Combination Strategies and Issues for TRF / CRF / EOPs

Part 3: Combination / comparison of EOPs (xp, yp, UT1/LOD, nutation), subdaily EOPs, impact of IAU Resolutions

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Summary: *The objective of the session is 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).*

1 IMPACT OF IAU 2000 RESOLUTIONS ON EOP

The impact of IAU 2000 Resolutions on all IERS Products was thoroughly discussed at the preceding 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). Here we shall mention only those that concern the Earth Orientation Parameters (EOP).

1.1 The changes in the EOP

Probably the most affected products of the IERS will be the EOP, published in different form by the following Product Centres (PC):

- EOP PC;
- Rapid Service and Prediction PC.

The most important changes are those introduced by IAU Resolutions B1.6 (IAU 2000 Precession-Nutation Model), B1.7 (Definition of Celestial Intermediate Pole) and B1.8 (Definition and Use of Celestial and Terrestrial Ephemeris Origins), the resolution B1.6 having the dominant role. Although it is not directly mentioned in the Resolutions, the new precession-nutation model is accompanied by a new formulation for the transformation between the celestial (*CRS*) and terrestrial (*TRS*) reference systems, in the form (McCarthy et al. 2002):

$$[CRS] = Q(t) \cdot R_3(-\theta) \cdot W(t) \cdot [TRS],$$

in which $Q(t)$, $R_3(-\theta)$ and $W(t)$ are time-dependent transformation matrices to account for the precession-nutation, proper rotation of the Earth about the axis corresponding to CIP and polar motion, respectively:

$$Q(t) = \begin{pmatrix} 1 - aX^2 & -aXY & X \\ -aXY & 1 - aY^2 & Y \\ -X & -Y & 1 - a(X^2 + Y^2) \end{pmatrix} \cdot R_3(s), \quad a = \tfrac{1}{2} + \tfrac{1}{8}(X^2 + Y^2)$$

$W(t) = R_3(-s') \cdot R_2(x) \cdot R_1(y)$.

Stellar angle (or Earth rotation angle) is given in terms of UT1 by a simple linear relation

$$\theta(T_u) = 2\pi(0.7790572732\ 640 + 1.0027378119\ 1135448\ T_u),$$

where T_u = JD(UT1) − 2451545 .0 .

Here X, Y, s and x, y, s' describe the position of the Celestial Intermediate Pole (CIP) and the Celestial/Terrestrial Ephemeris Origins (CEO, TEO) in the Geocentric Celestial Reference System (GCRS) and International Terrestrial Reference System (ITRS), respectively. The novelty are the quantities X, Y, s whose developments into Poisson series, based on the IAU 2000A precession-nutation model, are published by Capitaine et al. (2002).

Celestial pole offsets

Precession-nutation is referred to CIP that exhibits, by definition, only long-periodic motions (i.e., with periods of two days and longer) in space. Now the IERS is obliged to publish the celestial pole offsets referred to the new model IAU 2000. This is possible to achieve, in principle, in two different ways:

- either using the classical precession-nutation angles, i.e., the celestial pole offsets in longitude and obliquity $\delta\Delta\psi, \delta\Delta\varepsilon$ respectively, referred to the new model;
- or switching to the new formalism, using the offsets from the celestial coordinates of the CIP, i.e. X, Y, s .

In order to clearly distinguish between the old and new system, the IERS chose the second possibility, by intending to publish the values *X, Y* (calculated from the new model) and the offsets from the model *dX, dY* (derived from the observations, mainly by VLBI). It is necessary to say that the latter values are very small at present (of the order of 0.2 mas), reflecting mostly the effect of the Free Core Nutation (FCN) that is not predictable and therefore not incorporated into the new model. Due to the smallness of these values, they are linked with the celestial pole offsets referred to the new precession-nutation model by simple relations $dX \cong d\psi \sin\varepsilon, dY \cong d\varepsilon$. The position of the CEO, given by *s*, is insensitive to any reasonable change of the precession-nutation model, so only its model values are to be published.

Parallel to these values, the values of 'classical' celestial pole offsets $\delta\Delta\psi, \delta\Delta\varepsilon$, referred to the old IAU 1976 precession and 1980 nutation model, will also be published after January 1, 2003, for the people who are not yet ready to switch to the new system. However, it is absolutely necessary to 'label' all IERS products so that it is clear which of the existing *a priori* precession-nutation models is used in which case.

