying local station displacements due to global fluid changes based on all known effects. Ideally, the results should be made available in a timely way to facilitate use with space geodetic results (subject to the conventions recommended in #IERS-2). A global gridded format will probably be required but it should be suited to merging with geodetic results in SINEX format. (1 December 2003)

ACTION IVS-2:

The IVS ACs are strongly urged to account for mechanical, gravitational, and thermal deformations of the VLBI antennas in results for station heights. (ASAP)

ACTION IGS-1:

The IGS needs to improve the tracking of equipment changes at GPS stations, especially changes that affect apparent station height. Rigid recommendations are needed for how to accomplish such changes with minimal impact. Particular attention needs to be paid to antenna-related effects and the use/change of radomes. (ASAP)

ACTION IGS-2:

Improved methods for handling the effects of non-ideal GPS satellite and receiver antenna patterns are needed. Until this can be done satisfactorily, the GPS TRF scale cannot be regarded as independently reliable. (ASAP)

ACTION ILRS-1:

The ILRS is urged to work with its ACs to implement methods to minimize the effects of errors in SLR tracking station ranging biases. (ASAP)

4.4 Produce combined single-technique EOP + TRF solutions

- rigorously combined, complete, single-technique solutions are needed from all Services, at least for EOPs + TRF
- IAG Services are the technique "experts"
- single-technique combinations should provide highest reliability and essential quality control
- problems are exposed and (hopefully) resolved by Services
- metadata is maintained, checked, and verified by Services
- "analysis noise" can be attenuated
- IGS meets this goal already
- further progress awaits ILRS, IVS, and IDS combined solutions

ACTION ILRS-2/IVS-3:

The ILRS and IVS should begin to produce combined EOP + TRF solutions no later than 1 July 2003. Results should be distributed using the SINEX version 2.00 format and should be updated in a regular operational mode. The IERS Analysis Coordinator should resolve any outstanding issues raised by the Services related to parameterizations, formatting, etc. Site coordinates should assume linear motions (except for discrete discontinuities) and EOP variations should be modelled with 1-day resolution (assuming the IERS subdaily EOP model) including offsets and rates with no constraints (or removable) between arcs.

ACTION CRC-1:

Suitable methods are needed to combine large multi-technique EOP + TRF solutions efficiently. Care must be taken to recognize systematic errors/differences among techniques and to attenuate their effects. This is most serious when combining LOD results from satellite techniques. But excluded parameters (especially orbits) may also be important and should be considered. In addition, it is necessary to study how best to perform both global (for TRF coordinates and velocities) and time series combinations (for EOPs and station residual motions). The available AC SINEX solutions can be used until technique combinations are ready. (1 October 2003)

4.5 Study and resolve IERS role in monitoring geocenter motion

- periodic and non-periodic motions of the Earth's total center of mass are well established w.r.t. the ITRF origin
- however agreement among the satellite techniques has not been impressive
- orbit modelling effects have been significant
- a better understanding of the performance of each technique is needed in order to form suitable combined products for users

ACTION IERS-3:

The IERS Working Group on the ITRF Datum and the GGFC are asked to work with the technique Services to clarify the current quality of geocenter results. Based on this analysis, recommendations are sought on the utility of geocenter combinations and approaches to user product formation. (in 2003)

4.6 Study CRF combinations

- a rigorous combination of individual VLBI solutions for the radio source coordinates should be developed and evaluated
- differences among analysis software and strategies should be understood as far as possible
- improved approaches for maintaining the ICRF need to be developed
- the impact of combining with satellite-based results, including EOP + TRF information, should be investigated

ACTION CRC-2/IVS-4:

The IVS and CRCs should begin to study how best to form CRF combined solutions and to use these with results from other techniques. (in 2003)

ACTION IERS-4/IVS-5:

Based on study results, the ICRS Center and IVS should prepare a brief report for the IERS on how best to maintain the ICRF in the future.

4.7 Evaluate SINEX combinations versus single reductions

- reduction of multi-technique data at the observation level has been proposed as an alternative to inter-technique SINEX combinations
- reported results are inconsistent with expectations and intuition
- this idea should be tested quantitatively and evaluated

ACTION CRC-3:

The IERS CRCs should critically evaluate the utility of single multi-technique solutions at the observation level (by FFI and others) as a realistic alternative to SINEX combinations. The results should be documented and reported to the IERS. (1 August 2003)

4.8 GGFC and gravity combinations

- the geophysical effects that cause surface displacements and gravity field changes need to be evaluated quantitatively and the results made readily available, preferably in a form easily used with SINEX-format geodetic results
- ideally, it would be desirable to use an aggregate of GGFC results to "correct" combined geodetic results to obtain improved results for EOPs (for instance)

ACTION CRC-4:

The GGFC and CRCs need to consider how the joint use of geodetic and geophysical information can be done efficiently and effectively. A report on suggestions and recommendations is requested. [See also #IERS-2 and #GGFC-1] (1 January 2004)

4.9 Produce combined multi-technique EOP + TRF solutions

- IERS should strive to routinely produce rigorous multi-technique solutions as soon as possible, at least for test and evaluation purposes
- if SLR and VLBI combined solutions are not available, then AC solutions should be used instead

ACTION IERS-5:

The IERS should begin to distribute rigorously combined EOP + TRF products, at least in test/evaluation mode, by 1 January 2004.

5 Summary of recommended actions

5.1 Improve observing networks

IVS-1:

The IVS is strongly urged to implement regular observing networks with the largest possible number of stations and global extent. It is also highly desirable to develop the capability of observing Earth-orbiting satellites. (ASAP)

IERS-1:

The IERS is asked to establish an inter-Service working group to evaluate the number and distribution of inter-technique collocation sites, as well as problems with ties. A new IERS Collocation Coordinator should chair this WG with overall responsibility for global network issues. The WG should make specific recommendations designed to improve the global reference system. (ASAP)

5.2 Improve station heights/TRF scale

IERS-2:

The IERS Analysis Coordinator and Conventions Center should clarify which effects should be handled in the internal data reductions of the individual techniques (e.g., tropospheric modelling) and which should be handled a posteriori at the combination level. This is vital to ensure meaningful multi-technique combinations. (1 March 2003)

GGFC-1:

The GGFC should begin to distribute estimates of the time-varying local station displacements due to global fluid changes based on all known effects. Ideally, the results should be made available in a timely way to facilitate use with space geodetic results. A global gridded format will probably be required but it should be suited to merging with geodetic results in SINEX format. (1 December 2003)

IVS-2:

The IVS ACs are strongly urged to account for mechanical, gravitational, and thermal deformations of the VLBI antennas in results for station heights. (ASAP)

IGS-1:

The IGS needs to improve the tracking of equipment changes at GPS stations, especially changes that affect apparent station height. Rigid recommendations are needed for how to accomplish such changes with minimal impact. Particular attention needs to be paid to antenna-related effects and the use/change of radomes. (ASAP)

IGS-2:

Improved methods for handling the effects of non-ideal GPS satellite and receiver antenna patterns are needed. Until this can be done satisfactorily, the GPS TRF scale cannot be regarded as independently reliable. (ASAP)

ILRS-1:

The ILRS is urged to work with its ACs to implement methods to minimize the effects of errors in SLR tracking station biases. (ASAP)

5.3 Produce and evaluate combined solutions

ILRS-2/IVS-3:

The ILRS and IVS should begin to produce combined EOP + TRF solutions using SINEX-2.00. (1 July 2003)

CRC-1:

Suitable methods are needed to combine large multi-technique EOP + TRF solutions efficiently. Care must be taken to recognize systematic errors/differences among techniques and to attenuate their effects. This is most serious when combining LOD results from satellite techniques. (1 October 2003)

IERS-3:

The IERS Working Group on the ITRF Datum and the GGFC are asked to work with the technique Services to clarify the current quality of geocenter results and to report recommendations on future geocenter combinations and products. (in 2003)

CRC-2/IVS-4:

The IVS and CRCs should begin to study how best to form CRF combined solutions and to use these with results from other techniques. (in 2003)

IERS-4/IVS-5:

Based on study results, the ICRS Center and IVS should prepare a brief report for the IERS on how best to maintain the ICRF in the future. (in 2003)

CRC-3:

The IERS CRCs should critically evaluate the utility of single multi-technique solutions at the observation level (by FFI and others) as a realistic alternative to SINEX combinations. The results should be documented and reported to the IERS. (1 August 2003)

CRC-4:

The GGFC and CRCs need to consider how the joint use of geodetic and geophysical information can be done efficiently and effectively. A report with recommendations is requested. (1 January 2004)

IERS-5:

The IERS should begin to distribute rigorously combined EOP + TRF products, at least in test/evaluation mode. (1 January 2004)

Table 1 Action timeline

Month	Events	High Priority Tasks	Other Tasks
ongoing in 2003 …			VLBI antenna modeling (IVS-2)
… …			GPS metadata tracking (IGS-1)
… …			GPS antenna modelling (IGS-2)
… …			minimize SLR range biases (ILRS-1)
… …			update on geocenter motions (ILRS-3)
… …			study CRF combinations (CRC-2/IVS-4)
… … …			report on CRF maintenance (IERS-4/IVS-5)
Nov 2002 …	IERS Workshop	Collocation WG and Coordinator (IERS-1)	
Dec …	Fall AGU Meeting		
Jan 2003 …			larger VLBI networks (IVS-1)
Feb …			
Mar … …		specify internal/external model effects (IERS-2)	
Apr …	EGS/AGU/EUG		
May ...			
Jun ...			
Jul …	23rd IUGG GA 25th IAU GA	Combined EOP+TRF solutions (ILRS-2/IVS-3)	
Aug … …			evaluate single multi-technique solution (CRC-3)
Sep …			
Oct … …		Multi-technique EOP+TRF combination methods (CRC-1)	
Nov …			
Dec …	Fall AGU Meeting	GGFC displacements (GGFC-1)	
Jan 2004 … …		IERS combined EOP+TRF products (IERS-5)	evaluate geodetic+GGFC combinations (CRC-4)

Combination of Multi-Satellite Techniques at the Observation Level

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Section 1.2 “Development and Operation of Satellite Mission”

1 Introduction

Satellite techniques are very important for the IERS products EOP (incl. nutation) and terrestrial reference frame (station coordinates and their velocities). Currently the results from various satellite techniques are combined together at the normal equation level. The only link between them are the local ties of the collocation sites. For some years now, however, quite a number of satellites have been launched, which are equipped with instruments of more than one technique. In this paper we call it ‘collocation (of multi-techniques) on board satellites‘. Examples are: GPS35 and GPS36 (GPS sender + SLR); ENVISAT (SLR + DORIS); Jason and T/P (GPS receiver + SLR + DORIS); CHAMP and GRACE (GPS receiver + SLR). In order to fully exploit on-board collocation, combination at the observation level is necessary.

The laser reflector on board the GPS 35 and 36 satellites have proved to be useful for detecting systematic errors between the two systems. Combining the two data types at the observation level helps to improve the solution slightly, as shown in (Zhu et al. 1997). But the amount of SLR data available is far from enough to do this on a routine basis.

T/P is a different example. A few institutes have used both SLR and DORIS tracking data for the orbit restitution. In this case, these two techniques have already been combined at the observation level. As the adjustment is done with SLR and DORIS data simultaneously, the correlation block between SLR and DORIS stations of the comprehensive covariance matrix is non-zero after the reduction of the dynamical orbit parameters. This provides a strong link between the two systems, and it plays a role as a complement to the ground collocation.

GPS receiver on board LEO satellites is a very important development. For the routine orbit determination of CHAMP and GRACE, a so called ‘two-step’ method is adopted. First, GPS data from ground stations are used to determine the orbits of the GPS satellites, then they are fixed in order to restitute the LEO orbit by the on-board GPS data. The ‘one-step’ method, by contrast, is to combine the ground and on-board data together at the observation level and determine simultaneously the orbits of the LEO and GPS satellites, together with the EOP and station positions. The geocenter and scale are weak points of the GPS (ground) solutions, see Zhu et al. (2002). As a LEO satellite is much lower than GPS satellites, it is much more sensitive to the gravity field, including the first degree terms (i.e. geocenter). Tropospheric zenith delays (TZD) need not to be solved. For ground stations, TZP are highly correlated with the height. This is one of the major reasons why the scale of the GPS terrestrial system is not stable. These weaknesses of the GPS technique could be improved by LEO missions. LEOs form a middle altitude layer. Together with ground layer and GPS high altitude layer, this three layers construction makes the GPS solutions more robust and consistent, see Rothacher (2003). This structure also improves the LEO orbits (accordingly the gravity solutions), as can be seen in the tests of the next section.

A more comprehensive case is to combine LEO and ground GPS data together with other observation types, such as SLR and DORIS. In order to do this combination effectively, some difficulties needed to be overcome, e.g. the arc length problem. GPS ground data processing adopts 1–2 day arc length due to the CPU time and the large amount of unknowns. But such short arc lengths are not sufficient to determine SLR and/or DORIS site positions with adequate accuracy.

Above are only a few examples of the on board collocation pattern. With the increasing number of LEOs, the method of combination at the observation level will become more and more important.

2 Test results

In this section a few test results are given in order to show the improvements brought by the method of combination at the observation level. We take the GRACE twin-satellites as an example. The software EPOSOC of GFZ is used.

The results of two 1.5-day arcs are given in Table 1. The values given in the second row are from the two step method. GPS data from more than 40 ground sites are used to compute the GPS orbits and clock corrections; then GRACE GPS data are used to compute the GRACE orbits. In this run SLR, K-band range and range rate data are used only for quality control, and do not play a role in the adjustment. The corresponding results of the one step solutions are shown in the third row. From these numbers one sees clearly the benefit brought by the one step method. Actually, in the two step method, the orbits of grace A and B are independently solved, there is no correlation between the two normal equations. But in the latter case, the orbits are correlated, similar as the coordinates of two neighbouring ground stations. This correlation reduces the uncertainty of the orbit differences between GRACE A and B, and thus improves significantly the residuals of K-band data. The quality of the absolute orbit positions, as judged by the SLR residuals, is also improved, but not so drastically. For the gravity solution the improvement of the relative position between two satellites is of substantial importance.

The one step method is not only profitable for GRACE orbits, but the GPS orbits and GPS reference frame are improved, too. For instance, comparing the GPS orbits of the two step method with IGS orbits, the rms difference was about 6 cm, while that of the one step was 5 cm. If data from more LEO are used, the improvement could be more significant.

In the last row of Table 1 the orbits were restituted by using also the GRACE SLR data. This is a complete combination at the observation level. About one hundred SLR data per day are available, less than 1% of the GPS data amount (of the GRACE). Therefore the improvement is small. But the trend is as we expected.

Table 1 Comparison of various processing methods (rms residuals).
arc 1 (020503.0h–020504.12h) / arc 2 (020504.12h–020506.0h)

	K-band Range cm	Range Rate mm/s	SLR cm
2 step	1.55 / 1.88	.0129 / .0188	4.89 / 4.21
1 step	.823 / 1.327	.00632 / .00954	4.05 / 4.09
1 step + SLR	.799 / 1.325	.00599 / .00950	3.70 / 1.47

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Zhu, S.Y., Reigber, Ch., Kang, Z., Apropos laser tracking to GPS satellites. Journal of Geodesy, vol. 71, pp. 423–431, 1997

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On Systematic Differences in Individual Solutions and IERS Products

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1 Present status

Proper determination, modelling, and accounting for systematic differences between contributed series is of the great importance in compilation of the IERS products. In this paper some problems in handling of systematic differences are discussed and possible improvements of commonly used procedures are proposed.

Possible sources of systematic differences are:

- Different reference systems (e.g. TRF, CRF, geopotential, time scale).
- Different models (e.g. short-term EOP variations, ocean loading, atmospheric pressure, VLBI antenna thermal deformations, pole tide).
- Different strategy of parameter estimation (e.g. atmosphere gradients, seasonal variations, constraints).
- Different data set (e.g. Lageos, Lageos 1&2, Lageos&Etalon).
- Dependence on a priory values of estimated and non-estimated parameters (mainly for satellite techniques).
- Technique-related errors (e.g. network configuration in VLBI, short-term periodic terms in EOP obtained with satellite techniques).
- Errors in software.

Analysis of individual EOP, TRF and CRF series shows that systematic differences between them often are much more complicated than it is supposed in most of commonly used combining procedures:

- Systematic differences between individual TRF and CRF solutions modelled as simple rotation/translation(/scaling) model depend on subset of stations/sources used for comparison, they differ for geographical regions (TRF) and parts of celestial sphere (CRF).
- Different models of pole tide, daily and subdaily EOP variations, atmospheric loading used in individual series produced by various ACs cause systematic differences in (mainly) pole coordinates.
- Results of determination of station coordinates and velocities depend on parameterisation used during computation. In particular, final station positions depend, sometimes heavily, on including seasonal variations in the estimation procedure.
- Differences between EOP and TRF time series show, almost in all cases, seasonal variations caused mainly by different modelling of various geophysical effects and sometimes by different astronomical models.
- Long-time term mutual trends between individual EOP series are mostly non-linear.

2 Models of systematic differences

2.1 EOP

Linear trend
Most commonly used, but not appropriate for most cases.

Linear trend + seasonal variations
More adequate, but not always appropriate for long-time series.

Optimal model
Non-linear trend + periodic terms determined from spectral/covariance analysis.

2.2 TRF

Linear translation-rotation-scaling model
Commonly used, but not appropriate for all cases.

Optimal model
Piece-wise coordinate / velocity model; regional deformations determined from analysis of 2D or 3D difference field.

2.3 CRF

Slope-rotation-scaling model
Seems not adequate for local / regional deformations.

Optimal model
To be advanced. Optical astrometry and TRF combination techniques with appropriate modifications can be used for compiling ICRF “Fundamental Catalog”.

3 Conclusions

- Advanced models of systematic errors in input EOP/TRF/CRF time series/catalogues based on adequate models of long term variations (including discontinues) and covariance analysis of discrepancies fields should be implemented.
- Individual combined EOP+TRF(+CRF)(+GP) solutions should be used for compilation of ITRF and ICRF, however all EOP solutions routinely submitted to the IERS should be computed in fixed ITRF and ICRF which should be timely updated for new stations, sources, and events.
- More detailed description of input solutions is needed (corresponding IERS questionnaire and/or SINEX format should be extended).
- All non-conventional models used by ACs should be tested (by authors or coordinators) for systematic differences of results with conventional models.

Acknowledgments

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Numerical Aspects of Combination at the Observation Equation and Normal Equation Level

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1 Introduction

During combination work for an TRF, the DGFI obtained normal equations which caused numerical difficulties. We presume that these problems have their origin in reduced parameters (clock offsets in the case in point) which were given an insufficient approximate value of zero – most likely, as the observation equations are linear with respect to these parameters. The author of the normal equations was not aware of this problem, as he himself worked with the unreduced observation equations.

These circumstances drew our attention to the numerical differences between normal and observation equations, and particularly to the equilibrium of the parameter corrections.

2 Notation

Denote measurement and modelling by $m+\delta m = f(p)+\delta f(p)$, where $m, \delta m \in \mathbf{IR}^m$ are the vectors of measurement results and measurement errors, $f, \delta f \in \mathbf{IR}^m$ are the model function and model error, and $p \in \mathbf{IR}^n$ is the vector of the unknown parameters. A linearization with approximate value $p^{(0)}$ introduces a linearization error $\delta l(p, p^{(0)})$ of the order of $(p-p^{(0)})^2$.

All three types of errors are combined in the a priori error vector $e(p^{(0)}) = \delta f(p) - \delta m + \delta l(p, p^{(0)})$. The residuum "observed − computed" is loosely called the observation vector $b = [f(p) - f(p^{(0)})] + [\delta f(p) - \delta m]$. These elements comprise a system of observation equations

$$b - e(p^{(0)}) = f(p) - f(p^{(0)}) - \delta l(p, p^{(0)}) = \frac{\partial f}{\partial p}(p^{(0)})(p - p^{(0)}) = Ax \qquad (1)$$

The notation is summarized thus: the **linearized observation equations** or error equations denoted by Ax = b–e, the **normal equations** denoted by Nx = y with N = $A^T PA \in \mathbf{IR}^{n\times n}$ and $y = A^T Pb \in \mathbf{IR}^n$. Given any solution $\hat{x}$, we determine

- the estimated parameters: $p^{(1)} = p^{(0)} + \hat{x}$
- the a posteriori error vector:
  $e(p^{(1)})$ or $e(\hat{x}) = b - A\hat{x} = f(p) - f(p^{(1)}) + \delta f(p) - \delta m + \delta l(p^{(1)}, p^{(0)})$
- the weighted sum of squares of the residuals or, mathematically speaking, the **error norm**:
  $\|e(p^{(1)})\|_P^2 = e(p^{(1)})^T P e(p^{(1)})$.

3 Sensitivity of the Least Squares Problem

Let $\tilde{x}$ and $\tilde{e}(\tilde{x})$ be the solution of the perturbed least squares problem

$$\|\tilde{e}(x)\|_P = \|\tilde{b} - \tilde{A}x\|_P = \min$$

with the components $\tilde{A} = A + \delta A$ and $\tilde{b} = b + \delta b$. How do the perturbations δA and δb influence the solution of the linear least squares problem?

Under the precondition of rank conservation, $rg(A+\delta A) = rg(A)$, it holds (Golub and Wilkinson, 1969):

$$\|\tilde{x} - x\|_2 \le \frac{cond(A)}{1-\varepsilon} \cdot (\alpha \|x\|_2 + \beta) + \left(\frac{cond(A)}{1-\varepsilon}\right)^2 \cdot \alpha \frac{\|e(x)\|_P}{\|A\|} \qquad (2)$$

$$\|\tilde{e} - e\|_P \le \|\delta A\| \cdot \|x\|_2 + \|\delta b\|_P + \frac{cond(A)}{1-\varepsilon} \cdot \alpha \|e(x)\|_P \qquad (3)$$

$$\text{with } \alpha := \frac{\|\delta A\|}{\|A\|}, \quad \beta := \frac{\|\delta b\|}{\|A\|}, \quad \varepsilon := \frac{lub(\delta A)}{glb(A)} < 1. \qquad (4)$$

For $\|e(x)\|_P > 0$, it is the term with $cond(A)^2 \|e(x)\|_P$ in equation (2) which is the most important. In addition to the condition number of the weighted design matrix it depends on the consistency of the linearized observation equations.

It is well known that the solution of a least squares problem by means of normal equations is not as stable as a direct inversion of the design matrix by orthogonalization methods. Moreover, the calculation of the error norm ($\|e(\hat{x})\|_P^2$) from the norm of the observation vector ($b^T Pb$ or "$l^T Pl$") is a technical error. These statements do not hold in an unlimited way!

The relation between the norms of the observation vector and the a posteriori error vector can be written as

$$\|e(p^{(1)})\|_P^2 = e(p^{(1)})^T Pe(p^{(1)}) = b^T Pb - y^T \hat{x}.$$

This subtraction produces numerical cancellation of mantissa digits! If observation equations are available, the error norm can be calculated by inserting the solution $\hat{x}$ into the equations and summing up – a time-consuming but sure procedure. If normal equations only are the basis for calculation, then the latter formula is unavoidable. Such is the case for the ITRF combination, where only normal equations or solutions, which allow the reconstruction of the normal equations only, are available. Thus, we want to know the conditions for the mantissa being numerically cancelled in the latter difference. For this reason, we investigate the effect of poor approximate values on the solution and its error bounds.

4 Effects of Unbalanced Approximate Values

Let a subset of the unknown parameters $\{p_j : j \in J\}$ with index $J \underset{\neq}{\subset} \{1, 2, \ldots, n\}$, and a significant influence on the system of equations, have approximate values substantially worse than the remaining parameters. It will be shown that, for this case, the formulas for

- the calculation of the error norm from the norm of observation vector,

- a transformation to suitable approximate values, and
- the reduction of the parameters with poor approximate values

are subject to numerical cancelling of the mantissa. The presentation method used consists in comparing a well-balanced least squares problem with a perturbed problem, which results from the good one in such a way that the approximate values of the parameters $\{p_j : j \in J\}$ are tampered with a relatively large value Δp_j:

$$\begin{matrix} \tilde{p}^{(0)} = p^{(0)} - \Delta p \\ \\ \tilde{x} = x + \Delta p \end{matrix} \quad \text{with} \quad \left\{ \begin{matrix} |\Delta p_i| > \max_k |x_k| & for\ i \in J \\ \\ \Delta p_i = 0 & for\ i \notin J \end{matrix} \right\}$$

The unperturbed system of equations, $Ax = b - e$, is assumed to be consistent, balanced in x and b, and near-linear with respect to the parameters $\{p_j : j \in J\}$. For ease of notation, these equations, for which the parameters $\{p_j : j \in J\}$ provide a numerically not vanishing contribution, are placed at the beginning of the system.

$$\begin{matrix} k = 1, 2, \ldots, m_1 \le m: & \left| \sum_{j \in J} A_{kj} \Delta p_j \right| \ge \varepsilon > 0 \\ k = m_1 + 1, \ldots, m: & \left| \sum_{j \in J} A_{kj} \Delta p_j \right| \approx 0 \end{matrix} \tag{5}$$

The first m_1 equations are written as $A_1 x = b_1 - e_1$, and the remaining $m_2 = m - m_1$ equations as $A_2 x = b_2 - e_2$. In addition, we assume b_1 and b_2 to be uncorrelated.

$$A = \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} \begin{matrix} \} m_1 \\ \} m_2 \end{matrix}, \qquad b = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}, \qquad P = \begin{pmatrix} P_1 & 0 \\ 0 & P_2 \end{pmatrix} \tag{6}$$

Now, the terms of the perturbed system shall be represented by those of the unperturbed system of equations. For indices $k = 1, \ldots, m_1$ it holds that

$$\tilde{b}_k = b_k + \sum_{i \in J} A_{ki} \Delta p_i = \left(1 + \frac{b_k}{\sum_{\nu \in J} A_{k\nu} \Delta p_\nu} \right) \sum_{i=1}^{n} A_{ki} \Delta p_{i,}$$

and for the remaining indices, that $\tilde{b}_k = b_k$. Let us introduce δ_k ($k = 1, \ldots, m_1$) by

$$\delta_k := b_k / \left(\sum_{\nu=1}^{n} A_{k\nu} \Delta p_\nu \right) \quad \text{and} \quad \Delta := \operatorname{diag}\left(\delta_1, \ldots, \delta_{m_1} \right)$$

The perturbation must have a significant impact on the system of equations. For that, it is not sufficient to require $|\tilde{x}_j| \approx |p_j| \gg \max_k |x_k|$ but

$$|b_k| = \left| \sum_{i=1}^{n} A_{ki}\, x_i + e_k \right| \ll \left| \sum_{i=1}^{n} A_{ki}\, p_i \right| \qquad (k = 1, 2, \ldots, m_1), \tag{7}$$

where "$\ll$" means a difference in size of several powers of ten. As to the normal equations mentioned in the introduction, a clock offset of 10 microseconds corresponds to a range correction of 3 km, while the station coordinate corrections lay in the range of a few centimetres. Direct consequence of (7) is $|\delta_k| \ll 1$.

Now we have it. The terms of the perturbed observation and normal equations in a decomposition conformable to (6) are written as

$$\tilde{b} = \begin{pmatrix} (I+\Delta)A_1\Delta p \\ b_2 \end{pmatrix}$$
$$\tilde{y} = A^T P\tilde{b} = A_1^T P_1 (I+\Delta) A_1 \Delta p + A_2^T P_2 b_2$$
$$\tilde{b}^T P\tilde{b} = \Delta p^T A_1^T (I+\Delta) P_1 (I+\Delta) A_1 \Delta p + b_2^T P_2 b_2 \tilde{A} = A = \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} \qquad (8)$$
$$\tilde{N} = N$$
$$\tilde{e}(\tilde{x}) = e(x)$$

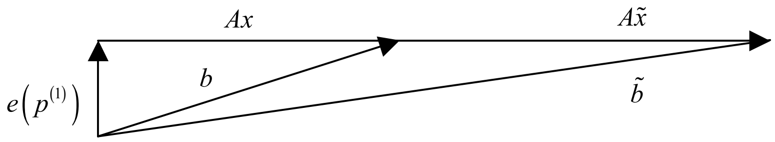
4.1 Calculation of the error norm (with normal equations)

We compare the perturbed with the unperturbed problem. From $\tilde{e}(\tilde{x}) = e(x)$ we get

$$\tilde{y}^T\tilde{x} - y^T x = \tilde{b}^T P\tilde{b} - b^T Pb = (\Delta p)^T \; A_1^T \; (I + 2\Delta) P_1 A_1 \Delta p.$$

Thereby we have shown that the perturbation increases the left as the right term in $b^T Pb - y^T x$ by the same large amount which cancels on performing the difference.

Poor approximate values are the only cause of cancellation. This could be geometrically recognized by



One is tempted to improve the system of equations by transforming it to better approximate values.

4.2 Transformation to suitable approximate values

Let us write the formulas of the transformation of variables $\tilde{x}_j \mapsto x_j$ ($j \in J$), using the representation (8):

$$b = \tilde{b} - A\Delta p = \begin{pmatrix} (I+\Delta)A_1\Delta p \\ b_2 \end{pmatrix} - \begin{pmatrix} A_1\Delta p \\ 0 \end{pmatrix}$$
$$y = \tilde{y} - N\Delta p = A_1^T P_1 (I+\Delta) A_1 \Delta p - A_1^T P_1 A_1 \Delta p + A_2^T P_2 b_2$$
$$b^T Pb = \tilde{b}^T P\tilde{b} - [\,2(A\Delta p)^T P\tilde{b} - (A\Delta p)^T P(A\Delta p)] =$$
$$= \tilde{b}^T P\tilde{b} - (\Delta p)^T A_1^T P_1 (I + 2\Delta) A_1 \Delta p =$$
$$= (\Delta p)^T A_1^T (I+\Delta) P_1 (I+\Delta) A_1 \Delta p - (\Delta p)^T A_1^T P_1 (I+2\Delta) A_1 \Delta p + b_2^T P_2 b_2$$

Since the components of $A_1\Delta p$ are large compared to those of b (see (7)), the right-hand sides of both normal and observation equations likewise suffer from numerical cancellation. For the norm $b^T Pb$, the cancelled digits are twice as many.

4.3 Reduction of parameters with poor approximate values

The variables to be reduced, $\{ x_j : j \in J \}$, are placed at the beginning of the vector:

$$x = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad with \begin{cases} x_1 \in \mathrm{IR}^{n_1}: & \text{variables to be reduced,} \\ x_2 \in \mathrm{IR}^{n_2}: & \text{variables to be preserved.} \end{cases}$$

The corresponding partitioning of columns of the design matrix leads to a refinement of the partition (6) :

$$A = \begin{pmatrix} A_{11} & A_{12} \\ \underbrace{0}_{n_1} & \underbrace{A_{22}}_{n_2} \end{pmatrix} \begin{matrix} \} & m_1 \\ \} & m_2 \end{matrix}, \quad \Delta p = \begin{pmatrix} \Delta p_1 \\ 0 \end{pmatrix} \begin{matrix} \} n_1 \\ \} n_2 \end{matrix}$$

The submatrix A_{21} vanishes, because parameters from $\{ p_j : j \in J \}$ are per definition not included in these observation equations. For x_1 being reducible, the existence of the pseudoinverse $A_{11}^{+} = \left(A_{11}^T P_1 A_{11} \right)^{-1} A_{11}^T P_1$ is a necessary condition. This representation is to be applied on the perturbed systems of equations. Using (8), we get

$$\begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix} = \begin{pmatrix} (I+\Delta) A_{11} \Delta p_1 \\ b_2 \end{pmatrix}, \begin{pmatrix} \tilde{y}_1 \\ \tilde{y}_2 \end{pmatrix} = \begin{pmatrix} A_{11}^T P_1 (I+\Delta) A_{11} \Delta p_1 \\ A_{12}^T P_1 (I+\Delta) A_{11} \Delta p_1 + A_{22}^T P_2 b_2 \end{pmatrix}$$

and $\tilde{b}^T P \tilde{b} = (\Delta p_1)^T A_{11}^T (I+\Delta) P_1 (I+\Delta) A_{11} \Delta p_1 + b_2^T P_2 b_2$.

Finally, the equations to reduce parameters p_j with dominant corrections x_j are written to show the numerical cancellation feature,:

$$\tilde{b}^{red} = \begin{pmatrix} (I+\Delta) A_{11} \Delta p_1 - \left(I + A_{11} A_{11}^{+} \Delta \right) A_{11} \Delta p_1 \\ b_2 \end{pmatrix}$$

$$\begin{aligned} \tilde{y}^{red} &= A_{12}^T P_1 (I+\Delta) A_{11} \Delta p_1 + A_{22}^T P_2 b_2 - \\ &\quad - A_{12}^T P_1 \left(I + A_{11} A_{11}^{+} \Delta \right) A_{11} \Delta p_1 \end{aligned}$$

$$\begin{aligned} \left(\tilde{b}^T P \tilde{b} \right)^{red} &= (\Delta p_1)^T A_{11}^T (I+\Delta) P_1 (I+\Delta) A_{11} \Delta p_1 + b_2^T P_2 b_2 - \\ &\quad - (\Delta p_1)^T A_{11}^T (I+\Delta) P_1 \left(I + A_{11} A_{11}^{+} \Delta \right) A_{11} \Delta p_1 \end{aligned}$$

5 Conclusions

Let us come to a decision between normal equations and observation equations.

At the moment, we can live with normal equations as long as the design matrix A and the observation vector b are sufficiently balanced. The balance depends on the equilibrium of the approximate values. Seriously unbalanced normal equations cannot be repaired afterwards; they must be rebuild from the beginning.

There are still some problems left which might call in question the usability of normal equations. They concern the behaviour of reduced variables and the variance component estimation and the robust estimation methods.

IERS SINEX Combination Campaign

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Abstract: This position paper briefly summarizes the present status and still existing deficiencies regarding the combination of space geodetic techniques concentrating thereby on a rigorous and consistent combination of ITRF, EOP (and ICRF). Further subjects include the intention, goal and setup of the IERS SINEX combination campaign, as well as a list of participants, a summary of the data pool and of the individual solution characteristics. Finally, we propose some future steps in view of the goals of the SINEX combination campaign.

1 Introduction and motivation

The space geodetic observation techniques (e.g. VLBI, SLR/LLR, GPS, DORIS) contribute in a different and unique way to the determination of geodetic parameters (e.g. site positions and velocities, EOPs, atmospheric parameters, gravity field coefficients) and each technique has its strengths and weaknesses concerning the determination of various parameters (e.g. Rothacher, 2000, Angermann, 2002). The goal of the combination is to make optimal use of the complimentary properties of the different techniques. Besides this it has to be considered that the accuracy achieved today is mainly limited by technique-related and/or solution-related systematic effects (biases), which are often poorly characterized or quantified. This can lead to highly optimistic precision estimates that provide too optimistic accuracy expectations. Both, the different characteristics of the various space techniques for determining several parameters and the existing differences between space techniques observations (solutions) strongly require the development of rigorous integration and combination methods. This is of vital importance to exploit the full potential of the space techniques and to provide highly accurate and consistent results.

Currently the IERS products (e.g. ICRF, ITRF, EOPs) are computed (combined) separately by the responsible product centers. Consequently, they are not fully consistent, and not tolerable systematic biases between the different IERS products may exist. To overcome this problem it is necessary to develop suitable combination methods to generate consistent IERS products. To achieve this ambitious goal, the SINEX combination campaign was initiated by the IERS Analysis Coordinator. Objective of this campaign is to combine daily, weekly or monthly solutions from SINEX files of different techniques (VLBI, SLR, GPS and DORIS) with station coordinates and earth orientation parameters (EOPs) and to assess systematic biases between the individual space techniques. Finally, new combination strategies should be developed by the IERS Combination Research Centers (CRCs) and other participating groups. The final goal is that these new combination methods should be implemented by the IERS product centers for the computation of the IERS products.

2 Present status of combination issues and deficiencies

Within IAG a large number of organizations and institutes significantly contribute to the integration and combination of space geodetic observations, such as the IERS, CSTG, and the technique centers (IGS, ILRS, IVS and

IDS). It would exceed the scope of this position paper to review the present status regarding all these different institutes/services and to cover the entire field of combination and integration issues. Therefore we concentrate on aspects that are relevant for the objectives of the SINEX combination campaign and we try to minimize duplications with other sessions of this IERS workshop. We summarize the present status and still existing deficiencies regarding the intra- and inter-technique combination:

2.1 Intra-technique combination

The combination of data (solutions) of the same observation technique is one of the major tasks of the corresponding technique centers.

- The IGS (see http://igscb.jpl.nasa.gov) was established in 1994 with the primary objective to provide products for a wide variety of GPS applications. To fulfil this role IGS computes a large number of different combined products, such as satellite orbits, station and satellite clocks, station positions and velocities, troposphere, etc. on a weekly basis (Weber and Springer, 2002). In addition NRCan combines sets of station coordinates, velocities, EOPs and apparent geocenter positions provided by the analysis centers, to produce the IGS official combined station position and EOP solutions (Ferland, 2002).
- The ILRS (see http://ilrs.gsfc.nasa.gov) was established in 1998 in order to support programs in geodetic, geophysical, and lunar research activities and to provide the IERS with products important for the realization and maintenance of the ITRF. Within the ILRS the Analysis Working Group (AWG) coordinates and stimulates analysis activities. The AWG has initiated a number of pilot projects on "positioning and earth orientation" aimed at the development of an unique and official ILRS product on EOPs and station coordinates/velocities. Besides this, a pilot project aims at the benchmarking of software and analysis procedures in use by the various analysis groups. Recently a call for participation "Positioning & Earth Orientation" for two types of contributions was released: (i) providing individual SLR solutions and/or (ii) the quality control and combination of such individual solutions to an official ILRS product (Noomen et al., 2002).
- The IVS (see http://ivscc.gsfc.nasa.gov) was established in 1999 to support VLBI programs for geodetic, geophysical and astrometric work on reference systems, Earth science research, and operational activities. The responsibilities of the IVS Analysis Coordinator include regular dissemination of high quality EOPs as an official IVS product. In this respect a first pilot project was initiated to compare individual EOP series produced by several IVS Analysis Centers and to achieve a rigorous combination into a single series (Nothnagel and Steinforth, 2002). A second pilot project concentrates on the comparison and combination of EOP on the basis of fixed ITRF2000 station coordinates and ICRF source positions for a period of 2 years (1999–2000). The results of an IVS analysis pilot project on troposphere parameter comparison are very satisfactory (Böhm et al., 2002) and a proposal was announced to make combined VLBI troposphere parameters a regular IVS product.
- The creation of an IDS (see http://ids.cls.fr) was initiated by a DORIS pilot project experiment (e.g. Tavernier, 2000). This scientific service will structure the DORIS community in order to provide scientific products for a broad range of potential users. This will be done in a similar way to what is done in the IGS, ILRS and IVS.

At present, IGS is the only technique center providing a single-technique combined solution with station positions and EOPs. Considering the ongoing activities within the other services, we assume that those will be able to provide these combined solutions in near future.

2.2 Inter-technique combination

Since several years the combination of data (solutions) of different space techniques is done by the responsible IERS product center on a routine basis. A review of the status of combination issues, deficiencies, future recommendations, etc. related to the IERS product centers (responsible for ICRF, ITRF, and EOPs) are subject of separate sessions of this IERS workshop and are described elsewhere in this volume. In this position paper we address some specific aspects that are important for the IERS SINEX combination campaign.

- Currently, the IERS products (ITRF, ICRF and EOPs) are computed (combined) separately by different product centers. Consequently, the results are not fully consistent, e.g., different ITRF realizations produce offsets and drifts in the EOP series (Rothacher, 2000). There is an urgent need to develop optimal methods (and software) for the combination of the relevant parameter types to obtain fully consistent IERS products. This is the main task of the IERS Combination Research Centers and is the final goal of the SINEX combination campaign.
- Systematic effects (biases) between solutions/techniques are one of the major problems and can be considered as a limiting factor for the accuracy of the space geodetic observations. Hence it is an important issue to investigate these differences with regard to several aspects (e.g., modeling, parameterization, software-related aspects, analysis strategies, datum definition) and to identify the source of the existing inconsistencies.
- Concerning the combination methodology more investigations are necessary regarding the level, on which the combination should be performed (e.g., observation level, normal equation level, solution level).
- The current situation regarding co-location sites and the accuracy and availability of the local ties is still not satisfactory. This can be considered one major limiting factor with regard to the consistency and long-term stability of the reference frames and the IERS products. It is important to achieve further improvements regarding co-location sites and local ties, and to study their impact on the combination results.

3 The IERS SINEX Combination Campaign

3.1 Intention and goals of the campaign

The deficiencies in the actual combination processes for ITRF and EOP series mentioned above led to the initiation of a special campaign with the aim of developing new combination strategies with consistent ITRF and EOP (and ICRF) as result. The analysis centers of the different space geodetic techniques or other interested groups are asked to produce solutions with at least station coordinates and EOPs. When solutions of all space geodetic techniques (VLBI, GPS, SLR, DORIS) are available the existing systematic biases between these different techniques can be studied and tried to be solved. As preparation for the combination the individual solutions must be tested with regard to rank deficiencies of the normal equation, the ability of removing the constraints applied to the solution and reconstructing the solution. The experiences of these tests should result in a feedback to the analysis centers. Furthermore, recommendations about common standards of modeling and parameterization in the technique solutions, derived from the combination experiences during this campaign should be compiled and provided to the analysis centers. At the end of the campaign, combined solutions of high quality that can be used as the basis for consistent TRF and EOP series will

Table 1 Participating groups in the IERS SINEX combination

Participants		Step 1	Step 2
AIUB	Urs Hugentobler	*Weekly global GPS (2 series)*	
ASI	Giuseppe Bianco	*Monthly + weekly SLR*	*Combination*
BKG	Volkmar Thorandt, Gerald Engelhardt	*Session VLBI*	
DGFI	Detlef Angermann	*Session VLBI* *Monthly SLR* *Weekly regional GPS*	*Combination*
FESG	Markus Rothacher		*Combination*
FFI	Per-Helge Andersen	*VLBI + SLR solution, combined at the observation level*	
GFZ	Shengyuan Zhu		*Combination*
IGN	Zuheir Altamimi		*Combination*
JCET	Erricos Pavlis	*Monthly + weekly SLR*	*Combination*
NCL	Konstantin Nurutdinov		*Combination*
NRCan	Rémi Ferland	*Weekly global GPS*	*Combination*

be available. In the long term, the IERS SINEX combination campaign is a contribution to the replacement of the separate combinations of TRF and EOPs by a common and consistent combination process.

3.2 Setup of the campaign

The IERS SINEX combination campaign is divided into two parts:

As a first step, solutions for each space geodetic technique have been and are generated by different analysis centers or other interested groups. These solutions must contain station coordinates and EOPs (at least x-pole, y-pole, UT1–UTC; if possible LOD, rates for x-pole and y-pole, and nutation parameters). The solutions themselves can be daily (as usual for VLBI), weekly (as usual for GPS; preferred time span for all solutions) or monthly (as usual for SLR), and should be delivered at least for the entire year of 1999. The SINEX (= Solution INdependent EXchange) format was chosen for delivering the individual solutions because it has many advantages:

- it is already in use for GPS, SLR, VLBI (and DORIS);
- a consistent format description for all techniques is now available, i.e. SINEX 2.00 (see <[1]>);
- statistical information, a priori information and constraints are included;
- the full variance-covariance information is available;
- the possibility of delivering free (reduced) normal equations is given, which avoids the problematical procedure of removing constraints.

All series of individual solutions contributing to the campaign have been collected in a data pool.

The second step is dedicated to the combination of the SINEX solutions stemming from the first step. The IERS Combination Research Centers (CRCs) and other interested groups should combine the terrestrial reference frame together with EOPs by using the strengths of one technique to compen-

[1] ftp://alpha.fesg.tu-muenchen.de/iers/sinex/format/

sate the deficiencies of another technique. The combination of more techniques must make use of the local tie information that is available in SINEX format as well.

The time table for the campaign looks as follows:

- May 27, 2002: Call for participation (see IERS Message No. 27)
- June 15, 2002: Deadline for submitting proposals
- August 15, 2002: Envisaged deadline for submission of SINEX series of step 1
- August 23, 2002: First status report (see IERS Message No. 31)
- November 18–21, 2002: IERS Workshop in Munich: Presentation of first results; discussion of the experiences, encountered problems, etc.
- April 6–11, 2003: EGS General Assembly in Nice: Presentation of (final) results, recommendations on strategies and standards for modeling, parameterization, etc.

3.3 Participants

Table 1 summarizes the participating groups, the primary scientists and their contributions to the campaign. The proposals of all participants are collected on the web site of the IERS SINEX combination campaign (see <[1]>). Altogether eleven groups have sent a proposal: six groups are delivering SINEX series for the first step of the campaign, eight groups are participating in the combination step, and one group delivers a solution that is combined already at the observation level.

3.4 Data pool

The data pool contains all files and information that is necessary for the combination step of the campaign and is accessible via the web site of the IERS SINEX combination campaign (see <[2]>).

In detail, the data pool contains the following files:

- All SINEX solution series stemming from the first step of the campaign, i.e., 3 weekly global GPS solutions, 1 weekly regional GPS solution, 3 monthly SLR solutions, 2 weekly SLR solutions, 2 session (= daily) VLBI solutions (Attention: BKG files were resubmitted Nov. 6, 2002 !), and 1 combined (at observation level) VLBI / SLR solution.
- Some additional solution series are available and can be used in the combination step, but there is no official proposal from these groups:
  - session VLBI solutions from GSFC (2 series: from a recomputation and from an older computation),
  - weekly global GPS solutions of all seven IGS analysis centers for the entire year 1999, i.e., GPS weeks 991 – 1042 (the series from AIUB and NRCan that are officially contributing to the campaign stem from a recomputation, therefore they are not identical with the routine solutions),
  - monthly SLR solutions from the ILRS pilot project ‘positioning and earth orientation’ (altogether 11 analysis centers, but three of them are official participants of the IERS SINEX Combination Campaign, i.e., ASI, DGFI, JCET),
  - weekly DORIS solutions from IGN,
  - session VLBI solutions from IAA, but only with station coordinates.
- The ITRF2000 SINEX files are available as one file per technique.
- The local tie information that was used in the ITRF2000 combination is available in two forms: one SINEX file per site and a table with all local ties in text format.

[1] http://alpha.fesg.tu-muenchen.de/iers/sinex/sinex_campaign.html
[2] http://alpha.fesg.tu-muenchen.de./iers/sinex/datapool.html

3.5 Characteristics of individual solutions contained in the data pool

Comparing the individual solutions with respect to the parameters that are included in the solution, see Table 2, it is clearly visible that there are some differences, especially regarding the EOPs. At the moment the ICRF is not yet included, because in both VLBI series that are directly contributing to the campaign (BKG and DGFI) the ICRF-Ext.1 was kept fix.

Regarding the variance-covariance information respectively the (reduced) normal equation contained in the SINEX files, all analysis groups deliver the variance-covariance information using the SOLUTION blocks MATRIX_ ESTIMATE, MATRIX_APRIORI, APRIORI and ESTIMATE, but in some solutions the apriori information has been omitted. Only the VLBI solutions from BKG, DGFI and the recomputed GSFC solutions include normal equations in addition to the variance-covariance information.

Differences between the individual solutions are also present concerning the constraints that are used for generating a solution: For the terrestrial reference frame both, inner constraints for rotation, translation, scale with respect to an a priori reference frame as well as loose constraints directly on the station coordinates are used. The EOPs are loosely constrained but in some solutions not all EOPs are constrained. In addition to the sort of constraints, the size of the constraints differs from analysis center to analysis center as well.

4 Ongoing activities and proposal for future steps

The major goal of the IERS SINEX combination campaign is to develop methods (and tools) for a rigorous and consistent combination of ITRF, EOP (and ICRF), which should eventually replace the separate combinations by different IERS product centers. To achieve this ambitious goal a wide range of combination aspects has to be considered and the success will fundamentally depend on the cooperation of the participating groups and on well-coordinated activities. In the following we summarize ongoing activities and we address relevant scientific topics, which need to be studied in future.

Table 2 Parameters contained in the SINEX solutions available in the data pool

SINEX solution		**Station coord.**	**x-/y-pole**	**UT**	**Pole rates**	**LOD**	**Nutation**	**Additional parameters**
GPS	AIUB	***X***	***X***	*UT1-UTC*	***X***	***X***		
GPS	NRCan	***X***	***X***		***X***	***X***		*Geocenter*
GPS	DGFI	***X***						
SLR monthly	ASI	***X***	***X***	*UT1-UTC*				*Range bias*
SLR monthly	DGFI	***X***	***X***	*UT1-UTC*				*Range bias, Time bias*
SLR monthly	JCET	***X***	***X***	*UT1-UTC*	***X***	***X***		*Range bias*
SLR weekly	ASI							
SLR weekly	JCET							
VLBI	BKG	***X***	***X***	*UT1*	***X***	***X***	***X***	
VLBI	DGFI	***X***	***X***	*UT1-UTC*			*Corrections to the model*	
VLBI	GSFC new	***X***	***X***	*UT1*	***X***	***X***	***X***	
VLBI	GSFC old	***X***	***X***	*UT1*		***X***	***X***	
VLBI	IAA	***X***						
DORIS	IGN	***X***	***X***	*UT1-UTC*	***X***	*LODR*		

CRC Mail Exploder:

An e-mail exploder "CRC Mail Forum" has been installed at the webpage of the IERS Analysis Coordination at Technical University of Munich (see <[1]>) together with the IERS Central Bureau at BKG for the exchange of mails between CRCs and other interested groups. We propose that all participants of the IERS SINEX combination campaign should be members of this mail exploder to ensure an effective communication between different groups. Individuals that would like to be included in this exploder should send an e-mail to <lothhammer@iers.org>. This mail exploder <crc_forum@iers.org> should be used for all communications concerning the SINEX combination campaign.

