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).

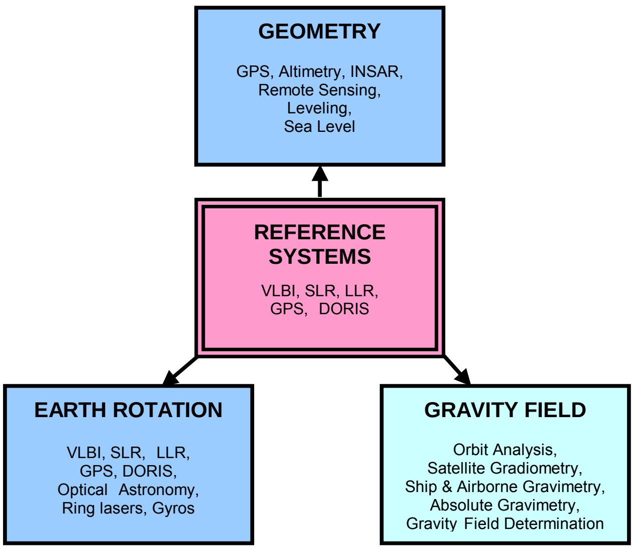

Fig. 1 The three major pillars of space geodesy. The IERS is heavily involved in three of the four boxes, namely geometry, Earth rotation, and reference frames.

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.

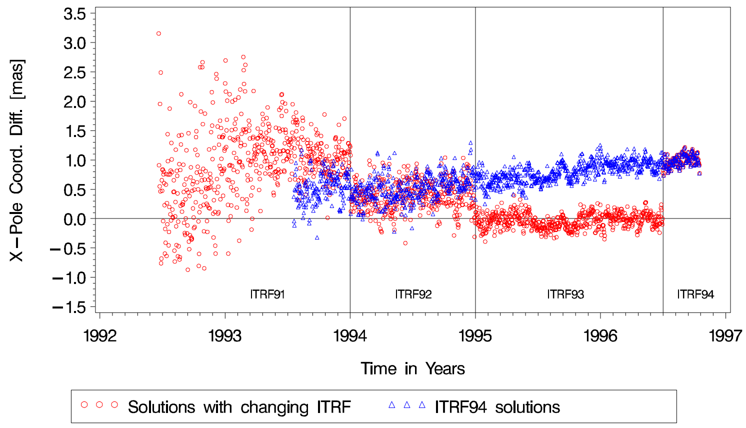

Fig. 2a Different ITRF realizations used to estimate polar motion (X-component) from GPS data. Jumps are evident in the time series where the ITRF realization was changed.

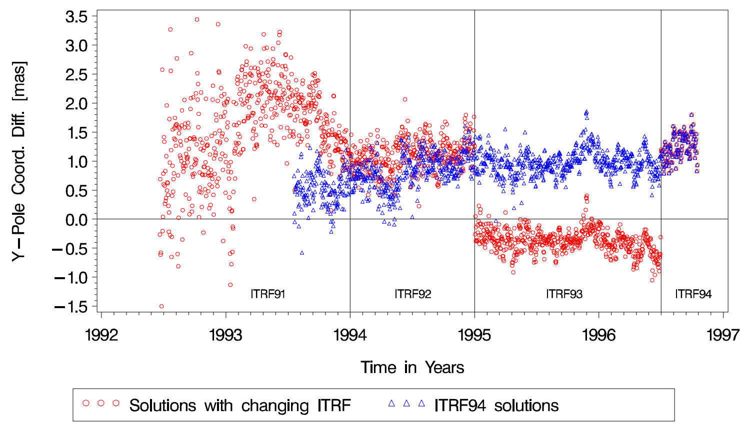

Fig. 2b Different ITRF realizations used to estimate polar motion (Y-component) from GPS data. Jumps are evident in the time series where the ITRF realization was changed.

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.