Polar motion

Polar motion is much less affected by adopting the IAU 2000 resolutions. One should only stress that polar motion contains also (relatively small) diurnal and sub-diurnal parts, due to ocean tides and high-frequency nutation terms. These are *not* part of the polar motion values published by the IERS at daily intervals; they are represented by a model (see McCarthy et al. 2002, Chapters 5 and 8) and should be added after the interpolation. The position of the TEO, given by *s'*, depends on the actual polar motion but the value of *s'* is so small that a simple linear approximation (Lambert & Bizouard 2002) is sufficient:

$$s' = -47\,\mu as(t - 2000.0)/100 \; .$$

Universal Time

Again, the values UT1-UTC are affected only very little by the resolutions. Although the transformation is now different, and the Greenwich Sidereal Time is replaced by the Earth rotation angle, the definition of CEO (represented by s) and the linear relation between the Earth rotation angle θ and universal time UT1 are chosen to assure that there is no step in UT1 at the time of the change, i.e. January 1, 2003. There are short-periodic (diurnal, semi-diurnal) variations in UT1 due to ocean tides that are treated similarly to polar motion – the IERS publishes the daily values from which these terms have been removed, and they are to be added back after the interpolation.

2 General Combination of EOP series.

Introduction.

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) are under investigation. They might in future be used for EOP monitoring. Life time of observational techniques are limited (technology evolution, agencies funding priority, ..). Still, there is a need of long-term EOP monitoring for reference frames metrology and space geodesy on one hand and on the other for geophysical researches.

Another important need is the determination on a rapid turnaround basis of the Earth orientation for principally high-accuracy navigation and positioning, particularly in real-time and near real-time modes (Space probes, GPS orbits and reference frames monitoring, ..) and predictions for various purposes.

Moreover, the different Earth Orientation Parameters (EOP) series currently derived from the individual techniques are inhomogeneous in their temporal length, quality, 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, the various following points should be considered (the list is non-exhaustive): individual time series characteristics (temporal resolution, internal precision, internal stability at various time scales, systematic individual series corrections bias, rate, seasonal) statistical analysis (proper scaling of individual series, weighting, smoothing, interpolation), comparisons and checks of the final combined solution: with respect to individuals series and between combined series derived by independent centres.

What means combinations?

The word "combinations" covers different meanings:

1. Intra-technique combinations; different analysis centers of a same technique like GPS make available time series given for identical dates. We are faced with a weighted averaging. The critical points are the real error estimation of data, stability and systematic errors evaluation.

2. Multitechnique combinations. The process includes to deal with
   Various time resolutions
   Various internal precision
   Systematic errors/ deviations
   Weighting, interpolation , smoothing ..
   Operational/ long-term solution

3. "Rigorous" Global Combinations at different levels:
   Observations processing, Covariance matrices analysis
   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 session 2 on Tuesday.

Characteristics of ideal combined EOP solutions

- Continuous
- Given at equidistant intervals (1 day), no gap
- Homogeneous
- Stable (reference system maintenance)
- Best accuracy at the various time scales
- Negligible systematic errors, no jump
- Can be smoothed to remove the high-frequency noise
- In permanent evolution to take advantage of the re-computation of contributing series and
- the procedure improvement
- Ability to include new series, maintaining the stability of the system

Particularities of different techniques

Time series characteristics

- Time resolution (1d, 3d, 7d ..)
- Internal precision
- Stability at various time scales
- Systematic corrections (bias, rate, seasonal, ..)

Why do we need at least 3 independent techniques ?

- Complementary, none of the technique is able to derive all products
- Redundancy necessary, systematic errors, solution.

Contributions of the different techniques

(the number of * matches the relative contribution of techniques)

"PRODUCTS	LLR	VLBI	SLR	GPS	DORIS
Extragalactic ref. Frame		***			
Tie to solar system	***				
Tie to Earth					
Precession-nutation	**	***	*	*	
Universal Time	*	***			
Earth Rotation					
High-frequency UT		***	*	**	
Polar Motion		***	**	***	*
Terrestrial Reference Frame					
Network coverage		*	*	**	***
Long-term geocentre	*	***	**	*	
Tectonic plate motion		***	**	***	***
Densification		*	*	***	**
Reference Frame Propagation					
Tie of Space programs to the IERS System	***	***	***		

Main challenge to achieve

- Conservation of EOP system, the maintenance of the reference systems and its long-term stability
- Evaluation of systematic errors, biases, drift, seasonal .. The formal uncertainties estimated by the analysis centres being an internal consistency value, an external calibration has usually to be made in order to reflect the real uncertainty of the estimates.
- Methodology for weighting of the combined individual results : rms of individual series, Allan's variance, Helmert variance, ..
- Outliers detection in the course of the computations: 3 sigma criteria, M-Huber, ..