Validation of individual SINEX Files:

The number of individual solutions from the different space techniques and their characteristics is very heterogeneous. In view of the goals of the SINEX combination campaign the available solutions had to be checked concerning various aspects, such as format and suitability for a rigorous combination:

- Focus on a set of solutions as homogeneous as possible concerning time interval, parameterization and modeling
- Check SINEX format
- Ensure that all constraints can be removed successfully
- Perform rank deficiency analysis
- Make sure that a correct solution can be produced

As a result of this step a report for each individual solution should be generated and then distributed to the analysis centers (ACs). If necessary, corrected SINEX files should then be resubmitted by the ACs asap.

Form concerning modeling and parameterization:

A form has been distributed in December 2002 to all ACs that are contributing to the SINEX campaign. This form should be filled in and returned to the IERS Analysis Coordinator to archive it together with the solutions in the SINEX data pool.

Consistent modeling and parameterization:

The SINEX series of the various techniques have to be as consistent as possible. Based on the forms common standards have to be defined and updated series complying with the standards should be produced by the ACs.

Scientific Studies / Combinations:

The participating combination groups presented results of the IERS SINEX combination campaign at the EGS-AGU-Meeting in Nice (6–11 April 2003), Session G15 "Interactions and Combination of Space Geodesy Techniques". The results have shown, that various shortcomings and deficiencies regarding a rigorous and consistent combination still exist. To achieve the final goal of the IERS SINEX combination campaign a wide spectrum of combination issues has to be considered and need to be studied in more detail. Below some relevant topics are outlined:

- Local ties: Assess the quality of the local tie information and study the impact of local ties on the combination.
- Study the weighting of solutions in the intra- and inter-technique case. Develop weighting methods, study variance component estimation, etc.

[1] http://alpha.fesg.tu-muenchen.de/iers

- Investigate how to handle non-linear site motions (e.g. sites located in deformation zones).
- Study datum definition issues for combined solutions.
- Study systematic biases between the techniques concerning, e.g., scale, geocenter, LOD (and nutation rates) from satellite techniques, biases in time series of station coordinates (especially for co-location sites), biases in time series of EOPs.
- Study consistency between TRF and EOPs, and impact of combination on the ICRF realization.

Some open issues which probably need further discussions among the relevant groups are:

- Who (which groups) will participate in all these activities? Besides the analysis centers and combination centers of the IERS SINEX combination campaign (see Table 1) we would like to encourage also other groups (e.g., CRCs, WG on ITRF Datum) to participate.
- Another question is how the work should be organized?
  - Definition of work packages ?
  - Different groups for different tasks ?
  - Relationship to the goals of other groups (e.g., CRCs, ITRS Combination Centers, WG on ITRF datum) ?

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Multi-technique Combination of Time Series of Station Positions and Earth Orientation Parameters

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Summary: CATREF software used to generate ITRF solutions was enhanced in order to rigorously combine station positions (and velocities) together with Earth Orientation Parameters (EOP). As a first test analysis, we present in this paper some results of time series combination of TRF and EOP using data provided by various Analysis Centers contributing to the IERS SINEX Combination Campaign. The main focus of this paper is to examine the EOP consistency, through residual analysis, between the main IERS techniques: VLBI, SLR, GPS and DORIS.

1 Introduction

Up to now, the ITRF, ICRF and EOP are determined separately and consequently their consistency is difficult to assess. The IERS SINEX Combination Campaign was organized by the IERS Analysis Coordinator in order to initiate rigorous combination of TRF and EOP targeting improvement and consistency of the IERS products. This paper presents a first tentative to simultaneously combine TRF and EOP which will be extended in the future to include CRF.

2 Combination model

The initial model implemented in CATREF software allows simultaneous combination of station positions and velocities. Assuming that for each individual solution s, and each point i, we have position X_s^i at epoch t_s^i and velocity $\dot{X}_s^i$, expressed in a given TRF k.

- The combination consists in estimating: Positions X_c^i at a given epoch t_0 and velocities $\dot{X}_c^i$, expressed in the combined TRF c
- Transformation parameters T_k at an epoch t_k and their rates $\dot{T}_k$, from the combined TRF c to each individual frame k.

The general combination model is given by the following equation:

$$\begin{aligned} X_s^i &= X_c^i + \left(t_s^i - t_0\right)\dot{X}_c^i + T_k + D_k X_c^i + R_k X_c^i \\ &\quad + \left(t_s^i - t_k\right)\left[\dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i\right] \\ \dot{X}_s^i &= \dot{X}_c^i + \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i \end{aligned} \tag{1}$$

where for each individual frame k, D_k, T_k and R_k are the scale factor, the translation vector and the rotation matrix, respectively. For more details, see (Altamimi et al., 2002a).

CATREF Software is now upgraded to include Earth Orientation Parameters. Using pole coordinates x_s^p, y_s^p and universal time UT_s as well as their daily time derivatives $\dot{x}_s^p$, $\dot{y}_s^p$ and LOD_s, the corresponding equations are :

$$\begin{cases} x_s^p & = & x^p + R2_k \\ y_s^p & = & y^p + R1_k \\ UT_s & = & UT - \frac{1}{f} R3_k \\ \dot{x}_s^p & = & \dot{x}^p + \dot{R}2_k \\ \dot{y}_s^p & = & \dot{y}^p + \dot{R}1_k \\ LOD_s & = & LOD + \frac{\Lambda_0}{f} \dot{R}3_k \end{cases} \quad (2)$$

where $f = 1.002737909350795$ is the conversion factor from UT to sideral time. Considering $LOD = -\Lambda_0 \frac{dUT}{dt}$, Λ_0 is homogenous to time difference, so that Λ_0 = 1 day in time units.

Note that the link between EOP and TRF is ensured through the 3 rotation angles $R1$, $R2$, $R3$, and their time derivatives $\dot{R}1$, $\dot{R}2$, $\dot{R}3$.

In order to precisely define the datum of the combined frame, minimum constraints equations were implemented in CATREF software, allowing to express the combined solution in any external frame. For more details concerning equations of minimum constraints and their practical use, see for instance Altamimi et al. (2002b).

3 Analysis Test

We used the following data:

- SLR: ILRS Pilot Project Monthly Solutions provided by ASI, CSR, DGFI and JCET analysis centers
- GPS: IGS weekly combined solutions
- VLBI: GSFC and BKG 24h-session SINEX files
- DORIS: IGN/JPL weekly solutions

We adopted the following analysis strategy:

- Apply minimum constraints equally to all loosely constrained solutions (all SLR solutions)
- Use as they are the minimally constrained solutions (GPS, VLBI, DORIS)
- Perform intra-technique combinations (TRF + EOP), all expressed in ITRF2000 using equations of minimum constraints
- Combine the intra-technique combinations adding local ties
- Estimate variance components and iterate as necessary

Figure 1 shows the origin and scale consistency of some ILRS monthly solutions over 1–3 years. Figure 2 illustrates the polar motion post fit residuals of the per technique combinations for the year 1999 and for April 2001. Similarly, Figure 3 illustrates polar motion rates and LOD.

4 Conclusion

Small T_z and scale differences exist between some SLR analysis centers. SLR and VLBI current networks and collocations are very poor which impacts the long term maintenance of TRF scale. VLBI collocations with other techniques are not always the same at weekly or monthly interval. We find good agreement of X-pole, Y-pole and LOD estimates between the different techniques. VLBI and SLR rate estimates of X-pole and Y-pole seem to degrade polar motion estimates of these two techniques.

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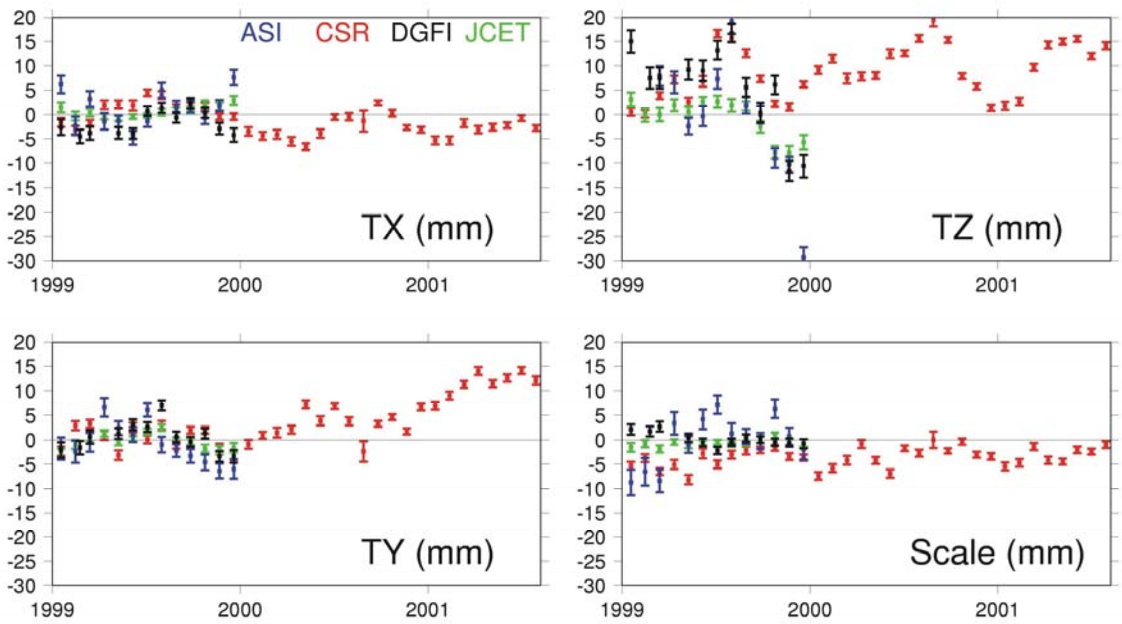

Fig. 1 The origin and scale consistency of some ILRS monthly solutions over 1-3 years

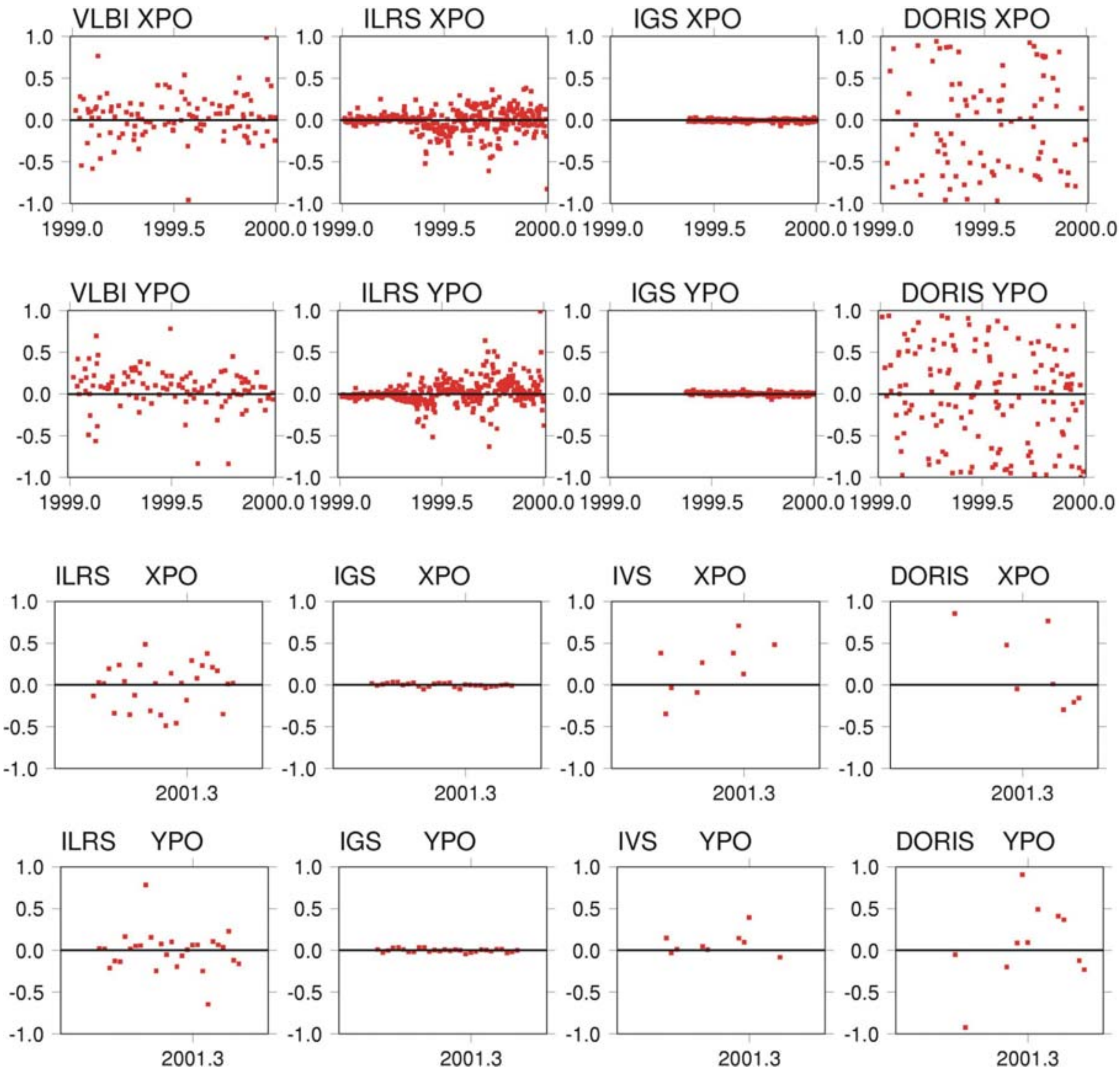

Fig. 2 The polar motion residuals of the per technique combinations for the year 1999 and for April 2001

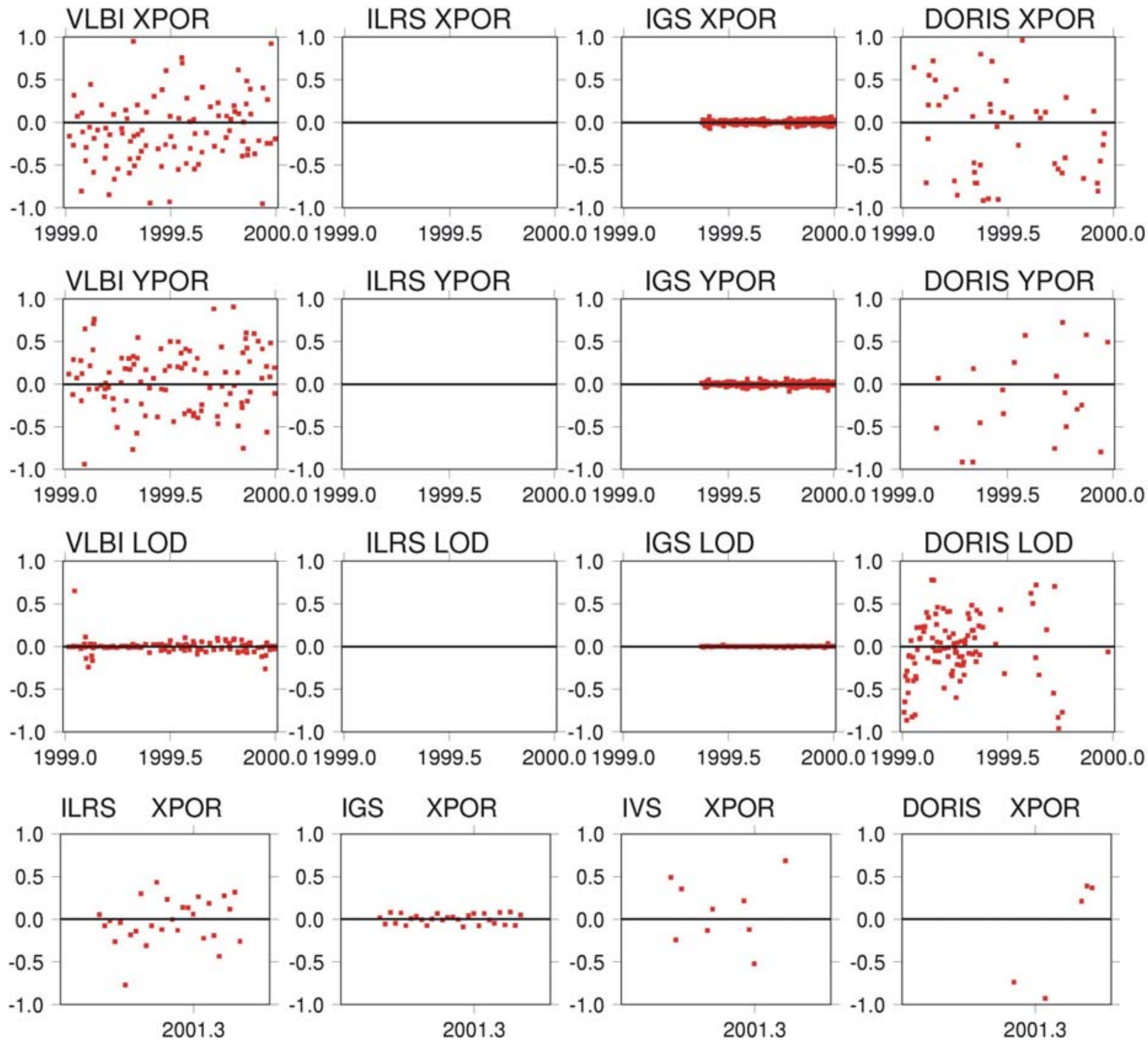

Fig. 3 The polar motion rates and LOD residuals of the per technique combinations for the year 1999 and for April 2001

Combination of Loosely Constrained Solutions

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1 Introduction

The Center for Space Geodesy (CGS) of Matera, Italy, has implemented a combination strategy of site coordinates, velocities and Earth Orientation Parameters (EOP) that generates a combined set of geodetic parameters referred to a unique terrestrial reference system. The strategy has its strength in the automatic combination of solutions without the estimation and removal of the relative rotation between their reference frames and is based on the assumption of solutions with large uncertainties on the reference frame, i.e., loosely constrained solutions (Heflin et al., 1992; Blewitt, 1998; Davies and Blewitt, 2000).

Loosely constrained solutions can be combined regardless of the datum definition of each contributing solution. The solution reference frame is defined stochastically by the input data and is basically unknown but, on the other hand, there is no need to impose any external constraint for their combination. Since the datum is treated as a stochastic noise, it is not necessary to estimate or to apply relative rigid transformations (rotation-translation-scale) between reference frames and this naturally leads to a combined solution not distorted by any constraint or transformation.

2 Procedure

The input solutions are accepted as SINEX files containing parameters of the following categories: site coordinates, site velocities, EOP and EOP rates. In principle also tightly constrained solutions could be accepted; in this case, the *a priori* constraints should be given to allow their removal and a loosening transformation (Davies and Blewitt, 2000) should be applied in order to achieve the desired reference frame uncertainty.

Denoting with X_i the site coordinates of the i-th solution and with Y_i the EOP of the i-th solution at times t_{ij} and P being the time propagation operator, the following equations show the relationship between two different solutions:

$$\begin{pmatrix} \mathbf{X}_1(t_1) \\ \dot{\mathbf{X}}_1 \\ \mathbf{Y}_1(t_{1j}) \\ \dot{\mathbf{Y}}_1(t_{1j}) \end{pmatrix} = P \begin{pmatrix} \mathbf{X}_0(t_0) \\ \dot{\mathbf{X}}_0 \\ \mathbf{Y}_0(t_{0j}) \\ \dot{\mathbf{Y}}_0(t_{0j}) \end{pmatrix} = \begin{pmatrix} \mathbf{I} & (t_1 - t_0)\mathbf{I} & 0 & 0 \\ 0 & \mathbf{I} & 0 & 0 \\ 0 & 0 & \mathbf{I} & (t_{1j} - t_{0j})\mathbf{I} \\ 0 & 0 & 0 & \mathbf{I} \end{pmatrix} \begin{pmatrix} \mathbf{X}_0(t_0) \\ \dot{\mathbf{X}}_0 \\ \mathbf{Y}_0(t_{0j}) \\ \dot{\mathbf{Y}}_0(t_{0j}) \end{pmatrix} \quad (1)$$

The combination of the solutions is obtained by solving in a least squares sense the above design equation. Denoting with X_c,Y_c respectively the coordinates and EOP of the combined product, and with C_i the i-th solution covariance matrix, the least squares problem can be solved in the following recursive formulation:

$$\begin{pmatrix} \mathbf{X}_c \\ \dot{\mathbf{X}}_c \\ \mathbf{Y}_c \\ \dot{\mathbf{Y}}_c \end{pmatrix} = \left(\mathbf{C}_0^{-1} + \mathbf{P}^T\mathbf{C}_1^{-1}\mathbf{P} + \cdots\right)^{-1} \left[\mathbf{C}_0^{-1} \begin{pmatrix} \mathbf{X}_0 \\ \dot{\mathbf{X}}_0 \\ \mathbf{Y}_0 \\ \dot{\mathbf{Y}}_0 \end{pmatrix} + \mathbf{P}^T\mathbf{C}_1^{-1} \begin{pmatrix} \mathbf{X}_1 \\ \dot{\mathbf{X}}_1 \\ \mathbf{Y}_1 \\ \dot{\mathbf{Y}}_1 \end{pmatrix} + \cdots \right] \quad (2)$$

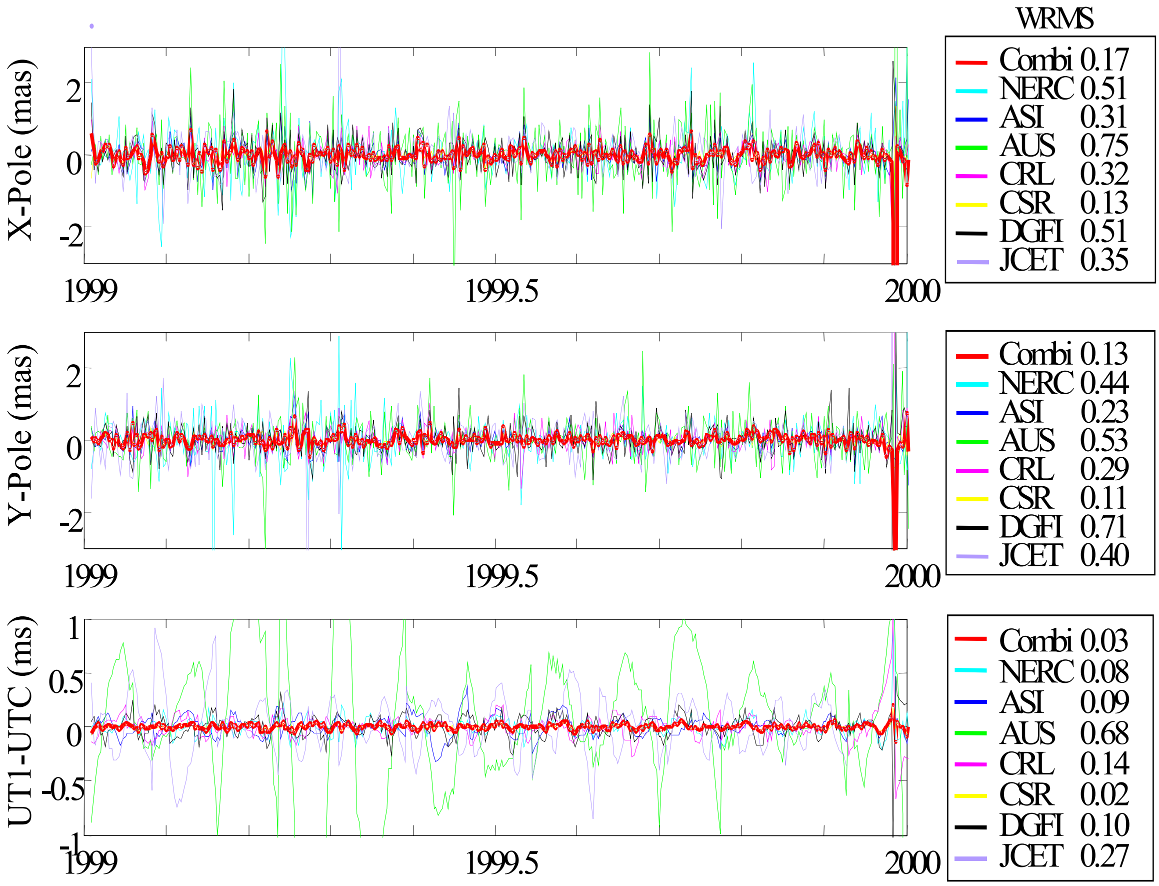

Fig. 1 EOP residuals with respect to IERS-C04 values for one year of SLR combination: the red line refers to the combined EOP. Large deviations among contributors are observed in the UT1–UTC parameter: this is a consequence of an intrinsic degeneracy in the SLR technique and therefore UT1 estimates cannot be interpreted and directly compared.

A scaling of the covariance matrix of the i-th solution is required because the relative weight of the contributing solutions may be incorrectly balanced. Imposing χ^2=1 for the combination residuals and requiring that each contribution to the total χ^2 is equally balanced, one obtains the relative scaling factors (σ_i) iteratively with R_i being the solution residuals (with respect to the combined product) and Σ_i the solution covariance matrix, the imposed conditions are:

$$R_1^T\left(\sigma_1\Sigma_1\right)^{-1}R_1 = \cdots = R_i^T\left(\sigma_i\Sigma_i\right)^{-1}R_i \quad and \quad \chi^2 = R_1^T\Sigma_1^{-1}R_1 + \cdots + R_i^T\Sigma_i^{-1}R_i = 1$$

In the year 2000 the ILRS Analysis Working Group promoted a pilot project on the combination of SLR analysis products, namely a time series of 4-weekly site coordinate solutions and daily EOP over 1 year of LAGEOS-I and LAGEOS-II observations. The test solutions were provided by eight ILRS Associate Analysis Centers that adhered to the pilot project. The loosely constrained monthly solutions from each agency have been combined and compared to the official ITRF values. Figures 1 and 2 show the residuals of EOP and site coordinates with respect to the IERS-C04 time series and the ITRF2000 coordinates. The combined product shows the smoothest time series and the residuals are considerably smaller than each single solution. The EOP residuals have a weighted root-mean-square (WRMS) on the order of 130–170 µarcsec whereas the site coordinate residuals are on the order of a few mm (3-D) with rare exceptions in the range 10–20 mm. The global monthly WRMS of the coordinate residuals demonstrates a stable value between 5–10 mm throughout all the year.

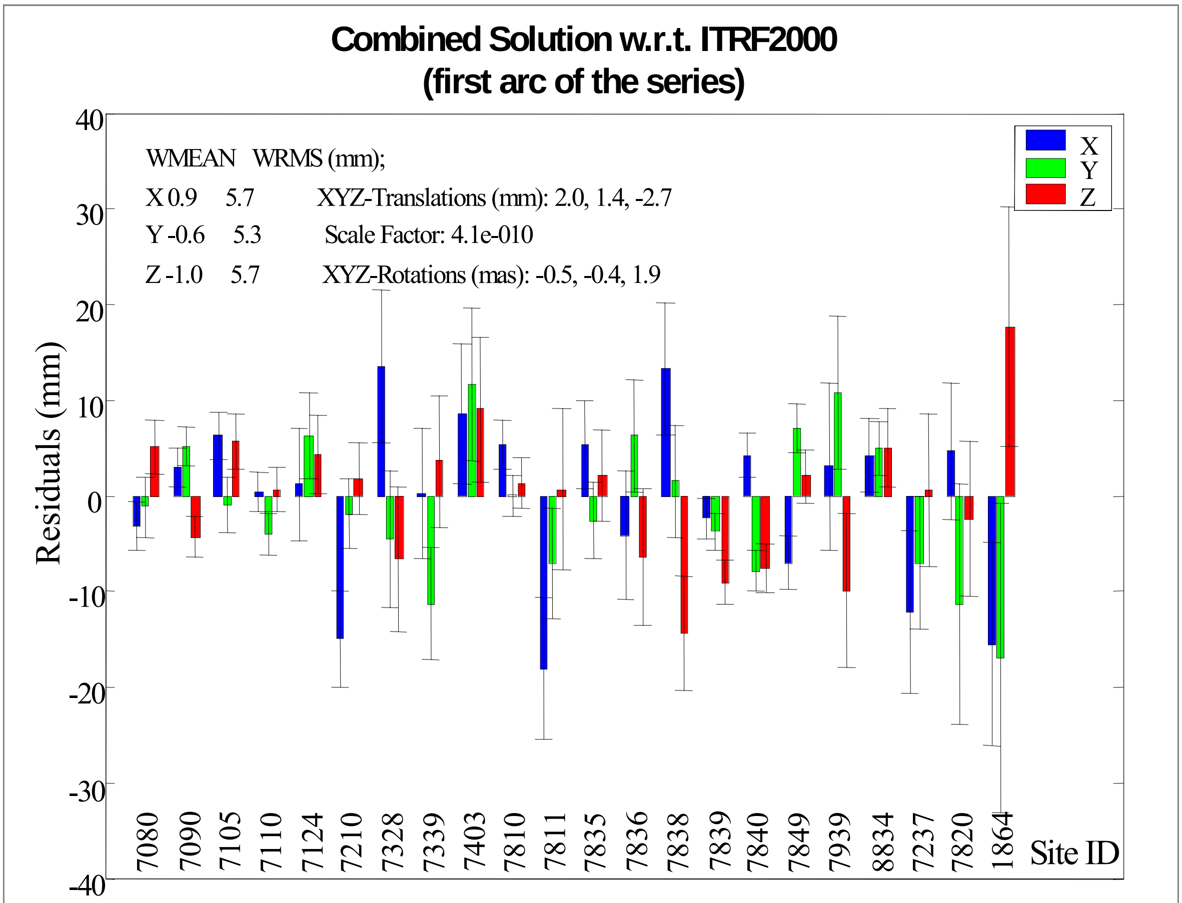

Fig. 2 Site coordinate residuals of a sample month (first arc) with respect to ITRF2000 values. The scatter of the site residuals is at the level of 5 mm in the three directions.

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IERS SINEX Combination Campaign: First Results at NRCan

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This is a contribution to the research activities of the IERS SINEX Combination Campaign. The objective of this campaign is to simultaneously combine weekly station coordinates and daily ERPs from various techniques, using all the available covariance information, and analyze the results. Several solutions from four techniques (GPS, SLR, VLBI, DORIS) and inter-technique local ties were provided for this research activity by various centers for year 1999.

In this preliminary analysis, 3 inter-technique combinations were computed. The combinations were limited to the first month of 1999 and all included the IGS weekly solutions. Two inter-technique GPS/SLR combinations used SLR solutions provided by DGFI and JCET, while the GPS/DORIS combination involved the solution provided by IGN. All the provided solutions were aligned to the ITRF2000 reference frame and included weekly/monthly estimates of station coordinates and daily ERPs along with fully populated covariance matrices. The combined solutions were realigned to ITRF2000 using the 54 reference frame stations routinely used by IGS for the alignment of its products. Due to the short time span, no station velocities were estimated. The combined IGS-DGFI and IGS-JCET solutions have 3D-RMS station coordinates residuals at 5–6 mm. Ties from 11 stations were used to connect the solutions. Figure 1 shows the daily X&Y pole position residuals time series of the IGS, DGFI and combined IGS-DGFI solutions with respect to Bulletin A.

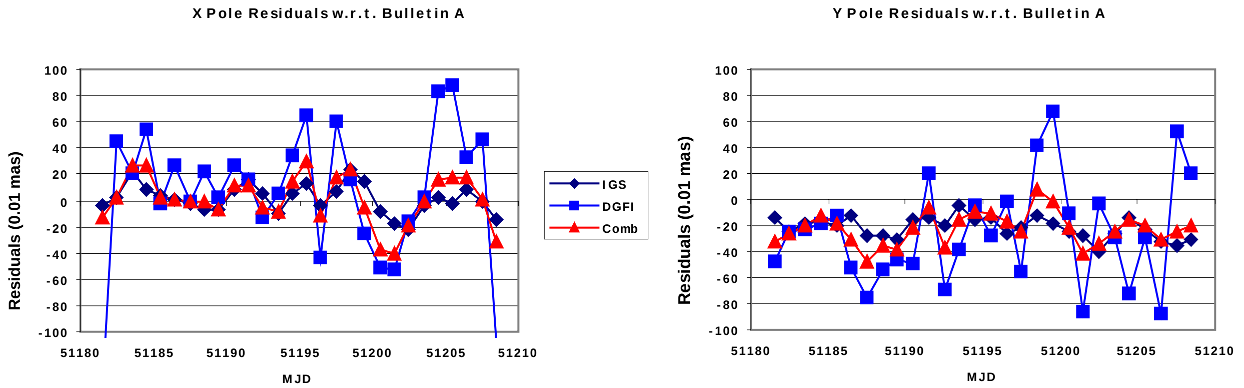

Fig. 1 X & Y pole time series residuals of the IGS, DGFI and IGS-DGFI combined solutions with respect to Bulletin A

The GPS/DORIS combination between the IGS and IGN solutions has 3D-RMS coordinates residuals of 6mm for IGS and 52mm for IGN. In this case, 16 ties were connecting the solutions. Table 1 below summarizes the statistics of the daily X&Y pole residuals with respect to Bulletin A for each solution used and each of the inter-technique combination.

Table 1 X & Y pole statistics for each solution (IGS, DGFI, JCET, IGN) and their individual combination with IGS with respect to Bulletin A

	Solution Statistics				Combined with IGS statistics			
	X Pole (mas)		Y Pole (mas)		X Pole (mas)		Y Pole (mas)	
	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.
IGS	0.01	0.11	0.22	0.08				
DGFI	0.07	0.52	0.26	0.40	0.01	0.19	0.22	0.12
JCET	0.14	0.81	0.13	0.73	0.01	0.19	0.22	0.12
IGN	0.42	3.16	0.03	2.16	0.01	0.11	0.21	0.08

The solution statistics suggest that the bias observed by IGS in the Y pole component with respect to Bulletin A may also be present in the SLR solutions (DGFI, JCET). A longer combination interval may confirm/infirm this hypothesis. When DGFI, JCET and IGN solutions are individually combined with IGS, the daily combined pole estimates are dominated by the IGS pole estimate. The addition of more solutions may somewhat diminish this effect, however, the IGS contribution to a multi-technique combined solution is expected to remain important.

A cumulative solution for year 1999 including all weekly IGS station coordinates and daily ERPs was also estimated. All station coordinates available in the weekly IGS solutions were used in the combination. For each station, the combined solution included an initial position and a velocity estimate. The main objective of this analysis was to assess the effect of the accumulation of station coordinates on the ERPs. The combined solution was also aligned to the IGS realization of ITRF2000 using a subset (54) of high quality stations by estimating and applying a 14-parameter (3 translations, 3 rotations, 1 scale & rates) unweighted transformation on the cumulative solution. The comparison between the daily pole position estimates of the weekly and cumulative solutions shows an average bias below 0.01 mas with a standard deviation of about 0.03 mas. The corresponding standard deviations on the station coordinates north, east and height components residuals are 2.0 mm, 2.7 mm and 6.3 mm respectively. Comparisons of the ERPs from the weekly IGS combination and the annual combination with Bulletin A show for both cases average differences in X and Y pole position of 0.03 mas (±0.09 mas) and 0.21 mas (±0.08 mas). Note that during 1999, the IGS SINEX production/combination activities were in their pilot phase.

Although the above inter-technique combination results are very preliminary, they validate the multi-technique combination strategy. They already indicate that the IGS solution will likely have a very significant (if not overwhelming) contribution in station coordinates & ERPs multi-technique combined product. Some issues, such as the proper interpolation and combination of ERPs provided at different epochs need further work.

Rank Defect Analysis and Variance Component Estimation for Inter-Technique Combination

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1 Introduction

The SINEX files, which are stored in the SINEX pool of the IERS SINEX Combination Campaign project, contain normal equation systems and/or solutions of individual space techniques. When the solution is given we try to reconstruct the normal equation system by using the constraints with which the solution was obtained. Before the combination the number and type of rank defect of each normal equation matrix should be determined in order to get an insight of the constraint characteristics. Theoretical considerations and first numerical results for this rank defect analysis are presented here. One of the problems in the inter-technique combination is the correct weighting of the input normal equation systems. The variance component estimation may be considered as a potential weighting method. First experiences with this method are reported here.

2 General combination model

The inter-technique combination is defined here as the computation of a unified solution with input solutions being stochastically independent from each other and may be the result of an arbitrary space technique (SLR, VLBI, GPS and/or DORIS). The estimated target parameters of each input solution k are station coordinates as well as EOP (pole and UT1) and their rates . Hence the parameter input vector for solution k may be defined as $\mathbf{p}_k$ and the total parameter input vector for n_f independent solutions as

$$\mathbf{p}_f^T = \left[\mathbf{p}_1^T \ \mathbf{p}_i^T \ \mathbf{p}_{n_f}^T \right] \tag{1}$$

Additionally, for the collocation site l local tie coordinates x_l are required and for n_s local ties the coordinate vectors are presented as

$$\mathbf{x}_s^T = \left[\mathbf{x}_1^T \ \mathbf{x}_i^T \ \mathbf{x}_{n_s}^T \right] \tag{2}$$

The target parameters to be solved for in the combined solution are station coordinates $\mathbf{x}$ and station velocities $\dot{\mathbf{x}}$ as well as EOP values $\mathbf{m}$ and their rates $\dot{\mathbf{m}}$ within a unique terrestrial reference frame. Hence the general deterministic combination model may be defined as a Gauss-Markov model:

$$E\begin{bmatrix} \mathbf{p}_f \\ \mathbf{x}_s \end{bmatrix} = f\left(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{m}, \dot{\mathbf{m}}\right) = f\left(\mathbf{p}\right) \tag{3}$$

and after linearization w.r.t. a priori parameters

$$E\begin{bmatrix} d\mathbf{p}_f \\ d\mathbf{x}_s \end{bmatrix} = \mathbf{A} \begin{bmatrix} d\mathbf{x} \\ d\dot{\mathbf{x}} \\ d\mathbf{m} \\ d\dot{\mathbf{m}} \end{bmatrix} \quad \text{or} \quad E\left[d\mathbf{r}_f\right] = \mathbf{A}\, d\mathbf{p} \tag{4}$$

Assuming that the input solutions as well as the local tie solutions are stochastically independent from each other, following normal equation system of the general combination model results:

$$\mathbf{A}^T \mathbf{N}\,\mathbf{A}\,d\mathbf{p} = \mathbf{A}^T\,d\mathbf{r}_f \quad \text{with} \quad \mathbf{N} = \begin{bmatrix} \mathbf{N}_{ff} & 0 \\ 0 & \mathbf{N}_{ss} \end{bmatrix} \qquad (5)$$

$\mathbf{N}_{ff}$ and $\mathbf{N}_{ss}$ consist of block diagonal normal equation matrices for each solution.

For the optimal case that all input solutions are based on free networks, $\mathbf{N}$ should be singular, because each block matrix should represent rank defects which are characteristically for the specific space or local tie technique. Hence, before applying the general combination model a rank defect analysis is required for each normal equation matrix .

3 Rank defect analysis

The objective of the rank defect analysis is to find the number and the type of rank defect in the normal equation matrices by numerical methods. Input normal equation matrices which are to be used for terrestrial reference frame combination should have following rank defect characteristics seen from the theoretical and modelling point of view: For SLR and DORIS there should be 3 rank defects w.r.t. the rotation of the coordinate reference system which may be slightly smeared because of dynamical modelling, and one UT1 offset because of the linear dependency on the right ascension of ascending node of the satellite orbit. In principal, the same holds for GPS. Depending on the modelling and the extension of the network, GPS may additionally have 3 translational rank defects. VLBI should have 3 rotational and 3 translational rank defects w.r.t. the terrestrial reference system when fixing the nutation parameters. A simulated 3D distance network is analysed for test purpose and because the rank defects are rigorously defined: 3 translational and 3 rotational defects. For the numerical analysis following input solutions are chosen: for VLBI 3 solutions on 04-10-1999, first GPS week in October 1999 for GPS (14 solutions) and DORIS (1 solution), for SLR 9 four-week solutions in October 1999.

4 Eigenvalue analysis

The rank defect may numerically be determined by computing the eigenvalues of the normal equation matrix. In theory, the number of zero eigenvalues equals the rank defect. As well known, in practice, the numerical eigenvalue computation is sensitive to algorithm and round-off error deficiencies. Hence smearing effects have to be expected from this point of view, also.

The eigenvalues of the simulated distance network are obtained as expected: The first six smallest eigenvalues are in the range of 10^{-11} following a 10^{15} jump to the next smallest eigenvalue. Concerning the 3 VLBI solutions, the "best" one yield 6 smallest eigenvalues in the range of 10^{7} with a jump of 10^{6}, the next "best" solution has 6 smallest eigenvalues in the range of 10^{-4} with a jump of 10^{4}. The eigenvalues of the third VLBI solution does not represent the rank defect behaviour as expected. 3 out of the 9 SLR solutions contain eigenvalues as expected. The interpretation of a significant jump between the third and fourth smallest value requires further investigations. Only one out of 14 GPS solutions contains 4 near zero eigenvalues with jumps similar to the SLR solutions. All other solutions seem to be over constrained, or the reconstruction of the normal equations was not successful. The one week DORIS solution presents a not-expected eigenvalue behaviour: The first 14 eigenvalues scatter around zero, then a significant jump of 10^4 follows.

5 Rank defect type analysis

The rank defect type of a normal equation matrix **N** may be determined by computing the matrix $\mathbf{Z} = \mathbf{H}^T \mathbf{N} \mathbf{H}$ with **H** being the coefficient matrix of those similarity transformation parameters for which the rank defects are searched. In theory, those diagonals of **Z** which are zero signify the rank defect types.

The diagonals of **Z** for the simulated distance network are in the range of 10^{-8} for the 3 translations, 10^{-3} for the 3 rotations and 10^{13} for the scale – a result which may be expected. The computation of **Z** was not successful for all input solutions. Further investigations are required.

6 Variance component estimation

Because the normal equation matrices in (5) may be differently scaled and weighted, the respective scale factors should be estimated within the general combination model (4) additionally. This may be performed by variance component estimates as e.g. described in (Koch, 1999, chapter 3.6). The respective algorithms for model (4) have been derived for a rigorous and simplified version. The application of these algorithms for the input solutions has just started. First numerical results seem to be appropriate, but further research is needed in order to obtain a reliable solution.

7 Conclusions

The eigenvalue analysis is a sensitive tool to determine the number of rank defects in normal equation matrices. For GPS, SLR and VLBI, there are some input solutions in the SINEX pool which agree to theoretical considerations, and may be used directly in the general combination model. They are appropriate to determine the geodetic datum parameters of the combined network: scale (SLR, VLBI, may be GPS), origin (SLR, may be GPS), and UT1 offset (VLBI). The rotation of the combined network has to be fixed by applying minimal constraints. The other solutions have to be investigated in order to find out which contribution they may give to the geodetic datum of the combined solution. The investigations on the rank defect type analysis and the variance component estimation in model (4) have to be continued.

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The Global Geophysical Fluids Center (GGFC) of the International Earth Rotation and Reference Systems Service

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Abstract: The International Earth Rotation Service established a Global Geophysical Fluids Center (GGFC) in 1998, as one if its product centers. The purpose is to better support, facilitate, and provide services to the worldwide research community, in areas related to the variations in Earth rotation, gravity field and geocenter that are caused by mass transport in the geophysical fluids including the atmosphere, ocean, solid Earth, and core, and geophysical processes associated with tides, mass loading, and hydrological cycles. These services are administered through GGFC's Special Bureaus (SB). Today there are eight SBs worldwide; they are SB Atmosphere, SB Oceans, SB Tides, SB Hydrology, SB Mantle, SB Core, SB Gravity/Geocenter, and SB Loading. They maintain individual data archive and services.

1 Overview

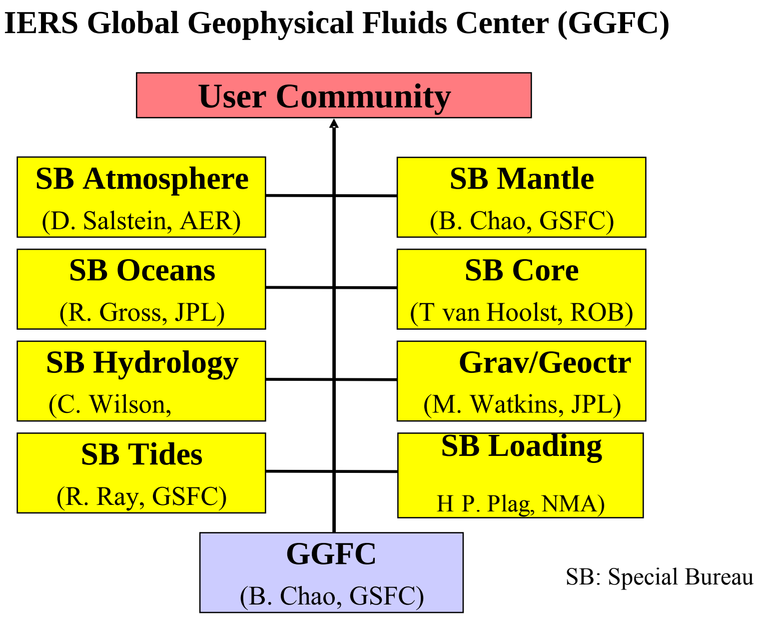
Established in 1998 by the International Earth Rotation Service (IERS, an organization sponsored jointly by the International Union of Geodesy & Geophysics and the International Astronomical Union), the GGFC is headed by Ben Chao, and located at the Laboratory for Terrestrial Physics of NASA's Goddard Space Flight Center. Under GGFC, eight Special Bureaus (SB) were selected worldwide, each to be responsible for facilitating research activities relating to a specific Earth component or aspect of the geophysical fluids of the Earth system (Chao et al., 2000). They are SB Atmosphere, SB Oceans, SB Tides, SB Hydrology, SB Mantle, SB Core, SB Gravity/Geocenter, and SB Loading.

The GGFC/SBs have the responsibility of supporting, facilitating, and providing services to the scientific research community, in areas related to the variations in Earth rotation, gravity field, geocenter, and surface deformations that are caused by mass transport in the atmosphere-hydrosphere-solid Earth-core system, or the global geophysical fluids. Under GGFC/SBs, the "value-added" data of the time variation of angular momenta and the related torques, gravitational coefficients, geocenter shift, and global mass loading will be computed for all geophysical fluids based on global observational data, and/or products from state-of-the-art models some of which assimilate such data. The computed quantities, algorithm and data formats are standardized (an IERS Technical Note for GGFC is in preparation), and results are documented, archived and made available to the public on dedicated individual SB websites via Internet. In addition, GGFC has been actively conducting scientific symposia, special sessions, and business meetings at international conferences.

The GGFC is fundamentally interdisciplinary in terms of NASA's Earth Science mission strategy and goals. The data products involved include:

- Geodetic measurements of temporal variations of Earth's rotation vector, gravity field in Stokes coefficients, geocenter, and surface deformations;
- Global geophysical fluids data directly related to the above, including pressure fields of atmosphere and oceans, wind and current fields, tides, and temperature/salinity profiles derived from atmospheric and oceanic general circulation models (GCM);
- Observed and/or modeled data sets for land water and snow/ice mass distribution, mass flow fields in the fluid core, and solid-Earth surface deformations due to tides, seismicity, tectonics, post-glacial rebound, environmental mass loading, and anthropogenic effects;
- Ancillary data products from satellite missions (some are assimilated into the GCMs in (2)), including ocean altimetry, (future) laser altimetry, ocean scatterometer, and geomagnetic field.

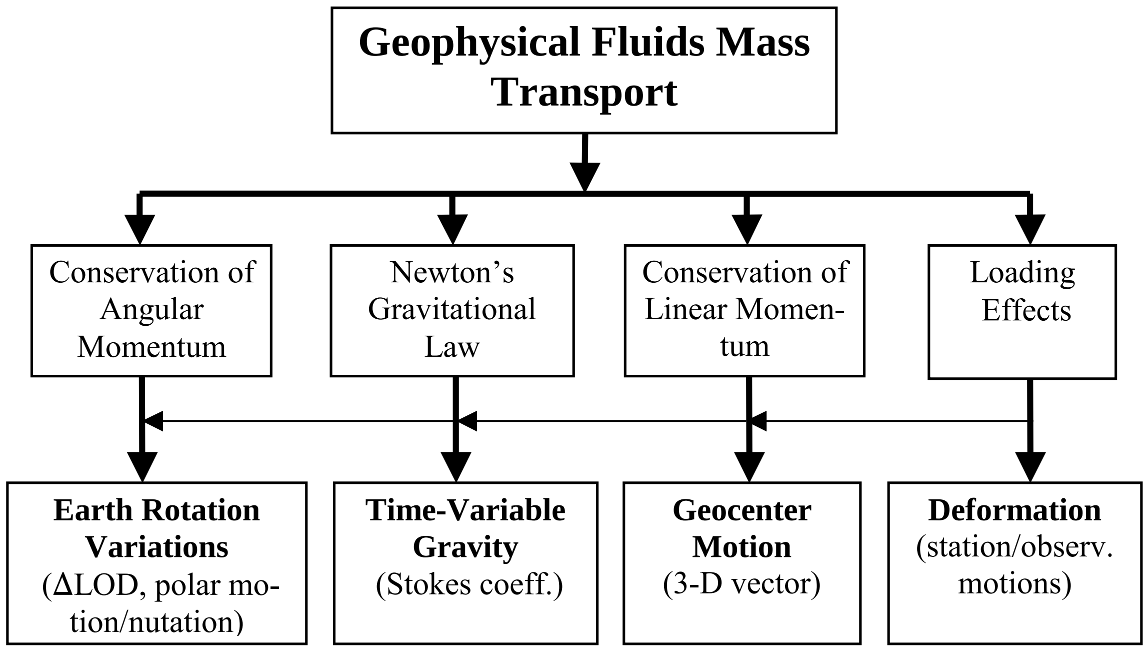
GGFC and the SBs are strictly scientific services supported by the individual hosting institutions or organizations, for which IERS assumes no financial responsibilities. GGFC's functions widely support and conform to the goals defined in the newly-released comprehensive report of NASA Solid Earth Science Working Group (SESWG) in a substantial way. Its work is tightly linked to the success of new space missions including GRACE, JASON, ICESat and planned future missions relying on precise geodesy. Its measure of success is dictated by the ever-stringent requirements on the precision and accuracy of observations and the definition of the fundamental terrestrial reference frame, as well as the ultimate impacts in geophysical interpretation of the observations.



