Martine Feissel-Vernier et al.: VLBI and Earth Rotation: Geophysical and Geodetic Challenges, IVS 2004 General Meeting Proceedings, p.22–31
http://ivscc.gsfc.nasa.gov/publications/gm2004/feissel

VLBI and Earth Rotation: Geophysical and Geodetic Challenges

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Abstract

We examine some current limitations in the interpretation of VLBI Earth rotation measurements due to factors inherent in existing observing programs and we propose directions for possible future improvements to enhance the contributions to geophysics.

1. The Roles of Earth Rotation Observations

We distinguish two roles for observations of the Earth's rotation (referred to in terms of Earth orientation parameters or EOPs): 1) to relate the terrestrial (rotating) and the celestial (inertial) reference frames; 2) for the study of signatures of the Earth's structure and dynamics. There are many applications (e.g., satellite tracking) that depend on accurate knowledge of the relationship between the terrestrial and celestial frames. VLBI contributes uniquely in this regard by providing direct measurements of Universal time (UT1) and precession-nutation; satellite-based techniques cannot provide comparably unbiased information.

The topics of interest here are both roles; i.e., providing geophysical insights as well as high-accuracy unification of reference frames. Space geodetic techniques contribute information both unique and complementary to that obtained from independent geophysical methods. The global scope, sub-ppb (parts-per-billion) sensitivity, accuracy, and stability are especially important, and, again, the VLBI ability to observe unbiased UT1 and nutation is critical.

1.1. Signal Spectrum

We consider the Earth rotation signal spectrum in three broad regimes. Tidal signals are strictly periodic, driven by the gravitational forcings of the sun, moon, and planets. Because the forcing properties are very well known, the unknown characteristics of the Earth can be inferred from the observed tidal responses limited only by the geophysical inversion itself and in some cases by overlying non-tidal signals. A weakness of tidal studies is that the Earth response can only be examined at discrete frequencies, corresponding primarily to periods near 12 h, 24 h, fortnightly, monthly, semiannual, annual, and some longer.

Non-tidal, quasi-periodic signals arise either from some feeback process operating on a recurring cycle (e.g., el Niño) or as an amplification of broadband geophysical “noise” near some natural resonant frequency (e.g., Chandler wobble). These phenomena provide an opportunity to explore the Earth's response over wider bandwidths but their interpretation is usually complicated by uncertainties in the underlying excitations as well as in the geophysical inversion.

The third spectral category is the background continuum. Geophysical processes normally generate "red" power-law variations (apart from the tidal and quasi-periodic signals already mentioned), with the largest power being in the longest temporal and spatial scales. These signals are usually the most challenging to understand because so many different factors can be entangled. The observed power level at any given frequency, which should be useful, is often difficult to evaluate accurately because the measurement and analysis processes can be sensitive to subtle or unintended filtering.

For a detailed discussion of Earth orientation excitation, please refer also to the review by B. Chao (this volume).

