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Role of VLBI for Investigating Earth Rotation

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Abstract

Very long baseline interferometry is the only space-geodetic technique capable of independently determining all of the Earth orientation parameters: polar motion, spin (UT1, length of day) and precession-nutation (celestial pole offsets). Currently, it is the unique technique for monitoring the celestial pole offsets and the long-term variability of UT1. Regular determinations, for more than 20 years, of the parameters of Earth rotation by VLBI contributed considerably to the progress in the research concerning Earth rotation.

This paper gives an overview of the recent advances in selected topics of the theory of Earth rotation, achieved on the basis of the VLBI observations. We also report on our own investigations related to these topics.

1. Introduction

Regular determinations of the parameters of Earth rotation begun in 1899 with the establishment of the International Latitude Service. Up to the 1970s the estimates were based on the observations by optical astrometry and suffered from different systematic errors associated with this technique. In the late 1970s a number of new methods of monitoring changes in Earth rotation with unprecedented accuracy potential entered into use. These are the space-geodetic techniques: very long baseline interferometry (VLBI), satellite and lunar laser ranging (SLR, LLR), global positioning system (GPS) and doppler orbitography and radiopositioning integrated by satellites (DORIS). Noteworthy is the fact that improving the optical observations from the middle of 19th century to the 1970s led to the polar motion uncertainty being reduced by an order of magnitude, whereas the progress achieved during the next two decades resulted in a two-order improvement both in the angular accuracy and temporal resolution of the Earth rotation parameters.

Among the techniques of space geodesy, VLBI plays a particularly important role in monitoring variations in Earth rotation. The VLBI observations have been used to establish the extragalactic reference frame which is a primary materialization of the International Celestial Reference System (ICRS) (IERS, 2004, Chap. 2). The non-rotating celestial reference system in turn is necessary for parametrization of Earth rotation. VLBI is the only space-geodetic technique capable of independently determining all of the Earth orientation parameters (EOP): polar motion—terrestrial coordinates of the pole x, y—, spin—universal time UT1—, and precession-nutation—celestial pole offsets $\delta X, \delta Y$ (or, equivalently, $\delta\psi, \delta\epsilon$). Currently, it is the only technique enabling the determination of the celestial pole offsets and the observation of the long-term variability of UT1. VLBI has been used for monitoring time variations of the EOPs since 1979. However, the quality of the VLBI celestial pole offsets prior to 1984.0 was relatively low due to insufficient data coverage, baseline configurations, etc.; therefore it is better to reject the observations prior to this date when studying such fine effects as the irregular geophysical signals in nutation.

The high quality observations of Earth rotation by VLBI contributed considerably to the progress in the research concerning Earth rotation. We selected for this review the following three topics:

Sec. 2: Development of the high-precision precession-nutation model IAU 2000;
Sec. 3: Analysis of the free core nutation signal;
Sec. 4: Observational evidence of the high frequency polar motion (diurnal, semidiurnal).

We give a brief overview of the recent advances within each of the subjects, achieved on the basis of the VLBI observations. We also report on our own investigations related to these topics.

2. Precession-nutation Model IAU 2000

The International Astronomical Union (IAU) adopted in 1980 a new conventional model of nutation, the IAU 1980 theory of nutation (Seidelmann, 1982) which had to be used together with the IAU 1976 precession model. The new model was developed as a combination of two distinct parts, the rigid Earth precession-nutation series due to Kinoshita (1977) and the transfer function for an elastic, oceanless Earth with a liquid core, computed by Wahr (1981). The new model was expected to be adequate for accuracies reached by the space-geodetic techniques entering that time into routine use for the determination of the Earth orientation parameters.

Unfortunately, already in mid 1980s the VLBI observations revealed systematic differences with respect to the adopted model, which were much larger than the standard errors of observations (Herring *et al.*, 1986)—see Figure 1. An analysis of the observed celestial pole offsets with respect to the conventional model showed that the main components are the retrograde annual nutation and the long periodic trend. After extending the offset curves to more recent times (Figure 2a) the trend appeared to be composed of the polynomial part contributing to precession and the harmonic terms with main periods 18.6 and 9.3 years.