2 Mass Transports and Their Geodynamic Effects

Mass transport is a fundamental process in the climatic, environmental, and geophysical variability, which is becoming observable by various space geodetic techniques, acting as remote-sensing tools, with ever increasing precision/accuracy and temporal/spatial resolution. Mass transports will cause the following geodynamic effects in the geophysical fluids on a broad time scale: (1) variations in the solid Earth's rotation (in length-of-day/universal time and polar motion/nutation) via the conservation of angular momentum and effected by torques at the fluid-solid Earth interfaces; (2) changes in the gravity field according to Newton's gravitational law; (3) motion in the center of mass of the solid Earth relative to that of the whole Earth ("geocenter") via the conservation of linear momentum; and (4) mass loading effects normally manifested in surface deformations and movements. Any geophysical process involving fluid mass transport will have its own geodynamic effects depending on its spatial distribution and temporal behaviour modified by loading effects. The sum of all the individual signals, with their spatial and temporal characteristics, is what's observed.

Geodynamic Effects of Mass Transport in Geophysical Fluids



The magnitude of the geodynamic effects produced by a particular mass transport is approximately proportional to the ratios (net transported mass)/(Earth mass) and (net transport-distance)/(Earth radius). Many fundamental geophysical processes do involve large-scale mass transports that cause measurable geodynamic effects – even then they still only produce signals typically no larger than 1 part in 10^{10}. The most prominent are perhaps weather effects, driven originally by solar radiation input, and related over much of the globe to the Earth's rotational Coriolis force and modified by atmosphere-ocean and atmosphere-land interactions. The meteorological pressure systems appearing on weather maps indicate that different masses of air move around the planet as part of the general circulation. The wind thus produced shows a variation on short timescales of these synoptic motions, but they are strong as well on longer scales related to intra-seasonal, seasonal, and interannual oscillations. Interannual anomalies associated with El Nino/ La Nina are of particular interest in this regard, especially because they are part of the system that produces very strong zonal wind anomalies across the Pacific Ocean and elsewhere from the tropics to higher latitudes. Remarkably, the length of day showed a very clear strong signal during the recent 1997–98 El Nino event and in earlier ones as well.

Mass transport also occurs in the oceans where it is mainly caused by tidal forcing, surface wind forcing, atmospheric pressure forcing, and thermohaline fluxes. Satellite altimetry can measure changes in the sea surface height caused by these forcing mechanisms, and the GRACE mission will soon be able to measure changes in the ocean-bottom pressure. Numerical models of the oceanic general circulation enable detail investigations of the response of the oceans to these forcing mechanisms, and allow quantities such as the angular momentum associated with oceanic mass transport to be modelled and compared with Earth rotation measurements. Recent studies have shown that non-tidal oceanic mass transport can measurably change the length of the day, and can also cause the Earth to wobble as it rotates.

Large mass transports/redistributions occur as tides at all tidal periods. The tides involve mass transports and angular momentum exchanges within the Earth system at periods ranging from subdaily to 18.6 years. Earth tides, ocean tides, and atmospheric tides all contribute to geodynamic variations, and all are readily observable with modern techniques. The Earth's body tide is responsible for large length-of-day variations at monthly and fortnightly periods; the ocean tides are the dominant cause of diurnal and semidiurnal variations in both rotational rate and polar motion. The geodetic measurements are stimulating improvements to all fluid and solid tidal models.

Redistribution of water mass stored on the continents occurs on a variety of timescales. Seasonal and shorter time scales involve precipitation, evaporation, and runoff, with storage of water in lakes, streams, artificial reservoirs, soil, and biomass. Over longer timescales, storage variations in ice sheets and glaciers signal climate change, while ground water storage changes take place in deeper aquifers. Some of these hydrological processes are fundamentally regulated by vegetation; but all are ultimately exchanged with and hence reflected in atmospheric water content and sea level in an intricate budget. Water mass redistribution involving these various reservoirs and mechanisms has been shown to have observable effects on Earth rotation, geocenter and gravity field changes. However, the diversity of transport mechanisms and storage reservoirs makes the task of monitoring land water storage globally an extremely challenging task. Indeed, this is considered to be a first order problem for the climate community, and is being pursued at every major climate research center.

The solid, non-rigid Earth is perpetually in motion as well. There are motions caused by external forces, including tidal deformation, atmospheric and hydrospheric loading, and occasional meteorite impacts. For internal processes, volcanic eruptions and pre-seismic, coseismic and post-seismic dislocations associated with an earthquake act on short timescales. On longer timescales, present-day post-glacial rebound, surface processes of soil erosion and deposition, and tectonic activity such as plate motion, orogeny, and internal mantle convection, all transport large masses over long distances. Finally, the entire solid Earth undergoes an equilibrium adjustment in response to the secular slowing down of the Earth's spin due to tidal friction.

Deeper in the solid Earth, the fluid outer core is constantly turning and churning in association with the geodynamo's generation of the magnetic field.

The variation of the core angular momentum can evidently be inferred from surface observations of the geomagnetic field or modeled by physical hypotheses and the equations of motion that drive and govern the geodynamo and hence the core flow. This core angular momentum has been compared to the observed variations of the length-of-day at decadal timescales, while torques at the core-mantle and inner core boundaries have been estimated. The recent seismological finding of a differential rotation of the solid inner core is also under evaluation in this context.

Subtler but significant interactions exist among the geophysical fluid components which would modify the Earth's response to mass transports. Most notable are the elastic and anelastic mass loading effects as a result of the solid Earth's non-rigidity. The loading effects occur at every solid-fluid interface – atmospheric loading, oceanic and tidal loading, hydrological loading, and even pressure loading at the core-mantle boundary, and also at the atmosphere-ocean interface manifesting as the so-called dynamic inverted-barometer effect.

Another dynamic effect to consider is the extent of coupling at the core-mantle and inner core boundaries, which determines, for example, how "willing" the core is in participating in Earth rotation excitations exerted from the surface, or how much angular momentum the core can exchange with outside. In this regard, various types of torques acting on the boundaries between the geophysical fluids exchange angular momentum among the fluids. These torques include: (i) frictional torque, in the form of wind stress over land and ocean surfaces, ocean bottom drag, and viscous stress at the core-mantle and inner core boundaries; (ii) pressure torque acting across topography that exists between atmosphere-land, ocean-land, and core-mantle boundaries; (iii) gravitational torque acting on density anomalies at distance and across boundaries; (iv) electromagnetic torque generated by the geodynamo that acts on the core-mantle and inner core boundaries. These effects are in general functions of the timescale under which the torque in question applies.

3 Geodetic Measurements

These minute geodynamic signals have been observed by various space geodetic techniques with ever increasing precision/accuracy and temporal/spatial resolution. In this sense, space geodetic technologies have become an effective remote sensing tool for monitoring global mass transports.

The Earth's rotation can be represented by a 3-D vector whose components consist of the rotational speed which determines the length-of-day, and the orientation of the rotational axis (variations of which are called nutations relative to inertial space, or polar motion relative to an Earth-fixed frame). It is a superposition of a very complex suite of phenomena. For over three decades, space geodetic measurement precision has improved at the rate of one order of magnitude per decade (something of a "Moore's law"). Satellite laser ranging (SLR) and very-long-baseline interferometry (VLBI) have been the workhorse in measuring Earth's rotation. Recent years have seen an increasing application of the Global Positioning System (GPS) data especially for higher temporal resolution, and radio tracking data from the DORIS (Doppler Orbitography and Radio positioning Integrated by Satellite) system. Sub-milliarcsecond (mas) precisions (1 mas corresponding to 3 cm if projected to the Earth's surface) are now routinely achieved in daily Earth orientation measurements, and a new VLBI project called CORE is being implemented in phases, which promises even higher precision, high-temporal resolution and continuous measurements.

Measuring Earth's global gravity field and its temporal variation requires special consideration. An external observer can sense gravity only if he is not "in orbit", i.e., not in free-fall, as is an orbiting satellite – a satellite cannot directly "feel" the gravity (that's why a space-borne gravimeter is useless). However, a (near-Earth) satellite's detailed orbital trajectory does reflect the gravity field through which it traverses. Decades of precise orbit tracking data of many geodetic satellites have led to generations of increasingly refined models for the Earth's static gravity field in terms of the Stokes coefficients of its spherical harmonic expansion. The precise SLR technique has detected minute temporal variations in the low-degree gravity field. Variations longer than monthly can now be clearly identified. The space gravity missions of CHAMP and GRACE now in orbit employing satellite-to-satellite tracking techniques, and GOCE that will carry a gravity gradiometer (which measures local gradient of gravity), will yield gravity information at much higher precision and geographical resolution. For example, GRACE promises to be able to resolve water-level-equivalent mass changes of only a centimeter over an area of a few hundred kilometers at a temporal resolution as short as 30 days.

On another front, satellite-based SLR, GPS and DORIS data are beginning to reveal geocenter motion at the centimeter level. This motion manifests itself as a translation of the ground station networks with respect to the center of mass of the whole Earth system defined by satellite orbits. Mathematically, the three components of the geocenter translation vector correspond directly to the 3 degree-1 Stokes coefficients of the gravity field. Although in its infancy and still beset by many technical and modeling problems, geocenter motion measurements have prompted a number of recent geophysical investigations and will undoubtedly continue to do so.

For more details and updated information, see:

Chao, B. F., V. Dehant, R. S. Gross, R. D. Ray, D. A. Salstein, M. M. Watkins, and C. R. Wilson, Space geodesy monitors mass transports in global geophysical fluids, *EOS, Trans. Amer. Geophys. Union, 81,* 247–250, 2000,

or, URL <http://bowie.gsfc.nasa.gov/ggfc/>.

The GGFC Special Bureau for the Atmosphere of the International Earth Rotation and Reference Systems Service

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1 Introduction

The mass and the angular momentum of the atmosphere are properties whose variability relates to both geodetic and climate signals. Total atmospheric dry mass is very nearly conserved, but water substance is exchanged with the oceans and Earth below. The horizontal distribution of atmospheric mass changes on a number of time scales, and varies both meridionally and zonally, often related to climate modes. Such variability is important to the overall terrestrial mass signal measured by the new "Gravity Recovery and Climate Experiment (GRACE)" satellite system. Atmospheric pressure, moreover, loads the crust, leading to small vertical deformations and thus impacts the geodetic reference frame.

The angular momentum of the atmosphere is a signal that changes on many climatic time scales due to the motion of winds and to atmospheric mass redistribution; angular momentum is exchanged, moreover, across the atmosphere's lower boundary. The atmospheric angular momentum signal responds to certain signals like the El Nino, which is observed in some geodetic properties such as Earth's rotation rate, reckoned by the small changes in the length of day, and the motions of the pole.

Global analyses, like that produced by the NCEP-NCAR reanalysis system, capture both mass and angular momentum signals with considerable success; additionally general circulation models have been used to simulate past variability and forecast future changes in these quantities. Relevant diagnostics are calculated, collected, analyzed, and archived by the "Special Bureau for the Atmosphere (SBA)" of the International Earth Rotation Service (IERS), and include: atmospheric angular momentum in the axial and equatorial directions, torque interactions that exchange angular momentum across the lower interface, and harmonics of surface pressure, including the global mean surface pressure.

2 Atmospheric Mass

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3 Atmospheric Angular Momentum

The angular momentum of a parcel of air in the perpendicular plane about an axis is given as its mass multiplied by the length of the radius arm to the reference axis, multiplied by the component of the velocity of the parcel in that plane, normal to the radius arm. The angular momentum of the global atmosphere about such an axis is the integration of all such parcels. When the axis is that of the Earth's rotation, then changes in the angular momentum of the atmosphere are compensated by those of other portions of the Earth, most notably the solid Earth itself; nevertheless a lesser amount does get exchanged with the oceans and between the ocean and solid Earth. Variability of angular momentum about the other two axes, namely in the equatorial plane may be related to the wobble of the Earth, causing motions of the Earth's pole.

Angular momentum variations in the atmosphere can be conveniently separated into those due to mass fluctuations, absolute angular momentum due to solid body rotation, and those due to the winds, the angular momentum relative to the solid Earth. An explicit formulation for the angular momentum that excites both variations of Earth's rotation rate, reckoned as length of day changes, as well as polar motion, were derived by Barnes et al. (1983). An additional element of importance here concerns the so-called inverted barometer (IB) hypothesis, in which the variability of the atmospheric pressure over the oceans is reduced by their isostatic response that quickly readjusts sea level in response to the overlying atmospheric load. A correction for the IB involves substituting the mean value of the atmospheric pressure over the oceans for atmospheric surface pressure at every point over the oceans. These excitations for the length of day and polar motion, given for mass, mass as corrected by the inverted barometer, and motion, are the basic angular momentum values collected by the SBA and are reviewed in Salstein et al. (1993; see that paper's Fig. 1 and 2 for formulas, and sample angular momentum series).

The SBA collects such excitation terms from several of the world's large weather centers, currently consisting of the U.S. National Centers for Environmental Prediction, the European Center for Medium-Range Weather Forecasts, the Japan Meteorological Agency, and the United Kingdom Meteorological Office. Besides analyses for a given time, forecasts are collected as well, out to 10 days. Such values are used operationally for navigation, especially involving that of planetary spacecraft, because the knowledge of the exact orientation, as well as projections into the future, are necessary and are helped by the angular momentum terms. Besides these operational series, values from reanalyses are collected so that there can be relative consistency among these excitation terms for Earth motions. Based on the NCEP-NCAR reanalysis, atmospheric angular momentum quantities were computed by Salstein and Rosen (1997) staring in 1948. These datasets are available from the Special Bureau for the Atmosphere at <[1]>.

We note first that the motions of the pole are related strongly to the pressure (inverted barometer) excitations. On subseasonal variations, moderate correlation exists between the excitations and the polar motion values. Values on longer time scales may be interesting, involving both the seasonal scale, and a natural response of the Earth at around 430 days, the Chandler wobble. The polar motions involve both the oceans and the atmosphere. On seasonal scales, climate modes can force polar motions because of the anomalous pressure patterns connected with such modes. Variability in certain regions due to the pressure patterns on a range of weather and climate time scales are stronger than others: those in the middle latitudes influence the motions of the poles the most because of geometric factors (Barnes et al., 1983). Nastula and Salstein (1999) have noted that fluctuations over Eurasia and North America have impacted polar motions most strongly. On very short time scales, we have noted that fluctuations as short as 8 and 12 hours are noted in both the atmospheric excitation terms for polar motion, and in polar motion as determined methods depending on Global Positioning Systems measurements (Weber et al., 2001).

The axial angular momentum of the global atmosphere, and particularly the relative term due to the winds is an index that mirrors many climate phenomena. Lengthy analysis of such values, since 1970, based on the NCEP-NCAR reanalysis demonstrates both the prominent seasonal and interannual signals present in the series. The seasonal signature, yielding maxima and minima in zonal mean belts (Rosen and Salstein, 1983) during boreal winter and summer, respectively, are due to the larger annual signature of the winds and hence the zonal angular momentum in the Northern Hemisphere compared to the Southern. Superimposed on the annual signal is a semi-annual one in which the boreal summer typically has a particularly steep minimum and the winter has a dip during the middle months.

The maxima in the interannual signatures occur during occurrences of El Nino when anomalous westerly zonal flow throughout much of the tropics and subtropics occur, sometimes moving as well into higher latitudes; the events in 1983 and 1997–98 are contain record high values of the angular momentum index. The global maxima derive from momentum anomalies that often start in the lowest latitudes and propagate toward poleward (e.g., Dickey et al., 1997) in the band-pass filtered analysis of belts (Rosen and Salstein, 1983) from NCEP-NCAR reanalysis data. In that analysis, the very strongest values occurred during the 1997–98 El Nino, in the subtropics of each hemisphere; interestingly a rapid transition occurred between positive and negative anomaly at the end of this event in middle of 1998. The global axial angular momentum is very strongly connected to values in the length of day; such connections occur on time scales between days and several years. Such common fluctuations relate to the annual and semiannual terms. Also noteworthy here, too, are subseasonal fluctuations, including the 30–60 day fluctuations associated with the Madden-Julian oscillation.

The atmosphere-solid dynamic link is the subject of a large number of studies that were related to the atmospheric series produced by the Special Bureau for the Atmosphere and other groups in the International Earth Rotation Service. Lengthy series of atmospheric angular momentum produced by our data center to geodesists have helped unravel several questions involving excitations of free oscillations, of the Chandler wobble, the role of diurnal and semidiurnal tides, and signals of atmospheric normal modes in the dynamics of the Earth (Brzezinski et al., 2002).

[1] http://www.aer.com/groups/diag/sb.html

4 Torque interactions

There are a number of torque mechanisms usually considered for the overall transfer of angular momentum from the atmosphere to the solid Earth. These involve the normal forces of surface pressures against topography, typically known as mountain torques. Those torques usually fluctuate on fairly rapid time scales, reflecting the weather systems that move across mountain ranges in the order of several days. A second torque is known as a friction torque, involving the tangential forces by the winds upon the Earth's surface. These appear to be somewhat steadier and with lower amplitude than the mountain torques. An additional torque seen in atmospheric models is gravity wave drag torque, which is a value created to simulate the frictional effects, typically near uneven topography, generated by gravity waves; this is a contribution from scales smaller than model grid resolution.

Another torque depends on gravitational interaction that depends on the changing mass of the atmosphere. It is only important on the equatorial directions, not in the axial, and reduces the amount of mountain, or pressure, torque in that plane. The difference between the angular momentum approach and the torque approach can be striking, leading to questions about the best formulation of the problem that investigates the difference between angular momentum of the atmosphere and the solid earth.

Acknowledgements

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Reliability of Atmospheric Torque for Geodesy

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1 Angular momentum balance approach and torque approach

The effect of the atmosphere on the Earth rotation can be computed from the equation of angular momentum conservation of an isolated system. For the system composed of the Earth and atmosphere, we have:

$$\frac{d\vec{H}_{Earth}}{dt} + \frac{d\vec{H}_{atmosphere}}{dt} = 0 \quad (1)$$

The angular momentum of the atmosphere is computed from the surface atmospheric pressure and the three-dimension horizontal wind fields at different altitudes, themselves coming from a general circulation model (GCM) constrained by observations. Alternatively, the effect of the atmosphere can be computed as an external forcing acting on the solid Earth. In that case, we have:

$$\frac{d\vec{H}_{Earth}}{dt} = \vec{\Gamma}_{atmosphere \to Earth} \quad (2)$$

When the Earth-atmosphere system is considered as isolated, the two methods can be linked together by

$$\frac{d\vec{H}_{atmosphere}}{dt} = \vec{\Gamma}_{Earth \to atmosphere} = -\vec{\Gamma}_{atmosphere \to Earth} \quad (3)$$

The interaction torque results from the action of three forces: the pressure force acting on the topography, the gravitational interaction between the solid Earth and the atmosphere, and the friction at the fluid-solid interface. The mathematical formula to compute those torques are given in the literature (see for instance de Viron et al., 2001).

The relative sizes of the different effects are very different for the different components of the torque affecting the Earth rotation rate (axial torque) or affecting polar motion/nutation (equatorial components of the torque). The torque associated with the Earth equatorial bulge and consisting of the sum of the pressure and the gravitational effects on that bulge, dominates the equatorial component of the budget at the 95% level in the time domain. It does not affect the axial budget. As shown by Bell (1994), the term associated with the equatorial bulge appears in both sides of the angular momentum budget equation of the atmosphere (eq. 3). This so-called ellipsoidal torque being much larger than any of the other effects in the equation, it is obvious that eq. (3) is automatically verified with a very high precision (at least at the 95% level), whatever the quality of the atmospheric model could be.

2 Advantage and disadvantage of the torque approach

The main advantage of the torque approach is that it allows to get a physical insight on the interaction processes. In particular, we can tell what process, where and how the angular momentum has been exchanged. Conversely, the angular momentum approach only gives the information that a given quantity of angular momentum has been exchanged. The main disadvantage of the torque approach is that the computation is very delicate, as it is highly sensitive to small errors in the data, unlike the angular momentum computation, which is more a global-average computation which smoothes out the small errors in the data. Consequently, the atmospheric angular momentum is usually a more accurate quantity, which allows to compute more accurately with a precision that matches the precision of the geodetic Earth rotation measures.

3 Test on torque reliability

In de Viron and Dehant (2003), the torques are tested in order to infer the precision of the computation by comparing the results obtained from three different reanalysis models and by checking the angular momentum budget of each model independently. In order to make the tests more relevant, we also removed, from the equatorial budget, the common ellipsoidal part, associated with the Earth equatorial bulge. A summary of the model comparison results is given by the chart here below.

	ellipsoidal		mountain			friction		
	X	Y	X	Y	Z	X	Y	Z
1–10	0	0	0	0	0	0	0	0
10–50	3	3	0	0	2	2	2	3
50–100	3	3	2	2	2	2	2	3
100–400	3	3	3	3	3	2	2	3
>400	3	3	3	3	3	2	2	2

0	The models are not coherent
2	Two models are coherent
3	Three models are coherent
X	Two models have similar spectrum
X	Three models have similar spectrum

The angular momentum budget tests (not displayed here) show that the angular momentum of the atmosphere is conserved in X and Y at any period longer than 10 days. When the bulge contribution is removed from the budget, the quality is about the same for the three components, with a reasonable agreement between AAM time derivative and torque between 10 days and the annual period, and not as good for the periods shorter and longer.

4 Conclusion for the torque approach

The torque approach is a powerful tool which enables us to study Earth-atmosphere interaction, but the precision which can be obtained from GCM reanalysis output is not good enough to use this approach in operational geodesy. Nevertheless, it can be used for getting insights about where and how the angular momentum is transferred, and about its causes in particular regions of the world.

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Time Variable Atmospheric and Oceanic Signals in Excitation Functions of Polar Motion

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1 Introduction

The atmosphere and ocean both play an important role in the excitation of polar motion variations on a broad range of time scales. This interaction between atmosphere, ocean and polar motion is expressed in terms of relationship of atmospheric, oceanic and geodetic excitation functions. These functions contain common signals which can include subdaily, daily, weekly, subseasonal, semiannual, annual signals and longer terms. The common signals and the correlation between atmospheric, oceanic and geodetic excitation functions are time-dependent. Below we consider three topics: the influence of addition of the ocean to the atmosphere on the spectral characteristics and agreement with polar motion excitation functions in time from 10 to 500 days, influence of El Niño on atmospheric excitation function variability in submonthly time scales, comparison of spectral variability of atmospheric and GPS (CODE) geodetic excitation functions for sub-daily time scale.

2 Variability

The atmospheric excitation functions for polar motion are given by variations of the equatorial components χ_1 and χ_2, projected on the two axes in the equatorial plane along the Greenwich and 90^o E meridians, respectively. These excitation function components, based on pressure (P) and wind (W) are expressed by the Barnes formulas (Barnes et al., 1983). For this study we use three sets of data: geodetic excitation function computed from the EOP (IERS) C04 pole coordinates, equatorial components of Atmospheric Angular Momentum (AAM) of NCEP/NCAR reanalysis and equatorial components of Oceanic Angular Momentum of M.I.T. model (Ponte et. al., 1999), for 1985–1995. The geodetic and atmospheric excitation functions were averaged to a five days frequency.

Polar motion and atmospheric circulation fluctuations occur on the wide range of time scales. It is widely known that annual and semiannual oscillations exist both in atmospheric circulation and in polar motion (see reviews by Eubanks, 1993 and references therein). Also fluctuations in subseasonal time scales (with periods shorter than 150 days) have been identified and tied to oscillations of atmospheric excitation function (Kosek et al., 1995; Kolaczek et al., 2000). Here the spectral bands are defined to provide some insight into annual, semiannual, subseasonal polar motion, although the cut-off periods are arbitrary. The subseasonal band is separated here between periods around 120 days oscillation (terannual band) and shorter than 90 days (short period band).

Time variable spectra of atmospheric and joint atmospheric and oceanic excitation functions, were computed by the Fourier Transform Band Pass Filter – FTBPF (Fig. 1). It is clear that oscillations have time variable amplitudes. Spectra of AAM, and joint AAM+OAM excitation functions are similar in the spectra range from seasonal to short period. There are similar oscillations annual, semiannual, 120, 60 40 days in AAM and AAM+OAM and they have similar amplitude variations. Amplitudes of the oscillations of joint AAM+OAM series are not always greater than the AAM. It means that their variations are not always in concert.

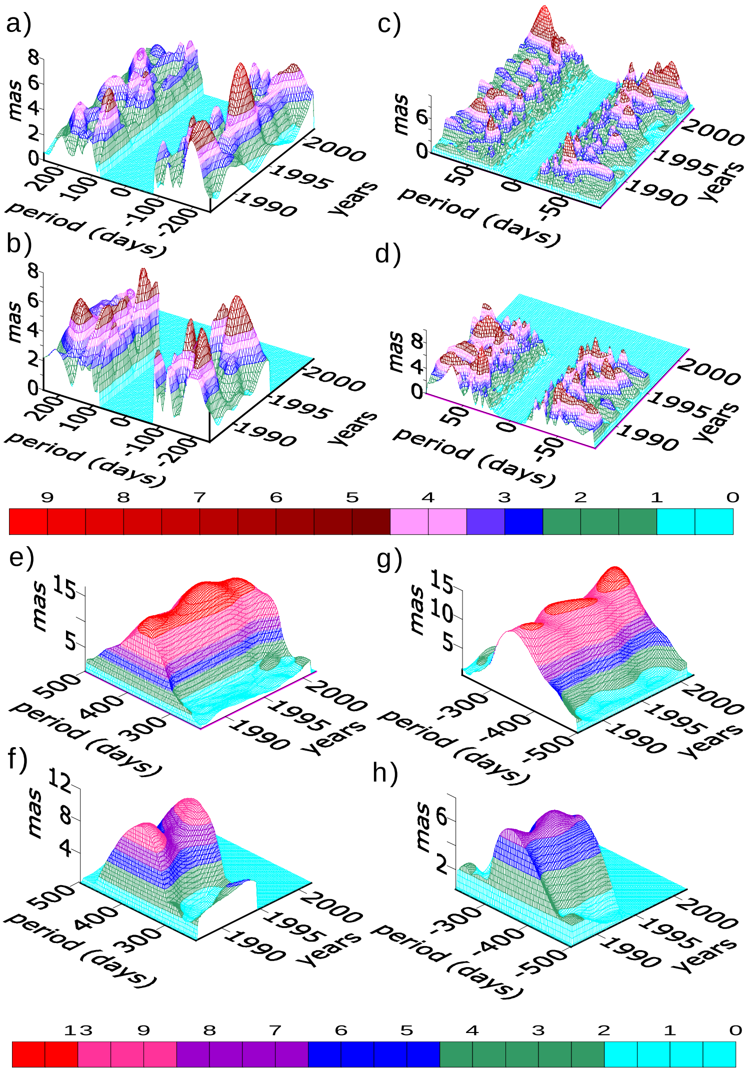

Fig. 1 Time variable spectra (a, c, e, g) of the AAM and (b, d, f, h) of the joint AAM + OAM variations in the period range from 10 to 500 days computed by the FTBPF (lambda = 0.006)

It is widely known that polar motion excitation at seasonal and subseasonal scales is strongly, though not completely related to atmospheric forcing (Nastula and Salstein, 1999; Nastula and Kolaczek, 2002). When the total correlation between atmospheric and geodetic excitation function is performed in time dependent manner, we note that the correlation coefficients vary with time and a timing of correlation coefficient depends on spectral band (Fig. 2). The correlation coefficient is the most stable for annual band. In the case of semiannual, teranual and shorter oscillations the correlation coefficients are lower and more changeable. Adding of the OAM to AAM results in increasing of the correlation level and smoothing their variations.

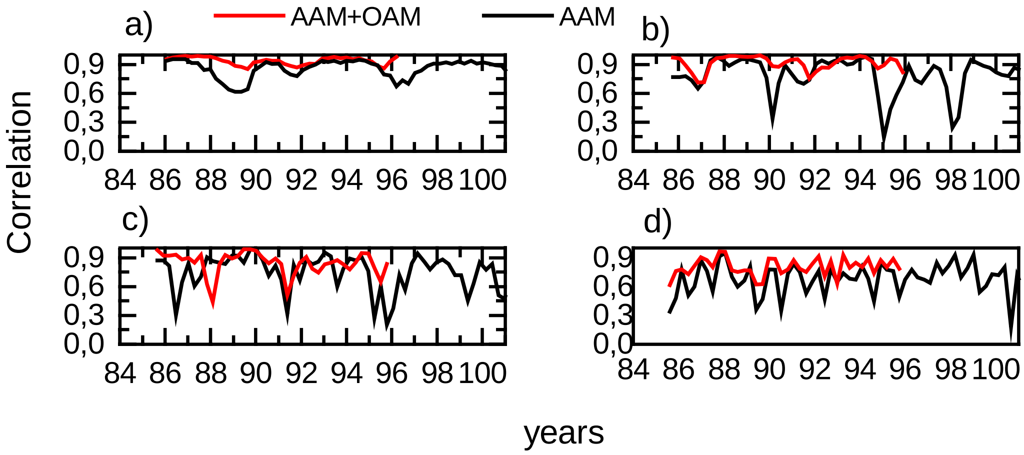

Fig. 2 Correlation coefficients between the complex-valued equatorial components of geodetic and AAM (black) and AAM + OAM (red) excitation functions for polar motion filtered by the Butterworth filter (a) 450–230 days, (b) 230–150 days, (c) 150–90 days, (d) 90–10 days intervals, starting each 100 days of a year since 1986, computed over (a) 2190 days, (b) 1095 days, (c) 730 days, (d) 540 days. (For a colour version of this Figure see the online version at http://www.iers.org/iers/publications/tn/tn30/.)

To isolate regions of atmosphere responsible for polar motion variations atmospheric excitation functions χ_1 and χ_2 are computed in 3312 equal-area sectors for the period January 1999 to December 1999 from meteorological fields on $2.5^o \times 2.5^o$ latitude-longitude grids from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR). In order to show sub-monthly variability we display monthly maps of the standard deviations of pressure term of complex valued $\chi = \chi_1$ and χ_2.

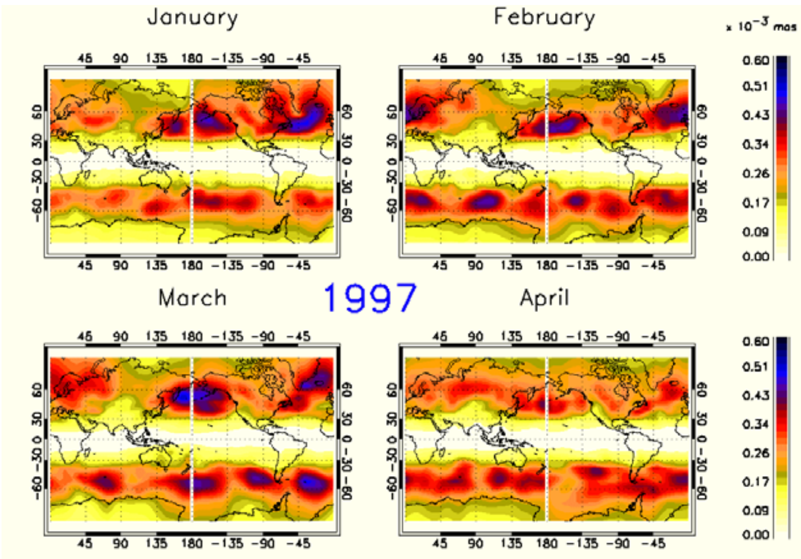

Fig. 3 Monthly standard deviations of complex-valued, pressure component of atmospheric excitation functions of polar motion

A sequence of such standard deviations were computed for each month during two years, in 1997 (El Niño) and in 1999 (Non El Niño). Example variations are shown in Fig. 3. The maps have spatial patterns with maxima over Eurasia, North Pacific, North Atlantic, and a broad maximum lasting over mid-latitude South Pacific from south tip of Africa to south tip of South America. The shape and intensity of maxima is time dependent. There are four sub-pattern (not shown here) connected generally with four seasons of the year. Additionally there are in the patterns differences in a non-El Niño and an El Niño year. Higher variabilities are often seen in El Niño year.

The GPS and VLBI techniques allow recently to determine Earth orientation parameters with high accuracy and resolution. It allows to determine sub-daily variations of polar motion. There are distinct 12 hours and 8-hours oscillations in the atmospheric and geodetic excitation functions, in the geodetic pole coordinates which have 2 hour resolution additionally 6 hours is detected. These oscillations have time variable amplitudes (Weber et al., 2000, 2001).

3 Conclusions

- Correlation between atmospheric-geodetic excitation functions is high but depends on spectral range. Adding oceanic excitation function increases correlation over whole spectral range (450–10 days), and smoothes variability especially for the seasonal oscillations.
- In subdaily range geodetic and atmospheric excitations functions have similar spectral characteristics.
- Regional submonthly variability has annual modulation. Higher variability is often seen in El Niño year.

Acknowledgements

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The GGFC Special Bureau for the Oceans: Past Progress and Future Plans

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Abstract: The oceans have a major impact on global geophysical processes of the Earth. Nontidal changes in oceanic currents and bottom pressure have been shown to be a major source of polar motion excitation and also measurably change the length-of-day. The changing mass distribution of the oceans causes the Earth's gravitational field to change and causes the center-of-mass of the oceans to change which in turn causes the center-of-mass of the solid Earth to change. The changing mass distribution of the oceans also changes the load on the oceanic crust, thereby affecting both the vertical and horizontal position of observing stations located near the oceans. Recognizing the important role that nontidal oceanic processes play in Earth rotation dynamics and terrestrial reference frame definition, the International Earth Rotation and Reference Systems Service (IERS) has created a Special Bureau for the Oceans (SBO) as a component of its Global Geophysical Fluids Center (GGFC) in order to facilitate research into these and other solid Earth geophysical processes affected by the oceans. Through the IERS SBO web site, data relating to nontidal changes in oceanic processes affecting the Earth's rotation, deformation, gravitational field, and geocenter can be obtained along with a bibliography of over 200 relevant publications

1 Introduction

The Earth's rotation, encompassing both the rate of rotation as well as the terrestrial location of the rotation pole, is not constant but changes on all observable time scales from subdaily to secular. This rich spectrum of observed Earth rotation changes reflects the rich variety of astronomical and geophysical phenomena that are causing the Earth's rotation to change, including, but not limited to, ocean and solid body tides, atmospheric wind and pressure changes, oceanic current and bottom pressure changes, torques acting at the core-mantle boundary, and post-glacial rebound.

Recognizing the rich variety of processes affecting the Earth's rotation, the International Earth Rotation Service (IERS) created a Center for Global Geophysical Fluids on January 1, 1998 in order to help relate dynamical properties of the atmosphere, oceans, and core to motions of the Earth, including its rotation (Dehant et al., 1997; Chao et al., 2000). The IERS Global Geophysical Fluids Center consists of a Central Bureau and eight Special Bureaus including the Special Bureau for the Oceans (SBO). As part of the IERS Global Geophysical Fluids Center, the Special Bureau for the Oceans is responsible for collecting, calculating, analyzing, validating, archiving, and distributing data relating to nontidal changes in oceanic processes affecting the Earth's rotation, deformation, gravitational field, and geocenter. The oceanic data sets available through the IERS SBO are produced primarily by general circulation models of the oceans that are operated by participating modeling groups and include oceanic angular momentum, center-of-mass, bottom pressure, and torques. Brief descriptions of the computation of these data sets from the products of oceanic general circulation models and their relevance to solid Earth science is given below.

2 Oceanic Angular Momentum and Earth Rotation

In the absence of external torques, the angular momentum of the entire Earth does not change. However, if the angular momentum of one component of the Earth, such as the oceans, changes, then the angular momentum of the other components of the Earth must change in order for the angular momentum of the entire Earth to remain constant.

Since observing stations are located on the Earth's crust, observations of the Earth's rotation determine the rotation of the solid Earth. As the angular momentum of the solid Earth is exchanged with that of the other components of the Earth, the rotation of the solid Earth will change. Interpreting the observed changes in the rotation of the solid Earth, which encompasses changes in both the length-of-day and in the location of the Earth's rotation axis with respect to the crust (polar motion), therefore requires knowledge of the changes of the angular momentum of the other components of the Earth, such as the oceans.

Two different series of oceanic angular momentum (OAM) are currently available from the IERS Special Bureau for the Oceans: (1) a series computed by Ponte et al. (1998) and Ponte and Stammer (1999, 2000) from the products of a simulation run of the MIT ocean general circulation model (OGCM) which spans January 1985 to April 1996 at 5-day intervals, and (2) a series computed by Johnson et al. (1999) from the products of version 4B of the Parallel Ocean Climate Model (POCM) which spans January 1988 to December 1999 at 3-day intervals. Since these OAM series were produced, ocean modeling groups have extended the duration of their model runs and have developed data assimilative models. We plan, through collaborative efforts with the modeling groups, to compute, analyze, and validate the oceanic angular momentum from the products of these current generation ocean models, making the results available to the solid Earth science community through the IERS SBO web site.

3 Oceanic Center-of-Mass and Earth Geocenter

In the absence of external forces, the location of the center-of-mass of the entire Earth does not change. However, if the center-of-mass of one component of the Earth, such as the oceans, changes, then the center-of-mass of the other components of the Earth must change in order for the center-of-mass of the entire Earth to remain constant.

Artificial satellites of the Earth, which orbit about the center-of-mass of the entire Earth, or geocenter, are tracked by a global network of stations located on the surface of the Earth's crust. From these tracking measurements, the offset of the entire Earth's center-of-mass from the center-of-figure of the network of tracking stations can be deduced. Since the tracking stations are located on the Earth's solid surface, changes in the location of the center-of-figure of the network of tracking stations reflect changes in the location of the center-of-mass of the solid Earth. Interpreting the observed offset of the geocenter from the center-of-figure of the network of tracking stations therefore requires knowledge of the changing locations of the center-of-mass of the other components of the Earth, such as the oceans.

Two different oceanic center-of-mass series are currently available from the IERS Special Bureau for the Oceans, both computed by Dong et al. (1997) and both spanning February 1992 to December 1994 at 3-day intervals: (1) a series computed from the results of a version of the Modular Ocean Model (MOM) run at JPL, and (2) a series computed from the results of running the Miami Isopycnal Coordinate Ocean Model (MICOM) at JPL. These series are quite short, spanning only 3 years. Observations of the Earth's changing geocenter are much longer, spanning the last decade. We plan, through collaborative efforts with ocean modeling groups, to compute, analyze, and validate longer ocean center-of-mass series from the products of current generation ocean models, making the results available to the solid Earth science community through the IERS SBO web site.

4 Ocean-Bottom Pressure and Crustal Deformation

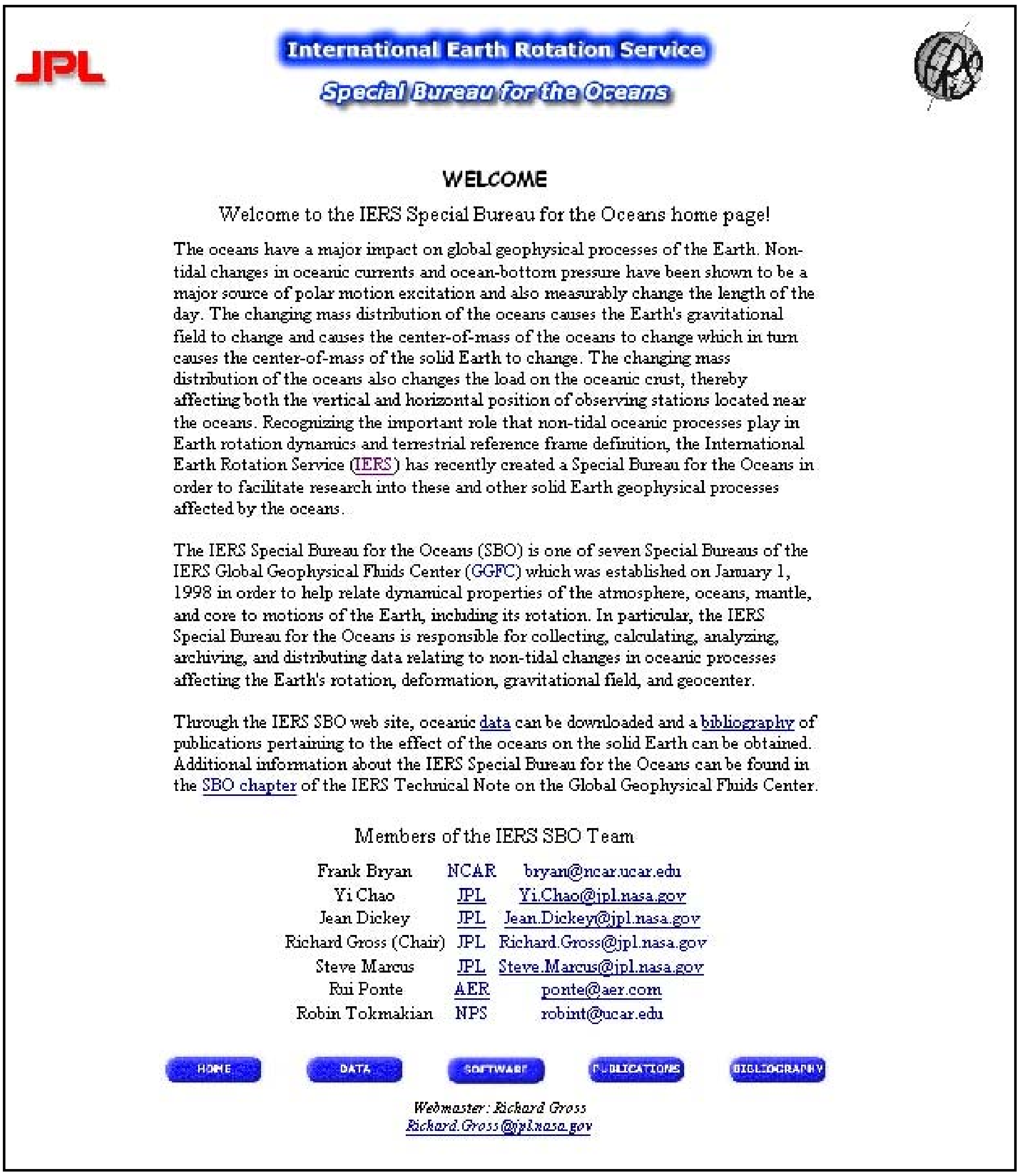
The changing mass distribution of the oceans causes the load on the ocean floor to change. As the oceanic crust and mantle yields to this changing load, the position of stations located on the crust near the oceans will change, and the geoid will deform. Computing station displacements and perturbations to the geoid caused by ocean loading requires knowledge of the pressure at the bottom of the oceans caused by the weight of the overlying oceanic mass.

Links are provided through the IERS SBO web site to the GLObal Undersea Pressure (GLOUP) data bank of ocean-bottom pressure measurements and to the Estimating the Circulation and Climate of the Oceans (ECCO) web site from which modeled ocean-bottom pressure fields produced by the ECCO project can be obtained. However, the ocean-bottom pressure fields archived by the ECCO project are not immediately useful to the solid Earth science community because of artificial changes in the ECCO-modeled bottom pressure fields due to the use of the Boussinesq approximation by the MIT OGCM used by ECCO to produce the bottom-pressure fields. General circulation models of the oceans that are formulated using the Boussinesq approximation conserve volume. Artificial mass variations in such models can be introduced if there are density changes due to internal mixing or imposed surface heat fluxes. Since volume is conserved, the changing density will artificially change the mass of the ocean model. Mass conservation can be imposed on Boussinesq ocean models by adding a uniform layer to the surface that has the appropriate time-dependent thickness (Greatbatch, 1994; Greatbatch et al., 2001). The effects of this mass conserving layer have been computed and is included in the oceanic angular momentum and ocean center-of-mass series available through the IERS SBO. We plan to provide through the IERS SBO corrections to the ECCO ocean-bottom pressure fields by computing the effect of this mass conserving layer on the bottom pressure. In addition, we plan, through collaborative efforts with ocean modeling groups, to compute, analyze, and validate ocean-bottom pressure fields from the products of other current generation ocean models, making the results available to the solid Earth science community through the IERS SBO web site.

5 Gravitational Field Coefficients

The changing mass distribution of the oceans causes the Earth's gravitational field to change, an effect that is being measured by the CHAMP and GRACE satellite missions. Interpreting the observed gravitational field changes over the oceans requires knowledge of the ocean-bottom pressure. Expanding the time-dependent ocean-bottom pressure field in spherical harmonics (using appropriate spatial averaging functions, if desired) yields time-dependent gravitational field coefficients that can be compared to those observed by CHAMP and GRACE.

No series of gravitational field coefficients are currently available from the IERS SBO. We plan to remedy this major deficiency of the IERS SBO by computing, analyzing, and validating series of gravitational field coefficients from the products of current generation ocean models, making the results



JPL

International Earth Rotation Service

Special Bureau for the Oceans

WELCOME

Welcome to the IERS Special Bureau for the Oceans home page!

The oceans have a major impact on global geophysical processes of the Earth. Non-tidal changes in oceanic currents and ocean-bottom pressure have been shown to be a major source of polar motion excitation and also measurably change the length of the day. The changing mass distribution of the oceans causes the Earth's gravitational field to change and causes the center-of-mass of the oceans to change which in turn causes the center-of-mass of the solid Earth to change. The changing mass distribution of the oceans also changes the load on the oceanic crust, thereby affecting both the vertical and horizontal position of observing stations located near the oceans. Recognizing the important role that non-tidal oceanic processes play in Earth rotation dynamics and terrestrial reference frame definition, the International Earth Rotation Service (IERS) has recently created a Special Bureau for the Oceans in order to facilitate research into these and other solid Earth geophysical processes affected by the oceans.

The IERS Special Bureau for the Oceans (SBO) is one of seven Special Bureaus of the IERS Global Geophysical Fluids Center (GGFC) which was established on January 1, 1998 in order to help relate dynamical properties of the atmosphere, oceans, mantle, and core to motions of the Earth, including its rotation. In particular, the IERS Special Bureau for the Oceans is responsible for collecting, calculating, analyzing, archiving, and distributing data relating to non-tidal changes in oceanic processes affecting the Earth's rotation, deformation, gravitational field, and geocenter.

Through the IERS SBO web site, oceanic data can be downloaded and a bibliography of publications pertaining to the effect of the oceans on the solid Earth can be obtained. Additional information about the IERS Special Bureau for the Oceans can be found in the SBO chapter of the IERS Technical Note on the Global Geophysical Fluids Center.

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HOME DATA SOFTWARE PUBLICATIONS BIBLIOGRAPHY

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Fig. 1 The home page of the IERS Special Bureau for the Oceans web site

available to the solid Earth science community through the IERS SBO web site.

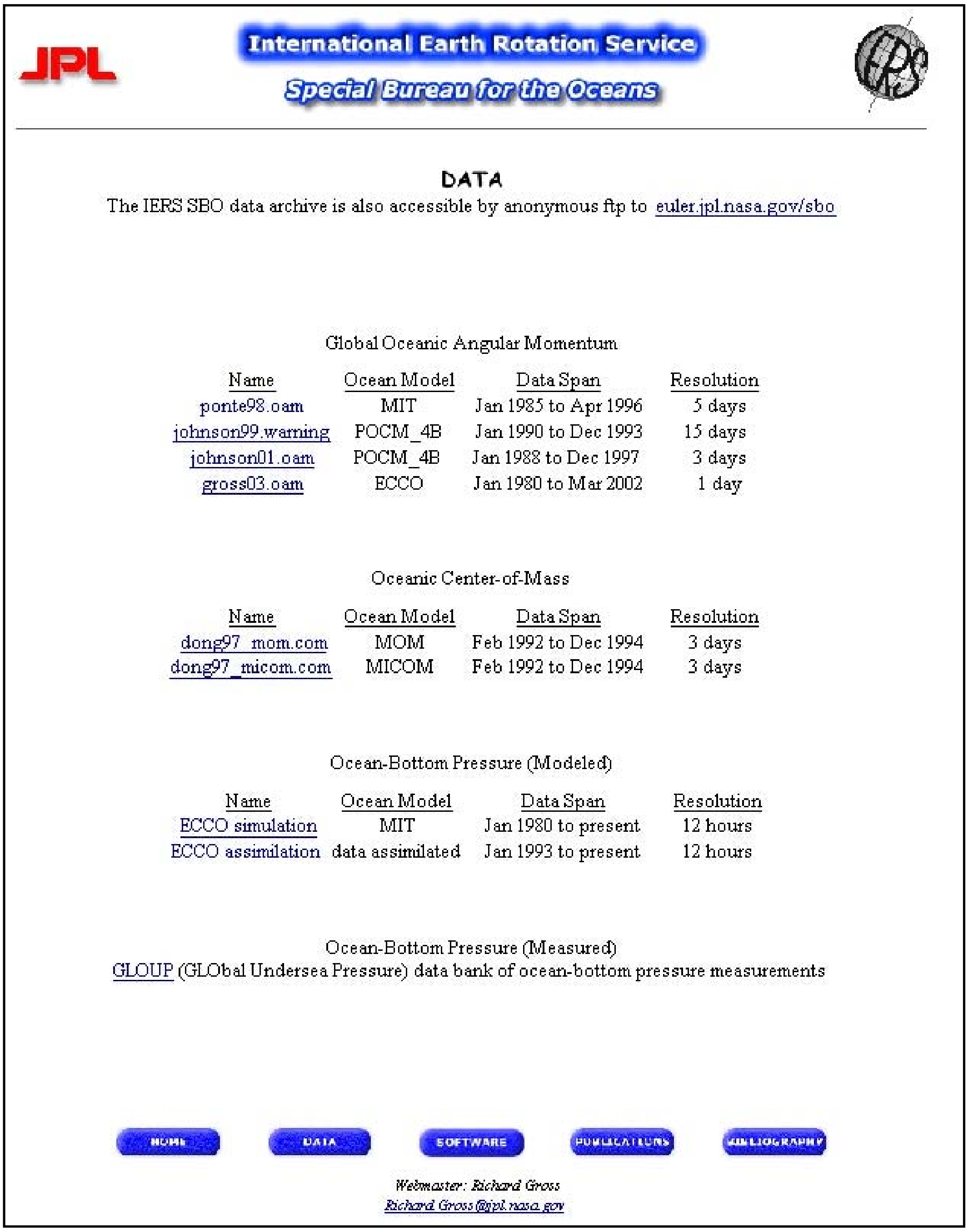
6 Oceanic Torques

Torques exerted by the oceans on the bounding solid Earth effect changes in the rotation of the solid Earth. These torques are due to either frictional stresses acting on the solid boundaries of the ocean basins, or due to pressure gradients acting on topographic features of the ocean basins. Investigating how the oceanic angular momentum is transferred to the solid Earth requires knowledge of these various torques.