2. VLBI EOP Measurements Today – The Radio Sources

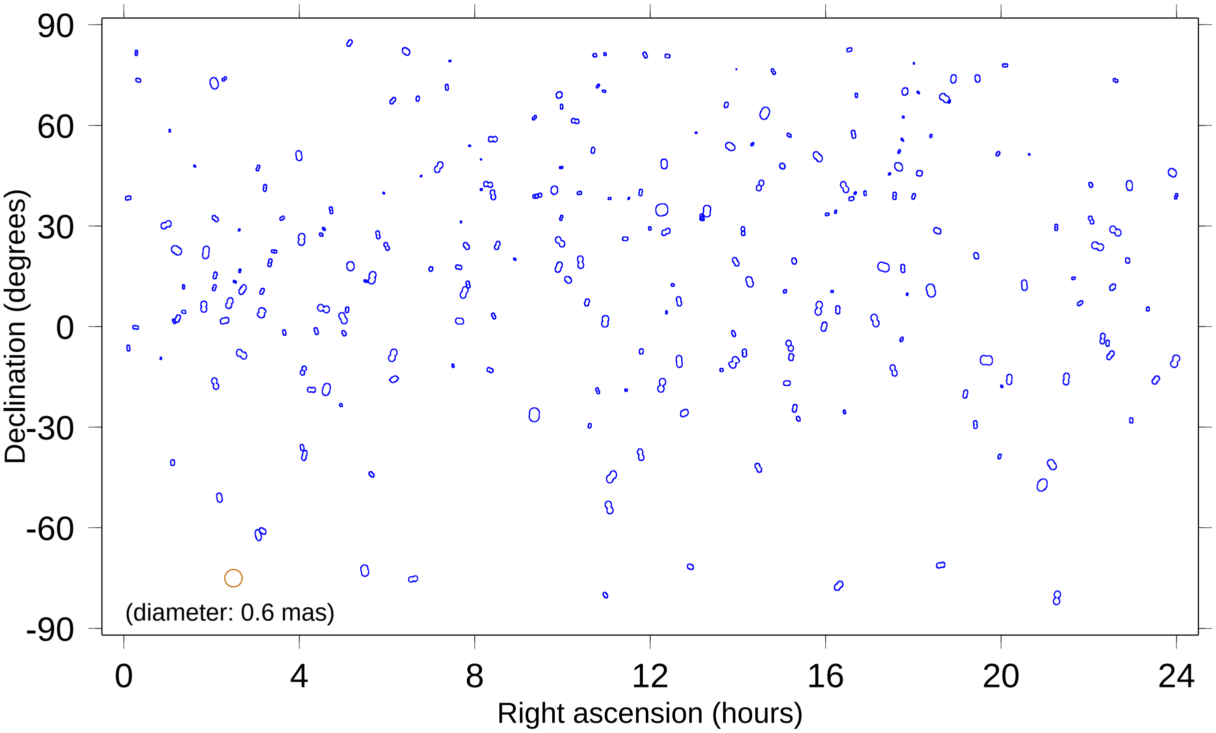

Figure 1. Map of 245 well-observed radio sources (1989.5-2002.4) with one-year standard deviations smaller than 0.35 mas. Envelopes show the standard deviation of the yearly average coordinates in local equatorial frames ($\alpha \cos\delta$, δ).

The celestial reference frame is materialized by a set of quasars and galactic nuclei that are compact when observed at X-band (4 cm) and S-band (13 cm) with terrestrial baselines. However, at the current level of sub-milliarcsecond (mas) precision, no object is really pointlike. Most of the known quasar activity takes the form of jets; i.e., aligned emissive structures that cause an apparent motion of the observed brightness center. While the background source structure is assumed to stay fixed, oscillations may exist in the observed direction as well as apparent drift rate which are unlikely to continue indefinitely; the temporal characteristics are not well known. In principle, it is possible to accurately correct this effect if repeated maps are available (P. Charlot, this volume). However, such source structure corrections are not implemented in existing astrogeodetic analysis software. As a result, most objects exhibit time variations of their position in some preferred direction. This is illustrated in Figure 1, which shows the envelopes of the standard deviation of yearly weighted average source positions in local equatorial frames for the most stable sources. The deficiency of sources south of declination -30^o is an effect of their relatively sparse observation history due the biased network distribution (§3).

2.1. Effects of Source Instability

Studying the influence on nutation of the variable torque exerted by the atmosphere and the ocean, Dehant et al. [3] showed that apparent variability in the celestial frame can lead to changes in estimates of precession or long-period nutation coefficients at a level comparable to that of the variable nutation excited by the Earth's fluid layers (a few tens of μas). Figure 2 shows an example of the sensitivity of the estimates of the precession constant, the obliquity rate, and the 18.6-year nutation term to source selection. While the common practice to estimate these terms is to use observations of all sources, the figure shows that, depending on the set of radio sources considered in the analysis, the precession and obliquity rates may change by 20 μas/year and the 18.6-year prograde component by 30 μas.