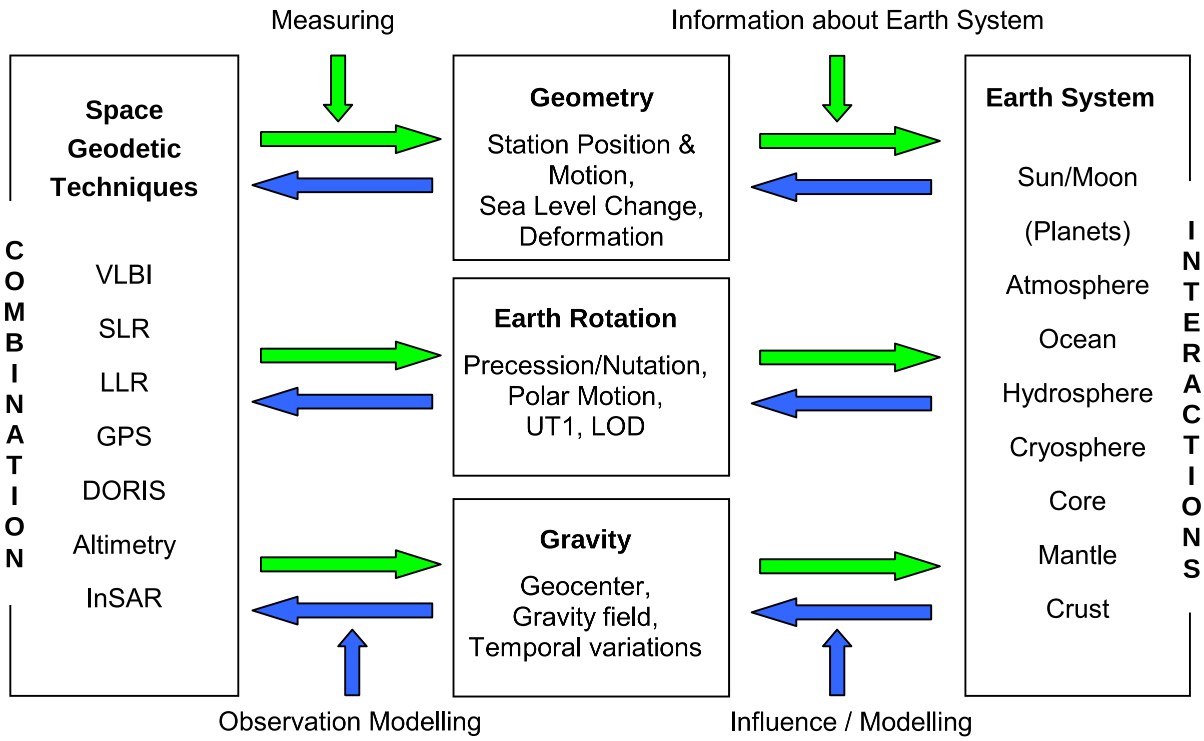

Fig. 3 Combination of the space geodetic techniques, the three pillars of space geodesy, and the interaction with the components of the Earth's system (e.g., global geophysical fluids)

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.