No oceanic torque series are currently available from the IERS SBO. We plan, through collaborative efforts with ocean modeling groups, to remedy this major deficiency of the IERS SBO by computing, analyzing, and validating series of oceanic torques from the products of current generation ocean models, making the results available to the solid Earth science community through the IERS SBO web site.

7 The IERS Special Bureau for the Oceans Web Site

Figure 1 shows the home page of the IERS SBO web site located at URL <http://euler.jpl.nasa.gov/sbo/>. After a brief welcoming message describing the importance of oceanic processes to the solid Earth sciences and the mission of the IERS Special Bureau for the Oceans, the members of the IERS SBO team are listed along with their affiliations and email addresses. Through the buttons at the bottom of the home page and hot links within the welcoming message, the user can subsequently navigate to the data, software, and publications pages. The user can also download a bibliography of over



International Earth Rotation Service
Special Bureau for the Oceans

DATA

The IERS SBO data archive is also accessible by anonymous ftp to euler.jpl.nasa.gov/sbo

Global Oceanic Angular Momentum

Name	Ocean Model	Data Span	Resolution
ponte98.oam	MIT	Jan 1985 to Apr 1996	5 days
johnson99.warning	POCM_4B	Jan 1990 to Dec 1993	15 days
johnson01.oam	POCM_4B	Jan 1988 to Dec 1997	3 days
gross03.oam	ECCO	Jan 1980 to Mar 2002	1 day

Oceanic Center-of-Mass

Name	Ocean Model	Data Span	Resolution
dong97_mom.com	MOM	Feb 1992 to Dec 1994	3 days
dong97_micom.com	MICOM	Feb 1992 to Dec 1994	3 days

Ocean-Bottom Pressure (Modeled)

Name	Ocean Model	Data Span	Resolution
ECCO simulation	MIT	Jan 1980 to present	12 hours
ECCO assimilation	data assimilated	Jan 1993 to present	12 hours

Ocean-Bottom Pressure (Measured)

GLOUP (GLObal Undersea Pressure) data bank of ocean-bottom pressure measurements

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Fig. 2 The data page of the IERS Special Bureau for the Oceans web site

Fig. 3 The software page of the IERS Special Bureau for the Oceans web site

200 relevant publications by clicking on the bibliography button.

Figure 2 shows the data page of the IERS SBO web site. Through this data page, the user can currently obtain two different data sets of oceanic angular momentum and two different data sets of oceanic center-of-mass. These data sets can also be obtained by anonymous ftp to <[1]>. In addition, links are provided to the GLObal Undersea Pressure (GLOUP) data bank of ocean-bottom pressure measurements and to the Estimating the Circulation and Climate of the Oceans (ECCO) web site from which modeled ocean-bottom pressure fields produced by the ECCO consortium can be obtained.

Figure 3 shows the software page of the IERS SBO web site. Through this software page, the user can currently obtain a Fortran subroutine which computes the core products of the IERS SBO (oceanic angular momentum, center-of-mass, and bottom pressure) from the temperature, salinity, and horizontal velocity fields produced by an oceanic general circulation model.

Figure 4 shows the publications page of the IERS SBO web site. Through this publications page, the user can currently obtain, in pdf format, a document describing the IERS Special Bureau for the Oceans and a bibliography of over 200 relevant publications.

As can be seen, these pages of the IERS SBO web site are quite basic and merely serve as an interface to the data sets, software, and publications archived there. We plan to improve this web site by incorporating tools by which the available data sets can be displayed and intercompared, including comparisons with the relevant solid Earth measurements such as those of the Earth’s rotation and geocenter. As additional data sets from other OGCMs become available and are archived at the SBO, the ability to intercompare the available series will be invaluable in aiding the user to decide which series is best suited for his purpose.

[1] ftp://euler.jpl.nasa.gov/sbo

Fig. 4 The publications page of the IERS Special Bureau for the Oceans web site

In addition, we plan to improve the bibliography. It is currently only available in the form of a list as a pdf file. We plan to make it browsable online with each entry tagged with searchable keywords such as “torques”, “angular momentum”, etc. As the number of bibliographic entries increases, having a browsable bibliography will enable the user to more quickly locate publications of interest rather than having to visually scan a lengthy list.

8 IERS SBO Data Archive and Formats

The data holdings of the IERS SBO are currently quite sparse, consisting of just two oceanic angular momentum series and two oceanic center-of-mass series. No oceanic torque, gravitational field, or ocean-bottom pressure data sets are archived at the IERS SBO. While a link is provided to the ECCO web site from which the ECCO bottom pressure fields can be obtained, as explained above, these pressure fields must be corrected for the effects of artificial mass variations in them before they should be used in solid Earth science investigations. We plan to provide such corrections through the IERS SBO web site.

We also plan to expand the data sets available through the SBO. For example, the ocean-bottom pressure fields of van Dam et al. (1997) are data sets that could potentially be included in the SBO today.

The oceanic angular momentum and center-of-mass series currently archived at the IERS SBO are available as ASCII text files. This is a convenient format for small data sets such as these series consisting of just a time tag and 3–6 values at that epoch. However, larger data sets such as time-dependent ocean-bottom pressure fields must be archived in a compressed format. For these larger data sets we propose to let the user select from a choice of formats including NetCDF and compressed ASCII text. Decompression routines for a variety of platforms will be provided to the user through the SBO software web page.

9 Summary

The IERS Special Bureau for the Oceans is committed to serving the needs of the solid Earth science community by providing via web and ftp servers relevant oceanic data sets to facilitate investigations into the effect of the oceans on the Earth's rotation, deformation, gravitational field, and geocenter. The Special Bureau for the Oceans was created by the International Earth Rotation Service to foster research by the solid Earth science community. Observations of the Earth's rotation, gravitational field, and geocenter are globally integrated quantities which change in response to natural and human-induced causes. The IERS SBO supports investigations into the observed changes in the Earth's rotation, gravitational field, and geocenter by providing relevant oceanic data such as angular momentum, bottom pressure, and center-of-mass to aid in the interpretation of these observed changes.

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Comparison of Oceanographic Signals with SLR-Derived Gravity Observations

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1 Introduction

The recent results of Cox and Chao (2002) identified a significant departure from the otherwise linear post-glacial rebound (PGR) dominated drift in the Earth's J_2 zonal harmonic. That study considered a number of potential causes, however it was not possible to firmly identify the source of the change. That analysis included Satellite Laser Ranging (SLR) data from a total of 10 different satellites, covering the period from 1979 up to 2002. That data series has since been extended through May of 2002. Figure 1 shows the complete data series. With the exception of the additional data in 2002, it is similar to Figure 2 of Cox and Chao (2002). In addition to the J_2 zonal, time series for J_3 was also estimated. The J_3 zonal, which describes north-south mass distribution does not show any significant anomalies corresponding to the timing of the J_2 event. Provided this result is accurate, it implies that whatever is causing the J_2 anomaly is symmetric around the Equator. So far the most consistent explanation is for an oceanic cause, which will be further investigated here. Further considerations about the other potential causes are also provided below.

2 Possible Causes

Several possible causes for the J_2 anomaly have been investigated, including the cryosphere, atmosphere, reservoirs, core, and oceans. A reasonable first guess as to the cause is accelerated melting of ice mass. The melt water must be transported from the high latitude regions to the equator to produce an effect such as the J_2 anomaly. As a hypothetical example of the magnitude of the event, Greenland would have to shed about 400 Gt of ice mass annually, with a net *additional* global sea level (GSL) rate of >1 mm/yr. However, Greenland and West Antarctica radar altimeter derived ice height changes for the 1992–1998 period show an equivalent GSL change of –0.22 mm/yr for Greenland, and –0.08 mm/yr for West Antarctica (based on preliminary results provided by J. Zwally and described in Zwally and Brenner, 2001). The green curve in Figure 1 shows the implied J_2 change caused by the ice height changes in Greenland and West Antarctica. East Antarctica, while generally considered to be in mass balance, is an unknown, but it would need to contribute ~1–2 mm/yr to GSL, depending on the scenario. Using relations based on the Meier (1984) estimates, mountain glaciers have a smaller effect on J_2 per unit mass than Greenland. The mass loss required to explain the observed J_2 changes would result a sea level contribution of ~2 mm/yr over the pre-1998 rate. All of these accelerated ice melt scenarios require huge GSL changes that simply have not been seen in the TOPEX/POSEIDON (T/P) GSL data. If the ice melt is going into the oceans, it must be accompanied by a significant cooling event in order to conserve GSL. Also, there is the remote possibility that the residual melt water is accumulating on land. In any case, the turn around of the J_2 anomaly in 2001 implies an ice mass accumulation.

The atmospheric gravity correction applied to the data in Figure 1 was computed from the monthly NCEP reanalysis pressure grids assuming a two-dimensional approximation. While the atmosphere explains a good portion of the variation from the monthly to annual periods, it does not explain the anomaly. Consideration has also been given to the effects of the two-dimensional assumptions. In this case the maximum difference between the two-dimensional and three-dimensional computations amounts to ~0.5x10^{-10} change in the annual amplitude, with no significant effect on the interannual variation.

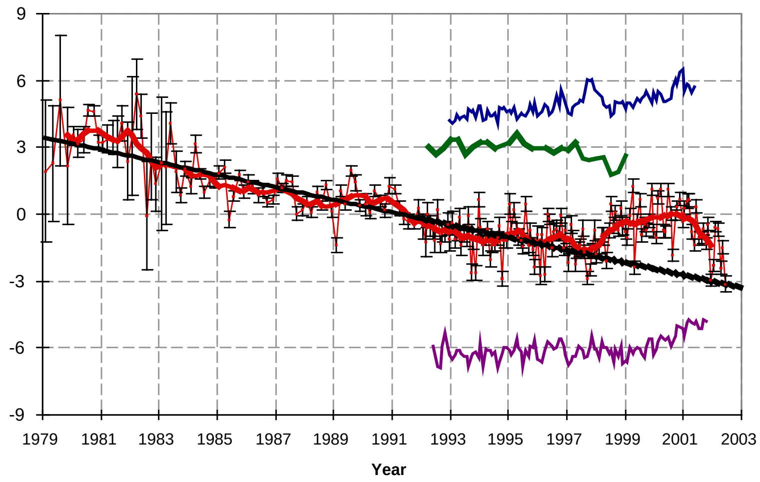


Fig. 1 Observed ΔJ_2, after subtraction of the IB corrected atmospheric signal and an empirical annual term, before (thin red line with error bars) and after an annual filter has been applied (heavy red line). Error bars are the observed J_2, uncertainties. The heavy black line is a weighted fit to the (unfiltered) pre-1997 data. The slope is –2.8x10^{-11} year^{-1}. The offset green line (second from top) is the J_2 implied by the Greenland + W. Antarctic ice heights derived from ERS-1/2 altimetry data. Also shown are the J_2 implied by the T/P uniform GSL change (blue, offset, top), and that considering the geographic distribution of the sea height changes (purple, offset, bottom). Neither sea height derived estimate includes steric effects. Sampling intervals are 90-days in 1979, 60-days from 1980 through 1991, and 30-day afterwards. No detrending of rates has been performed. Units are 10^{-10}. (For a colour version of this Figure see http://www.iers.org/iers/publications/tn/tn30/.)

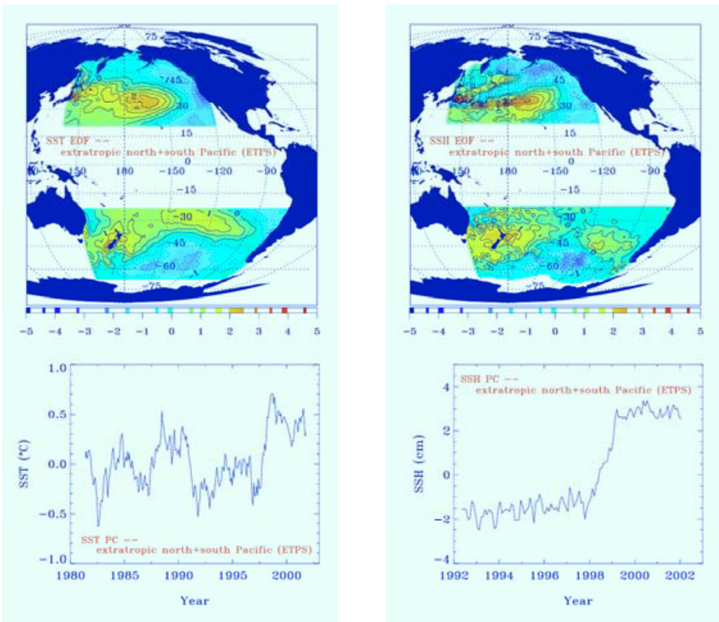
Terrestrial water impoundment is another possible factor. Large dams can individually cause a jump of ~0.2x10^{-10} in J_2, however, the cumulative effect since 1998 is far too small to explain the observed J_2 changes (Chao, 1995). Regrettably there is insufficient reliable data at the moment to make any assessment about the role of hydrology.

Changes in the Earth's mantle – specifically post-glacial rebound – result in the largest known interannual variation in the low degree gravity field. Such changes in the mantle occur over very long time constants due to the viscosities involved, so a mantle-originating cause for the post 1998 J_2 changes is unlikely. A more dynamic source of solid Earth variation is the core, which has generally been assumed to not be a contributor to gravity field changes. W. Kuang, (now at NASA GSFC, private communication, 2002), reviewed his geodynamo models and found that under some assumptions rates as large as ~0.5–1.0x10^{-11} per year are possible. While the core signal may be larger than previously assumed, it still does not explain the J_2 anomaly.

3 The Contribution of the Ocean

The timing of the J_2 anomaly onset corresponds to the last big El Niño event, raising the possibility of an oceanographic cause. If the T/P sea surface height (SSH) data is treated as being entirely caused by mass redistribution, the implied change in J_2 is consistent with the SLR results, if not a close match. A large uncertainty exists when interpreting the mass redistribution implications of the SSH data, because thermally driven changes in sea level have no gravity signal. Figure 2 shows the primary mode of an EOF/PC analysis of the Seas Surface Temperature (SST) and T/P SSH for the extratropic regions of the Pacific. Both the SST and SSH modes show a change around 1998. A breakdown of the SSH analysis for each region (not shown) indicates that the Northern pacific is the dominant contributor. The SST mode corresponds to the Pacific Decadal Oscillation (PDO), which is correlated with the observed J_2 data (Cazenave and Nerem, 2002). The implied gravity change associated with the SSH mode is several times too small to explain the observed change in J_2, but it is symmetric about the Equator, satisfying the J_3 constraint.

EOF/PC analyses of the assimilation mode output of the ECCO consortium ocean model (Stammer et al., 1999) yields similar results to those based on the observed SST and SSH data. Figures 3 and 4 show the EOF/PC analyses for the North and South Pacific, respectively. Despite the more abrupt jump in SSH seen in the Northern Pacific, the biggest jump in ocean bottom pressure occurs in the Southern Pacific. A break down of the temperature and salinity data along parallels traversing the northern and southern regions gives some indication as to the cause of this difference in behavior. While the North and South Pacific regions had similar behavior in terms of temperature and SSH, there was a significant difference in the salinity modes. This illustrates the need for care when making mass inferences based on SST and SSH data alone.



(a) (b)

Fig. 2 Primary modes of EOF/PC analyses of the (a) Sea Surface Temperature and (b) Sea Surface Height for the extratropic regions of the Pacific Ocean. The SST data series runs from 1980 through 2001, while the SSH series begins in 1992.

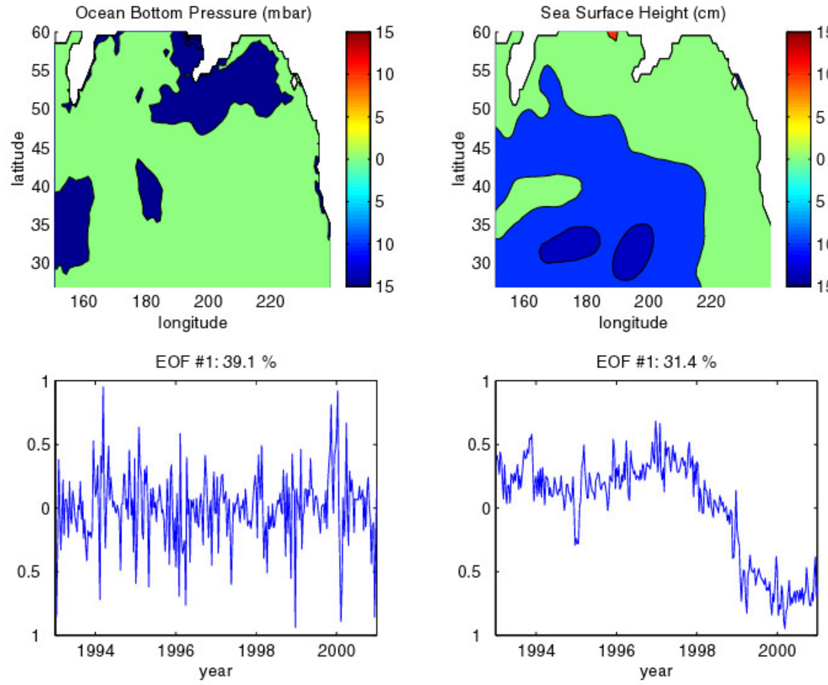


Fig. 3 Principle EOF modes for the ocean bottom pressure and sea surface height from the ECCO assimilation model for the North Pacific

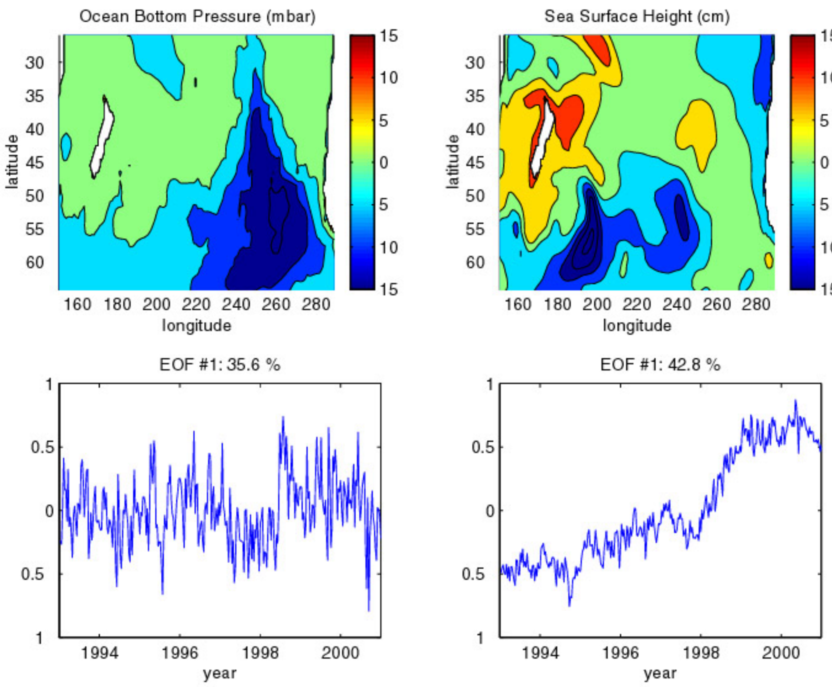


Fig. 4 Principle EOF modes for the ocean bottom pressure and sea surface height from the ECCO assimilation model for the South Pacific

Similar analyses have also been performed for the Indian Ocean, North Atlantic, and South Atlantic. The dominant contributor of the five regions to J_2 is the primary mode for the Southern Pacific, with some small change in slope or offset occurring in the rest of the regions. The net jump in J_2 predicted by the ECCO assimilation model is ~0.7×10^{-10}, or only about 25% of the observed anomaly. The correspondence between both the observational SSH and SST data and the ECCO model modes with the J_2 anomaly, as well as the correlation with PDO, supports the hypothesis that the ocean is a major contributor. However, some other source of mass redistribution (possibly driven or related to the ocean changes), or a more accurate accounting, is required to fully explain the anomaly. One early point of concern is the lack of coverage in the arctic sea for both the ECCO model and the radar altimetry data types.

4 Conclusions

First, a large anomaly in J_2 began sometime around 1998, and has persisted until the present time. There are indications that J_2 is returning to the nominal values and long-term trend dictated by post-glacial rebound. Consequently, the deviation may be interannual in nature, and therefore does not necessarily represent a departure from the long-term trend. Ice melting scenarios large enough to explain this deviation produce a large GSL change, which simply has not been observed. Likewise, the apparent recent turn in J_2 would then imply a recent accumulation of ice mass, which, while not impossible, is unlikely.

There is evidence that some component of the cause of the J_2 anomaly lies within the oceans. The timing corresponds to changes in the primary EOF modes for the SST and SSH in the extra-tropic regions. The primary SST EOF mode corresponds to PDO, which is generally correlated with the J_2 series. The timing also corresponds to changes primary EOF modes of the ECCO model bottom pressure. Analysis of that model's output shows that the most influential region is the Southern Pacific, but some effects are also seen in the other regions. However, the ECCO model bottom pressure data can only explain about 25% of the observed magnitude of the J_2 change. Nonetheless, the good overall agreement in the timing and nature of the event with the ocean activity warrants more detailed analysis of the ocean's role.

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Oceanic Excitation of Polar Motion and Nutation: An Overview

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Abstract: Exchanges of the angular momentum between the atmosphere, the ocean and the solid Earth have an important impact on polar motion at periods from a fraction of a day to years and contribute significantly to nutation. But while the role of the atmosphere in the excitation balance is well established, the importance of the ocean has been recognized only recently. This paper gives an overview of the non-tidal oceanic excitation of polar motion and nutation by taking into account recent advances in modeling the oceanic angular momentum.

1 Introduction

The coupled system of the atmosphere and oceans has a major impact on polar motion over a broad range of periods via exchanges of the angular momentum with the underlying solid Earth. The role of the atmosphere in the excitation of polar motion has been relatively well quantified, mainly due to the fact that time variations of the atmospheric angular momentum (AAM) are well constrained by the available meteorological observations; see, e.g., (Brzezinski et al., 2002a) for a recent review. The atmosphere, with its mass amounting only to 1 part in 10^2 of the oceanic mass, exhibits strong mobility, forced primarily by the diurnal and seasonal cycles, which causes the corresponding angular momentum changes to be able to exceed those in the ocean.

The oceanic excitation of polar motion does not have as good an observational evidence, although it is expected to be important. If we neglect tidal fluctuations in the ocean, including the so-called pole tide, the remaining variability of the oceanic angular momentum (OAM) is mostly driven by the atmospheric forcing and the thermohaline processes caused by heat and freshwater fluxes. A significant part of the oceanic excitation is the ocean response to the overlying pressure variations which has long been modeled implicitly by adding the so-called *inverted barometer* (IB) correction to the pressure term of the atmospheric angular momentum. This simple static model has proven to be a reasonably good approximation at periods of weeks and longer (Wahr, 1983). Estimating the remaining variability of the OAM, induced by surface winds as well as heat and freshwater fluxes, is much more complicated because it requires three-dimensional modeling of the global ocean dynamics. Only recently have there been successful attempts to produce such data, reported e.g. by Ponte et al. (1998) and Johnson et al. (1999). Further improvements of modeling the OAM, stimulated by the International Earth Rotation Service (IERS) Special Bureau for the Oceans (SBO), are under development.

Here we present an overview of the non-tidal oceanic excitation of polar motion and nutation taking into account recent advances in modeling the oceanic angular momentum. The excitation spectrum is split into seasonal effects, Chandler wobble, and other components of polar motion (intraseasonal, interannual and decadal). Special attention is paid to the non-tidal oceanic effects in the diurnal, subdiurnal and nutation bands which are still largely uncertain due to the lack of appropriate data and models.

2 Seasonal Effects

The seasonal component of polar motion consists of a slightly elliptical annual wobble with amplitude near 90 mas (milliarcseconds) and much weaker higher harmonics: semiannual (<5 mas) and terannual (<1 mas). Each of the seasonal wobbles can be further decomposed into the prograde (counterclockwise) and retrograde components. In case of the annual wobble the prograde component is dominant due to its vicinity to the Chandler resonance – its amplitude is about 30 times larger than that of the retrograde component. It has long been established that the main contribution to the excitation of the annual wobble comes from the atmospheric pressure variation corrected for the IB response of the ocean; see (Eubanks, 1993) for a review of the earlier results and (Brzezinski et al., 2002a) for an estimate based on the NCEP/NCAR AAM reanalysis series. The IB correction plays an essential role in the seasonal band as it reduces the variance of the AAM by the factor of about 3.7 (Brzezinski and Ponte, 2002). The total atmospheric contribution (IB pressure plus wind) to the prograde annual amplitude is only slightly bigger than the observed value, but the difference in phase is rather large, up to 30°.

The oceanic contribution to the seasonal wobbles was studied extensively by Ponte and Stammer (1999) who used the OAM time series derived by Ponte et al. (1998) spanning 1985–1996. In a more recent work, Gross et al. (2002) used substantially longer OAM series spanning 1980–2000 estimated from the output of a different OGCM. They arrived at the same conclusion that in the case of the annual wobble, adding oceanic excitation to that of the atmosphere brings the modeled excitation closer to the observed. The same is also true for most of the semi-annual and ter-annual prograde/retrograde wobbles. But the remaining discrepancy at the seasonal frequencies after removing the atmospheric and oceanic contributions is still significant. That can be partly attributed to errors in the polar motion and atmospheric/oceanic excitation data, but also certainly indicates that other seasonal processes contribute to the seasonal wobbles, such as seasonal variations in soil moisture, snow load, etc. (Eubanks, 1993; Wünsch, 2002), which are not as well constrained by observations as are the AAM and OAM. However, the seasonal excitation budget should be improved considerably after receiving observations from the CHAMP and GRACE satellite missions which will be measuring changes in the Earth's gravitational field caused by mass displacements over the surface of the Earth.

3 Chandler Wobble

The Chandler wobble is a free prograde oscillation in polar motion with a period of $T_C = 14$ month and a variable amplitude with mean value of about $A_C = 160$ mas. This oscillation is subject to damping which is taken into account by expressing the corresponding resonant angular frequency as $\sigma_C = 2\pi F_C(1 + i/2Q_C)$, where $F_C = 1/T_C$ denotes the frequency in cycles per time unit and Q_C is the dimensionless quality factor which is inversely proportional to the wobble energy dissipation rate. An analysis of 100 years of observations of polar motion yields values of Q_C between 150 and 180 which implies that the corresponding dissipation time is between 55 and 68 years. In the absence of excitation, this free wobble should decay during the period of its observation. But this is evidently not the case, which means that there exists a process (or a combination of processes) permanently exciting the wobble.

Table 1 Polar motion excitation on intraseasonal time scales (Nastula and Ponte, 1999)

	periods of 2 to 15 days		periods of 15 to 150 days	
correlation	χ_1: 0.43 ⇒ 0.48	χ_2: 0.54 ⇒ 0.52	χ_1: 0.53 ⇒ 0.80	χ_2: 0.75 ⇒ 0.88
variance (%)	χ_1: 18 ⇒ 38	χ_2: 26 ⇒ 42	χ_1: 45 ⇒ 88	χ_2: 27 ⇒ 49

Global processes taking place in the atmosphere have been considered as a candidate for the excitation of the observed Chandler wobble for a long time – see, e.g., (Eubanks, 1993) for a thorough review of earlier results and (Brzezinski et al., 2002a) for an estimate based on the 50-year NCEP/NCAR reanalysis AAM series. A common conclusion was that the AAM variations provide less than half of the power needed to maintain the observed Chandler wobble, with the dominant contribution coming from the pressure term. (The role of the wind term still remains controversial – see, e.g., Aoyama, paper presented at this Workshop.)

One possible candidate for explaining the remaining large gap in the excitation balance is the ocean. Gross (2000) and Brzezinski and Nastula (2002) investigated this problem using an 11-year OAM series estimated by Ponte et al. (1998). These two works, which used different methods of data analysis, nevertheless arrived at the similar conclusion that the combination of atmospheric and oceanic processes contained sufficient power near the resonant frequency and was highly coherent with the observed Chandler wobble between 1985 and 1996. The ocean-bottom pressure variations appeared to be the single most effective excitation mechanism. These conclusions were confirmed by the recent work of Gross et al. (2002) who used a 20-year OAM series based on a different OGCM.

Our analysis (Brzezinski et al., 2002b) of a 50-year OAM time series estimated by Ponte (2001, private communication) from a different ocean model and data assimilation system, showed again that the OAM contains sufficient power to close the excitation balance of the Chandler wobble; nevertheless, the coherence with geodetic data at the Chandler frequency decreased significantly in comparison to the previous studies. The lower coherence could be partly attributed to the inclusion in the analysis of earlier data of inherently lower quality. But comparison done over the common period 1985–1996 showed significant differences between the two OAM series.

The difference discovered between the OAM series at the Chandler frequency indicates that further improvements in the ocean models and data assimilation systems are still necessary. Comparison with the Earth orientation data is a useful tool in verifying the overall quality of the ocean analyses and checking the reliability of the OAM data.

4 Other Components of Polar Motion

In this section we will consider the ocean excitation of polar motion within the following three frequency bands: (1) intraseasonal – periods from several days to 1 year, excluding seasonal variations; (2) interannual – periods from 1 to 6 years, excluding annual, and (3) decadal – periods longer than 6 years. The role of the ocean will be conveniently expressed by two parameters, the first one expressing the correlation coefficient between the modeled excita-

Table 2 Polar motion excitation on intra-seasonal time scales (Gross *et al.*, 2002)

	periods of 5 days to 1 year	
correlation	χ_1: 0.61 ⇒ 0.78	χ_2: 0.69 ⇒ 0.82
variance (%)	χ_1: 37 ⇒ 61	χ_2: 48 ⇒ 67

tion expressed by the sum AAM+OAM and the observed excitation (that is inferred from the polar motion data), and the second one expressing the percentage of the observed excitation variance which can be explained by the modeled excitation. Selected estimates of these two parameters are given in Tables 1–3 for each equatorial component of the excitation separately, and then contrasted to the corresponding quantities computed for the atmospheric excitation alone (the arrows indicate the change from AAM to AAM+OAM).

Intraseasonal periods.

Table 2 gives the results obtained by Nastula and Ponte (1999) for a data span of 1993–1995, and Table 2 gives the results obtained by Gross et al. (2002) for a data span of 1980–2000.

Interannual periods.

Table 3 gives the results obtained by Gross et al. (2002) for a data span of 1980–2000. The dominant contribution comes from ocean-bottom pressure variations.

Table 3 Polar motion excitation on inter-annual time scales (Gross et al., 2002)

	periods of 1 to 6 years	
correlation	χ_1: 0.26 ⇒ 0.40	χ_2: 0.29 ⇒ 0.71
variance (%)	χ_1: 3.5 ⇒ 7.5	χ_2: 6.5 ⇒ 50.8

Decadal periods.

Brzezinski et al. (2002b) and Gross et al. (2002) concluded that neither atmospheric nor oceanic angular momentum has enough power to explain the observed low frequency variation in polar motion, consisting mostly of a 30-year “Markowitz wobble”.

5 Diurnal, Sub-diurnal and Nutation Bands

At diurnal and sub-diurnal periods, the ocean contributes significantly to polar motion by the tidal variations. However, as the global circulation of the atmosphere exhibits strong diurnal and semi-diurnal signals (Brzezinski et al., 2002a), we can also expect that the wind- and pressure-driven ocean variability contains diurnal and semi-diurnal signals. These high frequency signals in OAM can in turn contribute to the diurnal and semi-diurnal variation in polar motion and, in case of the retrograde diurnal excitation, to nutation. Questions of particular interest have to do with: (1) the oceanic contribution to the nutation amplitudes which can contain both the constant part that should be included in the conventional precession/nutation model and the time-dependent part, (2) the role of the ocean in the excitation of the observed free core nutation signal, and (3) the importance of the non-tidal oceanic contributions to the prograde diurnal and semi-diurnal polar motions. Any research on such problems requires a special kind of OAM data. First, a subdaily (at least 6-hourly) sampling of the OAM is necessary. Second, as the static IB model is not adequate at such high frequencies (e.g., Bizouard et al., 1998), the pressure forcing should be taken into account in the underlying OGCM. Most of the available OAM series do not fulfill these requirements.

The first attempt to assess the effect of the atmospherically driven ocean dynamics on nutation was reported by Petrov et al. (1998) who used the 6-hourly OAM series from a 3-year barotropic model developed by Ponte (1997). An important and promising finding was that the ocean contribution to nutation is of similar size as that of the atmosphere. However, due to the relatively short data span and much higher noise contents than in the AAM, they could detect in the OAM data only the S_1 wave corresponding to the prograde annual nutation. After accounting for the OAM, the agreement with the VLBI nutation data became worse in comparison to the pure atmospheric non-IB effect. One reason for that, pointed out by Ponte (1998, private communication), was that the corresponding OGCM was not reliable in the diurnal band due to its sensitivity to some poorly constrained parameters such as bottom friction coefficient. A possible criterion of constraining these parameters is to minimize the difference between the atmospheric plus oceanic excitation and that inferred from the VLBI observations.

6 Summary and Conclusions

Recent estimates of non-tidal oceanic angular momentum demonstrate the importance of ocean dynamics in driving polar motion at seasonal, intraseasonal and interannual periods. Adding the OAM to the AAM brings the modeled excitation closer to the observed; nevertheless the remaining discrepancy is still significant. Particularly important are results concerning the excitation of the free Chandler wobble. Several independent works demonstrated that the combination of atmospheric and oceanic processes contains sufficient power near the resonant frequency and is highly coherent with the observed free wobble. At periods longer than 6 years the OAM, similarly as the AAM, contains too little power to explain the observed variability in polar motion. At diurnal and subdiurnal periods, including the nutation band, the role of the OAM still remains uncertain due to the lack of appropriate data and models.

This brief review shows that the following two tasks related to the activity of the IERS SBO are important for a better understanding of the oceanic excitation of polar motion and nutation: (1) further improvements in both the model and data assimilation systems used to estimate the OAM series, and (2) development of the ocean circulation models which enable estimation of the OAM series containing high frequency signals, up to the semi-diurnal band.

Acknowledgements

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Possible Role of the Oceans in the Variations of Length of Day at High Frequencies

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At the U.S. Naval Observatory, there are a few research studies as well as operational tasks that use data available from Global Geophysical Fluid Center (GGFC) web and ftp sites. This research includes: investigating the excitation mechanisms of Earth rotation variability on all time scales, examining the global water budget and its role in exciting Earth rotation, researching the usefulness of ocean model nowcast/forecast models in predicting Earth rotation, and investigating the role of geophysical fluids in gravity field variations on GPS satellites.

This presentation will briefly cover USNO's ongoing research to examine high frequency variations in excess Length of Day (LOD). It will also highlight the GGFC datasets used in the study as well as raise some issues with respect to the currently available GGFC datasets and what this researcher would like to see in the future to make this type of research easier.

The excess LOD has variability at time scales ranging from the sub-daily to decadal. The research appears to indicate that on decadal time scales the variability in the core and core-mantle interactions can excite LOD variability on these longer time scales (Eubanks, 1993). For periods of less than a decade to a few years it appears that the oceans excite some of these variations in LOD (Johnson et al., 1999). While for periods of a year and less the atmosphere can explain about 90% of the variations in LOD (Eubanks, 1993) with the oceans and continental hydrology contributing at a much smaller amount at specific frequencies between a few weeks and a year (Marcus et al., 1998; Johnson et al., 1999; Chen et al., 2000).

This research comes out of USNO's efforts to improve the combination solution and the near-term predictions of UT1–UTC variations that are published in the IERS Rapid Service/Prediction Center Bulletin A. In the spring of 2000, USNO began re-evaluating the usefulness of a UT1-like product estimated from atmospheric angular momentum (AAM). The AAM examined in this study was the model estimates produced by the National Centers for Environmental Prediction (NCEP) operational model. These AAM data products are made available through the GGFC Special Bureau of the Atmosphere (SBA).

The results of this study indicated the existence of variability, with periods varying between 5 and 15 days, in the AAM UT1-like quantity (UTAAM) that was not present in the UT1–UTC combination solution and once this variability was removed the UTAAM became very useful in improving our near-term predictions of UT1–UTC. This led to a technique that uses an intermediate UT1–UTC solution to estimate and remove this unobserved variability from the UTAAM data product (Johnson et al., 2002). This approach has reduced the UT1–UTC prediction error by 42% at 10-days into the future.

However, this still leaves a very important question unanswered. What is the cause of this unexplained variability at periods ranging from 5 to 15 days. It could be the result of some model limitations or errors in the NCEP operational models, or was something else contributing to the variability.

Potentially, one of the larger sources of error in modern atmospheric models is the model's handling of water vapor and water vapor transport. Comparisons between NCEP Reanalysis, Goddard's Earth Observing System (GEOS), and the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric models indicate that one of the biggest differences between these models is the total amount of water vapor contained in each model as well as its distribution. To examine the water budget of the NCEP model, we compared its values with those observed by satellite microwave mapping and imaging (SMM/I) aboard weather satellite 13. These comparisons showed that there is reasonable agreement between the model estimates and the SMM/I observations for water vapor mass variability and its distribution.

In addition to examining the SMM/I observations, I examined the possible contributions from the ocean and hydrology using datasets available from the GGFC Special Bureau for the Oceans (SBO) and NCEP. The SBO web site provided the oceanic angular momentum (OAM) dataset named Johnson01.oam and the NCEP web site provided daily values of water equivalent of accumulated snow depth (WEASD) and soil moisture from NCEP's Climate Data Assimilation System-1 (CDAS-1).

An examination of the WEASD and soil moisture data produced by NCEP's CDAS-1 showed little to no variability on periods less than three months and therefore this could not explain the variability that was present in the atmosphere and not present in the UT1–UTC time series. This lack of high frequency variability in the NCEP's CDAS-1 data products may be due to the influence of the climatological data used in the model.

An examination of the OAM values from the Johnson01.oam dataset clearly showed that the oceans could be the source of this variability. The cross correlation indicates that the oceans are significantly correlated with the variability unaccounted for by the atmosphere on periods less than a few months. The coherence analysis indicates that for a number of frequencies between 22 and 36 cycles per year the coherence exceeds the 95% confidence level. Analysis of the power spectra indicates that the oceanic variability has power similar to the unexplained variability at few of these frequencies. Therefore, the oceans appear to be the leading candidate in explaining this variability.

This research would have been much more difficult to undertake without the datasets that are available through the GGFC. However, it is in the opinion of this researcher that the GGFC could improve their services and data products. These improvements include but are not limited to: (1) promoting the development of new data products and the improvement of existing data products, (2) promoting product center documentation, (3) promoting the release of existing datasets (especially datasets from GGFC collaborators), (4) monitoring the performance of GGFC Special Bureaus on quality of available datasets, and (5) promoting collaborations between researchers in the atmospheric, oceanographic, hydrological, climatological, and solid Earth sciences. The GGFC has the unique opportunity to become the major source of geophysical fluids for researchers world-wide and addressing these concerns would be a good step in securing that outcome.

In closing, this researcher would like to make the following two suggestions on what the GGFC could do to improve the usefulness of the GGFC datasets. First, the GGFC must make sure that the special bureaus properly document their existing datasets. This includes correcting the dataset documentation that is clearly inaccurate and incomplete. Finally, the IERS GGFC could work on expanding the number of regularly updated atmospheric datasets that are currently available, adding near-real time/daily updated atmospheric AM datasets that use Non-IB, IB, and dynamic barometer corrections, and adding nowcast/forecast global oceanic AM datasets. These improvements would greatly increase the usefulness of IERS GGFC datasets in addressing current and future research needs.

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The Hydrology Bureau of the Global Geophysical Fluids Center

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1 Goals of the Special Bureau for Hydrology (SBH)

The purpose of the SBH is to provide a bridge between the communities of climate sciences and geodesy. Modern space geodetic observations are influenced in a direct way by the variable distribution of water mass. The geodetic community requires a measure of the time variable load of water on the land surface over the entire Earth, as a function of time, in order to estimate both local effects on geodetic site displacements, and global effects on earth rotation, geocenter, and gravity field changes. The hydrologic problem of estimating water redistribution is considered one of the fundamental challenges in climate science. It is pursued aggressively by a community much larger than the geodetic community. Thus, it is sensible to tap the resources of the climate science enterprise, especially employing results from global numerical data-assimilating models.

We intend to use the SBH web page to distribute both water load time series data in gridded form, and commonly used global integrals of it. These global integrals would include time series of excitation functions of earth rotation changes, and variations in the global gravity field Stokes coefficients. The real challenge is to identify data resources, and to collaborate with those developing state-of-the-art land-surface models, and other data sources. There are two promising future resources for estimating water load variations on a global basis. One is the GRACE satellite mission, which will provide variations in Earth's gravity spherical harmonic coefficients on a monthly basis. A second resource would be estimates from Global Land Surface Models (LSM) under development at Goddard Space Flight Center, and perhaps at other centers. There exist other data resources on the web pertaining to global water budgets. For example, there is an interesting site at <[1]> (University of Delaware) holding gridded monthly mean soil moisture and snow load fields, and there may be other resources as well to be added.

2 SBH Website Current Contents

ECMWF and NCEP-NCAR models produce global gridded atmospheric reanalysis of all available weather observations for the past several decades. In a reanalysis, the numerical model is fixed. The surface boundary over land is given a primitive hydrologic cycle with some coupling to the atmospheric model. Generally, hydrologic parameters of the land surface are not connected to a river runoff model. Instead the hydrologic parameters are used to provide proper boundary conditions for the atmospheric calculations, that are of primary importance. Because the land surface model is of secondary importance, it is difficult to understand exactly how soil and snow values are calculated. Documentation tends to be poor because the hydrologic boundary conditions are not of primary interest. For both the NCEP-NCAR and ECMWF results we have drawn conclusions based on an inspection of the time series and global maps of the average seasonal behavior.

[1] http://climate.geog.udel.edu/~climate/

Variability in total water load is the sum of water changes in several soil layers, plus a snow load component. The water load changes are not based on observed precipitation and runoff, and may be considered representative, but not good measures of time variability. There is no obvious way to assess quantitatively the size of the errors in these time series. Qualitatively, we observe that NCEP-NCAR results show little inter-annual variation (they are dominated by near-sinusoidal annual variations). On the other hand, average seasonal ECMWF water loads resemble the global seasonal water balance climatology published in the mid-1980's by Willmott and Rowe. This climatology is not nearly so sinusoidal, and is based on many decades of evaporation, precipitation, and runoff data averaged by month, and gridded for the globe. ECMWF coupling to the atmosphere model seems to provide some interannual variability. Because neither NCEP-NCAR nor ECMWF includes coupling to ground water or continental ice sheets (both long term storage reservoirs), it is likely that no gridded model output now available correctly estimates long-term load variations that may arise in the hydrologic system.

Daily continental water storage, defined as the sum of soil wetness and snow water, is computed from the two reanalysis models. We obtained ECMWF results from a UCAR website (http://dss.ucar.edu/pub/ec-reanalysis.htm) instead of the official website (http://www.ecmwf.int). Refer to the websites for descriptions of the reanalysis models. The table lists information about data sets currently in the SBH website. In addition to gridded values there are also time series of hydrological excitations of polar motion and LOD computed from NCEP reanalysis daily water storage data. We also provide a table to list global major artificial reservoirs with water capacity exceeding 10 km^3 or 10^{13} kg.

	NCEP/NCAR	ECMWF
Time-span	Jan.1979–Dec.2001	Jan.1979–Dec.1993
Resolution (degrees)	2	2.5
soil layers	2	4
layer thickness (cm)	10, 190	7, 21, 72, 189
sampling	daily	6 hours
Monthly Means 1 x 1 degree NCEP Snow and soil	1993–1998	
LOD and PM daily exc.	1948–2001	
Daily grid water load NetCDF format	1948–2001	

3 New Land Surface and Climate Models

Although there is at present no global land surface model operating along the lines of the analysis and forecast atmospheric models (NCEP, ECMWF, with data assimilation) there are developments at a number of laboratories. One global data assimilating model that has been analyzed for its geodetic implications is that of Shmakin, Milly, and Dunne (J. of Hydrometeorology, v. 3, p. 311, 2002). This model has been developed at the Geophysical Fluid Dynamics Laboratory (GFDL) of Princeton University. Water storage variations from an early version were employed by van Dam and others (Crustal Displacements due to continental water loading, Geophysical Research Letters, 2000) to estimate load deformation at GPS sites. With ground water storage, and a river runoff scheme, the GFDL model provides land surface elements suitable for a global coupled model. It has been tested with a standard data set, the ISLSCP data, for forcing it over calendar years 1987–88. Lack of suitable data for assimilation in a real-time sense (especially precipitation) has been a limitation. Even for historical retrospectives, many data sets are monthly mean samples. Some interpolation to short time intervals is required to force the model at time step sizes suitable of a day or less. Thus, adjustment of monthly precipitation totals to estimate daily or subdaily forcing is required. The GFDL model has the potential to be forced by fields from data assimilating atmospheric models like ECMWF or NCEP. However, the precipitation estimates from these forecast models is widely recognized as being biased. There have been some bias-corrected precipitation data sets from NCEP and ECMWF that are being consider for the Goddard Space Flight Model, as described below.

At the Goddard Space Flight Center NASA's Global Land Data Assimilation System (GLDAS) is being developed. The goal is to develop a gridded numerical model that can assimilate observations from satellite sensors and other sources with the most promise for globally uniform coverage. The model has quarter-degree resolution, and provides for a complete water balance computation including runoff and ground-water storage. Development plans include simulations for a variety of forcings, including ECMWF and NCEP, and bias-corrected versions of these data sets, as well. Early indications are that the model possesses a realistic variation in water storage, including long-term variability. This contrasts with the NCEP and ECMWF data sets now available on the SBH website, which are dominantly seasonal, with little long-term variability. Members of the GLDAS development team participate in the SBH, and communication is therefore excellent. Some GLDAS results are therefore expected to be available on the SBH website by mid-2003.

4 Assessing the quality of global hydrologic data sets

It is possible on a local or even water-shed scale to compare the predictions of a hydrologic model with observations, but how is this done on a global scale? There are few obvious measures of the hydrologic cycle at the global scale that can be considered 'ground truth'. Currently only geodetic observations might be considered for such a global measure. We consider these possibilities in section 4.2, after a brief review of remote sensing opportunities for the future.

4.1 Remote Sensing of the Hydrologic Cycle

Space-based remote sensing of the hydrologic cycle offers the global perspective needed to assess hydrologic model performance. Some space-based data will be assimilated into models, as the GSFC is being designed to do. Thus, independent data, not planned for assimilation, are appropriate to test model performance. The NASA River & Wetland Processes Working Group headed by Doug Alsdorf of UCLA is studying prospects for monitoring surface water levels from space. There has been some success already in this field, notably from the use of radar altimeters, such as TOPEX, in monitoring levels in lakes and other water bodies, but the analysis is not yet a routine process with available satellites.

The most promising technologies in future satellite missions are active radar and lidar methods that measure inundation area, water heights, and changes. Radar altimetry has an along-track spatial resolution of several km and absolute height accuracy over rivers and wetlands of a few cm. Lidar altimeters, such as the GLAS instrument (Geoscience Laser Altimeter System) onboard the upcoming ICESat mission (Ice, Cloud and land Elevation Satellite), are capable of about 70 m along-track spacing and cm-scale height measurements in clear weather. SAR antennae with wavelengths capable of canopy penetration, e.g., L-band, can image inundation area with decimeter scale spatial resolution whereas passive microwave radars, e.g., SSM/I (Special Sensor Microwave/Imager), utilize differences in polarized brightness temperatures to estimate flooded areas with kilometer scale spatial resolution. Radar altimeters, specifically designed for oceanic applications, may lack the along track resolution necessary to define smaller rivers and wetlands with important discharge. It may be possible to improve spatial resolution of radar altimeters via a SAR-like processing mode, and there are satellite proposals (none yet funded) that show the feasibility of this idea.

4.2 Constraints from geodetic data

Redistribution of mass in the hydrologic cycle will change the gravity field, load the earth, and alter the Earth's rotation. Geodetic observations of these effects are now available with a precision that makes it feasible to monitor the time variable load of water. Generally these geodetic measures are global in scale. The relevant observations for Earth rotation are Polar Motion (PM), influenced by degree2-order 1 changes and Length of Day (LOD), influenced by degree 2 order 0 changes. For the gravity field variations, time series of low degree/order Stokes coefficients are available from satellite laser tracking, up to degree and order (4,4) or more. There should soon be available Stokes coefficient time series from satellite gravity missions such as GRACE and GOCE up to much higher degree and order, perhaps (100,100). GPS observations of station positions have recently been shown to measure degree-1 spherical harmonic loads (Blewitt et al., Science 294, p. 2342, 2001), and the estimation of higher degree loads, and related sea level change from GPS station positions is now a possibility.