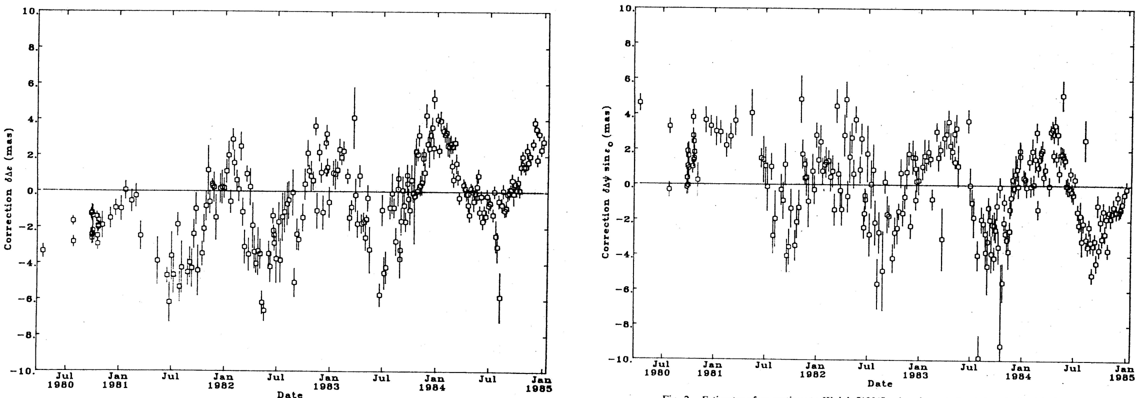

Fig. 1. Estimates of corrections to *Wahr's* [1981] values for nutation in obliquity, $\Delta\varepsilon$.

Fig. 2. Estimates of corrections to *Wahr's* [1981] values for nutation in longitude, $\Delta\psi \sin \varepsilon_0$.

Figure 1. Celestial pole offsets observed by VLBI with respect to the IAU 1976 precession model and the IAU 1980 theory of nutation (from Herring et al., 1985; 1986).

Gwinn *et al.* (1986) discussed the discrepancy between the IAU 1980 theory and the VLBI observations. They discovered that a large part of the discrepancies could be removed when changing the free core nutation (FCN) period in the resonance expression from its adopted hydrostatic value of 460 days to 430 days. This change of period in turn was interpreted as an increase of about

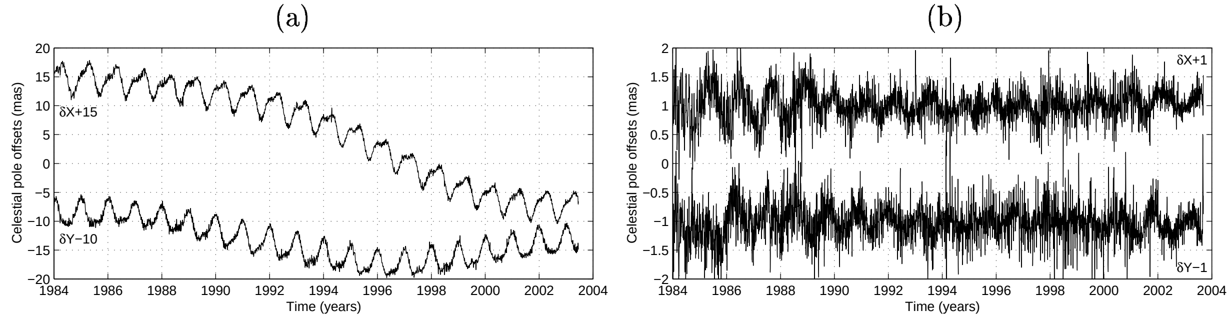

Figure 2. Celestial pole offsets observed by VLBI with respect to (a) the IAU 1976 precession model and the IAU 1980 theory of nutation and (b) the IAU 2000 precession-nutation model. The diagrams show the combination solution EOP(IERS)C04.