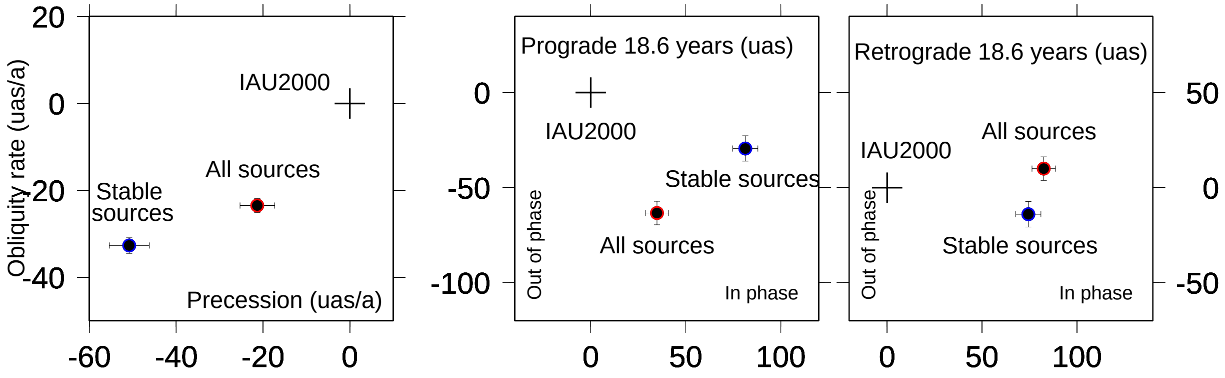

Figure 2. Corrections to IAU2000 precession-nutation components using all sources or selected stable sources.

The stable sources mentioned in Figure 2 result from a selection scheme proposed by Feissel-Vernier [5]. As shown by M. Feissel-Vernier (this volume), this source selection agrees only partially with the quality criteria for the original ICRF (Ma et al. [6]) that made use of qualitative and quantitative factors such as apparent drift, formal uncertainty of the global coordinates over 1980-1995, and source structure index. It is expected that replacing the ICRF defining sources by the stable ones for constraining the axes of a future ICRS realization would improve its long-term stability by nearly a factor of five (6 μas vs 29 μas).

The Free Inner Core Nutation (FICN) is a prograde free oscillation with an expected period between 930 and 1140 days according to the IAU2000 model (Mathews et al. [8]). The search for the FICN provides an opportunity to test the detectability of weak variable oscillations by VLBI in the interannual frequency band. V. Dehant et al. (this volume) studied the residuals between the observed nutation and the adopted IAU2000 nutation model. By considering the proposed stable sources selection, they found residuals more physically meaningful. They observed in the period 1990-1995 a large peak around 870 days, which is close to the FICN frequency as expected from the forced nutation [8]. Unfortunately, the theoretical estimation of a random noise excitation of the FICN by the ocean and the atmosphere is expected to be much smaller, below 1 mas. It is always possible, but not likely, that an harmonic excitation of the ocean and/or atmosphere would excite the FICN exactly at that time. But contamination by source instability must be considered. While VLBI estimates suggest a potential candidate for the detection of the FICN with an amplitude 37 ± 10 μas, when considering the stable sources the spurious celestial pole motion resulting from random apparent motions of the sources amounts to 20 ± 13 μas (M. Feissel-Vernier et al., in preparation). They therefore concluded that the prograde oscillation that appears in various VLBI spectra is probably an artifact due to radio source instabilities, although effects related to VLBI network variations could also play some role (see next section).