The different current methodologies for EOP combinations

- EOP-PC
- NEOS
- JPL
- AICAS

Statistical analysis

- Proper scaling
- Weighting
- Smoothing: Spline, Fourier, Vondrák (current and combined using both estimates and drifts)
- Interpolation
- Kalman filter

Current characteristics of EOP estimates, precision, accuracy

Precision gives an estimation of the agreement of various individual solutions with respect to combined solutions (EOP-PC, rapid service, JPL)

- Polar motion : 50-100 µas
- Universal Time: 4- 10 µs
- Nutation offsets: 200 µas

Accuracy reflects the real uncertainties of the solutions taking into account the in-consistency of the EOP system with respect to the terrestrial and celestial frames; inconsistencies, systematic errors, more critical than precision.

- Polar motion : 150-200 µas
- Universal Time: 15-20 µs
- Nutation offsets: 200 µas

- Temporal resolution 1 day and less (1 hour for VLBI, 2 hours for GPS)

Improvements

Use of other products

- Use of GPS LOD for near-real time UT1 extrapolation
- AAM estimates for near-real time UT estimation
- Pole rates for interpolation
- GPS nutation rates for nutation series densification

Predictions

Various methods:

Polar motion

- Modelling seasonal and Chandler
- Use of autoregressive method
- Kalman

Universal Time

- Modelling seasonal variations
- Use of autoregressive method

Improve predictions

based on non-linear (chaotic, SSA, neuronal) processes

Interest of initial intra-technique pre-combination

- What is available: Combined intra-technique combined solutions, IGS, IVS, Combined EOP-PC
- Study of systematic corrections
- Easiest final weighting of the inter-technique solution to compute the final multi-technique final EOP

Check and comparisons of the EOP combined solutions

- Internal consistency
- Difference between individual solutions and the combined solutions
- Difference between the different internally derived solutions (example: C02 andC04)
- Difference between independent solutions (EOP-PC, NEOS, JPL)

How performing more consistent and accurate products?

- General implementations of IERS conventions in the various packages
- Effect of network, station choice, sub-network effects
- Improve combination methodologies

3 The various EOP Combinations currently performed

3.1 Combination of EOP series at the IERS EOP Centre

General presentation of the IERS Earth Orientation Parameters (EOP), operational activities and yearly analyses are presented in the web site (http://hpiers.obspm.fr/eop-pc). 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 EOP-PC is collecting on two modes operational and yearly for long-term analyses, EOP time series derived by analysis centres 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 EOP-PC.

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 centres 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 variance 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).
- Use of Ultra rapid EOPs for real-time estimations.

New development under investigation

- Use of pole rates for the interpolation of GPS series
- Method of combined smoothing (Vondrák & Gambis, 2000; Vondrák & Čepek, 2000)
- 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. The predictions of the nutation offsets dψ and dε 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 short-term variations prediction, an autoregressive process is used. New procedures for prediction linked to Singular spectrum Analysis SSA (Bougeard et al., 2002) and neuronal networks are under investigation.

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, dψ, dε), 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 Centre 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

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

Due to this growth in the uncertainty of the Earth orientation parameters between measurements, when inter-comparing 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, can be obtained by anonymous ftp to <ftp://euler.jpl.nasa.gov/keof/combinations/2001>. 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 <ftp://euler.jpl.nasa.gov/keof/predictions>. 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 Astronomical Institute and Czech Technical University (CRC in Prague)

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

$$Q = S + \varepsilon F + \overline{\varepsilon}\overline{F} = \min. \quad \Rightarrow \quad \frac{\partial Q}{\partial y_i} = 0, \quad i = 1, 2, \ldots N.$$

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 has recently been used to combine VLBI and GPS observations, both UT1/l.o.d. and celestial pole offsets/celestial pole offset rates (Vondrák et al. 2002a, b, c).

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