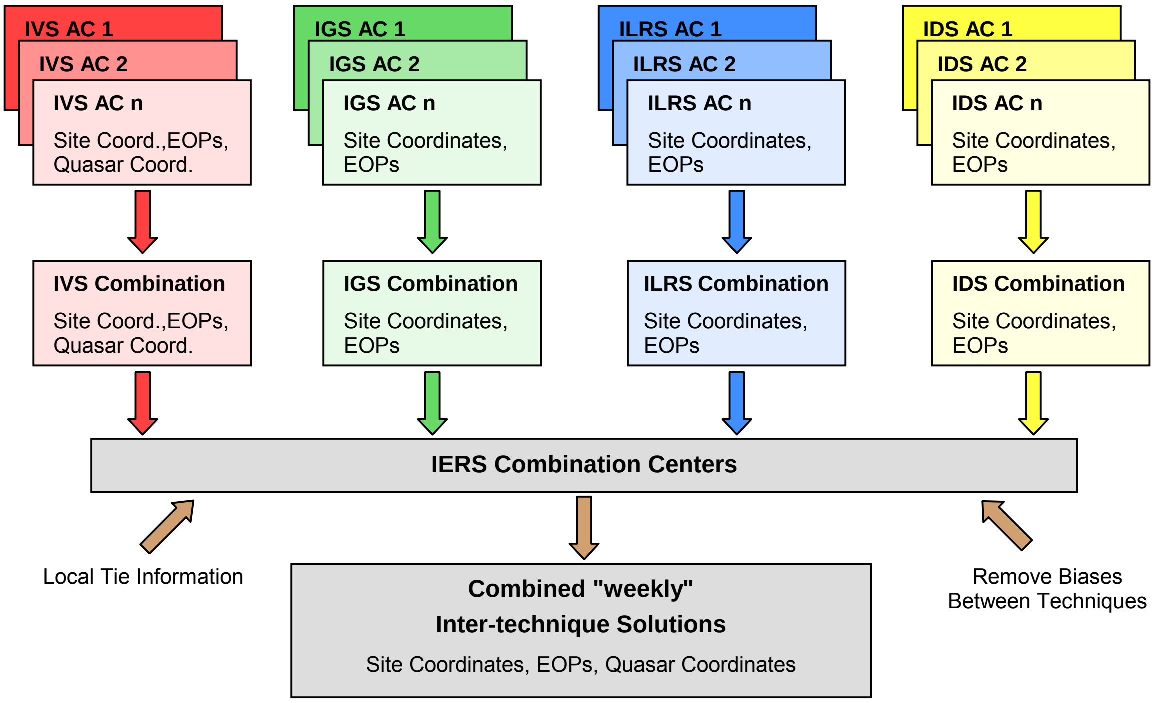

Fig. 4 Scheme for a rigorous combination of weekly inter-technique solutions

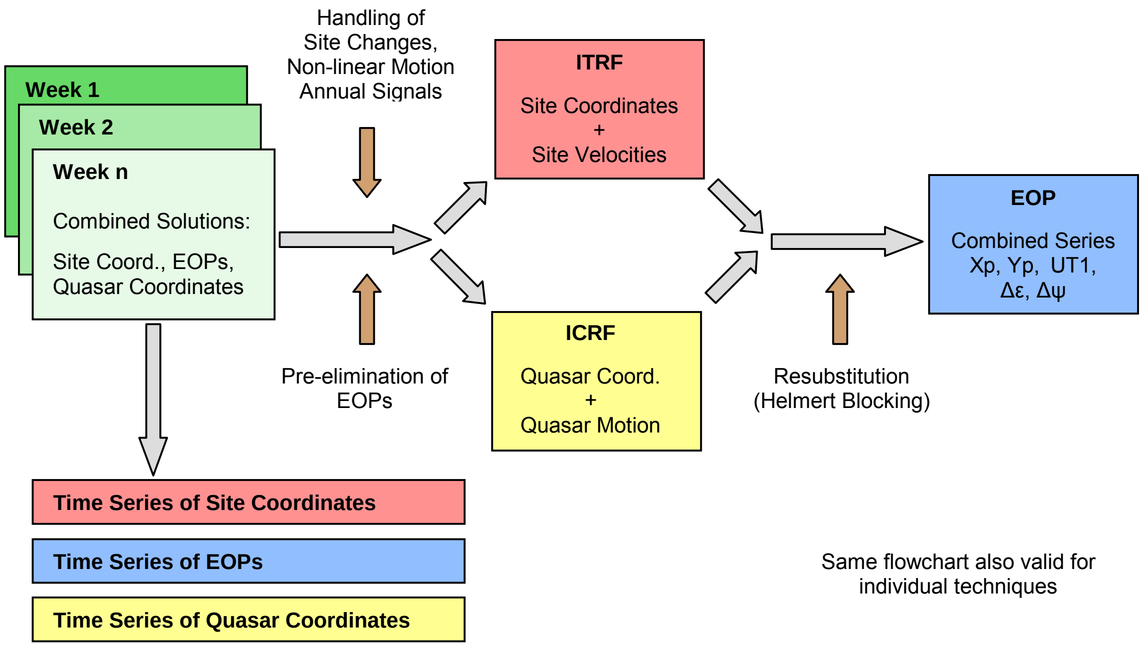

Fig. 5 Scheme for a rigorous combination of multi-year inter-technique solutions from weekly solutions

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.

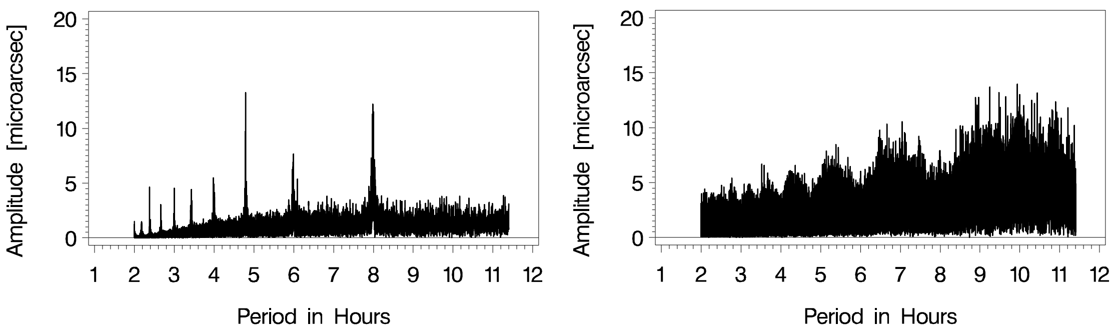

Fig. 6 Comparison of the prograde polar motion spectrum below periods of 11 hours derived from sub-daily GPS and VLBI EOP estimates, respectively

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.

References

Altamimi, Z., P. Sillard, and C. Boucher: ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications, J. Geophys. Res. 107 (B10), 2214, doi:10.1029/2001JB000561, 2002.

Ferland, R.: Activities of the International GPS Service (IGS) Reference Frame Working Group. In: J. Adam and K.-P. Schwarz (Eds.). Vistas for Geodesy in the New Millennium, International Association of Geodesy Symposia, Vol. 125, pp. 3–8, Springer, 2002.