3. VLBI EOP Measurements Today – The Antenna Network

3.1. The Antenna Network

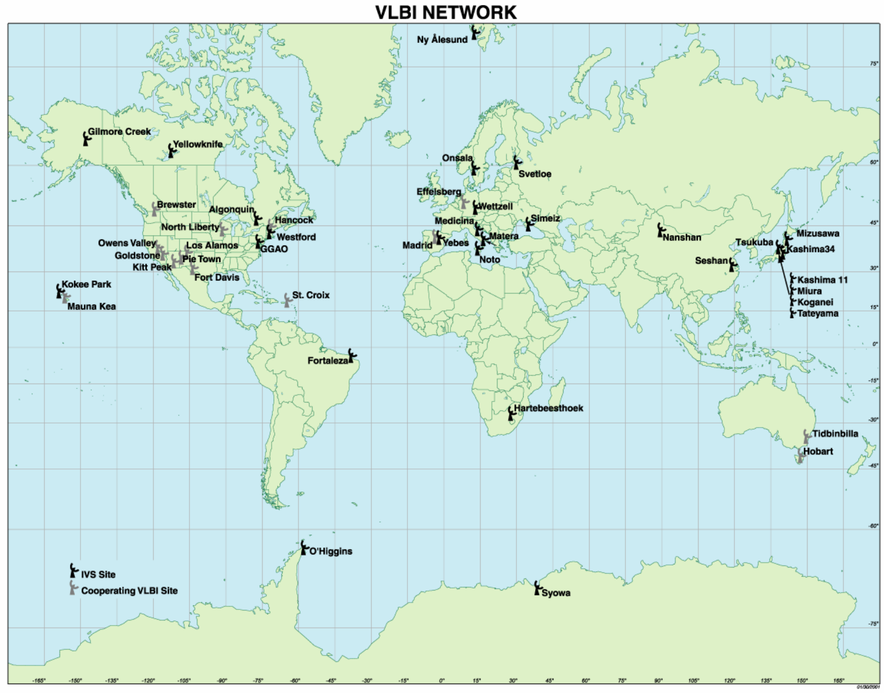

Figure 3. Geodetic VLBI network.

As seen in Figure 3, the most striking feature of the VLBI antenna network is its non-uniformity. Only a handful of stations are located in the southern hemisphere. The network is essentially two continental subnetworks (N. America and Europe) with a few stations scattered elsewhere. For measurements of global quantities, such as EOPs and the terrestrial frame, this can seriously limit performance. On account of the weak geometrical coverage of the Earth's surface, correlations among EOP estimates and among Helmert network parameters can often exceed 0.5. For instance, the weekly IVS R4 network normally has a correlation coefficient between polar motion X and UT1 of about -0.6.

3.2. Network Effects on EOP Measurements

We show three examples of the impact of network distribution on the consistency of the EOP results. The first concerns the weekly operation of the IVS R1 and R4 24-hour EOP sessions, each using different networks. They have run since 2002 on Mondays and Thursdays, respectively, and each includes five to seven stations. Three stations are common: Gilcreek, Wettzell and Conception. Table 1 gives estimates of the differences between the two EOP series, taking into account the Earth rotation changes during the three to four days between them. The magnitude of the differences is equivalent to 3 to 5 mm on the Earth's surface, probably reflecting station coordinate inconsistencies at a similar level.

Table 1. EOP differences between R1 & R4 sessions (2002.0-2003.8)

Parameter	Bias	Wrms residual
Nutation		
$d\psi\sin(\epsilon)$	-1 μas	114 μas
$d\epsilon$	2 μas	105 μas
Polar motion		
X	57 μas	132 μas
Y	-20 μas	110 μas
Orientation		
UT1	1.9 μs	9.6 μs