6% of the dynamical flattening of the liquid core corresponding to a change of the geometrical flattening of the core-mantle boundary by about 500 meters.

In 1994 the XXIInd General Assembly of the IAU (IAU GA) in the Hague established an inter-commission Working Group on the non-rigid Earth Nutation Theory under the leadership of Veronique Dehant (Resolution B8). At the same time the IAU GA asked the International Earth Rotation Service (IERS) to provide an empirical interim model of precession-nutation and to continue the observations of the celestial pole offsets with the most precise techniques available including the very long baseline interferometry (Resolution C1).

The Working Group continued its activity until 1999; see (Dehant *et al.*, 1999) for an extensive report. Finally, it came up with a proposal of a new precession-nutation model which was presented at the XXIVth IAU General Assembly in Manchester in 2000 and adopted by the IAU GA under the acronym IAU 2000 (Resolution B1.6). Implementation details of the model IAU 2000 were described in the IERS Conventions 2003 (IERS, 2004). In addition, the IERS Conventions Center provided the corresponding Fortran subroutines via the web (`http://www.iers.org/iers/ products/conv/`).

The new precession-nutation model is a combination of the rigid Earth nutation series REN 2000 (Souchay et al., 1999) and the nonrigid Earth transfer function MHB2000 (Mathews et al., 2002). The underlying structural model of the Earth, modified PREM, consists of the viscoelastic mantle, the liquid outer core and the solid inner core. It takes into account both the inertial and the electromagnetic coupling between the liquid core and the mantle. In addition, the MHB2000 transfer function includes contributions from the ocean tides and the influence of the atmospheric thermal tide S_1.

The accuracy of the full version of the new model, designated IAU 2000A, containing 678 lunisolar and 687 planetary terms, is at the 0.2 milliarcsecond (mas) level. Figure 2b shows the difference between the VLBI observations and the model IAU 2000. A short version of the model, designated IAU 2000B, has been developed for those who need a model only at the 1 mas level during the period 1995–2050. This simplified model contains less than 80 terms plus a bias correction to account for the effect of the planetary terms during the period of its validity.

A comparison of Figure 2a with Figure 2b shows that the IAU 2000 precession-nutation model agrees much better with the VLBI observations than the previous model IAU 1980. Nevertheless, this new model is not a perfect one; see, e.g., (Dehant *et al.*, 2003) for an extensive discussion. There