IERS 1998 Annual Report: First extension of the ICRF, ICRF-Ext.1, Chapter VI, D. Gambis (ed.), Observatoire de Paris, pp. 83–128, 1999.

Ma, C., E.F. Arias, T.M. Eubanks, A.L. Fey, A.-M. Gontier, C.S. Jacobs, O.J. Sovers, B.A. Archinal, P. Charlot: The International Celestial Reference Frame as realized by Very Long Baseline Interferometry, Astronomical Journal, 116, pp. 516, 1998.

Noomen, R., G.M. Appleby, P.J. Shelus: Call for Participation "Positioning & Earth Orientation", Version 2.1, E-mail: 19.12.2002.

Nothnagel, A. and C. Steinforth: IVS Analysis Coordination, CSTG Bulletin No. 17, pp. 84–90, Deutsches Geodätisches Forschungsinstitut, Munich, 2002.

Rothacher, M.: Towards an Integrated Global Geodetic Observing System. In: R. Rummel, H. Drewes, W. Bosch, H. Hornik (Eds.). Towards an Integrated Global Geodetic Observing System (IGGOS), International Association of Geodesy Symposia, Vol. 120, Springer, pp. 41–52, 2000

Rummel, R., H. Drewes, W. Bosch, H. Hornik (Eds.): Towards an Integrated Global Geodetic Observing System (IGGOS), International Association of Geodesy Symposia, Vol. 120, Springer, 2000.