The next example is based on two different combinations of unconstrained session solutions for station coordinates and EOPs together with the full covariance matrices (SINEX files). The global combination of these parameters in a unique terrestrial reference frame is done using the CATREF (Combination and Analysis of Terrestrial REference Frames) software (Altamimi et al. [1]). The datum definition attaches the results to ITRF2000 using a subset of stations that are judged reliable over the data span. Two combination strategies were compared: 1) a global analysis over 1990-2003, using an appropriate set of long-term reliable stations for the datum definition; 2) yearly analyses, with different suitable sets of datum stations for each year. The EOP differences derived from the two approaches are plotted in Figure 4 in the form of yearly weighted averages. The annual averages of the rotation angle A3 of yearly celestial reference frames from a similar computation [5] are also included in the figure, as errors in UT1 may result from either terrestrial or celestial frame axial instabilities. The year-to-year EOP changes, which increase after 1996, are significant with respect to their internal consistencies, reaching the few-mm level for rotation on the Earth's surface. The effects presumably reflect mostly inconsistencies with the VLBI terrestrial frame and weaknesses in the longer-term interconnection of the network.

The third example is also based on a rigorous combination of terrestrial frames and EOPs except that it includes both VLBI and GPS results over 1999-2003. The VLBI data are a subset of above while the GPS data are unconstrained SINEX files from the IGS containing weekly station coordinates and daily pole coordinates. The combination using CATREF included a weighting of the inputs according to their respective scatters. The datum definition uses a set of 23 sites with co-located VLBI and GPS stations and reliable local ties. The post-fit polar motion residuals are plotted in Figure 5 and the weighted RMS residuals are, for the X and Y components respectively:

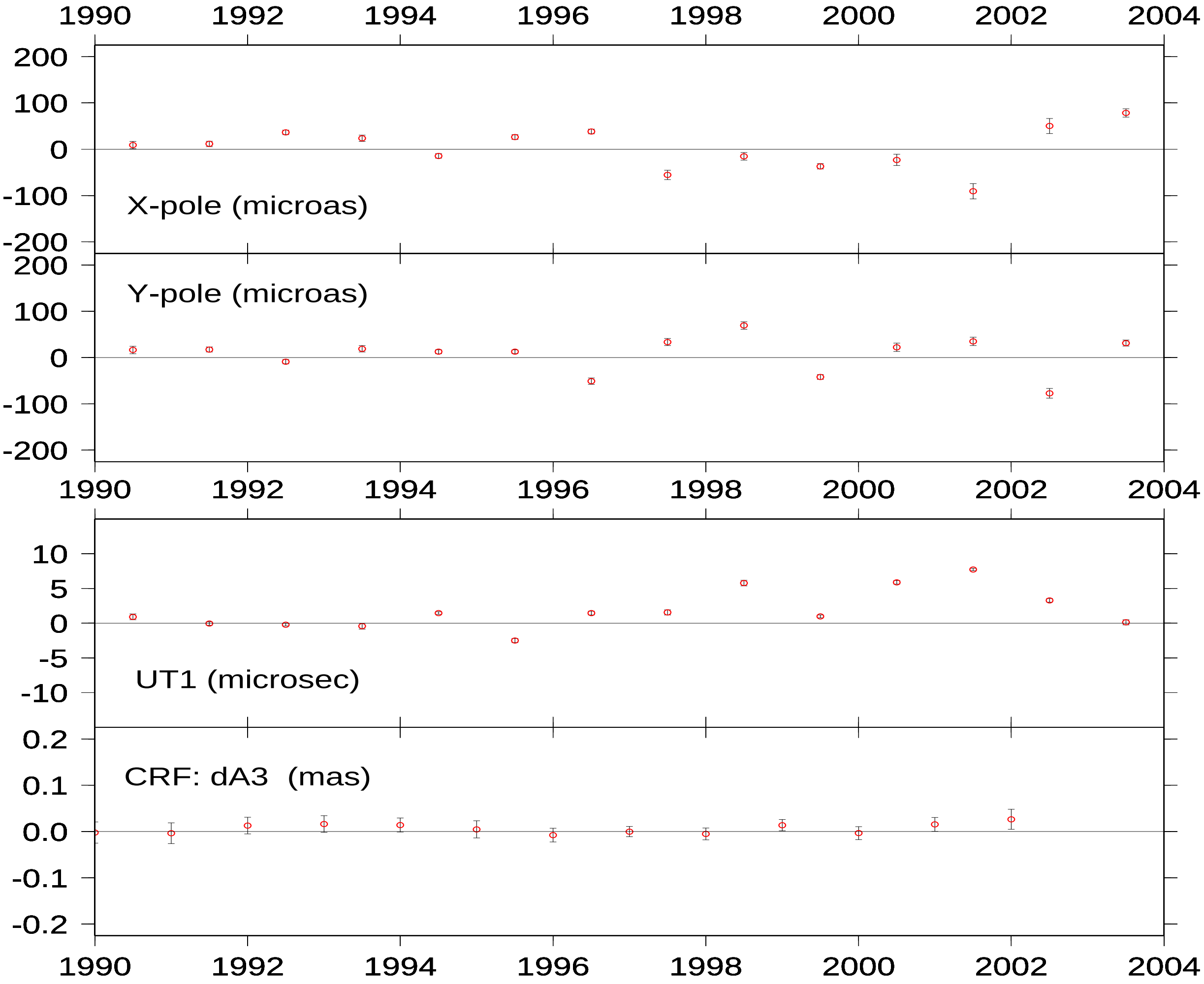

Figure 4. Yearly average EOP differences between solutions with the ITRF2000 tie performed separately each year and globally over 1990-2003. Similar variations of the axial rotation of yearly celestial reference frames are shown in the bottom panel. Note that all four plots have the same scale.

124 and 101 μas per VLBI session; 40 and 55 μas per day for GPS. The VLBI session scatters are equivalent to 3 to 4 mm on the Earth's surface, two to three times larger than for GPS. A difference in drift is also evident for the Y component, most likely due to discrepancies in the respective reference frames. One may question the precise source of the VLBI random noise and the extent to which terrestrial frame inconsistencies may be responsible versus other causes.

We conclude from the above tests that the effects of terrestrial frame inconsistencies on VLBI EOP measurements are equivalent to a few mm of surface rotation for individual sessions, and around 1 to 2 mm in the longer term. Further efforts in the direction of inter-technique combination and co-location, as well as in network stability studies generally, are necessary to improve the precision and accuracy of current EOP determinations.