It is proposed that these geodetic time series be employed to evaluate water load variations estimated by GLDAS and other models. For the moment, this reverses the traditional role seeking to validate Earth rotation observations. However, consider that many of the geodetic observations, especially of rotation, are now extremely precise, whereas there is virtually no global scale quality control on the hydrologic models. The other main contributors to geodetic variations are the atmosphere and oceans, both of which are modeled in a mature way at a variety of centers, with many resulting time series posted on the websites of the GGFC. Therefore, geodesy now provides, on a global scale, a realistic means of measuring the quality of the global hydrologic models. This evaluation can certainly begin with the seasonal cycle, and proceed to other frequency bands.

5 Conclusions

For the moment, the big challenge is to obtain global gridded data sets and put them on the website archive. In the near future, collaboration with groups constructing global land surface data assimilating models should yield geodetically interesting time series. Geodetic time series of Stokes coefficients, earth rotation, sea level and GPS station displacements now offer a reasonable way to test the predictions of global hydrologic models.

Time Variable Gravity Field: Using Future Earth Observation Missions for High Frequency De-Aliasing

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1 Introduction

The main objective of the future gravity field mission GOCE is the improvement of the static gravity field for wavelengths down to about 70 km by several orders of magnitude with respect to the current knowledge. CHAMP and GRACE have slightly less ambitious goals and aim at the determination of the static and time dependent gravity field for the long and medium wavelengths. Each mission has its own characteristics and contributes significantly to the overall goal. Due to the fluid and atmosphere dynamics in, on and above the Earth's surface, variations in the gravity field occur with time scales between a few hours and decades. The signals of these time variations of the gravity field are significantly above the sensitivity of the gravity field missions for wavelengths down to approximately 500 km. Therefore, if we want to determine the static gravity field with the prospected accuracy, the time variable effects in the gravity field have to be determined independently in order to be able to correct the observations beforehand. Up to now only models of the atmosphere, the oceans and the continental water, which only partly based on real observations are available to determine the time variable effects. Investigations for the atmospheric component have shown, that the accuracy of the atmospheric model parameters is not sufficient to compute atmosphere induced gravity field variations as correction for the static gravity field. With the sensors on ENVISAT and other Earth observation satellite missions, the first time an observation based approach to compute the oceanic and atmospheric mass variations and their impact on the gravity field can be developed. The extended abstract provides an overview of the scientific issues, the analysis methods and the missions and sensors applicable for atmospheric and oceanic mass de-aliasing. In summary the following tasks have to be investigated:

- Oceans: Determination of the steric (not mass related) effect over the oceans in order to reduce altimetric derived sea surface variations to real oceanic mass variations. The steric effect is computed by the ocean temperature and its salinity.
- Atmosphere: Computation of atmospheric mass variations from observed vertical pressure, temperature and humidity profiles.
- Combination of atmospheric and oceanic contributions for global gravity field analysis with special emphasis on the inverse barometer assumption.

2 Scientific Issues and Analysis Methods

2.1 Ocean

Altimeter data are providing the sea surface height above a reference surface. Variations of sea surface heights are caused by real water mass variations due to wind stress for example and by the so-called steric effect changing only the volume of water due to temperature and/or salinity changes. The issue is to develop methods for separating the real mass and the steric effects in the altimeter observations on a global scale. The individual processing tasks are:

- Computation of representative sea surface height maps for specific time periods from altimeter data taking into account the orbit characteristics and the applied altimeter corrections. Specific care must be given on mass related altimeter range corrections like tidal effects, in order to be compatible with the further processing of gravity field variations and their application in the gravity field modelling (e.g. gradiometer corrections). If necessary specific altimeter range correction terms have to be replaced or removed.
- Correlation of sea surface temperature maps with the altimeter maps. A careful space-time correlation of both fields must be done, because the satellite sensors for both parameters (radiometer, altimeter) cover different areas simultaneously. Methods have to be developed to perform the space-time interpolation of altimeter maps or sea surface temperature maps (or both) in order to make them compatible for the estimation of the steric effect.
- Ocean salinity data have to be acquired from other sources. For the near future salinity models from oceanographers are applicable. In the time-frame of the GOCE mission also the ESA Earth Explorer opportunity mission SMOS is planned to be in orbit, which will provide observations of the ocean salinity. At this time the only model data in the overall approach can also be replaced by satellite observations.

The combination of sea surface temperature and salinity to compute the steric height effect can be done with well known mathematical models. By subtracting this effect from the full altimeter signal the mass effect in the oceans can be determined.

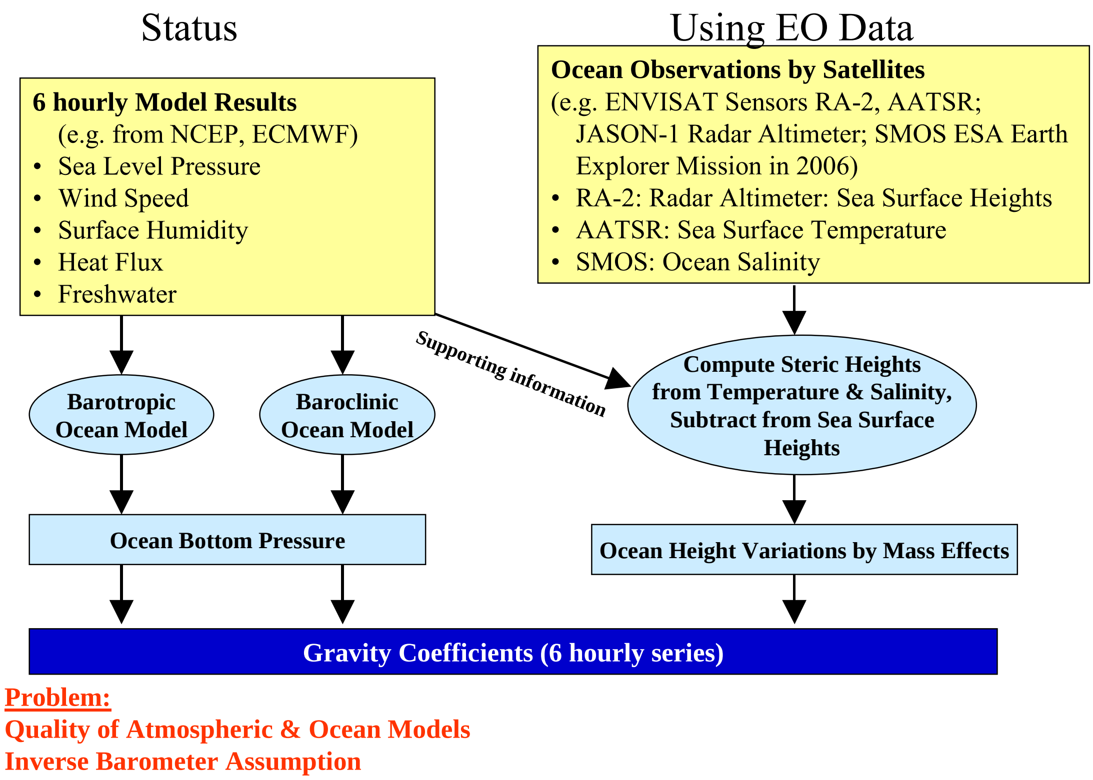

Fig. 1 De-Aliasing Concept Oceans

2.2 Atmosphere

Gravity field variations induced by atmospheric mass variations are apparent in different time-scales (from hours to seasons). They can be computed in a simplified approach from the surface pressure. This approach is not sufficient for the gravity field missions, because it does not take into consideration the distance of the attracting atmospheric masses from the satellites. Therefore the vertical structure of the atmospheric pressure plays an important role. Methods to use vertical profiles of pressure, temperature and humidity (water), observed by satellite sensors, which could replace the model data (at least partly) have to be developed. The individual processing tasks are:

- Combination of atmospheric observations from different sensors in different areas with different vertical resolutions in order to derive maps of vertical profiles for pressure, temperature and humidity. Limb and nadir observations have to be combined such that global maps for specific time intervals are available. Methods for data sampling and interpolation have to be developed for the atmospheric parameters.
- A mathematical model for the computation of the gravity effects from the vertical structure of the atmosphere has to be developed and tested. Comparisons with results based on data from atmospheric models (e.g. ECMWF) have to be performed in order to test one against the other for the purpose of determining the time variable gravity field effect.

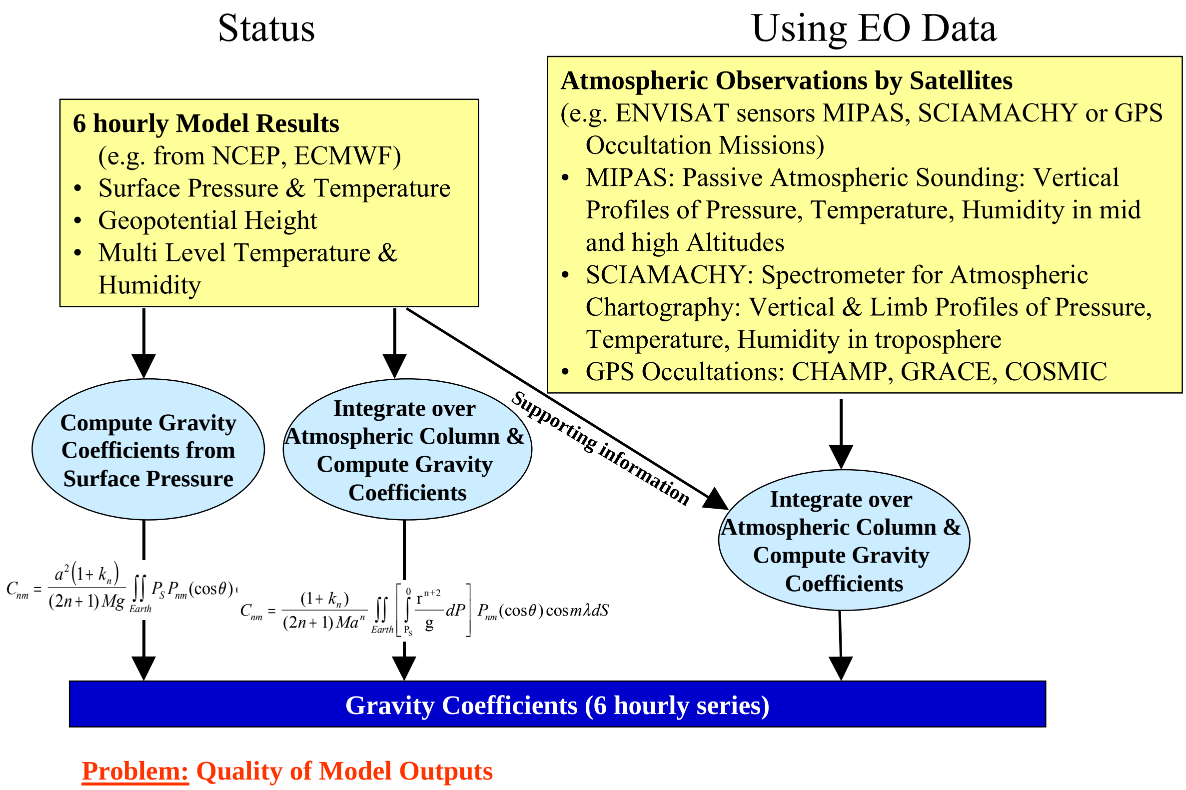

Fig. 2 De-Aliasing Concept Atmosphere

3 Combination

The mass variation contributions from the atmosphere and the oceans can not be regarded separately, because of the dynamic response of the oceans to atmospheric mass changes (inverse barometer effect). Therefore a combined approach for the determination of atmosphere/ocean gravity field variations has to be developed. This task includes:

- Investigations on the inverse barometer response of the oceans due to atmosphere and development of a regional strategy for the combination. Investigations can be performed by a correlation analysis of altimetric sea surface height changes with atmospheric surface pressure changes.
- Development of Software to compute the combined atmospheric and oceanic mass variation effects on the gravity field, according to the results of the previous investigations.
- Development of Software to compute corrections for the time variable gravity field for CHAMP and GRACE data processing and for GOCE gradiometric observations.

4 Related Earth Observation Missions

The ENVISAT mission with several sensors could play a key role to model high frequency mass variations from atmosphere and oceans. The MIPAS and SCIAMACHY instruments provide vertical profiles of atmospheric pressure, temperature and humidity in the mid and high altitudes by different techniques in different views. The radar altimeter (RA-2) and the radiometer (AATSR) provide in-situ sea surface height and sea surface temperature observations usable for modelling oceanic mass effects. In addition the future SMOS mission by ESA (planned to be launched in 2007) will provide ocean salinity, which represents the third parameter required for separating the steric and mass effects in the oceans. For atmospheric profiling also the CHAMP and GRACE missions and specifically the planned US/Taiwanese COSMIC multi-satellite mission can provide significant contributions for atmospheric de-aliasing. All these missions carry GPS receivers for limb sounding. The COSMIC mission could provide about 500 vertical atmospheric profiles per days.

5 Conclusions

Earth observation data from other satellite missions could be of major interest for modelling the high frequency atmospheric and oceanic mass variations. These variations currently are computed from model data, which are to some extent not sufficient in accuracy due to missing observations in large areas (e.g. Southern oceans). The combination of model and in-situ data together probably will be the best way to determine the high-frequency mass variations, which are essential for the determination of the static gravity field from CHAMP, GRACE and GOCE observations.

GGFC Special Bureau for Tides

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The IERS Special Bureau for Tides collects datasets related to the effects of tides on Earth rotation and geocenter motions. Like the other special bureaus of the GGFC, the Special Bureau for Tides generates most of its own product datasets by analyzing the results of numerical computer models of the relevant geophysical fluids, in this case of both ocean tides and atmospheric tides. For example, as more realistic numerical hydrodynamic models of ocean tides are developed, the Bureau endeavors to obtain the tidal elevation and current velocity data from these models and to determine and tabulate the implied Earth-rotation effects. Both pure numerical simulations and massive data assimilations (primarily of altimeter data and tide-gauge data) are used in these efforts.

The Bureau also collects tables of spherical harmonic coefficients of the tides. These have been used mainly for studies dealing with satellite orbit determination and (for the degree-2 terms) for studies of tidal energetics. Because of new satellite missions (CHAMP, GRACE, GOCE), very high-degree expansions of tides are soon needed, and the Bureau intends to collect and/or compute and archive such data. The extreme sensitivity of GRACE also requires that we begin considering some minor tides that have been traditionally overlooked; coefficient datasets of these tides must also be generated.

The data archive that the Bureau maintains has slowly grown as individual tidal investigators contribute their modeling results. Although there are many new ocean tide models still appearing in the oceanographic community as a result of the Topex/Poseidon altimeter mission, not all these models are appropriate for the Bureau because not all investigators are able to provide tidal currents, and currents are as necessary as elevations for predicting tidal variations in Earth rotation.

A major area of planned improvement over the near future is the addition of new data related to long-period tides and atmospheric tides. The latter are difficult to determine, because the most accurate simulations seem to be produced by the various national meterological centers, but these centers typically distribute their data at a 6-hour sampling, which is the Nyquist period of the S2 tide. Temporal interpolation procedures are being investigated to partially overcome this difficulty. Such work has already revealed phase lag errors in the tides from the NCEP and ECMWF centers. As more work continues in this area, it will be necessary to cooperate closely with the Special Bureau for the Atmospheres so that the tidal signals are handled consistently. One scenario for doing so has recently been published by Ponte and Ray (Geophysical Research Letters, 29(24), 2002).

Planned improvements in regards to long-period tides (i.e. species “0” tides with periods between a week and 18.6 years) require new estimates of the dynamical components of these near-equilibrium tides. This is, to a large extent, a significant research topic, because empirically determining long-period tides is difficult owing to their small amplitudes and the large, red background of oceanographic noise. Current IERS standards for long-period tides are a hodge-podge of equilibrium tides and incomplete and poorly constrained dynamical tides, a situation that the Special Bureau intends to address. The planned improvements, which rely on further research on oceanic dissipation and nonlinear interactions between short-period tides, will be a far more complete accounting of long-period tides. This will be extremely useful in length-of-day studies, in determining mantle anelasticity, and in reduction of GRACE SST data.

Finally, it was decided that the Special Bureau for Tides should maintain an archive of datasets relevant to tidal variations in the geocenter. These would be sets of harmonic coefficients, mostly deduced from ocean tide models. These coefficients could be used as input to the Bureau's web-based "tide prediction machine" if users require predicted time series of such motions.

Nearly all the data archived by the Special Bureau for Tides are relatively small ascii datasets and web-based tables. We expect that this will continue to be true in the future.

Recent Work on Theoretical Modeling of Nutation

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Abstract: In this note we make a brief sketch about the current state of the modeling of the Earth nutation, focusing on high frequency nutations. In particular, numerical nutations series are reported accounting for the harmonics (2,2), (3,1), (3,2) and (3,3) of the solid Earth potential, as well as for the case of the indirect effect due to the zonal harmonic of the second degree.

1 Introduction

In the last decade remarkable advances have taken place in the construction of theories that model the Earth rotational motion, aimed at improving the accuracy of the predictions of the Earth rotation. Several models have been developed both for rigid and non-rigid Earth nutations. The last theories involved with the rigid models claim to reach an accuracy about 0.1 μas (Souchay et al., 1999; Bretagnon et al., 1998; Roosbeck and Dehant, 1999; Navarro et al. 2002a; etc.). With respect to the non-rigid Earth models we would also like to underline the important progresses achieved in the last years, reflected in papers as those of Getino and Ferrándiz (2000), Shirai and Fukushima (2000), Huang et al. (2001), Mathews, Herring and Buffet (2002), etc. More details can be found in Johnston et al. (2000).

In order to select a nutation theory to replace the IAU 1980 theory of nutation, at IAU Colloquium 180 (Washington, 2000) three theories were selected as candidates to study for IERS 2000 or IAU 2000 nutations models: a) MHB2000 (Mathews, 2000); b) SF (Shirai and Fukushima, 2000); c) GF2000 (Getino and Ferrándiz, 2000). The first one, MHB, relies on an improved transfer function approach, based on a generalization of SOS equations. The SF theory uses a numerical convolution in the time domain, applied to Herring's transfer function. Finally, GF is a Hamiltonian, analytical theory for the Earth rotation, extending Kinoshita's one. Two theories reached an accuracy about 0.180 mas in Celestial Ephemeris Pole (CEP) offsets after being fitted to the official test series provided by USNO, namely: MHB2000 (two enhanced versions) and FGNH (GF theory plus planetary non-rigid series, Ferrándiz et al., 2000, plus oceanic corrections, Huang et al., 2001). At 24th General Assembly of the IAU, held in August 2000, MHB2000 was preferred by geophysical reasons (Dehant, 2000) and selected as IAU2000 nutation model, entering in force in 2003. There is also an agreement with respect to NASA/GSFC series about 150 μas, also using a model for FCN nutation. As the uncertainty of one daily value of CEP offsets is 0.3 mas (Gambis et al., 2001) we can conclude that there is a good agreement between theory and observation.

However, the constant improvement in the precision of the astrometric and geodetic techniques forces to examine the sources that may limit the present accuracy, both of the nutation models and the observational data. In our opinion there are two main obstacles that could stop the advances in Earth rotation studies. First, the use of "a priori" incomplete models in the observational data analysis and second, the existence of some difficulties in the fundamentals of the theories and inconsistencies among theories and practical procedures to reduce data. To overcome the first difficulty it should be necessary to improve the current nutation models by including the oceanic and second order effects as an intrinsic part of the theory, not as simple corrections. Besides, it should be expedient to take into account some effects previously disregarded, such as the case of the high frequency nutations (see next section). In order to avoid the problems related with the second obstacle, it should be necessary to re-examine comprehensively the construction procedure carried out in the elaboration of the theories themselves, and the way in which these theories are implemented to obtain practical procedures to reduce observational data. In this respect, the advances in Global Geophysical Fluids monitoring and International Terrestrial Reference Frame realization would help to solve possible inconsistencies (see reports by Chao and Altamimi et al. in this volume).

2 High frequency nutations

The Earth equatorial inertia moments A and B are not exactly equal but slightly different. As a consequence of this fact, known as triaxiality of the Earth, tesseral and sectorial harmonics appear in the expansion of the Earth potential, often referred to as tidal potential. These new terms give rise to a high frequency actual motion of the Earth figure axis in space, that is to say, to high frequency nutations (from now on denoted as HFN). HFN are due to both solid and ocean tides. The contribution of ocean tides can be estimated by using Topex/Poseidon based models (e. g. Ray et al., 1994), being nine times larger than that due to the tidal potential (Chao et al., 1996).

Empirical amplitudes of HFN have been obtained with the concourse of VLBI (Gipson, 1996) or GPS (Rothacher et al., 2001) observational data. Therefore, there is a real need of developing theoretical models to predict HFN amplitudes, as it was already claimed in Getino and Ferrándiz (2000). In this note we will pay attention to HFN of the non-rigid solid Earth arising from the tidal potential. The numerical contributions for the different kind of effects are reported in Tables 1, 2 and 4. In Table 1 we have kept the representation of the solution as nutations in longitude and obliquity. We think that this representation is the most adequate since it is the most natural for the physical motion that takes places. Nevertheless, B1.7 resolution adopted at the IAU XXIVth General Assembly recommends the inclusion of high frequency variations in the motion of the CIP in the International Terrestrial Reference System as polar motion (PM), what has motivated the inclusion in the tables of its corresponding X and Y components. Anyway, we have used the terminology polar libration, introduced in the pioneering work of Chao et al. (1991), in order to avoid confusion with the actual PM. For example, in Mechanics polar motion means the motion of the angular velocity vector with respect to a frame fixed in a body (the Earth, in this case). The remaining arguments appearing in the tables, P_{SF} and P_{TF}, denote the period of each luni-solar term, represented by a linear combination of Delaunay variables and the angle Φ, in the Space and Terrestrial Frames, respectively, in mean solar days. These results have been obtained from analytical formulae based on the Hamiltonian formalism of the non-rigid Earth developed by Getino and Ferrándiz. Specifically, we have considered a two-layer Earth model with mantle and core elasticity (Getino and Ferrándiz, 2001). The expansions of tidal potential are of an astronomical nature and have been worked out with the aid of the symbolic processor by Navarro (Navarro and Ferrándiz, 2002), using ELP and VSOP solutions.

Tables 1 and 2 are concerned with the **direct effect**, that is to say with the contribution due to the existence of (2,2), (3,1), (3,2) and (3,3) harmonics in the tidal potential expansion. A more detailed discussion about the way of obtaining these results can be found in Getino et al. (2002), for the (2,2) harmonic, and in Navarro et al. (2002b) for the third degree harmonics.

Table 1 Direct effect in µas : harmonic (2,2)

		Delaunay arguments					P_{SF}	P_{TF}	Polar libration (in µas)	
Φ_{SF}	Φ_{TF}	l_M	l_S	F	D	Ω	msd	msd	$X_{sin}=Y_{sin}$	$X_{cos}=-Y_{sin}$
2	1	0	0	0	0	0	.498634	.997269683	14.298	–8.207
2	1	0	0	0	0	–1	.498598	.997123413	1.938	–1.112
2	1	0	0	–2	2	–2	.500000	1.002745577	–4.768	2.737
2	1	0	0	–2	2	–2	.500000	1.002745577	–4.768	2.737
2	1	–1	0	0	0	0	.507826	1.034725222	.845	–.485
2	1	–1	0	0	0	0	.507826	1.034725222	.845	–.485
2	1	0	0	–2	0	–2	.517526	1.075810945	–11.385	6.536
2	1	0	0	–2	0	–1	.517569	1.075997464	–2.148	1.233
2	1	–1	0	–2	0	–2	.527441	1.119559097	–2.312	1.327

In addition to this direct effect, the triaxiality of the Earth couples with the zonal harmonics causing also HFN. This last effect is called **indirect effect** (Escapa et al., 2002a, b) and reflects the fact that Andoyer variables are not an action-angle set for a triaxial Earth. These contributions are shown in Table 4 for the case of the coupling between the triaxiality of the Earth and the second degree zonal harmonic. The expressions for these amplitudes have been computed using the formulae derived in Escapa et al. (2002b). They depend on the triaxiality of the whole Earth and on the triaxiality of the core, which provides a larger contribution. We have displayed some values derived for this parameter in Table 3 ($2d_c = 1 - A_c/B_c$). From these results it is clear that the core is not symmetrical and that there is some discrepancy in the values of d_c. The contribution of this effect for some terms is about 1 µas, so we think that to ignore core triaxiality and disregard this contribution is not a reasonable option. Therefore, our proposal is to consider a mean value of the triaxiality of the core ($d_c = 5.7010^{-6}$) as the best estimate available and incorporate the amplitudes obtained for this model (AV in Table 4) in HFN.

Table 2 Direct effect in µas: harmonics (3,1), (3,2), (3,3)

Type			Delaunay Arguments					P_{SF}	P_{TF}	Polar Libration	
	Φ_{SF}	Φ_{TF}	l_M	l_S	F	D	Ω	msd	msd	Y_{sin}	Y_{cos}
3 1	0	0	–3	0	–3	1	1	1.120	–9.107	.090	.734
3 1	–1	0	–1	0	–1	1	1	1.075	–13.719	.164	1.336
3 1	0	0	–1	0	0	1	1	1.035	–27.212	.304	2.476
3 1	0	0	–1	0	–1	1	1	1.035	–27.322	1.901	15.467
3 1	0	0	–1	0	–2	1	1	1.035	–27.432	–.105	–.854
3 1	–1	0	–1	2	–1	1	1	1.002	–193.560	.099	.803
3 1	1	0	–1	0	0	1	1	.998	–2.190.350	–.229	1.861
3 1	1	0	–1	0	–1	1	1	.998	–3.231.496	1.507	12.258
3 1	1	0	–1	0	–2	1	1	.997	–6.159.135	–.083	–.674
3 1	–1	0	1	0	2	1	1	.997	6.159.135	–.095	.773
3 1	–1	0	1	0	1	1	1	.997	3.231.496	1.973	–16.054
3 1	–1	0	1	0	0	1	1	.997	2.190.350	–.341	–2.775
3 1	1	1	–1	0	0	1	1	.995	438.360	.098	–.794
3 1	1	1	–1	0	–1	1	1	.995	411.807	.123	.997
3 1	1	0	1	–2	1	1	1	.992	193.560	–.257	2.089
3 1	0	0	1	0	2	1	1	.962	27.432	.107	–.866
3 1	0	0	1	0	1	1	1	.962	27.322	–2.048	16.660
3 1	0	0	1	0	0	1	1	.962	27.212	–.321	2.608
3 1	1	0	1	0	1	1	1	.930	13.719	–.158	1.282
3 2	2	1	–3	0	–3	2	2	.52752	1.119902988	–.254	–.174
3 3	3	2	–1	0	–1	3	3	.33652	.5079043940	–.224	–.114

Finally, let us point out that there are another two models that deal with HFN (Brezinski and Capitaine, 2001; Mathews and Bretagnon, 2001). These works are constructed by using different theoretical approaches and different tidal expansions and no reference is made to the indirect effect.

Table 3 Triaxiality of the core (unit 10^{-6})

Model	d_c	Citation Source	Author
GG	8.94	González & Getino 1997	Defraigne & Dehant 1997
BC	4.92	Brzezinski & Capitaine 2002	Morelli & Dziewonski 1987
SX	3.25	Szeto & Xu 1997	Mathews, Buffet, Herring & Shapiro 1991

Table 4 Indirect effect in μas

						Polar libration: X-component							
		Delaunay variables				Model SX		Model BC		Model GG		Model AV	
Φ_{TF}	l_M	l_S	F	D	Ω	sin	cos	sin	cos	sin	cos	sin	cos
1	0	0	−2	0	−2	.101	−.058	.109	−.063	.130	−.075	.113	−.065
1	0	0	−2	2	−2	.097	−.056	.134	−.077	.224	−.129	.152	−.087
1	0	0	0	0	0	−.735	.422	−1.113	.639	−2.022	1.161	−1.289	.741
1	0	0	0	0	−1	−.105	.061	−.160	.092	−.292	.167	−.186	.107
1	0	1	0	0	0	.026	−.015	.043	−.024	.082	−.047	.050	−.029

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GGFC Special Bureau for the Core

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1 Introduction

The Special Bureau for the Core (SBC) is one of the eight Special Bureaus (SBs) of the Global Geophysical Fluids Center (GGFC), established by the International Earth Rotation Service (IERS) on January 1, 1998 to facilitate the link between the space geodetic and the geodynamic communities. Within the GGFC, the SBC is responsible for the research and data service activities related to the core and plays a role in stimulating and coordinating research on this topic. In particular, the SBC focuses on theoretical modeling and observations related to core structure and dynamics (including the geodynamo), and on inner core – outer core – mantle interactions.

Flow in the fluid outer core, and also motion of the inner core with respect to the outer core, can result in various geodetic phenomena observable from the Earth's surface or space. These phenomena include variations in the Earth's rotation and orientation, surface gravity changes, geocenter variations, and surface deformations. Although small, these variations can or could be observed by very precise space geodetic techniques. Observation of these effects then yields unique insight into the core, which can not be observed directly.

Since its creation in 1998, the SBC has set up a web site <[1]> as the central mechanism for providing services to the geophysical community. The web site contains documented model data on core flow and core angular momentum, and an extensive bibliography to support and facilitate core research. In addition, to provide some guidance into the vast literature in core dynamics, a description is given of the relevant theories and of the dynamical assumptions used for constructing the flow.

This position paper gives a brief overview of the various scientific issues and covers past and future activities of the SBC. We first describe in Sect. 2 the length-of-day (LOD) variations, the main subject in this field, and treat the other effects in Sect. 3. Section 4, by W. Kuang, contains a critical overview of core-mantle coupling, and the importance of numerical models of core dynamics in this respect is shown. SBC activities are described in Sect. 5, and future plans in Sect. 6.

2 Length-of-day variations

2.1 Core angular momentum variations

The fluid outer core is in constant motion, and changes in core angular momentum (CAM) are known to be related to length-of-day (LOD) variations of a few milliseconds at decadal time scales (see Fig. 1). These variations can very accurately be measured (uncertainty of about 0.02 ms for daily LOD values) and were the main scientific reason behind the creation of the Special Bureau for the Core to stimulate, promote and aid in scientific investigations into the dynamics of the Earth's core by using Earth rotation variations.

[1] http://www.astro.oma.be/SBC/main.html

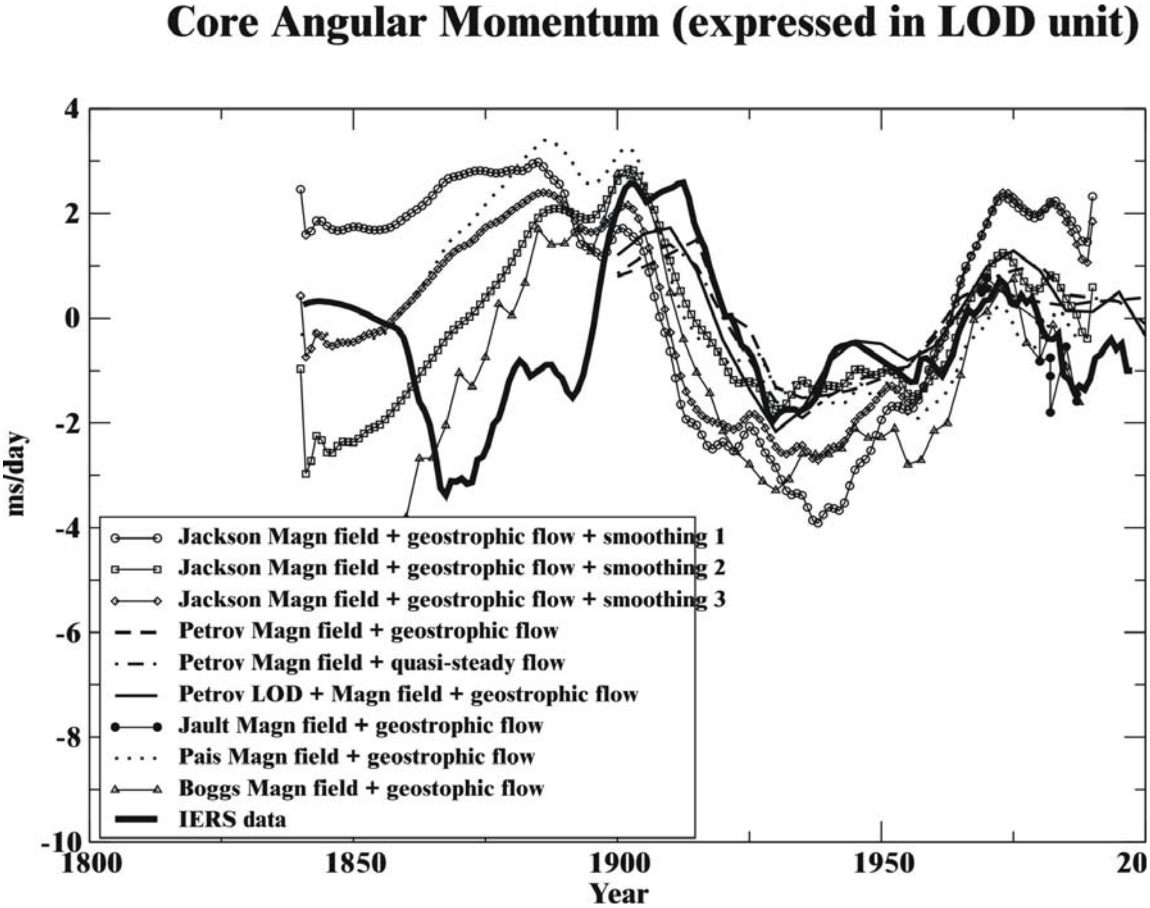

Fig. 1 Length-of-day variations for various models and IERS observational LOD data. The data can be found on the SBC website.

The core has been recognized as the major component in explaining the LOD variations at decadal scale since it was shown that the time-variations of parameters describing the geomagnetic field (such as the magnetic declination) are correlated with the variations of the LOD at these time scales. Furthermore, no other suitable reservoirs of angular momentum could be found. The core is considered to be able to exchange sufficient angular momentum with the mantle. By using $\vec{H}_m = C_m\vec{\Omega}$, where $\vec{H}_m$ is the angular momentum of the mantle, and C_m is the moment of inertia of the mantle, the change in mantle angular momentum can be estimated to be about 1.3×10^{26} kg m s^{-1}. Because of the conservation of angular momentum of the core-mantle system, this also gives an order of magnitude for the core angular momentum change. Given the total core angular momentum of about 6.5×10^{32} kg m s^{-1}, the core therefore changes its relative angular momentum by less then about 10^{-5}.

No direct observations of the core flow exist as do for the atmosphere (and to a lesser extent for the oceans), and core flows are derived from variations in the poloidal magnetic field observed at the Earth's surface. These calculations, however, invoke several simplifying assumptions and hypotheses related, on the one hand, to the downward continuation of the surface geomagnetic field to the core-mantle boundary (CMB), and, on the other hand, to the determination of the horizontal flow in the superficial layer of the outer core from the magnetic induction equation. According to Holme (2002), the implicit assumption, in resolving the non-uniqueness in the core flow determination, that the flow is large scale may be the cause of the fact that all calculated flows are very similar. One may wonder then, whether these flows, although they very well model the geomagnetic secular variations, give a good representation of the true core flow. In this respect, the decadal LOD variations play an important role. Since the pioneering work of Jault et al. (1988), it has been shown that the core flows derived from the geomagnetic observation agree remakably well with the observed decadal LOD variations, adding to our confidence in the obtained core flows (see Fig. 1). To model the LOD variations, core angular momentum (CAM) is calculated from the top core flow. This can be done since torsional oscillations govern the flow in the outer fluid core on decadal timescales (Braginsky, 1970). These oscillations describe differential rigid rotations around the rotation axis of coaxial cylinders, for which magnetism provides the restoring force. Since core flow is then supposed to be constant on cylinders parallel to the rotation axis, velocities everywhere in the core can directly be derived from the velocities at the CMB, and thus the CAM can be derived.

2.2 Torques between core and mantle

Physically, the cause of angular momentum exchange between core and mantle is through coupling torques between core and mantle. These torques can excite torsional oscillations in the core. To explain the observed decadal LOD changes, the torque $\vec{\Gamma}$ can be estimated from the change in angular momentum to be about $\Gamma = C_m d\Omega/dt \approx 10^{18}$ Nm. Four mechanisms have been suggested, but due to uncertainties in the flow and torque calculations, it has not been possible to definitely settle the relative importance of the different mechanisms.

- The topographic torque is related to the effects of the fluid pressure on the boundary topography. The presence of bumps at the CMB has been suggested by both seismological studies in which refracted and internally reflected seismic waves at the CMB are used and convection studies in which the CMB topography deformations are computed from the buoyancy fluxes associated with density lateral heterogeneities in the mantle (seismic tomography). The efficiency of this mechanism is rather controversial, partly because of differences in the assumptions made in the calculation method (does the topography significantly affect the pattern of the flow?) and partly because of the uncertainties in the CMB topography (see Ponsar et al., 2002). The topography is thought to be less than 2 km according to Garcia and Souriau (2000), but about 3 km according to Sze and van der Hilst (2002). For these topographies, the torques are either somewhat too small (e.g. Kuang and Chao, 2001; Wu and Wahr, 1997) or too large (e.g. Jault and Le Mouël, 1989). Considering that the pressure at the CMB derives, in a first approximation, from a tangentially geostrophic balance, the last authors obtain a torque proportional to the ratio of topography to core radius, δ. The other authors, working on diurnal time scales (Wu and Wahr, 1997) and decadal time scales (Kuang and Chao, 2001), consider the perturbation of the topography on the flow. An analytical approach is used for the calculation of the effect of topographic torques on nutation, and results of geodynamo simulations are used for the effect on LOD variations. Both studies give a torque proportional to δ^2. According to Wu and Wahr (1997), a topography of 6–7 km can explain the observed retrograde annual nutation, and Kuang and Chao (2001) obain an effect at the level of 20% of the observed LOD variations for a topography of 2–3 km.
- The electromagnetic torque is generated by the Lorentz force on an electrically conducting layer at the base of the mantle and is associated with the magnetic field (and its variations). The magnetic torque is usually decomposed into poloidal and toroidal parts. The poloidal torque is con-

nected to the poloidal part of the longitudinal component of the CMB magnetic field and its secular variation, which can be deduced from the observation of the magnetic field at the Earth's surface. The toroidal torque is connected to the toroidal part of the longitudinal component of the CMB magnetic field and its secular variation and can further be divided into the advective torque and the leakage torque. The advective torque is related to advection of the radial magnetic field and can in principle be calculated from models of core surface flow derived from measurements of geomagnetic secular variation. The leakage torque is associated with the diffusion of the core toroidal magnetic field at the top of the core into the mantle and is unknown. Holme (1998) has shown that electromagnetic coupling can be large enough to explain the observed LOD variations, if the conductance of the deep mantle layer is high enough (conductance of 10^8 S). Support for this hypothesis comes from nutation (see below). Such a layer could arise as a result of the cooling of the Earth. Cooling is associated with inner core growth and an increase in light element concentration, such as FeO, in the fluid outer core. These elements could be removed from the core and deposited as metallic solids at the base of the mantle (it is interesting to note here that an Fe-FeO system has a high melting temperature). Buffett et al. (2000) proposed that chemical reactions with mantle silicates can lead to silicate mineral deposits with interstitial liquid iron when excess light elements are created as a result of inner core growth.

- The viscous torque is related to the viscosity of the fluid core at the core-mantle boundary and is generally believed to be small. However, if the top flow is turbulent, turbulent mixing could increase the coupling by orders of magnitude (Kuang and Chao, 2002a).
- The gravitational torque is related to the gravitational interaction between lateral variations in density within the fluid core and mantle and is generally thought to be small because the density of the fluid can adjust when moving slowly through lateral variations in the gravitational potential. The gravitational interaction between the *inner* core and the mantle is thought to be more important for decadal LOD variations, and couples the inner core tightly to the mantle (Buffett, 1996). LOD variations can then result from electromagnetic coupling of torsional oscillations inside the fluid core with the inner core that changes the rotation of the inner core, which itself is effectively gravitationally locked to the mantle. Recently, Mound and Buffett (2002) developed a similar inner core–outer core–mantle coupling scheme to explain observed LOD variations with periods of about six to seven years and an amplitude of about 0.12 ms.

3 Earth orientation, geocenter, and gravity variations

In the previous section on length-of-day variations, only variations in the component of core angular momentum in the direction of the rotation axis have been considered. Variations in this direction are expected since torsional oscillations are considered to dominate the core flow at decadal time scales. However, this does not rule out the possibility that equatorial components of core angular momentum also vary (say at different time scales or through motion linked with the inner core), and that, through angular momentum exchanges between core and mantle, the core can lead to variations in all three components of Earth rotation. Both nutation and polar motion show features that are thought to be linked with the core, and therefore these variations hold the potential to put additional constraints on the core.

The very accurately observed nutations have proven to be very useful to determine values of several parameters of the Earth's interior. By considering electromagnetic coupling between mantle and core as the dissipative mechanism for the observed out-of-phase nutations, Mathews et al. (2002) showed that, to explain the observed nutation amplitudes, especially the annual retrograde nutation, the semi-annual prograde nutation, and the 18.6 retrograde nutation, a high conductance layer of about 10^8 S at the base of the mantle is needed. This supports the idea that electromagnetic coupling is the main element in explaining the decadal LOD variations and moreover gives the same order of magnitude for the conductance as the LOD studies. The radial magnetic field is estimated to be 0.69 mT at the CMB and 7.17 mT at the ICB. The value at the CMB slightly exceeds the extrapolated value of the geomagnetic field of 0.44 mT (Langel and Estes, 1982). At the ICB, geodynamo simulations give radial magnetic fields of between 2 and 3.5 mT (Kuang and Bloxham, 1999).

Polar motion shows decadal variations of several tens of milliarcseconds (present daily estimates of polar motion are accurate to ±0.1 mas, McCarthy 2000) that are difficult to explain by atmosphere or surface processes. These variations have first been claimed by Markowitz (1960), and the variations with period of about 30 yr are called the Markowitz wobble. Schuh et al. (2000) found several additional decadal periods going from 7 yr to 86 yr. The effects of oceans are not well known, and several authors have considered torques of the core on the mantle as the main origin of these observed polar motion variations. The main difficulties are that the needed torque is one order of magnitude larger than the torque necessary to explain the decadal LOD variations (which is difficult to reconcile given the same model for conductance and CMB topography to explain the LOD variations), and that at these time scales the torsional oscillations are dominant and only lead to core angular momentum variations in the polar direction. Greiner-Mai et al. (2000) used an angular momentum approach to study whether motions of the inner core can lead to similar polar motion variations as those observed. In particular, they assumed that the figure axis of the inner core is aligned with the geomagnetic dipole axis and follows the observed decadal variations of that dipole axis. They found that the mass redistributions, caused by the relative rotation of the denser flattened inner core with respect to the less dense outer core, give about the correct polar motion magnitude. However, no reason for this large inner core tilt is known, instead, strong pressure and gravitational forces tend to align the inner core axis with that of the Earth. In a follow-up study, Greiner-Mai and Barthelmes (2001) did not use the hypotheses on the inner core tilt anymore, and determined, from the excitation functions, the variations in the figure axis of the inner core necessary to explain the observed decadal polar motion. The angle between the figure axis of the inner core and the mantle is found by Greiner-Mai and Barthelmes (2001) to vary between 0.4° and 1.5°, and the figure axis rotates eastwards with a mean velocity of 0.7° yr^{-1} but showing large variations of several degrees. In a recent paper, Dumberry and Bloxham (2002) addressed the same problem, but from another point of view. These authors showed that an equatorial torque at the inner core boundary of about 10^{20} Nm is needed to explain the decadal polar motion, and that this torque tilts the inner core out of alignment with the mantle by 0.07 deg, the latter value being much smaller than the result of Greiner-Mai and Barthelmes (2001). Such a torque could be obtained by electromagnetic coupling between the inner core and the torsional oscillations in the outer core for a radial magnetic field at the inner core boundary of 3 to 4 mT, corresponding to the geodynamo simulations estimate.

Small variations in the Earth's gravity field can be induced by changing density structures in the core. Degree one variations describe the variations in the geocenter. Gravity field variations caused by the convective motions have recently been calculated from the output of geodynamo models by Kuang and Chao (2002b). They find gravity field variations of the order of 10^{-10} relative to the mean gravity field of the Earth. Their study was motivated by the observation, from satellite laser ranging (SLR), that the Earth's dynamic oblateness J_2 has suddenly, around 1998, changed its decreasing trend, mainly attributed to postglacial rebound, to an almost equally large increasing trend (Cox and Chao, 2002). Changes in core flow around that same period are expected from geomagnetic observations, notably the occurrence of a major geomagnetic jerk, or sudden change in the trend of the geomagnetic secular variation, in 1999 (Mandea et al., 2000). The results of the geodynamo models, however, indicate that these core flow changes can, depending on model assumptions, only account for about one tenth of the observed J_2 change. Greiner-Mai and Barthelmes (2001) estimated degree two gravity field variations for their model of relative inner core rotation to be of the order of 10^{-10} to 10^{-12}, with variations of the order of 10^{-12} yr^{-1}. These variations could possibly be measured by the GRACE mission and can then give information on core dynamics.

4 Modelling core-mantle interaction and interpretation of decadal length-of-day variations

Jault et al. (1988) first provided geomagnetic observational evidences for explaining LOD variations on decadal time scales with changes of the core axial angular momentum and concluded that the LOD variation on decadal time scales arise from the exchange of the axial angular momentum between the Earth's core and the solid mantle. Their conclusion is further supported by the following results from Jackson et al. (1993), and Holme and Whaler (2001). These observational evidences therefore demand a fundamental physical interpretation: what is (are) the mechanism(s) responsible for the core-mantle angular momentum exchange? Considering that the observed decadal LOD variation $\Delta \mathrm{LOD} \approx 2$ ms/decade, the required net torque $\Gamma_{\mathrm{net}} \approx 5 \times 10^{17}$ Nm. Therefore the fundamental question is then what core-mantle coupling mechanism(s) can produce the required net torque.

Understanding the physics is very important in several accounts: first of all, it could provide a reasonable explanation for the geodetic observations, thus helping identifying contributions of various solid Earth physics processes on observed LOD variation. In return, the observational results could provide insight and constraints on dynamical processes in the core that can only be partially and indirectly detected. More significantly, this can lead to multidisciplinary collaboration among geodesy, geomagnetism and geodynamo fields on the Earth's deep interior.

In general, there are four core-mantle coupling mechanisms: electromagnetic, topographic, gravitational and viscous core-mantle interactions. While the molecular kinematic core fluid viscosity ν is in general very small ($\nu \approx 10^{-6}\ \mathrm{m^2/s}$), and therefore the estimated viscous torque is more than an order of magnitude smaller than the required torque, the three other coupling mechanisms have been proposed separately to be the dominant core-mantle coupling for the core-mantle angular momentum exchange (e.g. Kuang and Chao, 2002a). Regardless, they depend on dynamical processes in the outer core, and on the mechanical and electrical properties in the mantle. For example, electrical conductivity of the lower mantle (e.g. D"-layer) is critical for the "traditional" electromagnetic core-mantle coupling that depends on the current density in the electrically conducting mantle (e.g. Bullard et al., 1950). On the other hand, topographic coupling arises from nonhydrostatic pressure in the core on heterogeneous core-mantle boundary (CMB) topography (Hide, 1969). Gravitational couplings arise from interaction between heterogeneous gravity fields of the mantle and the outer core (Jault et al., 1988), or of the mantle and the inner core (Buffett, 1996).

However, most of the studies on the core-mantle couplings have been focused on a single dominant coupling mechanism: evaluating the coupling torque from geomagnetic observations and a series of assumptions on force balances in the core (e.g. Stix and Roberts, 1984; Jault and Lemouël, 1989; Hide et al., 1993; Love and Bloxham, 1994; Holme, 1998). There are two potential problems in these studies. The first one is that all calculations are kinematic in nature, which could result in erroneous torque estimation due to dynamical inconsistencies (e.g. Kuang and Chao, 2002a). The other is that it could be misleading to identify one dominant core-mantle coupling mechanism responsible for the decadal LOD variation.

The kinematic studies can be summarized as follows. The poloidal part of the geomagnetic field $\vec{B}_P$ and its time variation can be observed at the surface of the Earth, and can be continued downward to the CMB by assuming the mantle is a good electrical insulator (good for much of the mantle). Assuming further that magnetic dissipation in the core is not important on decadal time scales ("frozen-flux" approximation), and that core flow is tangentially geostrophic, one could obtain the fluid flow $\vec{v}_H$ and the pressure p beneath the CMB. In addition, if the D"-layer is electrically conducting, one could then obtain the portion of the toroidal field $\vec{B}_{TA}$ in the layer advected from the $\vec{B}_P$ in the core via the core flow $\vec{v}_H$. Therefore, one could then evaluate the topographic torque given the CMB topography, or the electromagnetic torque given the electrical conductivity of the D"-layer.

The dynamic inconsistencies of above studies are apparent. For example, the core fluid flow $\vec{v}_H$ should be adjusted to the CMB topography in order to obtain the appropriate topographic coupling torque. The question is then whether such small adjustment is critical for correct torque evaluation. In kinematic studies, it can not be answered because this small adjustment could not be resolved from observations, due to both measurement errors and poor knowledge on the CMB topography.

On the other hand, the toroidal field $\vec{B}_T$ in the core can also be diffused into an electrically conducting D"-layer. This "leakage" toroidal field $\vec{B}_{TD}$ is ignored in the kinematic studies because $\vec{B}_T$ is simply not observable. One is certainly aware that $\vec{B}_{TD}$ depends on the electrical conductivity of the D"-layer. Therefore, its importance on evaluating electromagnetic coupling torque directly affects the assumptions on the properties of the lower mantle. The gravitational coupling torque could not be evaluated from any observations because density anomaly in the fluid core is not detectable [Though recent time-varying gravity observations (Cox and Chao, 2002a) could include some information on the core density anomaly, it still can not be used for the torque evaluation].