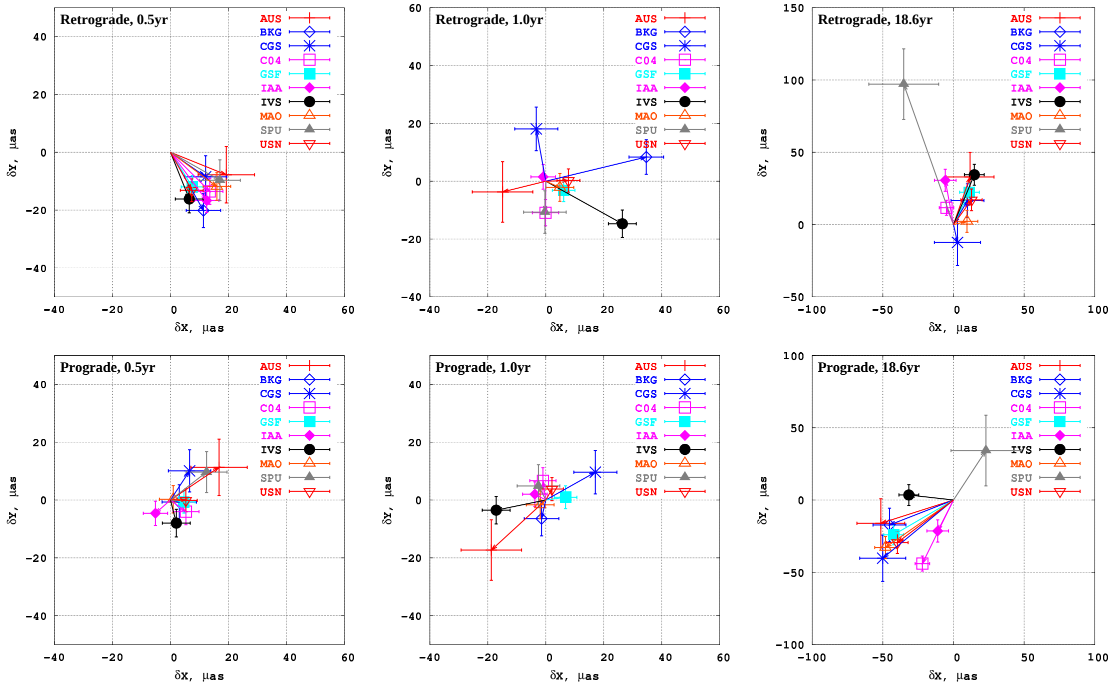

Figure 3. Corrections to the amplitudes of the IAU 2000 precession-nutation model derived from the time series of VLBI celestial pole offsets (from Bolotin and Brzeziński, 2005).

have been several attempts to improve its quality. An example is a new model of precession based upon the so-called P03 solution, which should replace the precession part of the IAU 2000 model (Capitaine *et al.*, 2005). Also the harmonic part of the IAU 2000 can contain imperfections. Bolotin and Brzeziński (2005) estimated corrections to the amplitudes of the conventional a priori model using different time series of the VLBI celestial pole offsets; see Figure 3. The corrections depend in general on the input solution with the following two exceptions. All the series yield similar results for the retrograde semiannual term (about 20 microarcseconds (μas)) and 6 of 10 series provide similar estimates of the prograde 18.6 year term (about 50 μas). Such common corrections indicate the difference between the a priori model and the observations at given frequencies.

But even with perfect coefficients of the model IAU 2000, it will be necessary that VLBI continue to monitor the celestial pole offsets. The reason is that the nutation contains components of geophysical origin which are partly unpredictable. These are the atmospheric and nontidal oceanic influences driven by the daily cycle in the solar heating. Such effects were estimated using the available subdiurnal estimates of the Atmospheric Angular Momentum (AAM) by Bizouard *et al.* (1998) and of the nontidal Oceanic Angular Momentum (OAM) by Brzeziński *et al.* (2004). They found non-negligible, up to 0.1 mas, contributions to the following nutation components: prograde annual, retrograde annual, prograde semiannual, and to the constant offset of the pole. [Note that in the IAU 2000 model the atmospheric and nontidal oceanic contributions are represented by the empirical "Sun-synchronous" correction to the amplitude of the prograde annual nutation (Mathews *et al.*, 2002, Tables 5 and 7).] But after removing the harmonic model, there still remains variability in AAM and OAM contributing to nutation at the level of several tenths of mas

(Brzeziński, *et al.*, 2004). The most important irregular effect of geophysical origin is the free core nutation, a pseudo-harmonic signal seen in time series of the celestial pole offsets (Fig. 2b), which will be considered in the following section.

3. Free Core Nutation

The free core nutation mode arises in the rotating body consisting of the spheroidal solid mantle filled by the liquid core. The mode is described by two parameters: the resonant period T_f and the dimensionless quality factor Q_f, which are usually combined into a single complex angular frequency $\sigma_f = 2\pi/T_f \cdot (1 + i/(2Q_f))$. The most up-to-date discussion of the FCN parameters is given by Mathews *et al.* (2002). They expressed the FCN angular frequency as

$$\sigma_f = -\Omega \left[1 + \frac{A}{A_m}(e_f - \tilde{\beta}) \right] \tag{1}$$

where Ω is the angular frequency of diurnal sidereal rotation, $e_f = (C_f - A_f)/A_f$ denotes dynamical ellipticity of the core, A and C are the mean equatorial and axial moments of inertia of the Earth with assumed axial symmetry $(A = B)$, A_f, C_f, A_m, C_m are the corresponding moments of the core and of the mantle, respectively. The complex quantity $\tilde{\beta}$ is the compliance parameter characterizing the deformability of the fluid core under the centrifugal forcing associated with the wobble of the core relative to the mantle. This parameter includes also anelasticity and ocean tide effects.