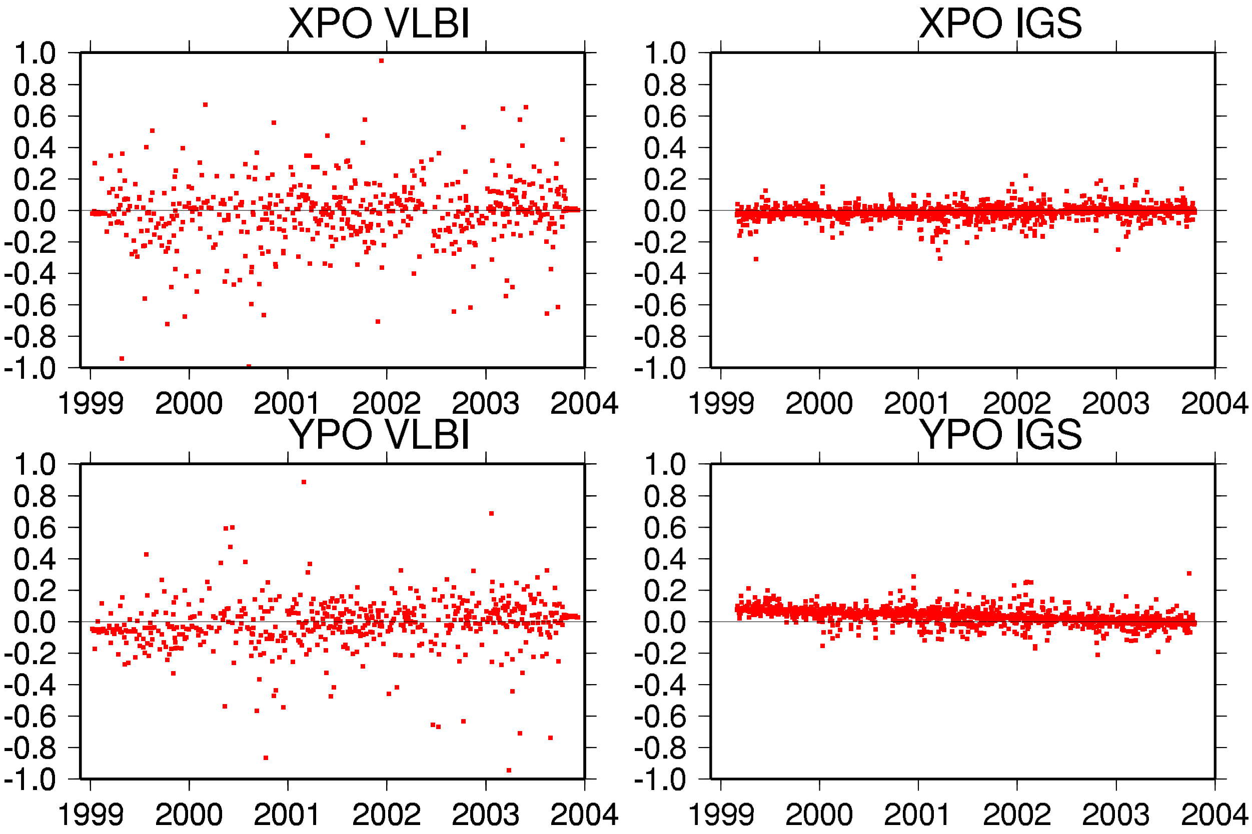

Figure 5. Post-fit polar motion residuals from a joint combination of VLBI and GPS solutions.

4. Geophysical Challenges in the Next Decade

4.1. Long-Term Changes in LOD and UT1

At long time scales, LOD variations are attributed to the interaction between the Earth's core and the mantle. Consequently they are supposed to be correlated with the core angular momentum (CAM). The dynamics inside the fluid core are presently not very well known, though, and LOD is the best proxy available for the long-term core angular momentum. Independent CAM series are also computed from magneto-hydrodynamics considerations, under strong hypotheses, and their success can be tested against the LOD variations (Van Hoolst et al. [9]). In that sense, monitoring LOD variations is very important for the future development of models for core dynamics.

In the last two years, the analysis of J_2 variations from Satellite Laser Ranging (SLR) data (Cox et al. [2]) has generated large interest from both the geodetic and geophysics communities. The study of this time series is very important as it reflects the global scale mass variations in the Earth system and is a big challenge for our understanding of the geophysical fluids (Dickey et al. [4]). Computing J_2 variations from SLR data necessitates an a priori knowledge of UT1 variations that is not currently possible without VLBI.

4.2. Inner Core Signature in Polar Motion

Theoretical studies (Mathews et al. [7]) predict the existence of a rotational normal mode in polar motion related to the presence of a solid inner core within the outer liquid core: the Inner Core Wobble (ICW). This mode has not been detected yet though its observation would increase strongly our knowledge of the properties of the inner core, in particular the density jump at the inner core boundary and the flattening of the inner core. Its period is predicted to be around 2400 days. Consequently, its observation would require high precision and long-term stability of the VLBI network.