To assess the impact of these dynamical inconsistencies on coupling torques, one must find a different approach that could combine core-mantle coupling and core dynamics studies. Currently, the most promising approach is to use numerical models on core dynamics to the core-mantle interactions, as is demonstrated by recent results of Buffett and Glatzmaier (2000) on gravitational coupling via inner core-mantle locking, and of Kuang and Chao (2001) on topographic coupling.

In particular, Kuang and Chao (2001, 2002a) used their dynamo solutions on electromagnetic and topographic couplings. Their solutions, which are dynamically consistent, are very different from those of kinematic results, primarily due to the dynamic inconsistencies in kinematic studies. For example, the consistency of the core flow to the CMB topography is critical for the coupling torque. Though the core flow is only perturbed by a small topography (with typical amplitude of several kilometers, compared to the CMB mean radius of 3500 km), numerical solutions demonstrate that it is this perturbation that contributes to the most of the coupling torque. This is very different from previous suggestions in the kinematic studies that such perturbation is not important in evaluating topographic torque. A direct consequence of these new results is that given the CMB topography, the coupling torque is much smaller than that from kinematic analysis. Therefore Kuang and Chao (2001) concluded that unless the CMB topography amplitude is at least on the order of 3 km, the resulting torque is too small for the decadal core-mantle angular momentum exchange.

In addition, Kuang and Chao (2002a) examined the effect of the "leakage" toroidal field $\vec{B}_{TD}$ in electromagnetic core-mantle coupling. They found that when the conductivity of the D"-layer is close to that of the core fluid (e.g. about one order of magnitude smaller), this part of the field is comparable to the "advected" toroidal field $\vec{B}_{TA}$, in both magnitude and time-varying frequency. This suggests that the offset between the full electromagnetic torque and that from the kinematic studies can be significant when a thin and highly conducting D"-layer is assumed. A more detailed analysis of their results indicates that contributions from both parts of the field can either negate or enhance each other during numerical simulation, raising the concern on the true net electromagnetic coupling torque in the Earth's core, and proper assumptions on the D"-layer structures. It should also be pointed out that the magnetic torque is estimated to be 50 % of the net torque required for the decadal LOD variation.

All these numerical modeling results indicate that it is unlikely that a single coupling mechanism dominates for the decadal LOD variation. Not only several mechanisms are capable of producing a significant portion of the required torque, they influence each other in very complicated ways. For example, a finite CMB topography shall introduce electromagnetic heterogeneity in the D"-layer, thus affecting electromagnetic core-mantle interaction. On the other hand, the inner core/mantle locking mechanism (Buffett) depends on the electromagnetic coupling across the inner core boundary (ICB), as well as on density anomalies in the outer core (that change the gravitational force on the inner core). Furthermore, density anomalies in the outer core may also contribute significantly to the overall core-mantle coupling. All these suggest that our near future research should include efforts of investigating multiple core-mantle coupling mechanisms simultaneously in numerical core-dynamics modeling.

5 Present status of the SBC

The SBC has about twenty members from the fields of geomagnetism, Earth rotation, geodynamo modeling (numerical and experimental), and gravimetry. In contrast to other geophysical flows such as the atmosphere and the oceans, the geophysical fluid under study for the SBC, the fluid outer core, can not be observed directly. This constitutes a problem, observational data on the core is limited and the calculation of various core effects is necessarily based on modelisations, but also an advantage, a lot is to be learnt about the core from studying observational data that is influenced indirectly by the core. The data on core flow are derived mainly from geomagnetism. This information is only indirect because the mantle and crust, between the observer and the core, influence the magnetic observations and partly hide the core field. One of the tasks of the SBC then is to keep contact with, e.g., the geomagnetism and geodynamo community.

The SBC promotes and stimulates research on core dynamics. As a first step in achieving this goal, the SBC has created a website <[1]>. Because of the multidisciplinary nature of our activities, we give there a description of the relevant theories and information necessary to understand and use the data. Subjects treated include: core convection, core flow, geomagnetism, CMB torques, inner core differential rotation, Earth's rotation changes due to the core, and core composition. Additionally, we have built a bibliography of articles relevant to the core that presently contains more than a thousand references.

The SBC collects and makes available relevant data for studies of core dynamics. The data we want to provide include (1) the observed magnetic field and its secular variation, (2) CMB topography derived from seismology or from steady-state convection computation, (3) core flows and angular momentum derived from computations constrained by the observed surface magnetic field and its secular variation, (4) angular momentum derived from LOD data, (5) core flows and angular momentum derived from both LOD variations and surface magnetic field data, (6) core flows and angular momentum from geodynamo modeling, (7) data on core-mantle torques, including viscosity, magnetic fields and core topography (8) data on inner core motion and structure.

The data on angular momentum can already be downloaded directly from the SBC website, for the other data, some web links are provided but most data must still be collected. To be able to make full use of the data, they are documented. In particular, the hypotheses used in the computations are described. Further, a special form for scientists wishing to provide data has been prepared and put on the web site.

Nine series of core angular momentum (CAM) data are at present available on the SBC website:

- Jackson's three different CAM series based on torsional oscillations using the hypothesis of fully time-dependent geostrophic flow and the surface magnetic field UFM1 model of Bloxham and Jackson (1992) (for three different smoothings, see Jackson 1997);
- Petrov's three different CAM series based on torsional oscillations using (a) the IGMF surface magnetic field and the geostrophic flow approximation, (b) the surface magnetic field and the quasi-steady flow approximation, and (c) the LOD observation, the surface magnetic field and the geostrophic flow approximation (Petrov and Dehant, EGS 2000 abstract);
- Jault's CAM based on the torsional oscillations using the tangential geostrophic flow and the surface magnetic field (Jault et al., 1988);
- Pais' CAM based on the torsional oscillations using the tangential geostrophic flow and the surface magnetic field UFM1 model of Bloxham and Jackson (1992), see Pais and Hulot (2000);
- Boggs' core angular momentum (CAM) based on the torsional oscillations using the tangential geostrophic flow and the surface magnetic field UFM1 of Bloxham and Jackson (1992), see Hide et al. (2000).

The various model LOD data are given in Fig. 1.

An AGU monograph, entitled "Earth's Core: dynamics, structure, rotation" has been prepared by V. Dehant, K. Creager, S. Karato, and S. Zatman (editors), and published in December 2002.

[1] http://www.astro.oma.be/SBC/main.html

6 Future steps and recommendations

After the initial phase of setting up the website and gathering data, we plan to revise and update the website and to add some new features. In particular, main and new references will be added to the science overview parts of the website. This will be flexible as new references can easily be introduced without the need to revise the concise explanatory texts. To make new results and methods easily available, we will add a section with recent news and highlights. To be able to do that, it would of course be very much appreciated if people would keep us informed of new papers relevant to the SBC. To aid scientists who work or intend to work in core-related studies, an extensive bibliography will be maintained on the SBC website, which is presently ordered alphabetically by first author, and it will be studied whether it would be useful and possible to additionally make a division by content (e.g. by topics from the science overview).

Providing reliable data and methods is one of the main tasks of the SBC. In particular, we plan to include all kinds of data that are needed to calculate the effects of the core on LOD variations, nutation, polar motion, surface gravity changes, geocenter variations, and surface deformations. At present, only data on polar core angular momentum in the form of LOD variations at one (or more) year interval are available on the SBC website. More extensive data sets are clearly needed. For LOD studies, data on torsional oscillations must be made available. But also data on other components of the core flow, and of core angular momentum in all directions is needed. To better understand the core-mantle coupling, data relevant to the different coupling mechanisms are important, such as data on top core flow with high resolution, data on the CMB topography, data on the lower mantle conductance, and data on magnetic field strengths. In this sense, data from geodynamo modeling seem very interesting. In addition, we plan to add data on the inner core (relative motion, magnetic field strength, ICB topography,…). It is recommended that the members of the SBC make these data available, and actively stimulate others to do so. We plan to test and validate the data by intercomparison and hypothesis testing to be able to provide reliable data sets.

One of the goals of the SBC is to make the geophysical community aware of the various geodetic effects that could be linked with the core and to stimulate research in this field. It is important to bring together different groups with expertise in different aspects of the relevant topics, so that, by sharing expertise and working together, the whole group can achieve more than the sum of their individual contributions. At the joint EGS-AGU-EUG meeting in Nice in April 2003, a session will be organized on “Earth Rotation and Polar Wander: Internal Processes”, and we also foresee a business meeting at that occasion with the SBC members to discuss future activities. The adaptation of our website as described above is foreseen for that period. The following items could be discussed: which data should be made available, which formats should be used, would it be interesting or needed to distribute software, what is the usefulness of the present services, which new activities need to be undertaken,...

Our work and our web site can only be up-to-date if sufficient interactions exist with the scientific community related to the Earth’s rotation and to the Earth’s core. Any constructive comment or information is welcome. Our webmaster, Lydia Van Camp, will receive them with great pleasure (lydia.vancamp@oma.be). You may of course also contact one of the SBC team members.

Current and future projects look very promising. Satellite mission like Oersted and CHAMP provide high-quality vector magnetic field data. We thus obtain a better resolution of the magnetic field, which will in turn lead to improved models of core flow. It is also likely that the secular variation can be obtained at spherical harmonic degrees higher than 13. The lithospheric field dominates at these high degrees, but as this field is believed to vary very slowly in time, the time variations of the high degree geomagnetic field can be used to probe the Earth's core. Several missions, such as CHAMP, GRACE and GOCE, will also (and already do) improve the resolution and precision of the gravity field to an extent that core processes can be detected. In the coming years, we can therefore expect significant new insight in core dynamics and an improved understanding of variations in Earth orientation and gravity field.

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GGFC Special Bureau for Loading: Current Status and Plans

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Abstract: The Earth's surface is perpetually being displaced due to temporally varying atmospheric, oceanic and continental water mass surface loads. These non-geodynamic signals are of substantial magnitude that they contribute significantly to the scatter in geodetic observations of crustal motion. In February, 2002, the International Earth Rotation Service (IERS) established a Special Bureau of Loading (SBL) whose primary charge is to provide consistent and valid estimates of surface mass loading effects to the IERS community for the purpose of correcting geodetic time series.

Here we outline the primary principles involved in modelling the surface displacements and gravity changes induced by surface mass loading including the basic theory, the Earth model and the surface load data. We then identify a list of operational issues, including product validation, that need to be addressed by the SBL before products can be provided to the community.

Finally, we outline areas for future research to further improve the loading estimates. We conclude by formulating a recommendation on the best procedure for including loading corrections into geodetic data. Success of the SBL will depend on our ability to efficiently provide consistent and reliable estimates of surface mass loading effects. It is imperative that we work closely with the existing Global Geophysical Fluids Center (GGFC) Special Bureaus and with the community to as much as possible to verify the products.

1 Introduction

Temporal variations in the geographic distribution of surface masses load the Earth and deform its surface. Surface displacements due to atmospheric mass circulation are dominated by the effects of synoptic scale systems (1000–2000 km wavelength) with periods of approximately two weeks. Peak-to-peak vertical displacements of 10 to 20 mm are common at mid-latitudes (Figure 1) (van Dam and Wahr, 1987; Manabe et al., 1991; Rabbel and Zschau, 1985). The effects are larger at higher latitudes due to the larger amplitude pressure systems found there.

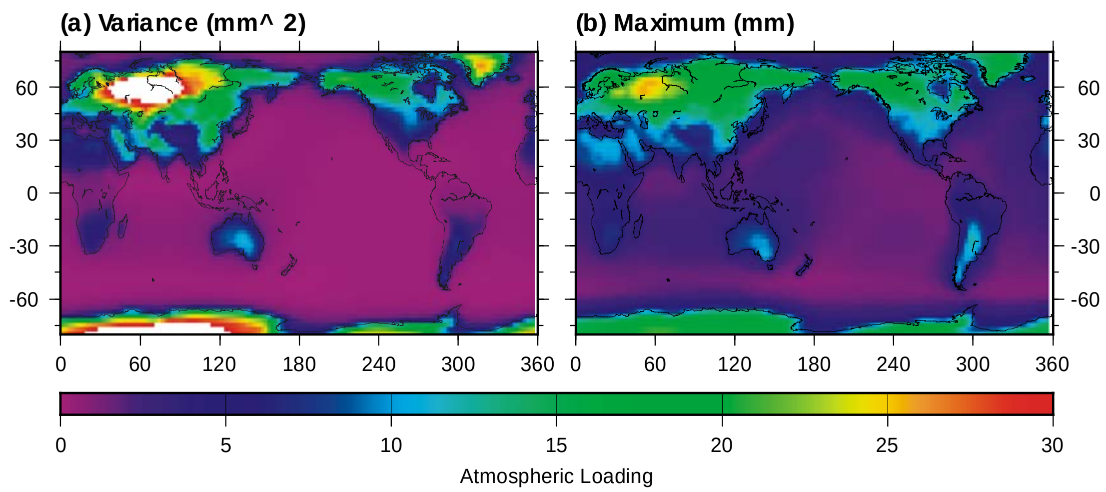

Fig. 1 Maximum range and variance in vertical crustal displacement during 1994-1998 (mm) due to changes in atmospheric surface pressure. (Figure provided courtesy of S. Desai.)

While surface displacements are largest for pressure systems with periods of approximately two weeks, annual signals are also significant having amplitudes between 0.5 and 3 mm. At annual periods, variations in continental water storage also become important. The modeled vertical displacements have root-mean-square values as large as 8 mm, with ranges of up to 30 mm (van Dam et al., 2001) (Figure 2).

Tidal and non-tidal motions of oceanic mass also contribute to the deformation spectrum at points on the Earth's surface. Variations in bottom pressure driven by uncompensated changes in sea surface height can induce vertical deformations at coastal sites of up to 20 mm with periods of approximately one month (van Dam et al., 1997; S. Desai, personal communication).

For all of these loading signals, the effects in the horizontal are approximately one-third the amplitude of those in the vertical.

Loading effects caused by the redistribution of surface masses have been observed in high-precision geodetic data for some time now (See for example, van Dam and Herring, 1994; van Dam et al., 1994; MacMillan and Gipson, 1994; van Dam et al., 2001). As these data are primarily being interpreted in terms of geodynamic processes (plate tectonics, post-glacial rebound, sea level rise, etc.), it is becoming necessary to remove loading effects from the data. Currently, however, there is no clear concensus on how this should be done.

On 1 January 1998, the International Earth Rotation Service (IERS) estab-

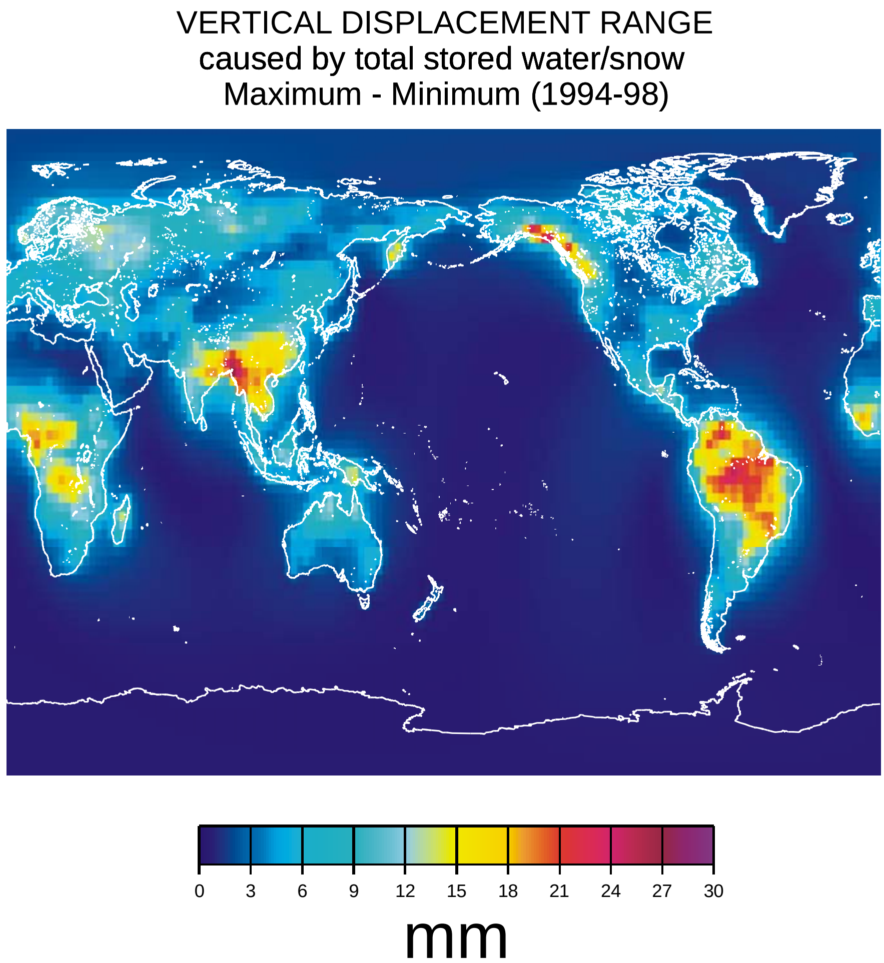

Fig. 2 Maximum range in vertical crustal displacement during 1994–1998 (mm) due to changes in total continental water storage.

lished the Global Geophysical Fluids Center (GGFC) in an effort to expand IERS's services to the scientific community. Under the GGFC, seven Special Bureaus (SB) were established (see <[1]>). Each of these is responsible for research activities relating to a specific Earth component or aspect of the geophysical fluids of the Earth system. However, until recently, there was no specific focus on the interaction of the different components through gravitational and surface forces on the boundaries. In particular, consistent models of the deformation of the solid Earth due to loading of the atmosphere, ocean and terrestrial hydrosphere are presently not available. This fact is reflected in the IERS Conventions (McCarthy, 1996), where standard models for solid Earth tides and ocean loading are discussed while no standard procedure is recommended for the case of other surface loading effects.

In order to foster the development of consistent models for predicting loading effects, the IERS on 31 October 2001 issued a Call for Proposals for a Special Bureau for Loading (SBL). In this call it was stated that the IERS conventions currently do not give comprehensive recommendations for treating the loading signals due to the full range of possible effects and that it therefore was timely to set up the tools that provide a basis for a future conventional treatment of loading effects in all IERS analyses. Furthermore, it was pointed out that meeting future requirements calls for considerable theoretical work, algorithm development, model compilations and studies of relevant observations.

Eventually, the SBL is expected to provide in near real-time (NRT) a consistent global solution data set describing at least the surface deformation, gravity signal and geo-centre variations due to the various surface loading processes, in reference frames relevant for direct comparison with existing geodetic observing techniques.

Table 1 Current Membership of the SBL. (Note that the chairs of the existing SBs are ex-officio members of the SBL. Currently, the ex-officio members include: Ben Chao (Mantle), Tim Van Hoolst (Core), Richard Gross (Oceans), Richard Ray (Tides), David Salstein (Atmospheres), Michael Watkins (Geocenter), and Clark Wilson (Hydrology)).

Name	Affiliation or function
Tonie van Dam	European Center for Geodynamics and Seismology (ECGS), Luxembourg (chair)
Hans-Peter Plag	Norwegian Mapping Authority (NMA), Norway (co-chair)
Geoffrey Blewitt	University of Nevada, Reno, U.S.A.
Jean-Paul Boy	Goddard Space Flight Center, U.S.A.
Olivier Francis	European Center for Geodynamics and Seismology (ECGS), Luxembourg
Pascal Gegout	Ecole et Observatoire des Sciences de la Terre, Strasbourg, France
Halfdan Pascal Kierulf	Norwegian Mapping Authority (NMA), Norway
Tadahiro Sato	National Astronomical Observatory, Mizusawa, Japan
Hans-Georg Scherneck	Onsala Space Observatory, Sweden
John Wahr	University of Colorado, Boulder, U.S.A.

On 1 February 2002, the SBL (see <[2]>) was formally established with a team of 10 members (see Table 1). The expertise of these ten members covers all areas relevant for accurately modeling surface deformations, namely: 1) the theory of Earth deformation and Earth models, 2) observations of surface loads, 3) computation of tidal and non-tidal loading effects, 4) and space-geodetic and gravimetric observations. The team also includes the 7 chairs of the existing SBs. These chairs are ex-officio members of the SBL and par-

[1] http://bowie.gsfc.nasa.gov/ggfc/
[2] http://www.gdiv.statkart.no/sbl/

ticipate in the SBL to insure close cooperation between their SBs and the SBL. Moreover, the combined membership provides the necessary links to other geodetic services and relevant projects, such as the IGS, IVS, ILRS, and the GGP.

The accuracy of the products provided through the SBL should, as much as model limitations allow, match the precision of the space-geodetic and gravimetric observing techniques. Achieving this ambitious goal requires major scientific advances with respect to the Earth model, the theory and algorithms used to model deformations of the Earth and the surface loading data of surface. Consequently, a scientific agenda has been established to perform the research necessary for the improvement of the models and algorithms, in parallel with an operational agenda which is directed towards establishing a service which provides validated loading products to IERS community.

Given that the most pressing objective of the SBL is to begin distributing reliable products, we will primarily report on the status of the operational agenda. We will report on the discussions held at the first SBL Workshop (Luxembourg, March 2002) and the 2002 IERS GGFC Workshop (Munich, November, 2002). The 'Action Items' and 'Recomendations' outlined in this document are the direct outcome of these workshops.

2 Overview of the basic components required for determining load responses

Figure 3 sketches the main elements required in the computation of loading predictions. These elements include: (1) an Earth model, which determines the geometry, with specific mechanical properties and, if necessary, the rheology, and (2) a mathematical model for the surface load including the boundary conditions at the Earth's surface and the extension of the load. Selected parts of continuum mechanics (e.g. elastic theory, or linear visco-elasticity) can be used to solve the boundary value problem to obtain the systems response to a unit load. For the problem of Earth deformation, the system's response is best described by Load Love Numbers (LLN) which can be used to compute the Green's functions of the boundary problem.

For the actual computation of the loading effects, surface load data are required for all relevant loads. These loads are then convolved with the Earth's response (either in the space or the wave number domain) to determine the loading effects (e.g. surface displacements, gravity variations, and geocenter displacements).

However, the Earth model and load data, as well as the theory selected to compute the Earth's response may not be adequate for describing the loading problem at the precision required for geodetic data analysis. For example, it is well known that the surface load data themselves can be inaccurate or incomplete. Therefore, a careful validation of the predictions both via model intercomparisons, as well as via comparisons to observations is required. After successful validation, operational processing can be set up to produce conventional products in near-real time. It is worth noting, that given the present state-of-the-art with respect to the theory of loading predictions, the quality of the surface load data, and the processing of space geodetic data, the need for additional improvements to the components of determining the loading predictions for research purposes will remain for a long time to come.

In the following three sections, we briefly describe the current state of the components required for determining the load response of the Earth, namely (1) the status of Earth models, (2) the existing surface load data, and (3) the numerical procedures for performing the computations themselves.

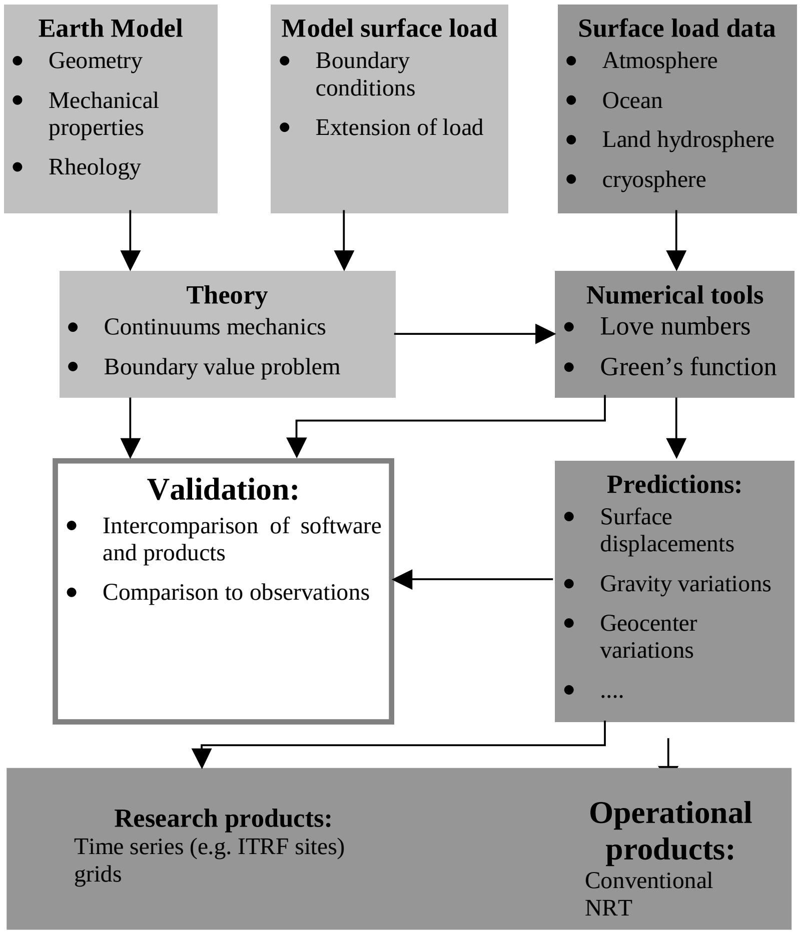

Fig. 3 Sketch of the scientific and operational loading predictions

3 Earth models

Earth models can be characterised by their geometry (i.e. spherical or elliptical, with or without undulations of the surface and inner boundaries), the space-dependency of their mechanical properties (i.e. the functions for density, bulk modulus, and shear modulus) and their rheology (i.e. the frequency dependency of the shear modulus). The most widely used models are Spherical Non-Rotating Elastic Isotropic (SNREI) models, assumed to be hydrostatically pre-stressed. For these relatively simple models, where all mechanical properties depend on radius alone, it is often assumed that computation of LLNs is a standard procedure. However, this is not necessarily the case. First, one has to select the functions describing the depth-dependency of density, bulk and shear modulus. The Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981) appears to be the natural choice (the LLNs given by Farrell (1972), which are based on the Gutenburg-Bullen A Earth model, are also still widely in use). Using the PREM poses at least three problems which leaves room for inconsistencies:

- the PREM has a global ocean of 3000 m depth, which needs to be replaced by a solid layer;
- the PREM is a visco-elastic model giving shear and bulk modulus for 1 s and 200 s. The PREM is based on the Anderson-Kanamori-rheology,

which cannot be used to compute elastic values for the shear and bulk modulus;

- the numerical computation of the LLN may require some parameterisation of the depth-dependency of the mechanical properties.

The popularity of the SNREI models is due to the fact that the Green's function for such models are rather simple, depending for a given Earth model only on the angular distance between the load and the observer. For laterally heterogeneous models (i.e. models with lateral heterogeneities in the distribution of the mechanical properties, boundary undulations, or a non-hydrostatic pre-stress) the Green's functions depend explicitly on the position of the load and the observer on the Earth, complicating the computation of the response considerably. For visco-elastic models, the Green's functions additionally become time-dependent.

SNREI models are most likely not sufficient to model displacements due to surface loads with an accuracy of 1 mm or better. In the future, issues such as anisotropy, lateral heterogeneity, visco-elasticity, and non-hydrostatic prestress will need to be considered.

4 Surface loads

The primary charge of the SBL is to provide reliable estimates of loading effects due to the temporal variability of the various surface loads. Thus, the SBL will need to obtain validated surface mass fields. As the IERS GGFC has within its umbrella, Special Bureaus for 1) Oceans, 2) Atmospheres, 3) Tides, and 4) Hydrology, the SBL will rely on these components of the GGFC to validate and provide access to the appropriate mass loading data sets. In this section, we outline the surface mass data currently available through the respective Special Bureaus.

The SBL should request from other SBs the input needed in terms of observations and models. This might also include the Earth models required for loading calculations.

Action item SBL-1: *The requirements of the SBL with respect to the other SBs should be clarified and the necessary input from the different SBs specified.*

4.1 Contributions from the SBs

4.1.1 Atmosphere

The SB Atmosphere, previously called the Special Bureau for Atmospheric Angular Momentum, is a cooperative effort of Atmospheric and Environmental Research, Inc. (AER) and the U.S. National Centers for Environmental Prediction (NCEP). AER provides scientific input, archives SBA parameters (see below) and maintains a liaison with IERS and the wider scientific community. AER calculates the SBA Atmospheric Angular Momentum parameters and receives data from other meteorological centres.

Ongoing efforts of the SBA focus on the combination of atmospheric data sets, and archiving torques related to Earth rotation, including the mountain and friction torque, and the interpretation of climate signals (e.g. the importance of El Nino) in Earth rotation and related parameters. Participating Centers in the SBA are NCEP, the Japan Meteorological Agency (JMA), the United Kingdom Meteorological Office (UKMO), and the European Centre for Medium-Range Weather Forecasts (ECMWF).

Parameters provided by the SBA describe the atmospheric angular momentum related to Earth rotation/polar motion due to winds and mass (surface pressure). What is important for the SBL is that the SBA uses surface atmospheric pressure to compute its products. In fact, the SBA converts the 6-hourly NCEP surface pressure into a spherical representation with and without modification for the inverted barometer ocean (harmonics for various truncations are available starting in 1975). The SBL can thus obtain the surface atmospheric pressure data as well as the spherical harmonic representation of the field from the SBA for some of the pressure fields.

4.1.2 Hydrology

Within the GGFC, the Special Bureau for Hydrology (SBH) is responsible for coordinating research activities related to continental water variations. The main goals of the SBH include the collection and distribution of data sets and numerical model results related to the changing distribution of water over the planet, especially over land, that are of interest to the geodetic community. The SBH is also responsible for developing working relationships with hydrological modelling groups, to insure that geodetically pertinent quantities are also computed during model runs. The current focus of the SBH is on data sets and model results which provide global estimates of water mass redistribution and to provide these sets in formats that will allow useful comparisons with geodetic observations, e.g. Earth rotation and the gravity field.

Data currently available at the SBH include the water storage and fluxes derived from NCEP/NCAR Climate Data Assimilation System I (CDAS-1): monthly soil moisture and snow for the period 1993 – 1998 on a 1° x 1° grid.

It is expected that the 1° x 1° degree data set will be available soon for the full NCEP reanalysis period (1948 – present) with a temporal resolution of 1 day. For selected periods, the data will be made available at six hourly sampling.

The NASA NSIPP hydrological model is a coupled model developed for prediction purposes and will provide data for the period 2010–2059.

Two additional global models exist: Huang et al. (1996), which provide monthly results for 1979–1993 and Shmakin and Milly (1999), which provide groundwater, soil moisture and snow for the period 1978–1998.

There are large uncertainties in all available hydrological models. Information on the effect of these uncertainties on predicted loading signals will need to be transmitted to the SBL user community.

4.1.3 Ocean

The global oceans have a major impact on global geophysical processes: Ocean currents and bottom pressure affect the Earth’s rotation (LOD, polar motion, nutation), and the redistribution of oceanic mass causes temporal variations of the Earth’s gravity field, affects the geocenter and loads the solid Earth leading thus to surface deformations. The IERS established a Special Bureau for the Oceans as part of the GGFC with three goals: (1) maintain liaisons with ocean modelling groups and advocate the calculation of relevant products, (2) archive and distribute these ocean-model products, (3) facilitate research on the effect of oceanic processes on solid Earth geophysics, including geodesy and geodynamics.

The SBL will initially rely on the SBO to provide reliable estimates of ocean bottom pressure. Two operational models currently exist: 1) Mercator, which plans to have an operational global ocean model available in 2003. The Phase 3 MERCATOR prototype planned for January 2003 will include real-time routine modelling of the global ocean at medium resolution (1/4 degrees), assimilating altimetry and in-situ data; and 2) ECCO (Estimating the Circulation and Climate of the Ocean), a consortium formed by a group of scientists at the Jet Propulsion Laboratory (JPL), the Massachusetts Institute of Technology (MIT) and the Scripps Institution of Oceanography (SIO). The ECCO consortium intends to bring ocean state estimation from its current experimental status to that of a practical and quasi operational tool for studying large-scale ocean dynamics, designing observational strategies, and examining the ocean's role in climate variability. The ocean-bottom pressure fields available from ECCO are at 1° resolution (telescoping to 0.3 degree meridionally in the tropics) and are produced by an ocean model that assimilates altimetry and in situ observations.

ECCO is planning to implement regular updates to the model at intervals no less than monthly. The bottom pressure data is available on request.

Ocean general circulation models used to predict ocean bottom pressure, use the Boussinesq approximation, i.e. volume but not mass is conserved. (Mass conservation is typically imposed after the fact by adding a surface layer of the appropriate time-dependent thickness.) The practical consequence of the Boussinesq approximation for loading predictions is that an artificial trend in the load and subsequently the load effects exists.

The ocean bottom pressure fields could be corrected by removing a trend from the time series for each grid unit. Unfortunately, this will also remove any real trend that might be associated, for example, with an increase in mass in the oceans, and so this solution is not acceptable. We will need to continue to investigate the optimum method for correcting the data for model induced trends.

The forcing of the ocean models typically includes surface wind stress, heat, and salinity fluxes, but not atmospheric pressure. However, the ocean response to atmospheric pressure could be obtained from barotropic models.

For operational purposes, model errors are important in addition to model resolution. Low degree errors might be important for high temporal resolution. We currently do no understand the spatial/temporal errors of the bottom pressure fields. The data (observations of bottom pressure over a large spatial wavelength at a high degree of temporal and spatial resolution) do not exist for evaluating the reliability of the models. Ocean modellers might benefit from feed-back from the SBL.

4.2 Status of ocean tidal loading

Computation of ocean tidal loading requires two ingredients, namely ocean tidal models describing the load and Earth models, on which the load acts. Two ways of computing the loading response can be distinguished, namely the convolution in the space domain (direct convolution of the load with the Green's function in the space domain) and the summation in the wave number domain (summation of the products of Love numbers and load potential). There are specific advantages and disadvantages of the two approaches, which in principle should give identical results. In practice, this is not the case. The 2-D function describing the tides is discontinuous at the coastlines. This generates instabilities in the loading computation in coastal regions (so-called Gibbs's effect). It is therefore recommended that the convolution be carried out in the space domain whenever possible.

For the ocean tidal models, a distinction can be made between global and local/regional models. For global models, the Schwiderski model covers the main semi-diurnal, diurnal and long-period tidal constituents. There are 15–20 models available, which are derived from Topex/Poseidon and which provide the main semi-diurnal and diurnal constituents. Finite Element models give quart-diurnal, semi-diurnal, diurnal and long-period tides. Local models generally provide finer grids and are likely to be superior locally. For some specific near-coast sites, a combination may be necessary.

Software available for computing of ocean tidal loading coefficients includes (but is not limited to):

- O. Francis: Research type program, not publicly distributed; large number of models
- D. Agnew: Publicly distributed; good representation of coasts; large number of models, including local ones; to be set up on the web to provide loading coefficients for arbitrary stations
- H.-G. Scherneck: Web based; Gutenberg-Bullen A Earth model; Coastline is treated very well
- Matsumuto: Available by ftp; primarily for Japanese islands
- ICET: Only solutions for the Schwiderski ocean tide model.

As ocean tidal loading represents a surface load, the responsibility of computing loading effects due to ocean loading should by definition fall under the purview of the SBL. However, unlike atmospheric pressure, continental water storage, and ocean bottom pressure, different investigators have developed and provided ocean tidal loading corrections to the geodetic community for years. As such, the SBL has no interest in duplicating the excellent efforts of so many individuals. Instead, the SBL will try to find a way to validate the different products that are currently available. Once validation has been performed the SBL will link to the appropriate web pages. At this point, it is not clear how validation of the loading coefficients can be achieved.

4.3 Status of atmospheric surface loads and issues to be addressed

Initially, the SBL will operationally generate 3-d deformations due to variations in atmospheric pressure variations. (Once the technique and Earth models have been validated for atmospheric pressure data sets, other surface loads will be added.) Because the ocean response to pressure is still not completely understood, deformations calculated with and without an inverted barometer ocean model will be supplied. Historic loading time series (going back to 1980) for all IERS sites will be generated first. Global gridded results as well as time series will be generated once the SBL becomes operational.

Initially, there will be two surface pressure data sets that will be considered by the SBL: the ECMWF surface pressure and the NCEP surface pressure data sets. The ECMWF and the NCEP data are provided as 256 and 126 quasi-regular Gaussian Grids, respectively. Both data sets can also be downloaded as 2.5° x 2.5° global grids. The latency period for obtaining both data sets is between 1 and 2 days.

In this section, we will report on the atmospheric load data issues that remain to be addressed. There are primarily three topics that need to be investigated: (1) model accuracy, (2) required spatial sampling for geodetic observations and (3) required temporal sampling.

4.3.1 Accuracy

The accuracy of SBL products will be limited by (among other things) the accuracy of the surface load data. Without independent global observations of the parameters of interest, the accuracy of the data sets is impossible to determine. On the other hand, we can investigate the differences in the data sets. This method will not reveal errors that would be common to both datasets. However, it does provide some estimate of the accuracy of the loading data.

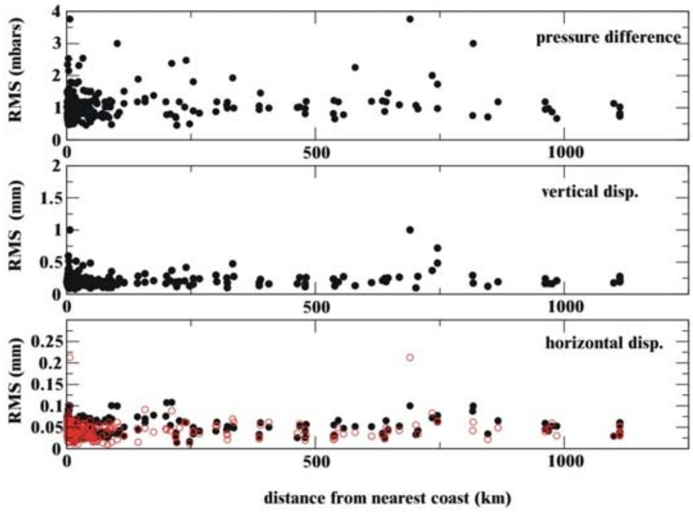

Fig. 4 RMS differences between deformations predicted using ECMWF and NCEP pressure data

A question of primary interest to the SBL is, are the differences in the deformations determined using the NCEP or the ECMWF data set, significantly larger than the current precision of the geodetic observations?

To investigate this question, predicted 3-d deformations for 225 IERS geodetic sites were determined using three years of NCEP and ECMWF 2.5° x 2.5° global surface pressure data sets. Deformations were determined for an Earth model with an inverted barometer ocean. The NCEP and ECMWF time series for each site were differenced and the RMS of the differences was determined. The results are presented in Figure 4. The results indicate that the RMS of the pressure difference is always less than 4 hPa. The RMS of the difference between the radial deformations predicted using the two surface pressure data sets is always less than 0.75 mm. On the other hand, maximum differences can be as large as 14 hPa and 3 mm in the local pressure and the radial crustal motion respectively. These differences are significant given the current precision of geodetic observations.

As we cannot determine which data set is more reliable, the SBL will produce loading effects for both the NCEP and ECMWF surface pressure data sets. The difference between the results will be reported as an error on the products.

As stated earlier, trends exist in the ocean bottom pressure and the continental water storage data. Trends may also exist in the air pressure data sets. The trends in these data affect the long term accuracy of the models. As such we propose:

Action Item SBL-2: *Study mass conservation of ocean and continental hydrosphere models.*

Action Item SBL-3: *Investigate the spatial distribution for the trend in air pressure.*

4.3.2 Spatial Resolution

The spatial resolution of the surface loads and the predicted loading should be sufficient to allow for an interpolation of the loading signals to any location on the 1 mm level or better. With respect to the spatial resolution of the surface pressure field for atmospheric loading, the following recommendation is proposed:

Recommendation 1: *The spatial resolution of the atmospheric pressure field should be 2° x 2°.*

The potential role of surface topography for atmospheric loading was pointed out at the Luxembourg Workshop. It can be questioned whether a resolution of 2° x 2° is sufficient to represent mountain ranges. However, before committing to include the surface topography it should be determined whether this is really necessary to obtain the desired accuracy of 1 mm or better. The following action item is proposed:

Action Item SBL-4: *Investigate the effect of topography on displacements.*

4.3.3 Temporal Resolution

Concerning atmospheric pressure variations, the temporal resolution of the products will be limited by the temporal resolution of the surface pressure data themselves (currently 6 hours). In most instances, this resolution is sufficient for geodetic investigations where daily or even weekly averages of position are desired.

The S_1 thermal tide is a large signal in atmospheric pressure but is not well represented in the atmospheric analyses. Recent studies indicate that the amplitude of the S_1 is between 0.67 and 0.71 mbars (Dai and Wang, 1999; van den Dool et al., 1997) with a spatial dependence of:

$$P(\phi,t) = P_{max} * \cos^3(\phi) * \sin(t + 12^\circ)$$

P_{max} is the maximum amplitude, ϕ is the latitude and the longitudinal dependence of the function (the argument of the sine) depends on the time of the day (i.e. the position of the sun). Modelling the spatial distribution of the pressure with this function on a solid earth (no oceans were applied to maximize the effect of the load), induces a diurnal deformation at the equator of -0.8 mm. (The deformation would be significantly smaller in the case of an inverted barometer ocean Earth model.) The deformation fall's off quickly away from the equator (to approximately 0.2 mm at 40 degrees for the solid Earth model). For daily averages of the station position, this diurnal signal would average to zero.

The amplitude of the S_2 atmospheric tide is about twice the amplitude of the S_1 tide. The loading effect is proportionately larger as well, having a peak-to-peak amplitude of approximately 3 mm at the equator where it is a maximum. The deformation falls to 1.5 mm peak-to-peak at 40 degrees either side of the equator.

The fraction of the geodetic community which might be interested in sub-daily estimates of pressure loading would be those groups interpreting the GPS data in terms of water vapour changes. For these data: $PWV = 0.04 X \delta h$ and the error in the PWV estimate would be approximately 0.04 mm for a load of 1 mm. Thus, it seems unlikely that we would have to consider improving the models of the S_1 and S_2 atmospheric tides in the atmospheric pressure data sets.

On the other hand, if the community states a need for sub-daily corrections, we will need to improve the model of the S_1 and S_2 atmospheric tides in the surface pressure data, where it is currently poorly modelled (R. Ray, personal communication).

It is imperative that we understand the temporal characteristics of all surface loading data sets. For example, it would be unwise to distribute products with a data sampling rate higher than the time variability of the signal of interest. In this case, erroneous corrections might be transmitted to the community. With this in mind, we propose the following action item:

Action item SBL-5: *Investigate the space-time spectrum for all surface load data.*

4.3.4 Reference levels for surface loads

Another issue in terms of accuracy, is the reference level to be used for the different surface loads. Care must be taken in selecting the reference level for computing the surface load anomalies. Using biased anomalies in the computation of load-induced surface displacements and gravity variations may change the radius of the Earth or, e.g., the mean gravity on the Earth surface. However, we emphasise that the corrections should not change the ITRF coordinates. This will require a very special selection of the reference levels.

We propose the following two recommendations:

Recommendation 2: *Biases in trends due to model insufficiencies need to be removed from surface loads derived from models.*

Recommendation 3: *The reference level for surface loads should be a space-dependent and should be computed long period average.*

5 Model Intercomparison

5.1 Love numbers

Generally, differences in the LLN due to different Earth models are assumed to be on the order of 1–1.5 percent. However, comparing the LLNs for different Earth models, much larger differences are found. Thus, Farrell's (1972) LLN's for vertical displacement computed for the Gutenberg-Bullen A Earth model differ by up to 10 % from LLNs for the PREM. Moreover, LLNs computed for the PREM by different groups show differences of the order of 1 % and more (see Fig. 5). The PREM LLNs differ due to the way the equations of motion are integrated by the different investigators and the applica-

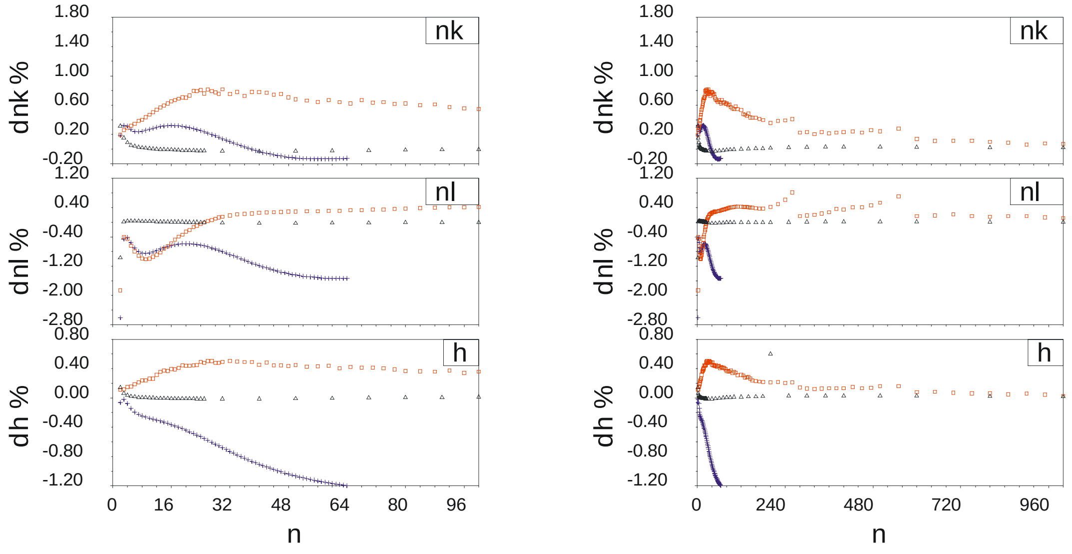

Fig. 5 Differences in LLNs for PREM computed by three different programs. The differences are given in percentage of the LLN (e.g., $dh_n = (h1_n - h2_n)/h1_n * 100$). Reference are the LLNs computed by P. Gegout. Red squares correspond to results obtained by H.-P. Plag, blue crosses to M. Tamisea, and black triangles to O. Francis. O. Francis and P. Gegout agree very well except for $n = 2$. The other two results show considerable disagreements for certain degrees.

tion of different boundary conditions.

A comparison of radial deformations determined for 4 different sets of Green's functions was performed. The Green's functions were derived from LLNs from 4 different Earth models including: 1) Gutenburg-Bullen A Earth Model (Farrell, 1972), 2) PREM (J. Zschau, personal communication), 3) PREM (P. Gegout, personal communication), and 4) PREM (H.-P. Plag, personal communication). Differences in the radial deformations determined for all the above Earth models were always less than 0.04 mm, indicating that the choice of LLNs (as long as they are for an SNREI model) will not have a significant influence on the estimated loading effects.

5.2 Load signal predictions

Loading responses to non-tidal surface loads are normally computed in one of two ways: 1) Point loading approach in which a gridded surface mass is convolved with Green's functions to determine the load response; 2) Spherical harmonics approach in which the LLNs are used directly to carry out the convolution with a given surface load in the wave number domain. This approach requires the surface loads to be given as a spherical harmonic expansion.

Clearly, the LLN approach is desired because of its computational speed. However, a potential problem arises when this approach is used for an Earth with an inverted barometer ocean. In this case, there is a discontinuity in the pressure anomaly at all the continental boundaries as the pressure anomaly

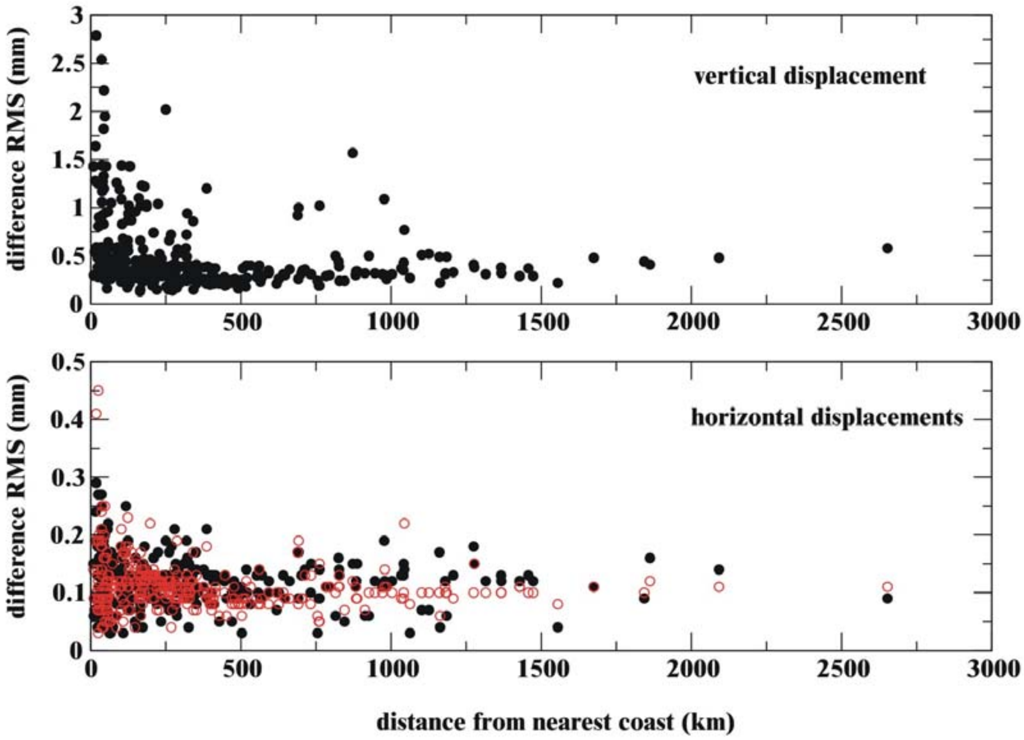

Fig. 6 A comparison of deformations obtained using the LLR approach and the Green's function approach. The RMS differences for the 360 sites are plotted as a function of distance from the nearest coastline.

goes from ambient over the continents to near zero over the oceans.