The period of the FCN resonance depends primarily on e_f, which in turn is directly related to the geometrical flattening of the core-mantle boundary (CMB). If the flattening is computed under the assumption of hydrostatic equilibrium, the corresponding space-referred period of FCN is about 460 days (Wahr, 1981) which is almost 30 days longer than the period observed by VLBI. An agreement can be obtained by increasing of the core flattening corresponding to an extra difference between the equatorial and the polar radii of about 500 meters. When accounting for the electromagnetic torque at the CMB (Mathews *et al.*, 2002) this extra difference is reduced to about 380 meters.

The FCN quality factor Q_f arises primarily from the dissipative part of the electromagnetic torque at the CMB, contributing to $\tilde{\beta}$ (Mathews *et al.*, 2002).

The FCN resonance influences nutation in two different ways. The first one is a direct influence, that is free celestial motion of the pole excited by the angular momentum transfer from fluid layers (atmosphere, ocean, etc.). There is also an indirect influence consisting in the resonant enhancement of the amplitudes of those nutation terms that are close to the resonance. Particularly sensitive to the FCN resonance is the retrograde annual nutation.

An important part of research concerning the FCN resonance is the determination of the resonant parameters T_f and Q_f from the observations of Earth rotation. This estimation is much more efficient from the indirect effect. The most up-to-date values are these adopted in the MHB2000 transfer function (Mathews *et al.*, 2002) used to construct the IAU 2000 precession-nutation model: $T'_f = -430.20$ days $(429.93, 430.48)$, $Q_f = 20\,000$ $(18\,870, 21\,280)$, where the values in parentheses give the uncertainty limits, and the prime indicates that the period is expressed in the nonrotating celestial system. An alternative method of estimation, similar to that applied for the determination of the Chandler wobble parameters, consists in extracting the freely excited FCN signal from the time series of the VLBI celestial pole offsets (Figure 2b) and fitting the resonance parameters. This estimation is considerably less accurate than that based on the indirect effect, and significantly less

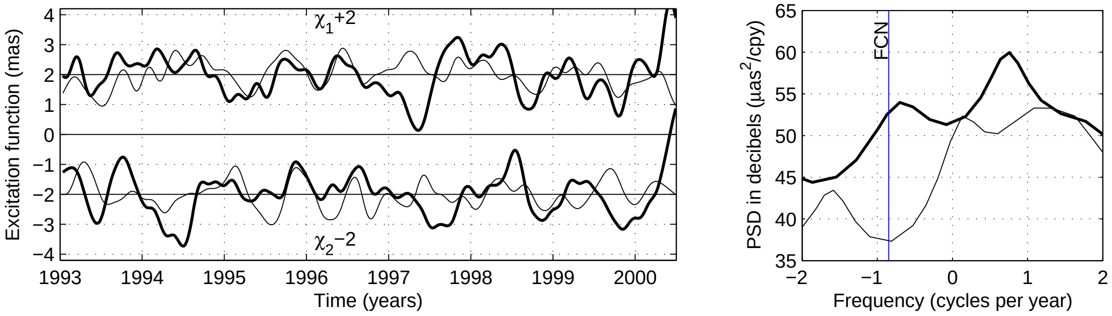

Figure 4. Comparison of the geodetic excitation of nutation (blue, thin) with geophysical excitation AAM+OAM (red, thick), in time domain (left) and in frequency domain (right) (from Brzeziński and Bolotin, 2006).

accurate than the corresponding procedure for the Chandler wobble (Brzeziński, 2005). Moreover, the result depends on the VLBI solution selected for the analysis and is sensitive to the initial reduction of the input series. Bolotin and Brzeziński (2005) analyzed eight individual solutions of the VLBI data analysis as well as two combined solutions, and estimated the FCN parameters from the maximum likelihood ARIMA modeling. The dispersion of estimates was quite large, between -435 and -418 days for the period and between 3000 and 14000 for Q. The best agreement with the indirect estimate was for the series `maotst01` (Bolotin, private communication): $T'_f = -431.0$ days $(418.8, 444.0)$, $Q_f = 7\,514 \quad (3\,870, 130\,400)$. Note, however, the large uncertainty limits of the last estimate.

