Issues of a Rigorous Combination

Jim Ray[1], Sheng Yuan Zhu[2]

[1] *National Geodetic Survey, Silver Spring, USA*
[2] *GeoForschungsZentrum Potsdam, Germany*

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)