A comparison of 3-dimensional deformations determined using the spherical harmonic approach and the Green's function approach has been performed to determine what, if any, is the loss in precision from using the LLN approach versus the Green's function approach (see Figure 6). The time series from 360 IERS sites were compared using 11 years of NCEP reanalysis data. RMS differences in the estimate of the vertical can be as high as 3 mm at coastal sites. However for most sites the RMS of the differences is less than 1 mm. Individual epoch differences for a single site can be as high as 11 mm.

If the near-real time constraint can be relaxed for the SBL products, the Green's function calculation would be sufficient. However, it is more likely that the SBL will produce two products, (1) a rapid product that uses the LLN approach, and (2) a precise product that uses the Green's function approach. For the products from a solid Earth, i.e. no oceans, the LLN approach would be identical to the Green's function approach.

In computing the load signals, special attention must be given to the reference frame (Blewitt et al., 2001). One possibility is to provide the loading products in various frames, for examples, center of mass of the entire Earth system (common in SLR), center of mass of the solid Earth (Farrell assumption), center of figure frame (common in GPS). To a large extent, the frame selected depends on the degree-one LLN chosen. Conversion of the degree-one LLN to the appropriate frame can be done prior to the computation or the frame correction can be done at the end by applying condition equations on the gridded displacements. In any case, a clear specification of the reference frame needs to be attached to the model predictions.

In the context of the atmospheric pressure loading effects, the response of the ocean to atmospheric forcing also needs to be considered. Currently, only two simple models are used for describing the atmosphere-ocean interaction at these time periods: 1) no oceans and 2) inverted barometer ocean. We propose to operationally generate global loading effects using both of these models. However, neither alternative results in sufficient accuracy and, particularly for broad coastal regions, both assumptions may be insufficient. Therefore, more complex models for the ocean response to air pressure and also wind will have to be considered providing estimates of bottom pressure.

6 Validation of Prediction Models

The question of how to validate the model predictions is not straight forward to answer. It has to be clear that validation does not mean verification. Following Oreskes et al. (1994) we emphasise that verification is not possible and that validation is a process of reaching a consensus on which model appears to represent nature (or the modelled aspect of nature) in a satisfactory way. Therefore, intercomparisons of models and comparison of model predictions to observations are valuable steps to model validation. However, comparison with only a few surface displacement series certainly is not enough to draw conclusions. Rather, these comparisons will have to be done by the whole IERS community with different types of observations (rotation, gravity, surface displacement, etc.) at a number of different sites. A coordinated IERS validation campaign would involve all IERS techniques (GPS, VLBI, SLR, DORIS) at all ITRF sites. It would involve a large number of users. Thus, such a campaign would provide a very broad comparison.

Action Item SBL-6: *Compute data sets for a reasonable number of sites and time interval for external validation through comparison with observations.*

7 Scientific Agenda for Improvements of Loading Predictions

There are many areas where model improvements might improve our estimates of the surface loading effects. Development of these models fall under the SBL's Scientific Agenda. We outline a few areas for future research here.

- Improvements of the theory
  - Height dependent load
  - Surface undulations
  - lateral heterogeneities
- Towards a 3-d Earth model
  - elastic-viscoelastic,
  - 3-d from seismology
- Surface Mass Loads
  - Atmospheric loading
    - inverted barometer/ocean response
  - Hydrological loads
    - How to improve the models?
  - Non-tidal ocean loading
    - Combined models for complete atmospheric forcing
    - Combined circulation/tidal models
  - Tidal loading
    - Validation of models made available through the SBL umbrella

8 Towards a Conventional Treatment of Loading

The IERS conventions currently do not provide a recommendation for the treatment of atmospheric pressure loading effects. We provide here a draft of a procedure which is based on the geophysical model approach for correcting geodetic data for atmospheric pressure loading.

8.1 Conventions for loading: The vision

This section is a draft for the new IERS Conventions

Temporal variations in the geographic distribution of atmospheric mass load the Earth and deform its surface. For example, pressure variations on the order of 20 HPa (and even larger) at mid-latitudes, are observed in synoptic pressure systems with length scales for 1000–2000 km and periods of approximately two weeks. Seasonal pressure changes due to air mass movements between the continents and oceans can have amplitudes of up to 10 HPa in particular over the large land masses of the Northern Hemisphere. At the interannual periods, basin-wide air pressure signals with amplitudes of several HPa also contribute to the spectrum of the loading signal.

Other surface loads due to changes in snow and ice cover, soil moisture and groundwater, as well as ocean-bottom pressure also contribute to surface displacements. For example, at seasonal time scales, it is expected that the contribution of hydrological loads to surface displacements exceeds the one from air pressure (Blewitt et al., 2001). However, while the atmospheric load is fairly well known from global air pressure data sets, no sufficient models for ocean bottom pressure, snow and soil moisture exists at this time. Therefore, in the following, focus is on atmospheric loading. However, the discussion applies also to any other surface load.

Theoretical studies by Rabbel and Zschau (1985), Rabbel and Schuh (1986), van Dam and Wahr (1987), and Manabe et al. (1991) demonstrate that vertical crustal displacements of up to 25 mm are possible at mid-latitude stations due to synoptic pressure systems. Annual signals in the vertical are on the order of 1–2 mm but maximum signals of more than 3 mm are possible over large parts of Asia, Antarctica, Australia and Greenland (Mangarotti et al., 2001; Dong et al., 2002). Pressure loading effects are larger at higher latitude sites due to the more intensive weather systems (larger in amplitude and more spatially coherent) found there. Effects are smaller at mid-latitude sites and at locations within 500 km of the sea or ocean due to the inverted barometer response of the ocean. In all cases, horizontal crustal deformations are about one-third the amplitude of the vertical effects.

Two basic methods for computing atmospheric loading corrections to geodetic data have been applied so far: 1) using geophysical models or simple approximations derived from these models and 2) using empirical models based on site-dependent data.

The standard geophysical model approach is based on the estimation of atmospheric loading effects (vertical and horizontal deformations, gravity, tilt and strain) via the convolution of Green’s functions with a global surface pressure field. The geophysical approach is analogous to methods used to calculate ocean tidal loading effects. However, due to the continuous spectrum of the atmospheric pressure variations, the computation of the atmospheric loading signal must be carried out in the time domain. The major advantage of the geophysical model approach is that loading effects can be computed in a standardized way for any point on the Earth’s surface more or less instantaneously. The geophysical approach currently suffers from a number of problems including: the requirement of a global pressure data set, a minimum of 24 hours in time delay in the availability of the global pressure data set, limitations of the pressure data itself (low temporal and spatial resolution), uncertainties in the Green’s functions and uncertainties in the ocean response model.

In the empirical approach, site-dependent pressure loading effects are computed by determining the fit of local pressure variations to the geodetic observations of the vertical crustal motion. This approach is likely to produce better results (than the geophysical approach) for a given site but has a number of drawbacks as well. 1.) Geodetic observations have to be available for a certain period of time before a reliable regression coefficient can be determined; this period of time may be as large as several years. 2.) The regression coefficients cannot be extrapolated to a new site (for which no data exist); 3.) The regression coefficient has been observed to change with time and with observing technique; 4.) Regression coefficients at coastal sites are time dependent due to interannual changes in the regional weather pattern (H.-P. Plag, personal communication, 2002); 5.) The regression coefficient can only be used for vertical crustal motions; and 6.) It is uncertain that other pressure correlated geodetic signals are not being ‘absorbed’ into the regression coefficient determination. So while this approach would lower the scatter on a given geodetic time series the most, one would always be uncertain whether only atmospheric loading effects were being removed with the correlation coefficient.

In a hybrid method, regression coefficients determined from a geophysical model instead of geodetic observations could be used to operationally correct observed vertical position determinations from local air pressure alone. The vertical deformation caused by the change in pressure, in this case, can then be given in terms of a local pressure anomaly. The regression coefficients can be determined by fitting local pressure to the vertical deformation predicted by the geophysical model. Regression coefficients determined in this manner would still suffer from both the uncertainty in the Green’s function and the quality of the air pressure data.

In February 2002, the Special Bureau on Loading (SBL) was established within the IERS. The charge of the SBL is to promote, stimulate and coordinate work and progress towards a service providing information on Earth surface deformation due to surface mass loading, including the atmosphere, ocean and continental hydrosphere. In establishing the SBL the IERS is recommending that the convention for computing atmospheric loading corrections will be based on the geophysical model approach.

At the 2002 IERS Meeting in Munich, the IERS adopted the convention that corrections for surface load variations including the atmosphere should be determined using the geophysical model approach. Further, these corrections should be obtained from the IERS SBL. The point of this recommendation is to insure that comparisons of geodetic time series between different observing techniques or within the same technique but at different times and locations have a consistent atmospheric pressure loading (and later also non-tidal ocean and continental hydrological loading) correction applied.

The ultimate goal of the SBL is to provide in near real-time a consistent global solution data set describing at the surface deformation due to all surface loads (including atmospheric pressure variations) in reference frames relevant for direct comparison with geodetic observing techniques. The SBL will provide global gridded solutions of 3-d displacements and time series of displacements for all IERS sites. Time series will be determined from 1985 to the present. Displacements will be determined for both the European Center for Medium Range Weather Forecasts and the National Center for Environmental Prediction operational pressure data sets for the inverted barometer and the non-inverted barometer ocean models. For more information see <[1]>.

Regression coefficients based on a geophysical model are available for a number of VLBI sites through the SBL web page and the IERS convention's web page <[2]>. The regression coefficients were computed using 18 years of the NCEP Reanalysis Data (1 Jan. 1980 to 31 Dec. 1997). The data are 6 hourly values of surface pressure given on a $2.5° \times 2.5°$ global grid. Vertical crustal motions at a particular site are modelled by convolving Farrell's (1972) Green's functions for a Gutenberg-Bullen A Earth model. The ocean was assumed to be inverse barometric for the calculations. The regression results (mm/mbar) are determined via a linear regression between the modelled crustal displacements and the local surface pressure determined from the NCEP data set. An inverted barometer model was used in determining the ocean's response to pressure.

For more information on atmospheric pressure loading and geodetic time series, see the references listed in the extended bibliography.

8.2 SBL Products to be Delivered

A key issue is the question of which products can or should be made available and when. Initially, data sets which can be used for the validation of the products against observational time series of surface displacements, gravity changes and geocenter variations will be produced. These data sets are here termed 'research' data sets to distinguish them from the operational products. The IERS community might be interested in loading time series for all ITRF sites. Ideally, these series should cover the total period of observation, which for VLBI dates back to around 1980.

Based on the rational that more recent observations are likely to be of higher quality, time series for initial validation purposes should be produced for the period 1995 to the present. However, GPS coordinate time series generated

[1] http://www.gdiv.statkart.no/sbl.
[2] ftp://maia.usno.navy.mil/conv2000/chapter7/atmospheric.regr

by different analysis centers display seasonal signals which are not present for the total time interval, indicating that changes in an analysis strategy would hamper the comparison with model predictions. Therefore, a much longer time interval for the loading time series might be more appropriate.

The temporal resolution of the products will be determined by the temporal resolution of the loading data. In the case of atmospheric pressure loading, this is 6 hours.

9 Conclusion

We have outlined the issues related to operationally producing surface load effects for use in correcting geodetic data. The primary focus of the SBL at this point, is to address the issues necessary to become operational with reliable products as soon as possible. Once we become somewhat operational, the SBL will focus on the scientific agenda, i.e. the issues that will improve our estimates of the loading effects.

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Time Series of Site Positions and Datum Parameters

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Abstract: This paper is a summary of the poster presented at the IERS Workshop in Munich. It focusses on the analysis of time series of site positions and datum parameters obtained from VLBI, SLR, GPS and DORIS solutions. We analysed the time series with respect to non-linear effects, periodic signals and systematic differences and compared the results obtained by different techniques at co-location sites.

Motivation

Technique- and/or solution-related systematic effects (biases) are often poorly characterised or quantified, and can be considered as one major limiting factor for the accuracy of space geodetic observations and combination results. The analysis of time series is important to get further insight into the solution characteristics and to identify possible problems. One major goal is to study the existing differences of techniques and to understand their origin in order to achieve further improvements.

Data

The characteristics of the individual solutions are summarised in Table 1. We applied 7-parameter similarity transformations to align the individual VLBI, SLR, GPS and DORIS solutions into the ITRF2000 datum.

Results

The results of this study include time series of station positions and datum parameters (origin and scale) obtained from the various technique solutions (Angermann et al., 2003). In this poster summary we present one example for the scale variations (see Figure 1).

Conclusion

The time series of the datum parameters have evidenced that VLBI and SLR are the major techniques to realize the TRF scale, whereas SLR provides the most stable results for the origin. The observed non-linear effects in the position time series (e.g. due to earthquakes, instrumental changes, deficiencies in the models) are in conflict with the assumption of constant velocities. This may degrade the accuracy and consistency of the ITRF. Hence a better monitoring of the terrestrial reference frame may require non-linear components in site positions.

Acknowledgements

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Angermann, D., M. Krügel, B. Meisel, H. Müller, V. Tesmer: Time Evolution of the Terrestrial Reference Frame, presented at IUGG General Assembly, Sapporo, submitted for publication in IAG Proceedings, 2003.

Table 1 Summary of solutions used for this study

Techn.	Analysis Center	Software	Data Time Span	Stat. #	Station Coord. Solutions
DORIS	IGN/JPL	GIPSY/OASIS	1992.8–2002.0	80	weekly SINEX files
GPS	CODE	Bernese	1996.0–2002.2	163	weekly SINEX files
GPS	JPL	GIPSY	1996.0–2002.2	180	weekly SINEX files
GPS	SIO	GAMIT	1995.0–2002.2	157	weekly SINEX files
SLR	DGFI	DOGS	1992.9–2002.2	75	weekly comb. solut., Lag1&2
VLBI	DGFI	OCCAM	1984.0–2002.0	56	2227 daily session solutions

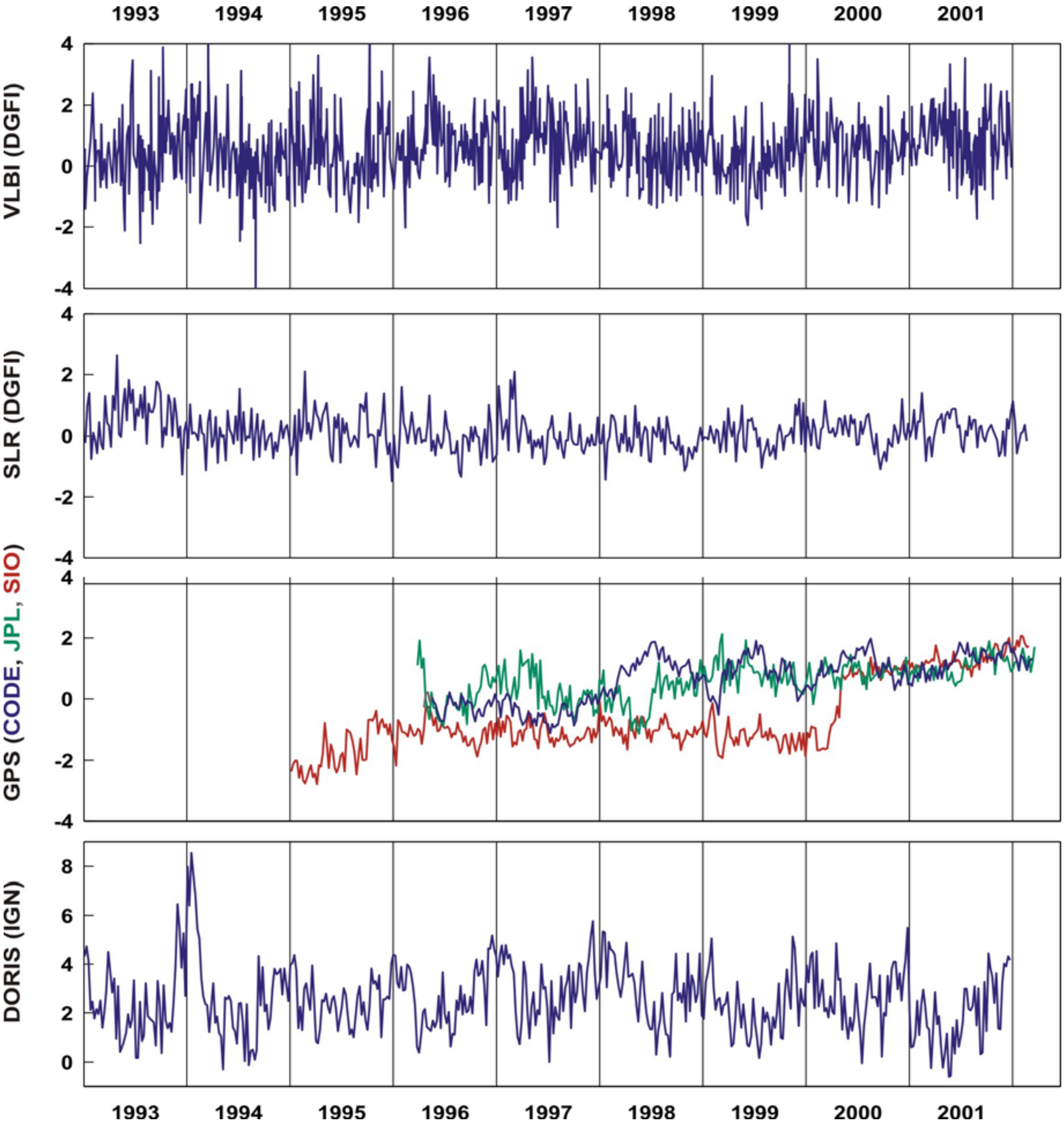

Fig. 1 Time series of scale variations [ppb]. Note that the VLBI results are based on single day session solutions, whereas the time resolution for the other techniques is one week. In case of VLBI typically only 4–7 stations observe simultaneously with changing network configuration from one to the other session, which is a second reason for the higher noise level of the VLBI series.

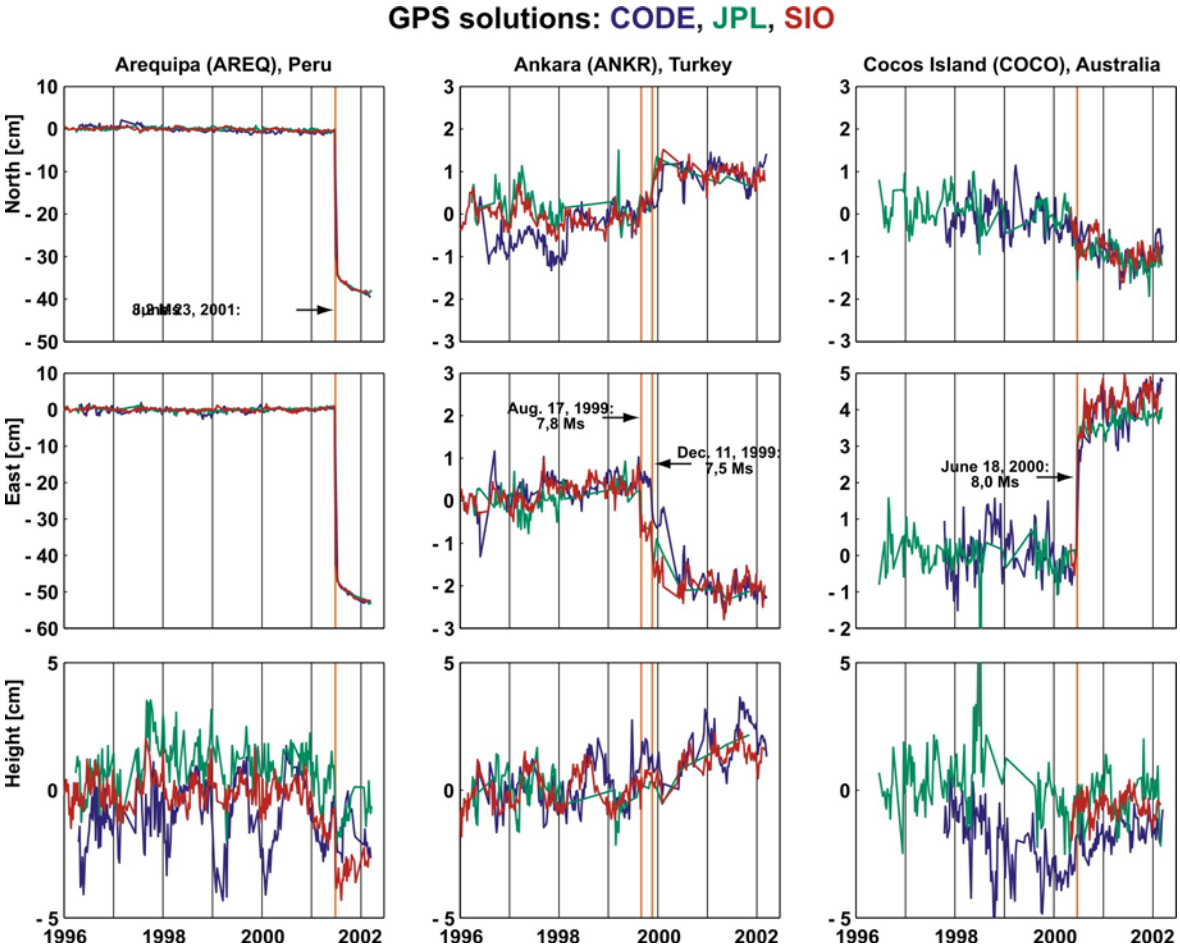

Fig. 2 Stations that are located in or close to plate boundary zones may be influenced by transient effects (e.g. due to earthquakes). The effect of large earthquakes is shown for three stations located at Arequipa (Peru), Ankara (Turkey) and Cocos Island (Australia). The co-seismic displacements of several centimeters up to half a meter in case of station Arequipa are often accompanied by time dependent or episodic motions after the event, which are difficult to be correctly modeled.

IVS Pilot Project – Tropospheric Parameters

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Introduction

Based on the very promising results of the 2nd IVS Analysis Pilot Project (Boehm et al., 2002) the IVS Directing Board decided in April 2002 to set up the 'Pilot Project – Tropospheric Parameters'. The Institute of Geodesy and Geophysics (IGG) of the Vienna University of Technology was appointed as coordination center of the new Pilot Project (PP). After the Call for Participation six IVS Analysis Centers (ACs) (see Table 1) agreed to contribute to the PP by regular submissions. They have been submitting results of tropospheric estimates of all IVS-R1 and IVS-R4 24h-sessions since January 1st, 2002.

Table 1 IVS ACs contributing to the Pilot Project

BKG	Federal Agency for Cartography and Geodesy, Leipzig	Germany
CGS	Centro di Geodesia Spaziale, Matera	Italy
CNR	Istituto di Radioastronomia, Bologna	Italy
IAA	Institute of Applied Astronomy, St. Petersburg	Russia
IGG	Institute of Geodesy and Geophysics, Vienna	Austria
GSF	NASA – Goddard Space Flight Center, Greenbelt	U.S.A.

Main features of the submissions

All ACs use cutoff elevation angles at or below 5°, and all but one (IGG) apply the Niell (1996) mapping functions. IGG uses the IMFh mapping function (Niell, 2001) for the hydrostatic part of the neutral atmosphere. Horizontal gradients (MacMillan, 1995) are estimated by all ACs; GSF and IGG introduce a-priori gradients from NWP (Numerical Weather Prediction) models. Three ACs fix the ITRF2000. Most of the ACs apply the CALC/SOLVE software package except IAA using the QUASAR software and IGG using OCCAM.

Combination strategy for the zenith path delays

The combination consists of a two-step procedure which is carried out site by site, week by week and parameter by parameter. So far, only total and wet zenith path delays have been combined by IGG. The comparison of gradients remains to be done.

In the first step combined zenith path delays are determined as unweighted means. This solution is used to derive mean standard deviations for each AC which are used for the weighting of the individual AC series in the the second step. There, the biases between the time series are removed and the VLBI values of the zenith path delays at each epoch are calculated as weighted means (Figure 1).

Finally, the combined wet and total delays are checked against each other by calculating the hydrostatic delays using the pressure values recorded at the stations.

Conclusion

Statistics show that the accuracies of the weekly offsets and the hourly values are at the level of 2 – 3 mm. More details can be found at the IGG homepage.

Thus, the combined VLBI time series can be compared with zenith path delays derived by other techniques such as GPS or WVR.

Acknowledgements: All agencies which have contributed to the IVS Pilot Project – Tropospheric Parameters by regular submissions are acknowledged for their great efforts.

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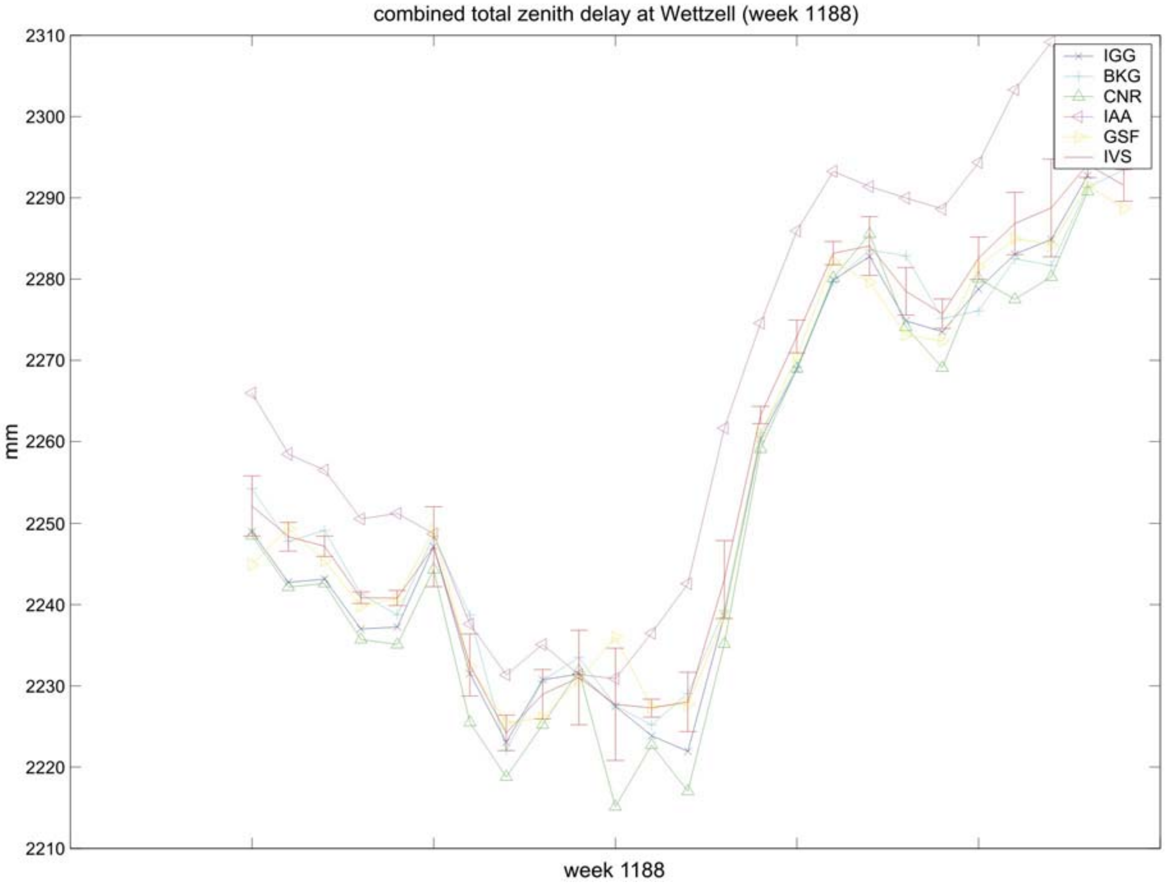

Fig. 1 Total zenith path delays at hourly epochs as submitted by the ACs and the combined VLBI solution with error bars for Wettzell, Germany (Oct. 14, 2002)

SINEX File Implementation in the VLBI Calc/Solve Analysis System

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Overview

The original design of the SINEX (Solution INdependent Exchange) format was for combining several GPS solutions. However, later this format evolved toward a common machine-readable form of solution listings for other space geodesy techniques, for example, VLBI and SLR. This process of evolution is not yet completed, therefore, different software systems implement different options for the Sinex format.

The solution listing in SINEX 2.10 format produced by Solve contains information about stations, sources, estimates of the parameters, their covariance matrix, the constraint equations, the right-hand side of constraint equations and weight matrix of constraint equations. In addition to these results, a portion of the decomposed normal matrix and normal vector can be included in the listing as well. A user has control over which blocks should be included in the listing. The current implementation of the SINEX format allows one to include in the listing the most important parameters, for example, station positions, source positions, and Earth orientation parameters. However, a user has control over which parameters among the parameters of the supported type are to be included or not included in the listing. A description of the SINEX implementation in VLBI analysis at GSFC is given in <[1]>.

Differences from the SINEX 1.00 standard

In Sinex 2.10 format, eight new blocks were added to the list of blocks of Sinex 1.00

- SOLUTION/CONSTRAINT_EQUATION_INFO
- SOLUTION/CONSTRAINT_EQUATION_MATRIX
- SOLUTION/CONSTRAINT_EQUATION_VECTOR
- SOLUTION/CONSTRAINT_WEIGHT_MATRIX

The purpose of these four blocks is to overcome problems in the original design of Sinex format and provide complete information about all constraints used in the VLBI solution.

- SOLUTION/DECOMPOSED_NORMAL_MATRIX **D**ii
- SOLUTION/DECOMPOSED_NORMAL_VECTOR **d**i

The purpose of these blocks is to provide information about the transformed normal equations before applying constraints. NB: one of the three items: covariance matrix, constraint equations and decomposed normal equations is redundant: having two of them one can derive the third one.

- NUTATION/DATA
- PRECESSION/DATA

The purpose of this section is to provide information about used nutation/precession model and to define parameter "estimates of nutation angles".

[1] http://gemini.gsfc.nasa.gov/solve_root/help/sinex.html

SOLUTION/STATISTICS block has new items:

- WEIGHTED SQUARE SUM OF O–C
  $\sum_{obs} y^T W y$
- WRMS OF POSTFIT RESIDUALS
  $\sum_{obs} [(Nx - y)^T W (Nx - y) / Tr(W)$

where y = the difference between the observed time delay and theoretical, N = normal matrix, x = vector of the parameter, adjustments, and W = weight matrix.

Summing is done over all observations used in parameter estimation. Comment: field WEIGHTED SQUARE SUM OF O–C is not computed in global mode.

The BLOCKS which keep elements of matrices do not have fields "Second Matrix Element" and "Third Matrix Element".

The purpose of this change is to facilitate the process of creation of the listing and to reduce significantly the probability of errors.

SOLUTION/MATRIX_APRIORI is not provided. The reason is that Solve does not use an apriori covariance matrix. It uses singular constraints that cannot be reduced to the form of an apriori covariance matrix. Full information about constraints is provided in other blocks.

Definitions

Let the normal matrix **N** and the normal vector **n** be partitioned in two blocks, i (included parameters) and e (excluded parameters). Let the matrix of constraints **C** be added to **N**. Let $\mathbf{C_{ii}} = 0$ and $\mathbf{C_{ei}} = 0$. If the matrix $\mathbf{N_{ee} + C_{ee}}$ is not singular, then there exists a matrix **M** such that

$$M \begin{pmatrix} N_{ii} & N_{ie} \\ N_{ei} & N_{ee} + C_{ee} \end{pmatrix} = \begin{pmatrix} D_{ii} & 0 \\ 0 & D_{ee} \end{pmatrix}$$

$$M \begin{pmatrix} n_i \\ n_e \end{pmatrix} = \begin{pmatrix} d_i \\ d_e \end{pmatrix}$$

The matrix $\mathbf{D_{ii}}$ is called the *decomposed normal matrix* and the vector $\mathbf{d_i}$ is called the *decomposed normal vector*. The matrix is partitioned to keep the parameters of interest in the i-block and the excluded parameters in the e-block.

The decomposed normal matrix $\mathbf{D_{ii}}$ can be computed from the blocks of the covariance matrix of the constrained (least squares) LSQ solution. Assuming that the normal matrix of constraint has blocks $\mathbf{C_{ei}} = 0$, we can express the covariance matrix **V** of the constrained LSQ solution as

$$\left(\begin{pmatrix} N_{ii} & N_{ie} \\ N_{ei} & N_{ee} \end{pmatrix} + \begin{pmatrix} C_{ii} & 0 \\ 0 & C_{ee} \end{pmatrix} \right)^{-1} = \begin{pmatrix} V_{ii} & V_{ie} \\ V_{ei} & V_{ee} \end{pmatrix}$$

In this case, the decomposed normal matrix $\mathbf{D_{ii}}$ and the decomposed normal vector $\mathbf{d_i}$ can be expressed as

$$D_{ii} = V_{ii}^{-1} - C_{ii}$$
$$d_i = D_{ii} x_i$$

where $\mathbf{x_i}$ is the i-block of the vector of estimates from the LSQ constrained solution.

SINEX file listing for a global solution

Parameters included in the listing:

- site positions (global)
- site velocities (global)
- radio source positions (global)

Parameters NOT included in the Sinex file:

- Antenna axis offsets (global)
- X pole, Y pole, UT1 and their rates
- Daily nutation offsets
- Clock function
- Baseline dependent clock offsets
- Atmosphere path delay
- Atmosphere gradients

Examples:

WEB pages <[1],[2]>

Source positions were not included in this listing. The solution description is in <[3]>.

SINEX file listing of daily solutions

Parameters included in the listing:

- daily site positions
- X pole, Y pole, UT1 and their rates
- Daily nutation offsets

Parameters NOT included in the Sinex listing

- clock function
- baseline-dependendent clock offsets
- atmosphere path delay
- atmosphere gradients

A collection of 3400 sinex files of daily solutions is in <[4]>.

The solution description is in <[5]>.

A new file is added within 24 hours after the correlation of each new 24-hour experiment session.

[1] http://gemini.gsfc.nasa.gov/solutions/2002c/2002c_all.snx
[2] http://gemini.gsfc.nasa.gov/solutions/2002c/2002c_trf.snx
[3] http://gemini.gsfc.nasa.gov/solutions/2002c/2002c_trf.snx
[4] ftp://cddisa.gsfc.nasa.gov/pub/vlbi/ivsproducts/daily_sinex/gsfd0001/
[5] ftp://cddisa.gsfc.nasa.gov/pub/vlbi/ivsproducts/daily_sinex/gsfd0001.dsnx.txt

Some Problems in the IERS Products from User's Point of View

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These notes do not pretend indeed to discuss all the problems confronting IERS which are well known to the IERS organizers and community. I would like only to draw attention to several points which we faced during our everyday work and that should be solved for better quality of individual ACs' and IERS products.

EOP products

- There are two main EOP products provided by two IERS Product Centers on Earth Orientation (Earth Orientation Center (EOC) and Rapid Service/ Prediction Center (RSPC)). Most of scientific users not connecting with (near-)real-time applications use EOC's series, and those who need operational data use RSPC's products (NEOS). It's evident, that these products should be highly consistent. However, this is not always the case. Systematic differences between two series are in some cases rather large, in particular in UT1 and especially in nutation (sometimes more than 100 microarcseconds in bias and/or seasonal terms).

  These systematic discrepancies between two EOP series can (and really do) yield differences in results obtained by users using different EOP products. In particular, that may affect input series provided by ACs submitting their results for the IERS combination. This does not matter for processing of '24h' VLBI series, but may be substantial for processing of VLBI Intensives and satellite observations, especially SLR ones.

  Perhaps, solution of this problem is not evident due to various scientific approaches used by EOC and RSPC for generating their products, but it should be found, in my opinion.
- A scientific user who wishes to analyze the IERS EOP series is interested in knowledge of more details concerning methods of computation of combined EOP series. However, some of these details are not available. In particular, systematic corrections and weights applied to input series are not always reported. Without that it is sometimes difficult to understand sources of systematic errors of individual series.
- For most accurate applications, users may need as accurate nutation model as possible. Such a model includes both determined IAU model and un-predictable components, in the first place FCN. However, the latter is not provided by the IERS. It seems to be important to compute and distribute this data including prediction.

ITRF

- Using ITRF in computation of EOP series produced by various ACs seems to be a necessary condition to provide the consistency between the IERS products. However, it is not always possible for several reasons:
  - Coordinates of some stations included in the ITRF are computed from relatively short period of observations and degrade with time.
  - With time, new stations start to operate after ITRF is issued.
  - Some events occurred at or near site (earthquake, landslip, telescope repair or modification, etc.) may cause change in station reference point position.

Under those circumstances ACs are forced to estimate station coordinates for some stations to provide accurate results. As a result, ACs used different TRF realizations for computation of EOP that leads to systematic disagreement between solutions.

To remedy this situation, it is very desirable to establish a procedure for timely update of ITRF. Evidently, there is no need to re-compute whole ITRF solution, but only to tie new stations to the current ITRF realization, introduce jumps, etc. Such a strategy would hopefully provide better consistency between individual solutions and make the IERS EOP products more stable.

- It is important to bear in mind that a user maybe actually needs not so much the accuracy of the ITRF catalog itself as the accuracy of coordinates of a given station at a given epoch. From this point of view, to properly use ITRF in practical applications without loss of accuracy one needs also to know in detail geophysical models corresponding to the used ITRF version. Such a model should include, reference temperature and atmospheric pressure for each station, mean pole (to be used in modelling of rotational deformations), atmospheric and ocean loading, tides, etc. Use of improper models can cause errors in station positions at the centimeter level bringing to nothing the original accuracy of ITRF.

  In turn, ACs providing input solutions to ITRF must use the same models (preferably defined by the IERS Conventions). If it's not the case, it seems crucially important that IERS ITRS Center, compiling the ITRF catalog, applies corresponding corrections to input series to provide maximum consistency and accuracy of the final product. To encourage ACs to provide such an information, it seems to be reasonable to include corresponding blocks in the SINEX standard format.

  Until a new ITRF realization is issued, it is desirable to perform special investigation to estimate reference temperature and atmospheric pressure for stations, and identify other geophysical models corresponding to the ITRF2000.

IERS Conventions

The astronomical and geophysical models used for data processing become more and more complicated with time as requirements to accuracy growth. Consequently, corresponding software becomes rather complicated. To simplify procedure of testing the software and eliminate number of errors in ACs' results it seems very desirable to provide test examples for all models and algorithms described in the IERS Conventions. Evidently, authors contributed to the IERS Conventions should provide such test data.

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Comparison and Combination of the Earth Orientation Parameters Submitted to the IERS Alignment Campaign 2002

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Introduction

Several Earth Orientation Parameters (EOP) series (pole coordinates, UT1–UTC, nutation coefficients) for the years 1999 and 2000 submitted by various Analysis Centers (ACs, see Table 1) to the IERS Alignment Campaign were edited, compared and combined. Only independent raw time series, i.e. without any preprocessing, with the station coordinates fixed to the ITRF2000, were used. Figure 1 shows the nine time series for the months June and July 1999 obtained from the VLBI Analysis Centers.

Table 1 Overview of the participating ACs

Abbr.	ACs	Submitted techniques
ASI	ASI, Italy	SLR
BKG	BKG, Germany	VLBI
CAN	NRC, Canada	VLBI
DGF	DGFI, Germany	VLBI
GAUS	GAUS, Australia	VLBI
GSF	NASA GSFC, USA	VLBI
IAA	IAA, Russia	SLR
IGG	IGG, Austria	VLBI
OSO	OSO, Sweden	VLBI
OS2	OSO, Sweden	VLBI
SHAO	SHAO, China	SLR, VLBI
CODE	AIUB, Switzerland	GPS

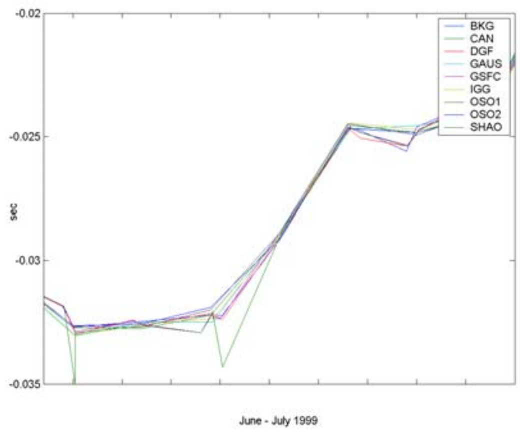

Fig. 1 Individual VLBI solutions for the xpol time series as submitted by the IVS Analysis Centers

Combination procedure

Before combining and comparing the various solutions from the different ACs it was necessary to edit the raw data and interpolate them to weekly epochs. Then, a two-step procedure for the combination was carried out (see flow chart in Figure 2). In a first step AC-dependent biases were removed and a combination within each technique was carried out. In Figure 3 the edited data and the combined VLBI series are displayed. In the second step, after removing technique-dependent biases, a combination of the different techniques was calculated. This step is carried out twice, first unweighted and then with assigned weights calculated from the standard deviations of the first, unweighted solution. In Figure 4 the individual solutions of each space geodetic technique and the combined weighted series are plotted.

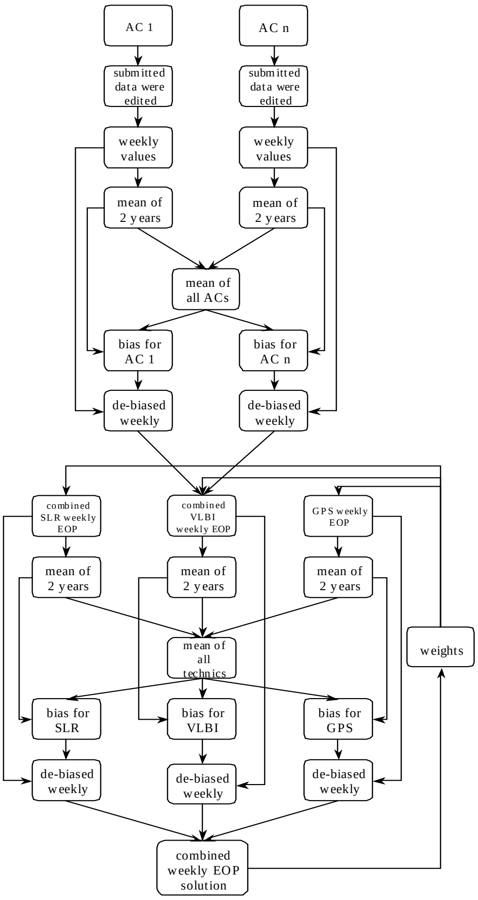

Fig. 2 Flowchart of the combination procedure

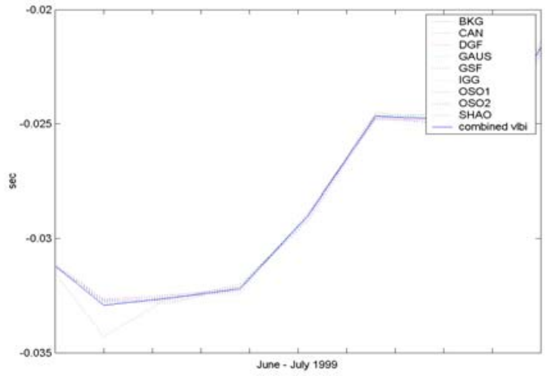

Fig. 3 Individual VLBI submissions and the combined VLBI time series for xpol

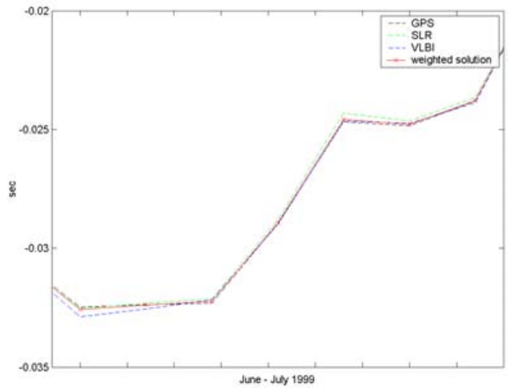

Fig. 4 Individual VLBI solutions of the different techniques and combined weighted solution for the xpol time series

Results, Discussion and Conclusions

Most problems occurred when editing and interpolating the raw data that were submitted to the IERS Alignment Campaign covering different time intervals, given on different time epochs, and the coordinates fixed to different reference frames with different a-priori models used for the analysis. For our combination only solutions with the station coordinates fixed to the ITRF2000 were used. The comparison shows a good agreement between most ACs. The two-step procedure (1^{st} step combination within each technique, 2^{nd} step combination of the various techniques) improved the quality of the results in terms of accuracy and robustness. However, clear descriptions are needed of the reference frames, a-priori models, and parameters to be determined.

Stand. dev. of the individual techniques w.r.t. the unweighted combined solution

	xpol [mas]	ypol [mas]
VLBI	0.155	0.134
SLR	0.147	0.170
GPS	0.095	0.095
Comb. solution	**0.138**	**0.143**

Stand. dev. of the individual techniques w.r.t. the weighted combined solution

	xpol [mas]	ypol [mas]
VLBI	0.173	0.122
SLR	0.154	0.205
GPS	0.064	0.059
Comb. solution	**0.100**	**0.099**

Combination of Terrestrial Reference Frames and ERP at University of Newcastle

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Introduction

The **TANYA** software, developed for the IGS Global Network Associate Analysis Centre (GNAAC) at University of Newcastle upon Tyne, UK, allows to check, to compare and to combine the IGS AC SINEX solutions (A-networks) for station coordinates. It has been updated to be able to combine Earth Rotation Parameters (ERP – x_p, y_p, LOD) obtained from IGS and ILRS ACs. The new ability has been tested for GPS data on four weeks interval. NCL GNAAC submits combined ERP starting May 2002.

Input data

- GPS SINEX weekly data from 7 ACs: COD, EMR, GFZ, JPL, NGS, SIO (4 weeks – 1108, 1109, 1110, 1111).
- IGS.SNX catalog file from IGS CB.
- CDDISA FTP data (to create SLR catalog file).
- SLR data for the year 1999 from ILRS Pilot Project.

Analysis procedure

The usual procedure consists of several steps as follows.
1. Validation. All Sinex files have been checked with TANYA for consistency with SINEX V1.0 format requirements. (On-line Sinex checker could be found on ***http://ucscgi2.ncl.ac.uk/~nkn3/*** web site). JPL and GFZ submit LODR – values of LOD with pole tides effects removed. We added that effects back to obtain LOD. No LOD bias correction has been made.
2. Deconstraining has been made to obtain AC's loose solutions.
3. Estimating the loose combined solution GNET (full covariance matrix used) consisted of non-global station exclusion, re-scaling of covariance matrices, combination of AC solutions.
4. Helmert transformation from AC loose solutions to GNET solution has been made to compute post-residuals of station coordinates in one coordinate frame.
5. Outlier removal has been made from analysis of the post-residuals.
6. Variance component estimation – to balance influence of ACs, to calibrate the outlier hypothesis test; Steps 3-4-5-6 are repeated, if necessary.
7. Product generation. Product consists of constrained solution G; Helmert parameters between AC loose, GNET and CORE (IGS2000, ITRF2000) solutions.
8. Reporting to CDDIS.

Combination results

Unfortunately, the SLR data can't be used for analysis because of number of data and format problems and reporting UT1 rather than LOD. We've made combination of **IGS station coordinates** and **ERP** – daily values of x_p, y_p, LOD for GPS weeks 1108, 1109, 1110, 1111 using GPS data from seven ACs.

Comparisons

The comparison of the following solutions for GPS weeks 1108, 1109, 1110, 1111 has been made:

- combined NCL solution with IGS AC (COD, EMR, GFZ, JPL, NGS, SIO) solutions.
- combined NCL solution with combined MIT GNAAC, IGS combined (EMR) and P01 (EOP IERC(PC) 97 P01).

Figures 1 and 2 represent RMS of the solution differencies for ERP. No Helmert transformation parameters have been applied to ERP values in comparison.

Conclusions and recommendations

- TANYA software is able to combine station coordinates and ERP simultaneously.
- NCL combined ERP solution for GPS data is the most close to the IGS combined solution.
- GNAAC at University of Newcastle upon Tyne, UK is able now to submit combined ERP to the IGS.
- ILRS ACs have to submit LOD rather than UT1 for the Combination Research Project.

Future Contributions

- Regular submission of combined ERP to IGS.
- Taking part in the ILRS AWG Pilot Project and IERS SINEX Combination Campaign.
- Combination of pole rates.
- Study of the influence of constraints, number of stations and station distribution on the combined solution (especially, for SLR).
- Combination of solutions from different space techniques.

Acknowledgements

This work has been funded by a NERC of UK.