Another part of research concerning the FCN is a search for the process, or for the combination of processes, that excites the free oscillation and maintains it against the energy dissipation. This can only be done by tracking the free signal observed by VLBI and comparing it to the geophysical excitation data. A simple algorithm of comparison, similar to that applied routinely in the excitation studies of the Chandler wobble, was proposed by Brzeziński (1994, 2006). The first step consists in computing the corresponding "geodetic" excitation from the time series of the celestial pole offsets observed by VLBI. The estimate of the geophysical excitation, such as the atmospheric and nontidal oceanic angular momentum (AAM, OAM) functions, should be sampled more frequently than 2 times per day. Before the comparison, the retrograde diurnal component of the excitation which influences nutation should be extracted by the so-called complex demodulation at frequency -1 cycle per sidereal day.

Preliminary results of the FCN excitation study were reported by Brzeziński and Bolotin (2006). Figure 4 shows a comparison between the excitation inferred from the VLBI data and that representing the aggregated influence of the dynamically coupled system atmosphere-oceans. The time domain comparison shows a rough agreement in size. The overall correlation is small, at the level of 0.2. However, when performing the sliding-window correlation analysis we could detect periods with high correlation, up to 0.8, but also periods with significant negative correlation. A comparison of the power spectral densities shows that geophysical excitation functions contain more power at the FCN frequency than needed to explain the observed signal, by a factor of about 30. The integration of cross-power spectrum in the vicinity of the FCN frequency, yields a high coherence magnitude, over 0.7. But surprisingly, the estimated argument of coherence is close to 180°, that is the geodetic and geophysical excitations are out of phase.

In conclusion we should say that the reported results concerning the atmospheric and oceanic excitation of the FCN, though promising in several aspects nevertheless have to be treated as preliminary. Such investigations should be continued using alternative subdiurnal estimates of the atmospheric and oceanic excitation of Earth rotation.

4. High Frequency Polar Motion

Polar motion contains high frequency signals which have been predicted from theory and, at least in some cases, confirmed by observations. The first group consists of the components associated with the atmospheric normal modes. These are the pseudoharmonic oscillations with the following standard codes, central periods and mean amplitudes:

ψ_3^1, retrograde period 10 days, amplitude up to 0.5 mas,
ψ_1^1, retrograde period 1.2 days, amplitude about 30 μas,
ξ_2^1, period about 0.6 days, amplitude of the order of 1 μas.

(Here by "mean amplitude" we understand square root of the total variance of oscillation). All those three components are clearly visible in the AAM data, but only ψ_3^1 could be detected so far in the space-geodetic observations of polar motion; see Brzeziński *et al.* (2002) for details.

The second group is a set of quasi diurnal and quasi semidiurnal harmonic terms with amplitudes up to 300 μas, excited by the ocean tides. The retrograde diurnal components of excitation contribute to nutation and have been taken into account in the conventional precession-nutation model IAU 2000 discussed in Sec.2. The remaining prograde diurnal and retrograde/prograde semidiurnal components contributing to polar motion are described by the model provided by the IERS Conventions 2003 (IERS, 2004; Tables 8.2a and 8.2b). In addition, there are also prograde diurnal terms in polar motion caused by the direct influence of the tidal gravitation on the triaxiality (that is inequality of the principal equatorial moments of inertia A and B) of the Earth; see Brzeziński and Mathews (2003) for an extensive discussion. This effect is considerably smaller than that due to the ocean tides—the maximum amplitudes are about 15 μas. Nevertheless the corresponding model is also included in the IERS Conventions 2003 (IERS, 2004; Table 5.1).