4.3. Nutations

Nutations are mainly excited by the gravitational action of the moon, sun, and planets on the equatorial bulge of the Earth. The Earth responds to that forcing as a complex system and, in particular, the Earth internal structure deeply impacts the amplitudes of the nutations. In addition, the external geophysical fluids (atmosphere and ocean) create additional nutational motion of the Earth, but of smaller amplitudes. In order to interpret the nutation observations in terms of Earth interior parameters, it is important to be able to separate external fluids and interior effects. Depending on the frequency, the relative amplitudes of these effects will be different. For periods close to the Free Core Nutation (FCN) resonance, the Earth interior effect strongly dominates, whereas the atmosphere impact is strong on the prograde annual nutation as it corresponds to one solar day in the terrestrial reference frame. For some other nutation periods, perturbations from both the interior and exterior of the Earth must be considered. From the first category, we can learn about the physics of the Earth interior, and the second category can be used to: (a) constraint the diurnal cycle of the fluid models and (b) determine which atmospheric model is the most relevant for nutation studies. This will allow us to separate atmospheric and interior effects in the case of the third category (both impacting). A consistent set of high-precision VLBI nutation data would immediately increase our knowledge of the Earth interior.

5. Geodetic Challenges in the Next Decade

5.1. Near-term Assumptions

Any attempt to assess future challenges should first try to specify the expected conditions likely to be influential:

- GPS, Galileo, and related satellite navigation systems will continue to provide the widest user access to the ITRF indirectly via precise orbits and directly through dense ground networks.
- While satellite methods already dominate determinations of polar motion, they will probably not improve much in measuring LOD or nutation rates, where only the high-frequency components provide useful geophysical information due to time-varying technique biases.
- Uncertainties in the absolute scale of satellite-based terrestrial reference frames will not be reduced to better than about 1 ppb due to lack of accurate knowledge of the satellite transmit antenna characteristics.
- The global VLBI geodetic network will continue to evolve but is unlikely to grow much. The VLBI observing program will continue to be constrained by costs.

- Optimal user benefits will increasingly require a balanced combination of VLBI and satellite geodetic results.

5.2. Priority Contributions from VLBI

If our assumptions of future trends prevail, the areas of global geodesy that will continue to require substantial VLBI contributions (preferably with improvements) are: 1) maintaining the celestial reference frame; 2) providing the definitive link between the ICRF and ITRF through UT1 and nutation observations; 3) establishing the absolute scale of the ITRF (together with SLR). In all these respects, it is vital to maintain the highest level of long-term stability, especially considering the older observing history of VLBI.

5.3. Goals for the Next Decade

To maximize the utility of VLBI during the coming years, we emphasize these objectives:

- Schedule more fully global VLBI networks as often as feasible. Doing so will strengthen the celestial and terrestrial frames by reducing the presently high internal correlations. Network-dependent biases in other parameters will also be reduced.
- Improve the UT1 accuracy and sampling by expanding and upgrading the current Intensive series. Better use of GPS results should be studied as a way to reduce the effects of polar motion errors.
- Improve the quality of the celestial frame by dynamic monitoring of radio source stability.
- Improve co-location ties with the other techniques, especially GPS and DORIS. This will allow a more robust combination of VLBI results with the satellite techniques and permit inter-technique biases to be identifiable. Doing so requires that the intra-VLBI components of the local ties be accurately modeled (i.e., antenna effects).

6. Summary

VLBI will remain the unique source of our knowledge of the Earth's sidereal rotation (UT1, precession-nutation) for at least one more generation. Some exciting new geophysical challenges facing the technique may remain unmet if further enhancements cannot be implemented, but the present data quality will continue to be needed to interpret aspects of the dynamical Earth system, including information useful for climatology, global change research, and for deep interior studies. To infer new levels of insight and to address the currently unsatisfied challenges will require heightened attention to instabilities in the celestial and terrestrial reference frames, among other concerns.

Until VLBI is operated worldwide and continuously (if ever), developers and analysts are urged to maximize the quality of the CRF and TRF that can be derived from VLBI observations, enhance the use of geodetic information from the satellite techniques (GPS, DORIS, SLR, and in the future Galileo), and actively participate in the IERS multi-technique combination effort. In the current context, VLBI will only attain its fullest potential significance by exploiting the complementary strengths of its competitors, the satellite techniques.

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