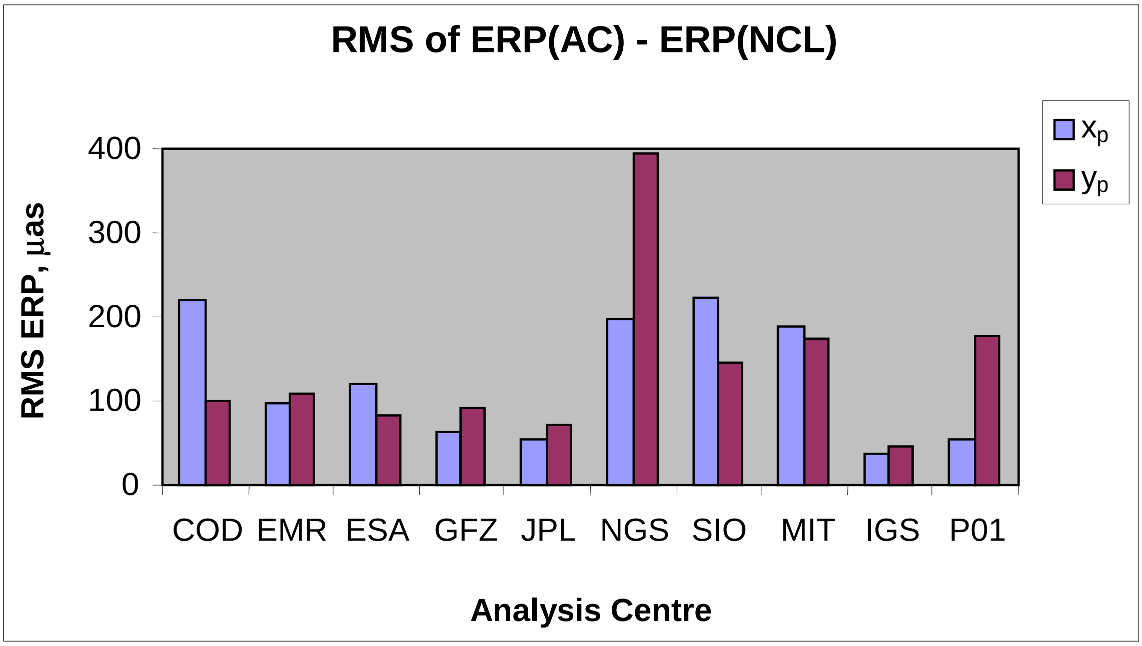

Fig. 1 RMS of solution differences for pole coordinates

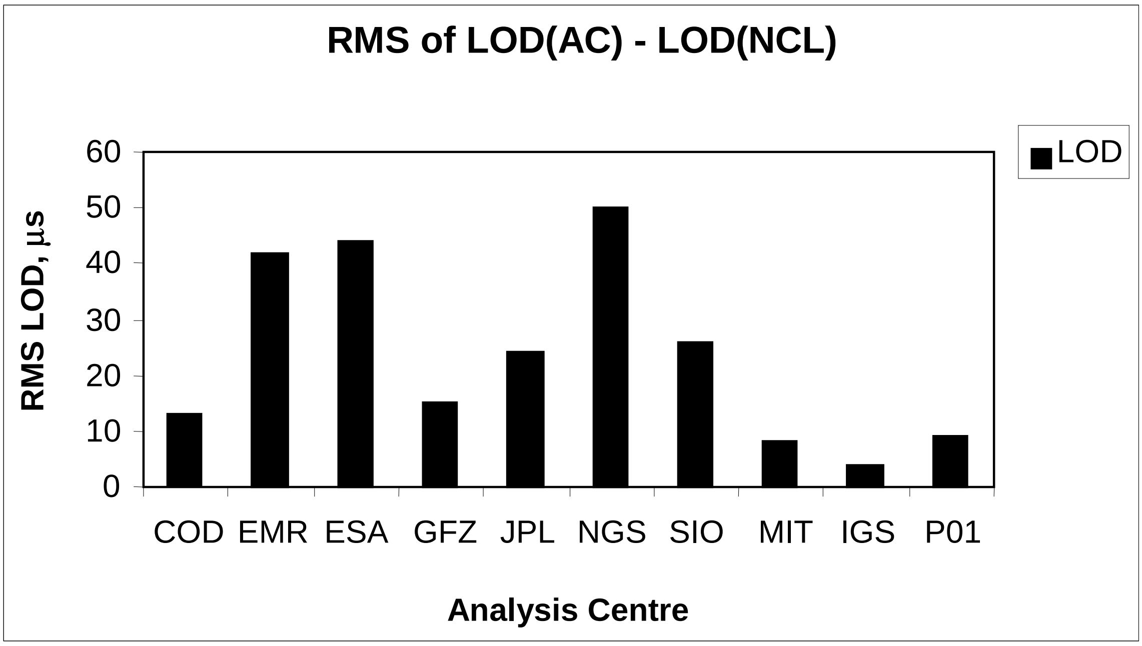

Fig. 2 RMS of solution differences for LOD

Determination of Station Coordinates and EOP from Combination of Different Techniques

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Description of the method

The method is designed to combine "non-SINEX" solutions for different techniques, where the normal equations matrix can not be restored. Input data: For each technique one or more sets of (x_p, y_p, UT1–UTC, dψ, dε) – Earth orientation parameters, EOP_m, and X_t – station coordinates, SSC_m. Result: "representative" set of orientation parameters (x_p, y_p, UT1–UTC, dψ, dε) for epochs T_i and seven transformation parameters $\mathbf{p} = p_1, ..., p_7$ for each input solution of station coordinates.

The method is based on combining fictitious observations – position vectors of the stations, transformed into the celestial reference frame, i.e. $\mathbf{X}_t \rightarrow \mathbf{X}_c$:

$$\mathbf{X}_c = PN(t)\ R3(-GST)\ R1(y_p)\ R2(x_p)\ \mathbf{X}_t$$

where PN, R1, R2, R3 are transformation matrices. The transformation yields observation equations

$$\sum_j \frac{\partial \mathbf{X}_c}{\partial \xi_j} d\xi_j = \mathbf{X}_c \big|_{obs} - \mathbf{X}_c \big|_0 + \mathbf{v} \ ,$$

with $\xi_j \equiv x_p, y_p$, UT1, ψ, ε, $\mathbf{p}$. Singularity of the system is removed using constraint of no-net rotation

$$\sum \mathbf{p}^T \mathbf{p} = 0 \ .$$

Corrections to nutation angles dψ, dε can be separated from the pole coordinates x_p, y_p by introducing the fictitious observations of the second kind, which are shifted from the basic epoch by ±8 hours, i.e. three observation equations correspond to each input data. The length of day, LOD, as produced by SLR and GPS, is converted to UT1–UTC by integration and parabolic fit to the VLBI data

$$\{UT1 - UTC\}(t) = \int_0^t LOD + c_0 + c_1 t + c_2 t^2 \ .$$

The EOPs for a particular epoch are derived independently of the other epochs, what results in false oscillations especially in UT1–UTC. Thus, to accomplish a tie of the LOD data to VLBI time corrections, "condition" observation equations

$$d\xi_i - d\xi_{i-1} = 0 + v, \qquad \xi \equiv x_p, y_p, UT1-UTC, \psi, \varepsilon,$$

are added for each non-VLBI epoch. Strength of the tie depends on the weight of these equations.

Only stations equipped by at least two techniques are included into the combination. Instruments are centered to one reference point. One day data referred to 12 h UT are created for all EOPs. Due to the constraints, the result of combination depends on the adopted preliminary values of the unknowns. As we expect only subtle effects arising from simultaneous processing of EOP and station coordinates, the weighted mean derived from all contributing individual solutions would be the most probable approximate value of the respective unknown.

Data and numerical solution

The method is tested using following VLBI, GPS and SLR input solutions:

GAOUA	97 R 01	EOP and SSC	x_p, y_p, UT1–UTC, dψ, dε
GIUB	97 R 01	EOP and SSC	x_p, y_p, UT1–UTC, dψ, dε
SHA	97 R 01	EOP and SSC	x_p, y_p, UT1–UTC, dψ, dε
GSFC1122	97 R	EOP and SSC	x_p, y_p, UT1–UTC, dψ, dε
GSFC	97 L 01	EOP and SSC	x_p, y_p and LOD
CODE	97 P ?	EOP	x_p, y_p and LOD
CODE	98 P 01	SSC	SSC do not correspond to EOP

Systematic differences of particular input EOP solutions cause false oscillations and steps. Hence, it is necessary to homogenize the data prior to the combination by removing

- biases and trends (determined from epochs containing all input solutions),
- long periodic variations in the GPS and SLR data.

The daily values of EOP were derived over the interval of 275 days between MJD 49724 and 49999. Dispersion of station coordinates decreased after the adjustment from 0.050 m to 0.024 m when VLBI and GPS were combined, and from 0.047 m to 0.029 m for combination of VLBI, GPS and SLR.

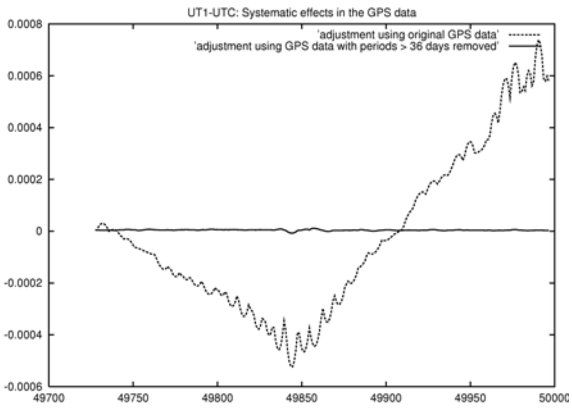

Fig. 1

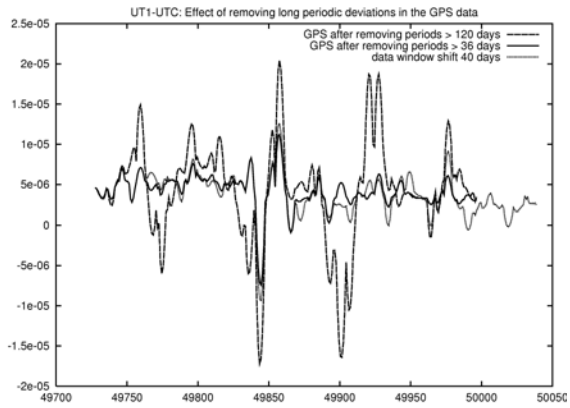

Fig. 2

Systematic deviations in the GPS data cause false quasi-periodic oscillations between VLBI epochs, to which GPS data are fitted as seen in Fig. 1. These false oscillations remain even when the condition equations are introduced to tie the solution to VLBI time corrections (dotted line). They disappeared after removing biases and long periodic terms from the GPS data (full line). (Displayed are in seconds, the increments to the adopted approximate values, as obtained from the adjustment).

The result of the combination gets the more stable the shorter periods are removed from the GPS data – see Fig. 2. To check stability of the solution, the data window was shifted by 40 days (dotted line).

Acknowledgement

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Electromagnetic Core-Mantle Coupling

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Introduction

We discuss electromagnetic core-mantle coupling computations at decadal and diurnal time-scales. This coupling mechanism can lead to decadal length of day variations and can also influence certain nutations to an observable level. If electromagnetic coupling is the only important coupling between core and mantle, insight into physical properties of Earth's deep interior can be provided.

Electromagnetic core-mantle coupling at decadal time scale

The torque of the core on the mantle generated by the Lorentz force in the mantle is (Holme, 1998):

$$\vec{\Gamma} = \int_M \vec{r} \times (\vec{j} \times \vec{B}) dV,$$

where the integral is over the volume of the mantle, $\vec{B}$ is the magnetic field and $\vec{j}$ is the current given by Ampère's law:

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{j},$$

where μ_0 is the magnetic permeability of the vacuum. Applying the divergence theorem, the z-component of the electromagnetic torque can be converted to a surface integral over the radius of the core-mantle boundary:

$$\Gamma_z = \frac{r_{CMB}}{\mu_0} \oint_{CMB} B_\phi B_r \sin\theta \, dS$$

where B_r and B_ϕ are the radial and longitudinal components of the magnetic field. The radial component B_r is purely poloidal whereas the longitudinal component B_ϕ has both toroidal and poloidal components. If the mantle is insulating, the radial magnetic field in the mantle can be computed by downward continuation of the measured field at the surface of the Earth. The above torque can be decomposed into a poloidal, an advective and a leakage torque. The poloidal torque is associated with the poloidal magnetic field. Given a time-dependent model of the geomagnetic field and of the mantle conductivity, the poloidal torque can be computed directly (Stix and Roberts, 1984). The advective torque is induced by the advection of the radial magnetic field; assumptions on the velocity field are necessary to compute it. The leakage torque is associated with the diffusion of the magnetic field at the top of the core, it cannot be determined from surface magnetic field measurements. Often, the leakage torque is considered to be unimportant on decadal time scales (Jault and Le Mouël, 1991), (see however Van Hoolst et al., this volume). The flow inducing the advective electromagnetic torque cannot be determined uniquely from the observations and further assumptions concerning the flow are necessary. Since the electromagnetic coupling can therefore not be accurately determined, Holme (1998) looked for flows consistent with the secular variation of the magnetic field and producing an electromagnetic coupling that leads to the observed length-of-day (LOD) variations. To compute the core flow from the observed magnetic secular variation, the frozen-flux hypothesis (the advection of the magnetic field dominates its diffusion) and the radial component of the diffusionless induction equation are used:

$$\frac{\partial B_r}{\partial t} + \nabla_H \cdot (B_r \vec{u}) = 0.$$

This equation contains two unknowns: the two horizontal components of the velocity field. Several approximations concerning the flow are used in the literature: steady flow / steady flow in a drifting frame (drift of the flow with respect to the mantle), toroidal flow and tangential geostrophic flow. The toroidal flow at the CMB has only a horizontal component which is assumed to be toroidal. The tangential geostrophic flow is governed by the balance between the (tangential components) of the Coriolis force and the pressure gradient at the core-mantle boundary. This assumption is most often used. To test these assumptions, the LOD observations are compared with the core angular momentum computed using these different assumptions for the flow. The figure shows the angular momentum predictions for three geostrophic flows (Jault et al., 1988; Jackson et al., 1993; Pais and Hulot, 2000) using different inversion parameters and a drifting flow (Holme and Whaler, 2001). From around 1920, the agreement between these curves is good but less good before this date (although the agreement for the drifting flow is perhaps slightly better than for the geostrophic flows).

The computations of the electromagnetic coupling have shown that an efficient electromagnetic torque between the core and mantle can exist only if a conductive layer of 10^8 S is present at the base of the mantle (Holme, 1998).

Electromagnetic core-mantle coupling at diurnal time scale

When no dissipative coupling is considered, discrepancies appear between the observed and modeled out of phase 18.6-year retrograde, annual and semi-annual prograde nutations. A dissipative torque such as the electromagnetic torque is necessary to remove these discrepancies. An electromagnetic interaction takes place between the fluid outer core and the mantle and between the solid inner core and the fluid outer core. At diurnal time scale, the relative motion of the outer core with respect to the mantle (resp. the inner core) is essentially a rigid body rotation (toroidal motion of order 1, degree 1). This nutation motion of the fluid core causes an advection of the magnetic

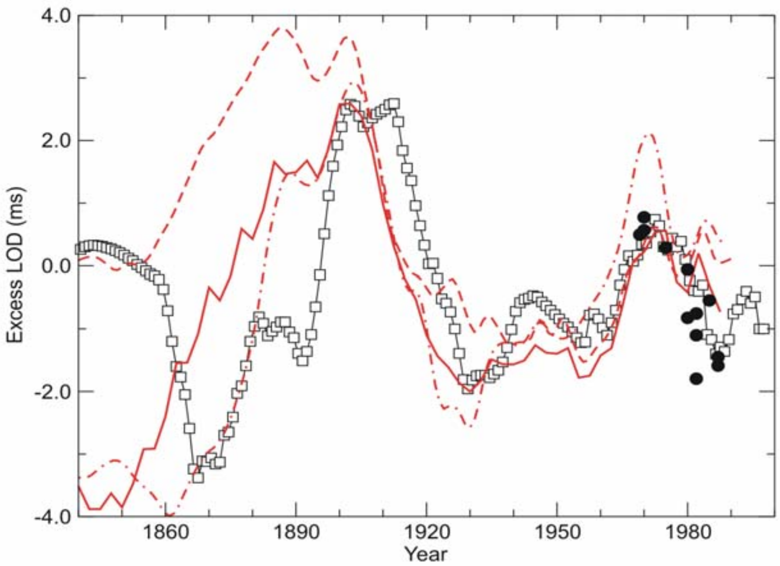

Fig. 1 Comparison of LOD observations (squares) with predictions from the tangential geostrophic flow obtained when using the inversion parameters of Pais and Hulot (2000) (dashed line), Jackson, Bloxham and Gubbins (1993) (solid line), Holme and Whaler (2001) (dot dashed line), Jault et al. (1988) (circles).

field at the CMB that induces a perturbation of the magnetic field. At first order, the electromagnetic torque associated to the Lorentz force can be expressed as (Rochester, 1960):

$$\vec{\Gamma} = \frac{1}{\mu} \int_S (\vec{r} \times \vec{b})(\vec{B} \cdot \vec{n}) dS$$

where $\vec{B}$ is the main magnetic field at the boundary, and $\vec{b}$ is the perturbation of the magnetic field associated to the advection of the main magnetic field by nutations. Using this expression, Buffett (2002) expresses the electromagnetic torque as a function of coupling constants and the differential rotation of the core with respect to the mantle. Mathews et al. (2002) compute the equatorial angular momentum budget of the Earth considering the electromagnetic coupling at the CMB and ICB. The coupling constants, which depend on the conductivities of the lower mantle, the inner core, the fluid outer core and the amplitude of the magnetic field at the outer core boundaries, are evaluated through the adjustment of a set of parameters to VLBI nutation amplitude observations so that the theoretical amplitudes of the nutations agree with the observed amplitudes. Assuming that the electromagnetic torque is the only one acting on nutations, it results (Buffett, 2002) that the conductivity of the lower mantle must be 5 10^5 Sm^{-1} over a 200 m thick layer, the magnetic field at the CMB has a radial dipolar component of 4.6 gauss and a ”uniform” component so that the radial field at the CMB has an amplitude of 6.9 gauss, and the radial magnetic field at the ICB is 72 gauss. Note that the conductance of the lower mantle provided by these two studies is consistent (10^8 S).

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Environmental Loadings: Effects on Height and Gravity

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Introduction

The Department of Physics of the University of Bologna has started to install during mid 1996 a permanent GPS network in order to study vertical crustal motions in the southeastern Po Plain and along the northern border of the Adriatic plate. At present, four permanent GPS stations (CGPS) are operational at Medicina, Bologna, Porto Corsini and Trieste. Time series of daily solutions are analyzed to provide significant information on both long and short-period height variations. Seasonal fluctuations were identified and interpreted. The removal of the seasonal oscillations allows the reliable estimate of long-term linear trends.

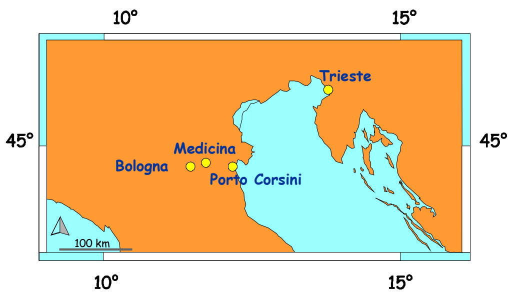

Fig. 1 Location of the CGPS and gravity stations

Independently from space geodetic techniques, another way to constrain vertical deformation is to use precise gravity measurements with cryogenic relative gravimeters and ballistic absolute gravimeters. The presently available accuracy enables to determine vertical changes in the sub-centimetric range corresponding to what can be achieved nowadays with precise vertical positioning. At Medicina, in addition to the GPS receiver, a superconducting gravimeter belonging to the Bundesamt für Kartographie und Geodäsie (Frankfurt am Main, Germany) is also operational since mid 1996. The continuous gravity series allows the study of ground deformation and signals related to global/regional processes and local environmental effects. A marked seasonal oscillation, becoming quite recognizable towards the end of 1997, is present both in the GPS and gravity data series. The observed oscillations have been interpreted and modeled as the sum of various environmental loadings for the height and gravity series and the Newtonian attraction components for gravity alone. In particular, atmospheric, hydrological and oceanic effects have been estimated. Thermal expansion of the structures supporting the GPS antennas has been also modeled. In the case of the Medicina station, also the settlement due to soil consolidation has been modeled.

CGPS data

Daily ellipsoidal coordinates of the reference benchmarks are derived by means of the Bernese software package version 4.2 with the adoption of IGS orbits, coordinates and velocities of five fiducial IGS stations in the region. The station coordinates are computed in the ITRF2000. A detailed description of the analysis procedure is given by Zerbini et al. (2001, 2002).

The series are characterized by a clear seasonal signal, which has been interpreted as the sum of different loading effects. The loadings induced by atmospheric pressure variations, local hydrology and non-tidal oceanic effects have been estimated and modeled (Zerbini et al., 2001, 2002). Thermal expansion of the structures supporting the GPS antennas has been also estimated. Additionally, for Medicina, the soil consolidation effect has been computed as well (Romagnoli et al., 2002). The model provides a quite satisfactory representation of the observed seasonal signal by reproducing up to about 70% of the oscillation (Fig. 2).

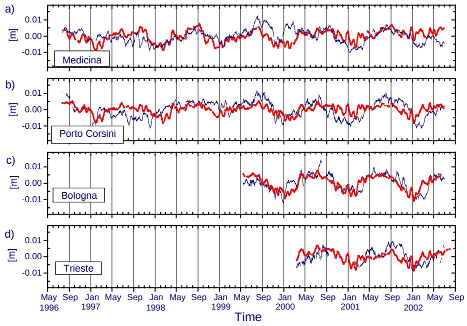

Fig. 2 Observed seasonal fluctuations in the CGPS height series (solid line) and relevant models (dotted line)

After removing the modeled seasonal oscillation, the linear trends were estimated. All the series are characterized by negative linear trends of different magnitude: Porto Corsini (–10.73±0.09 mm/yr) and Bologna (–18.44±0.23 mm/yr), in particular, exhibit considerable subsidence rates mainly of anthropogenic origin. Medicina (–1.56±0.08 mm/yr) and Trieste (–4.77±0.46 mm/yr) show moderate subsidence rates.

Gravity data

At Medicina, the superconducting gravimeter is installed in a temperature-controlled laboratory on a concrete pier, founded 1 meter deep into the ground. The 10-second sampled gravity data, filtered to 1-minute data are analyzed by means of the ETERNA, version 3.30, software package. After subtracting the Earth's and ocean tides and polar motion, the long-term stability of the absolute gravity measurements performed with AXIS FG5 absolute gravimeters is the basis to estimate the superconducting gravimeter drift and to remove the offsets between data blocks. Details on the data analysis procedure can be found in Zerbini et al. (2001, 2002).

The series of gravity values is characterized, as well as the CGPS heights, by a marked seasonal signal, which becomes quite clear after mid 1997. The gravity variations induced by loading and mass effects due to temporal changes in the geographical redistribution of atmospheric and hydrologic masses have been estimated and modeled (Zerbini et al., 2002). The seasonal settlement due to soil consolidation has been also estimated.

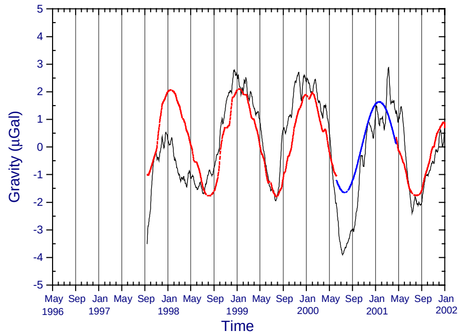

Fig. 3 Observed seasonal fluctuations in the gravity series (solid line) at Medicina and relevant model (dotted line)

The modeled seasonal variations reproduce quite well the observed seasonal signal in the gravity residuals. There are two periods during which the model fits the observed data less satisfactorily, namely the period end of 1997-mid 1998 and in mid 2000. In the first case, part of the difference is attributable to the magnitude of the long-term trend subtracted from the data, which in the initial period is considerably higher. An additional source of difference comes, most likely, from the non-tidal ocean modeling adopted. A preliminary analysis of bottom pressure data in the Northern Adriatic suggests that this model should be improved by accounting for a higher temporal variability of the ocean. After removing the modeled seasonal oscillation, a linear trend of +1.12±0.02 µGal/yr has been estimated.

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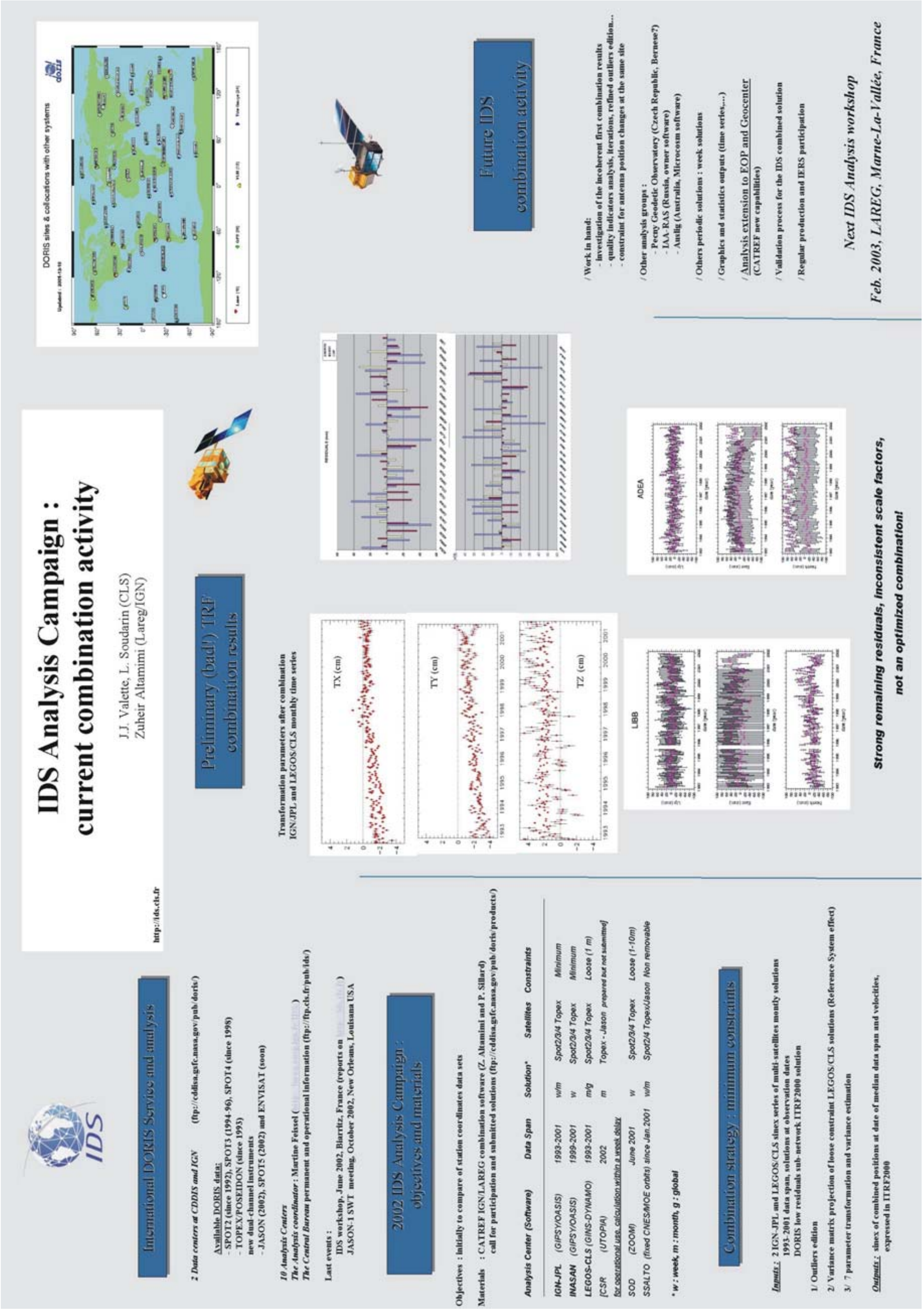
Zerbini S., M. Negusini, C. Romagnoli, F. Domenichini, B. Richter, D. Simon, 2002, Multi-parameter continuous observations to detect ground deformation and to study environmental variability impacts, Global and Planetary Change, 34, Nos. 1–2, 37–58.

IDS Analysis Campaign: current combination activity

J. J. Valette, L. Soudarin (CLS), Zuheir Altamimi (Lareg/IGN)



Recommendations and Action Items

Conventions

CON 1: ACs are encouraged to establish and document conventional procedures and software used to prepare the Technique Center products.
TCs should identify the conventions used by the TC and the dependence of each TC product on the adopted coordinate system conventions, models and software.

CON 2: Conventions Center together with the IERS Analysis Coordinator determine the relative importance of the component conventions to the final IERS combined solution.

CON 3: The IERS Analysis Coordinator and the Conventions Center should clarify which effects should be handled in the internal data reductions of the individual techniques (e.g., tropospheric modelling) and which should be handled a posteriori at the combination level.

CON 4: It is recommended that ACs either implement the new procedure for the transformation between the celestial and terrestrial reference frame or use the classical transformation updated with the IAU 2000 precession / nutation model to represent the position of the Celestial Intermediate Pole in the International Celestial Reference System.

CON 5: All IERS components (TCs, PCs, ...) are urged to implement the IAU 2000 Resolutions as soon as possible.

ICRF

ICRF 1: The IVS ACs are requested to generate coordinate time series for well observed sources to study the stability of radio source coordinates.

ICRF 2: For the maintenance of the ICRF the IVS is requested to secure future observation of the sources found to be stable over 1990–2002.
Observe regularly the sources used for the tie of the optical CRFs (Hipparcos, …).
Continue to extend the southern hemisphere coverage.

ICRF 3: Based on study results, the ICRS Centre & IVS should prepare a brief report for the IERS on how best to maintain the ICRF in the future together with the IAU working group.

ICRF 4: The IVS & CRCs should begin to study how best to form CRF combined solutions and to use these with results from other techniques.

EOP Combinations

EOP 1: A better interaction is required between the TCs and the IERS PCs.

EOP 2: The IERS GGFC SBA is encouraged to provide AAM in near real-time.

EOP Alignement Campaign

ALIGN 1: Create new database with comparable EOP series; reformatting of all series, resample, interpolation (until end of the year 2002).

ALIGN 2: Analysis of OFFSETs + DRIFTs in X_{pol}, Y_{pol}; find relations to the ITRF realization.

ALIGN 3: Develop strategies to combine / compare UT1 and LOD of satellite techniques with VLBI.

ALIGN 4: Final results until end of February 2003.

ALIGN 5: Conclusion and presentation at EGS General Assembly, April 2003.

Technique Centers

IGS

IGS 1: The IGS needs to improve the tracking of equipment changes at GPS stations, especially changes that affect apparent station height. Rigid recommendations are needed for how to accomplish such changes with minimal impact. Particular attention needs to be paid to antenna-related effects and the use / change of radomes. Improved methods for handling the effects of non-ideal GPS satellite and receiver antenna patterns are needed.

IGS 2: The IGS should study the inclusion of LEO satellites into their global solutions in order to help improving the geocentre estimates.

IGS 3: The IGS is encouraged to provide nutation rates series.

ILRS

ILRS 1: The ILRS is encouraged to investigate refinements of the SLR origin to reduce small, but still existing, discrepancies between the ACs and in particular in the Z component and its correlation with the SLR TRF scale.

ILRS 2: The ILRS is encouraged to recommend the installation of GPS receivers at all operational SLR sites.

IVS

IVS 1: The IVS is asked to schedule repeated global ITRF observing sessions with the largest possible number of stations.

IVS 2: It is also highly desirable to develop the capability of observing Earth-orbiting satellites with VLBI.

IVS 3: The IVS is asked to account for mechanical, gravitational, and thermal deformations of the VLBI antennas in results for station coordinates.

IVS 4: There should be redundancy for the future realisation of the ICRS.

IVS 5: ACs are encouraged to analyse past and future VLBI data using the IAU re-commended procedure for the transformation between the celestial and terrestrial reference frames.

IVS 6: ACs are encouraged to implement global CRF-EOP-TRF solutions from the best data (1990 onwards), with appropriate treatment for unstable sources and stations with non-linear motion when necessary.

IDS

IDS 1: The IDS is asked to consider installing DORIS beacons at SLR and near VLBI sites, starting with sites collocated with GPS in order to augment the number / distribution of 4-technique “primary” sites.

Combined Efforts

COME 1: The IVS, IGS and IDS are encouraged to refine / investigate their various modelling, such as the troposphere and antenna-related effects in order to improve the TRF scale consistency.

COME 2: The ILRS, IDS & IVS should begin to produce combined EOP + TRF solutions using SINEX-2.00.

GGFC / CRCs

GGFC 1: The GGFC should begin to distribute estimates of the time-varying local station displacements due to global fluid changes based on all known effects. Ideally, the results should be made available in a timely way to facilitate use with space geodetic results.

GGFC 2: The GGFC and CRCs need to consider how the joint use of geodetic & geophysical information can be done efficiently and effectively.
A report with recommendations is requested.

Rigorous Combination

The IERS aims at a rigorous combination of ITRF/EOPs/ICRF to produce a fully consistent set of products. After thorough and successful tests these combination products will complement / replace the existing products.

RICOM 1: Development of optimal methods for a consistent combination of ITRF, EOPs and ICRF (SINEX combination campaign, CRCs, others?).

RICOM 2: The IERS PCs should begin to distribute rigorously combined EOP + TRF products, at least in test / evaluation mode.

RICOM 3: The IERS CRCs should critically evaluate the utility of single multi-technique solutions at the observation level (by FFI and others) as a realistic alternative to SINEX combinations.
The results should be documented and reported to the IERS.

RICOM 4: New concepts for TRF combinations concerning non-linear site motions should be developed (e.g. ITRS Center, ITRS CCs, CRCs).

RICOM 5: Study the existing effects (biases) between different solutions / techniques and understand their origin (e.g. IERS PCs, ITRS CCs, ACs, CRCs).

RICOM 6: The TCs are encouraged to provide a unique solution for ITRF coordinates, EOP and ICRF to be combined with the results of other TCs.

RICOM 7: ACs should submit unconstrained normal equations, or solutions with ALL constraints properly reported.

IERS SINEX Combination Campaign

A.I.	Description / Task	Who?	Deadline
1	E-Mail exploder <crc_forum@iers.org> should be used for communications	All participants	ASAP
2	Validation of individual SINEX files regarding format, parameterisation, constraints, rank deficiencies, etc. Generate validation report, feedback to ACs Resubmission of corrected SINEX files (if necessary)	Different groups for different techniques? AC	15.01.2003 ASAP
3	Form concerning modelling and parameterisation Distribution of form to ACs All ACs should return this form to IERS AC	IERS AC ACs	30.11.2002 20.12.2002
4	Consistent modelling and parameterisation define common standards Submission of updated series	IERS AC All ACs	31.01.2003 28.02.2003
5	Scientific studies / combinations: Presentation of first results at the EGS-AGU meeting in Nice	CRCs + others	April 2003

Interaction Between IERS PCs, ITRS CCs, TCs and WGs

INTER 1: The ITRS PCs, ITRS CCs, WG on ITRF Datum and WG on Site Co-location are asked to set up selection criteria and to propose a list of TRF core sites. These sites should be of high geodetic quality so that they can be used in the definition of TRF datum orientation and its time evolution.

INTER 2: The TCs (IVS, ILRS, IGS, IDS) through their respective ACs, CRCs, ITRS CCs and other groups dealing with time series combination are encouraged to investigate non-linear motions of space geodesy observing sites starting with TRF core sites. ACs are urged to adopt a unique list of epochs or events with coordinate discontinuities. The ITRS CCs and TCs are also asked to ensure consistency of epochs in the co-location sites.

Working Group on Site Co-location (WGSC)

The Working Group on Site Co-location (WGSC) should be established by the IERS DB and integrated into the IERS structure (charter, members). The WGSC will work cordially in cooperation with IAG and other IAG WGs. It should involve all the Technique Centres and representatives from potential agencies willing to contribute to this issue.

WGSC 1: The WGSC is asked to evaluate the number and distribution of inter-technique co-location sites, as well as problems with ties.

WGSC 2: The WGSC is asked to organize repeated local surveys at the co-location sites.

WGSC 3: Per-site local tie components (at the survey epoch) and their time variations should be provided in SINEX format with full variance-covariance matrix.

WGSC 4: The WGSC should make specific recommendations designed to improve the global reference system.

WGSC 5: The situation concerning co-location sites and local ties needs urgently to be improved (e.g. IERS, TC, CSTG, subcommission ISGN + others)

WGSC 6: In order to improve co-location site distribution and observing networks an international effort is needed to improve VLBI-SLR co-locations by installing new SLR systems (e.g. SLR2000) at VLBI sites. These are very critical for the long term TRF scale maintenance.

Working Group on the ITRF Datum (WGID)

The Working Group on the ITRF Datum (WGID) should be "integrated" into the IERS structure with an updated charter and member list.

WGID 1: The IERS Working Group on the ITRF Datum is asked to work with the Technique Centres to clarify the current quality of geocentre results and to report recommendations on future geocentre combinations and products.

Special Bureau for the Atmosphere

SBA 1: Explore atmospheric data from more data sources, especially new reanalyses are needed (e.g. higher vertical extent and higher temporal resolution).

SBA 2: Create combined atmospheric data sets. Problem: errors in atmospheric excitations are not known, so it is difficult to create optimal solution.

SBA 3: Understand the relationship between the torque and angular momentum approach.

SBA 3: Explore new formulations and constants for excitation terms.

SBA 4: Model link with oceans should be improved.

SBA 5: Atmospheric mass terms: recalculation based on more accurate coordinate approach and gravity field
- for earth rotation/polar motion
- for loading
- for gravity missions

SBA 6: Assess forecasts as well as analyses of atmospheric forecasts of AAM.

SBA 7: Relationship of AAM to climate and weather signature:
- El Nino/Southern Oscillation
- North Atlantic Oscillation
- Moving weather systems over continents
- Understanding the atmosphere with AAM as a diagnostic: model intercomparison projects, century-long simulations and projections.

SBA 8: Other needs of atmosphere in geodetic missions. Can we help?

General Discussion

GEN 1: **Rigorous Combination**: The IERS aims at a rigorous combination of ITRF/EOPs/ICRF to produce a fully consistent set of products. After thorough and successful tests these combination products should replace/complement the existing products.

GEN 2: **Interactions** between GGFC and IERS PCs, CRCs and TCs:

- What would PCs, TCs, CRCs, like to have from GGFC? (e.g. SBs provide "best" estimates of seasonal terms of degree 1 for geocentre motion).
- What would GGFCs like to have from PCs?
- Contributions of GGFCs, PCs, TCs to conventions, consistency of conventions (GGFC work with Convention Centre by recommending new geophysical models or improvements to existing models for inclusion in future versions of the IERS Conventions.)

GEN 3: **Role of altimetry** in the IERS.

GEN 4: **Role of IERS** in new satellite missions, mission-independent source for GGFs ?

GEN 5: **All IERS components** should be proactive in promoting IERS products and GGF sciences to wider scientific community as well as to public.

GEN 6: **General goals of IGGOS:**

- IGGOS brings different techniques, different models, different approaches together, in order to achieve a better understanding of geodetic, geophysical, geodynamical processes.
- IGGOS provides geodesy's contribution (products and discoveries) to Earth sciences.
- IGGOS integrates the three pillars of geodesy – *geometry and kinematics*, *Earth orientation and rotation*, and *gravity field and dynamics* – to achieve maximum benefit for the scientific community and society in general.
- IGGOS aims at ensuring the stability and ready access to the geometric and gravimetric reference frames by establishing uninterrupted time series of state-of-the-art global observations related to the three pillars of geodesy.
- IGGOS views the Earth system as a whole by including the solid Earth as well as the fluid components, the static and time-varying gravity field in its products.

Annex 1 Programme of the Workshop

MONDAY – NOVEMBER 18:

08:00 – 09:00 Registration
09:00 – 09:30 Welcome and general remarks
09:30 – 10:00 Introduction (Rothacher)
10:00 – 10:30 *Break*

Combination Strategies and Issues for TRF / CRF / EOPs:

10:30 – 12:00 ***Part 1**:* Combination of station coordinates, velocities, local ties, datum definition, non-linear motion (Altamimi / Boucher / Drewes / Ferland)

- 10:30 Position Paper (Z. Altamimi, IGN)
- 10:50 ITRF WG status/views (K. Larson, Colorado Univ., presented by J. Ray)
- 11:00 ITRS Center status/views (C. Boucher, IGN, presented by Z. Altamimi)
- 11:10 Remarks on some general problems in the combination of station coordinate and velocity solutions (H. Drewes, DGFI)
- 11:20 TRF combination at NRCan; Status report (R. Ferland, NRC)
- 11:30 Discussion

12:00 – 13:30 *Lunch*

13:30 – 14:20 ***Part 2**:* Celestial reference frame issues (Souchay / Ma)

- 13:30 Introduction on the Position paper (J. Souchay)
- 13:40 The status of the ICRF (C. Ma)
- 13:55 Internal consistency of the celestial reference frame based on time stability (M. Feissel-Vernier)
- 14:10 Discussion

14:20 – 15:50 ***Part 3**:* Combination / comparison of EOPs (xp, yp, UT1/LOD, nutation), subdaily EOPs, impact of IAU Resolutions (Gambis / Vondrak)

- 14:20 Position Paper (D. Gambis, J. Vondrak)
  EOP Combinations:
- 14:35 D. Gambis, Earth Orientation Center
- 14:50 T. Johnson, Rapid Service/Prediction Center
- 15:05 R. Gross, JPL
- 15:15 J. Vondrak, AICAS
- 15:25 Discussion

15:50 – 16:15 *Break*

16:15 – 17:30 ***Part 4**:* EOP Alignment Campaign, IGS / IVS / ILRS combinations, systematic errors (Nothnagel / Dill)

- 16:15 Introduction to session (A. Nothnagel, R. Dill)
- 16:20 Comparisons of IGS EOP series contributed to IERS Alignment Campaign (R. Ferland)
- 16:35 EOP Combination within IVS: Status and Problems (A. Nothnagel and C. Steinforth)
- 16:50 Comparison of EOP series from the IERS analysis campaign to align EOPs to the ITRF2000/ICRF (R. Dill)
- 17:05 Evolution of consistency between EOP series and reference frames (D. Gambis, C. Bizouard, T. Carlucci)
- 17:20 Discussion

TUESDAY – NOVEMBER 19:

Issues of a Rigorous Combination (Coordinates + EOPs (+ CRF), and Other Parameter Types):

09:00 – 10:00 *Part 1:* Conventions and models for a rigorous combination, consistency aspects, systematic errors (McCarthy / Petit)

09:00 Status and Future of the IERS Conventions (D.D. McCarthy, G. Petit)
09:15 Impact of IAU Resolutions on EOPs (N. Capitaine)
09:35 Discussion

10:00 – 10:30 *Break*

10:30 – 12:00 *Part 2:* Aspects of a rigorous combination, combination of several parameter types, different combination levels (Ray / Zhu)

10:30 Position Paper and discussion (Jim Ray, NGS)
11:00 Combination of multi-satellite techniques at the observation level (Sheng-Yuan Zhu, GFZ)
11:15 Program and first results at GRGS in the framework of CRC (Richard Biancale, GRGS)
11:30 Systematic differences in individiual solutions and IERS products (Zinovy Malkin, IAA)
11:45 Numerical aspects of combination at the observation equation and normal equation level (Michael Gerstl, DGFI)

Lunch

13:30 – 15:30 *Part 3:* SINEX Combination Campaign (Angermann / Thaller / Rothacher)

13:30 Presentation of Position Paper (D. Angermann, D. Thaller)
14:00 Multi-technique combination of time series of station positions and Earth orientation parameters (Z. Altamimi, C. Boucher)
14:15 Combination of loosely constrained solutions (G. Bianco, R. Devoti, V. Luceri)
14:30 First Results at NRCan for the IERS SINEX Combination Campaign (R. Ferland)
14:45 Rang defect analysis and variance component estimation for inter-technique combination (R. Kelm)
15:00 Discussion

15:30 – 16:00 *Break*

16:00 – 17:30 Final discussions / conclusions

WEDNESDAY – NOVEMBER 20:

08:30 – 09:15 GGFC overview (Chao)

09:15 – 10:45 Special Bureau for the Atmosphere (Salstein)

09:15	Update of the SBA (D. Salstein)
09:30	Atmospheric loading effects on Earth's time-variable gravity (J.-P. Boy and B.F. Chao*)
09:45	Reliability of atmospheric torque for geodesy (O. de Viron* and V. Dehant)
10:00	Atmospheric excitations of the Chandler wobble estimated from ECMWF reanalysis datasets (I. Naito, Y. Aoyama*, T. Iwabuchi and N. Yamazaki)
10:15	Time variable atmospheric and oceanic signals in excitation functions of polar motion (J. Nastula*, D. Salstein, and B. Kolaczek)
10:30	Discussion

10:45 – 11:15 *Break*

11:15 – 12:30 Special Bureau for the Oceans (Gross)

11:15	Comparison of Oceanographic Signals with SLR-Derived Gravity Observations (C. Cox* and B.F. Chao)
11:30	Oceanic Excitation of Polar Motion and Nutation: An Overview (A. Brzezinski)
11:45	Possible Role of Oceans in Variations of Length-of-Day at High Frequencies (T. Johnson)
12:00	The IERS Special Bureau for the Oceans: Past Progress and Future Plans (R. Gross)
12:15	Discussion

12:30 – 13:45 *Lunch*

13:45 – 15:00 Special Bureau for Hydrology (Wilson)

13:45	SBH goals and the SBH Website (C.R. Wilson)
13:55	New directions and capabilities in hydrologic land surface models (M. Rodell via C.R. Wilson*)
14:05	Future plans for satellite remote sensing capabilities of the hydrologic cycle (D.E. Alsdorf via C.R. Wilson*)
14:15	Using space geodesy to constrain global loads (P. Clarke)
14:30	Recent hydrology studies at GSFC (B.F. Chao* and A.Y. Au)
14:45	Discussion

15:00 – 16:15 Special Bureau for Gravity / Geocentre (Watkins / Gruber)

15:00	SBGG status and prospects (M. Watkins via T. Gruber*)
15:15	Using future observations for time-variable gravity work (T. Gruber)
15:30	Recent SLR results (C. Cox* and B.F. Chao)
15:45	Short-time atmosphere and ocean de-aliasing for GRACE (F. Flechtner)
16:00	Discussion

16:15 – 16:45 *Break*

16:45 – 18:00 Special Bureau for Tides (Richard Ray)

16:45	Overview of SBT, issues and plans (R. Ray)
17:15	Recent work on theoretical modeling of nutation (J.M. Ferrandiz Leal)
17:30	Oceanic tidal torque on the solid earth (O. de Viron*, J.-P. Boy)
17:45	Discussion

THURSDAY – NOVEMBER 21:

08:45 – 10:00 Special Bureau for Mantle (Chao)

- 08:45 SB Mantle status and plan (B.F. Chao)
- 09:00 On the secular drift component of global Earth deformation (E. Ivins)
- 09:15 Co-seismic Excitation of Earth Rotational and Gravitational Changes (B.F. Chao* and R. Gross)
- 09:30 Geophysical Inverse Solutions Using Long-Term SLR-Derived Gravity Rates (C. Cox* and B.F. Chao)
- 09:45 Discussion

10:00 – 10:30 *Break*

10:30 – 11:50 Special Bureau for the Core (Van Hoolst)

- 10:30 SBC overview (T. Van Hoolst)
- 10:50 Core mantle interactions (V. Dehant*, D. Jault, S. Ponsar, T. Van Hoolst)
- 11:10 Geodynamo modeling, core-mantle interactions, and Earth rotation variations (W. Kuang)
- 11:30 Discussion

11:50 – 13:00 *Lunch*

13:00 – 14:15 Special Bureau for Loading (Van Dam / Plag)

- 13:00 SBL Introduction (T. van Dam)
- 13:05 Status of loading predictions (Earth Model, Model Surface Loads, Theory, Numerical Tools) (P. Gegout)
- 13:25 Products of the SBL (Predictions, Research Products, Operational Products (H.-P. Plag)
- 13:40 Validation of loading predictions (Intercomparison, comparison with observations) (T. van Dam)
- 14:00 Discussion

14:15 – 15:00 Poster summary, remaining scientific discussions

15:00 – 15:30 *Break*

15:30 – 17:00 Interactions and support (various, all) IERS Product Centres – GGFC, CRC-GGFC (Chao / Rothacher / Zhu)

Annex 2 List of Posters

Angermann, D., Meisel, B., Krügel, M., Müller, H., Tesmer, V.:
Analysis of VLBI, SLR, GPS and DORIS Site Position Time Series.

Boehm, J.:
IVS Pilot Project – Tropospheric Parameters.

Bougeard M., Gambis, D., Carlucci, T.:
Robust M-fit algorithms and EOP combination procedures.

Carlucci, T., Gambis, D., Bizouard, C., Francou, G.:
Comparative Study of EOP Series Derived for the IERS Alignment Campaign.

Gambis, D., Carlucci, T.:
Study of the long-term stability of IERS C04 with respect to the various techniques.

Gennero, M.-C., Cazenave, A.:
A global geofluids data base for hydrology and oceanography studies.

Hugentobler, U., Schaer, S., Beutler, G.:
Retrieving Free Solutions on the Basis of Constrained SINEX Results.

Jean-Alexis, D., Gambis, D., Francou, G.:
Combined EOP series derived from intra-technique solutions.

Lambert, S.:
Time variable cyclic processes in the polar motion excitation.

Devoti, R., Luceri, V., Bianco, G.:
Combination activities at the Matera Space Geodesy Centre, Italy.

Ma C. and Petrov, L.:
SINEX File Implementation in the VLBI Calc/Solve Analysis System.

Malkin, Z.:
IAA Combination Research Center activity in 2002.

Malkin, Z.:
IERS products from user's point of view.

Messerer, E., Boehm, J., Schuh, H.:
Comparison and combination of the EOP submitted to the IERS Alignment Campaign 2002.

Nurutdinov, K.:
Combination of terrestrial reference frames and ERP at University of Newcastle.

Pavlis, C.:
Temporal Gravitational Variations of the TRF and the SLR Contribution to IERS EOP series.

Pavlis, C.:
EOP from laser ranging to the LAGEOS and ETALON satellites.

Kostelecky, J., Pesek, I.:
Determination of station coordinates and EOP from combination of different techniques.

Ponsar, S., Dehant, V., Van Hoolst, T.:
Electromagnetic core mantle coupling.

Titov, O.:
Geoscience Australia – ICRF and ITRF solutions.

Valette, J.-J., Soudarin, L., Altamimi, Z.:
IDS analysis campaign: current combination activities.

Zerbini, S., Romagnoli, C., Lago, L., Richter, B., Simon, D.:
Environmental loadings: effects on height and gravity.

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