Finally, there are also high frequency variations in Earth rotation associated with the atmospheric thermal (radiational) tides S_1 and S_2. These are the diurnal and semidiurnal terms modified by the oceanic response to the atmospheric forcing. Among them only the effect of the Sun-synchronous S_1 term has been included in the IAU 2000 precession-nutation model in the form of a correction to the amplitude of prograde annual nutation. Our estimation of the atmospheric and nontidal oceanic contributions yielded the amplitudes of 9 μas for both diurnal prograde and semidiurnal polar motions (Brzeziński *et al.*, 2004).

Theoretical models of the ocean tide contributions to diurnal and semidiurnal polar motion could be constrained from VLBI observations by Sovers et al. (1993), Herring and Dong (1994), Gipson (1996). In addition, several special VLBI campaigns like CONT94, CONT02, CONT05, have been organized to estimate less regular high frequency geophysical signals in Earth rotation and compare them with the existing theoretical models.

But even from the routine VLBI observations with one session in 3 to 5 days, it is possible to determine quasi-periodical geophysical signals within diurnal and subdiurnal frequency bands. The method, proposed originally by Herring and Dong (1994) and further developed by Mathews and Herring (2000), Brzeziński (2000), relies upon the so-called frequency demodulation technique.

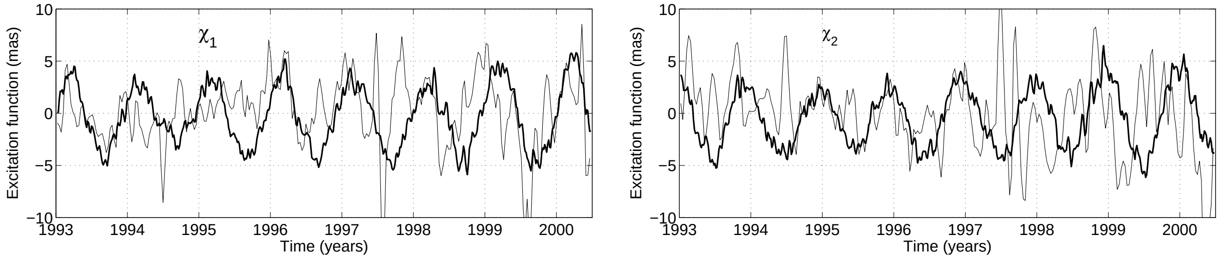

Figure 5. Excitation of the prograde diurnal polar motion by the dynamically coupled system atmosphere-ocean: geodetic excitation inferred from VLBI data (blue, thin) and AAM+OAM (red, thick). Data sets were taken from Kudryashova and Petrov (2006) and Brzeziński *et al.* (2004).

Kudryashova and Petrov (2006) applied this technique to estimate the prograde diurnal polar motion form 1989 to 2004. We converted this signal into the “geodetic” excitation function and compared it to the corresponding atmospheric and nontidal oceanic angular momentum data taken from Brzeziński *et al.* (2004); see Figure 5. Both signals are highly coherent which proves that the diurnal polar motion series estimated from the VLBI observations is a real physical signal. Our recent study (Bolotin and Brzeziński, 2006) described in detail the procedure of extracting the high-frequency (diurnal, semidiurnal, etc.) signals in polar motion and UT1 from the standard VLBI observations, which can be used for comparisons with the available geophysical excitation data.

5. Concluding Remarks

The VLBI observations provide important data sets for modeling changes in Earth rotation and for their geophysical interpretation. Currently, VLBI is the only technique for monitoring the motion of the celestial pole. The time series of the celestial pole offsets estimated from the VLBI observations are important for further improvements of the conventional precession-nutation model. This is also the only way of representing the irregular geophysical signals such as the free core nutation, which cannot be predicted perfectly. VLBI observations are also very useful for constraining the high frequency signals in Earth rotation, though not the whole potential of the technique has been utilized so far. It is extremely important for both practical reasons and the scientific studies concerning global dynamics of the Earth that VLBI continues its mission of monitoring the Earth orientation parameters on a regular basis. An optimal representation of the Earth rotation data would be achieved if the VLBI observing sessions could be conducted with daily spacing.

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