Part 6.

Daily and Subdaily Polar Motion

Gerhard Beutler, Yaroslav Yatskiv, Claudine Guinot, and Bernard Guinot

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Polar Motion with Daily and Sub-daily Time Resolution

G. Beutler and M. Rothacher

Astronomical Institute, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

J. Kouba

Geodetic Survey of Canada, 615 Booth Street, Ottawa, Ontario K1A 0E9, Canada

R. Weber

Department of Theoretical Geodesy, Technical University of Vienna, Gusshausstrasse 27-29, Vienna, A-1040, Austria

Abstract. Since 1992 the IGS ACs (International GPS Service Analysis Centers) have delivered daily estimates of polar motion (PM) and length of day (LOD) to the IERS (International Earth Rotation Service). The IGS combined PM and LOD series are available since January 1, 1995. Since June 1996 the IGS rapid and the final combined orbits are accompanied with two distinct IGS combined PM series with the same time resolution of one day. Both, the IGS final and rapid combined PM series also include combined PM rate data as well as LOD, starting in March 1997.

Since 1995 the CODE Analysis Center of the IGS has produced PM and LOD estimates with a two-hour time resolution on a routine basis. A study of the time series with sub-daily time resolution clearly shows the half-daily and daily tidal signals. The results correspond very well to those obtained from satellite altimetry.

These sub-daily time series are based on the same observational data from the IGS tracking network as those time series with a one-day time resolution. It would thus be possible with a minor analysis effort, *without* additional observational effort, to come up with a long and consistent series of PM and LOD with a time resolution of about 1 to 2 hours.

1. Introduction

We address the issue of establishing routine polar motion monitoring with a high time resolution using the GPS observation technique. With the advent of the International GPS Service (IGS), daily estimates for polar motion (x and y components of the pole on the surface of the Earth) and $UT1 - UTC$ drift estimates, or, what is equivalent, length of day (LOD) estimates, became readily available to the scientific community.

GPS-derived PM and LOD estimates are (at least) of the same accuracy as the corresponding estimates from other space geodetic techniques, in particular VLBI (Very Long Baseline Interferometry) and SLR (Satellite Laser Ranging). Other techniques, in particular VLBI, will hopefully soon start providing such time series (see, *e.g.*, (Clark *et al.* 1997)). In the case of VLBI this would be particularly interesting for maintaining the long-term stability of $UT1$.

In our review we focus on the GPS technique and refer to other space geodetic techniques only for comparison purposes. In section 2. we give an overview of the recent achievements of the IGS concerning Earth rotation monitoring. We refer to (Kouba *et al.* 1999) in this volume for an in-depth analysis of the PM and LOD series from individual IGS Analysis Centers and of the combined (official) IGS PM and LOD time series.

In principle it is easily possible to set up PM and LOD with a higher than daily time resolution. This was done at the CODE Analysis Center of the IGS. Since 1995 PM and $UT1$ parameters are set up with a 2-hour time resolution in the routine CODE solutions. The procedure is fully integrated into the CODE/IGS processing. The procedure and results based on a time series of about three years are given in section 3.

2. The International GPS Service and its ERP Series

2.1. Development and Structure

Towards the end of the 1980s it became clear that for regional and global high accuracy applications of the Global Positioning System (GPS) in the fields of geodesy, geodynamics, and fundamental astronomy, the orbit accuracy was the crucial factor limiting the accuracy. This was the primary motivation for the creation of the IGS, the International GPS Service.

The IGS Call for Participation in 1991 (Mueller 1992) fostered contributions in the areas *Network, Data Centers, (Associate) Analysis Centers, Analysis Coordination, and Central Bureau.* Basically, this structure still is in place today. There are in particular seven IGS Analysis Centers, eight for the IGS rapid products, three global data centers plus a number of regional data centers, and, last but not least, around 200 IGS stations.

Figure 1 gives an impression of the IGS network as of July 1999. It is an achievement in itself that daily observation files from such a rich global GPS tracking network are readily available for each day over a time period of more than seven years. All IGS sites are equipped with geodetic-type GPS receivers tracking all satellites in view, with at least 30-sec measurement sampling.

The Jet Propulsion Laboratory (JPL) serves as the IGS Central Bureau since the creation of the IGS. A vital element of the Central Bureau is CBIS, the Central Bureau Information System. The current IGS structure (including all the changes made by the end of 1998) is very well documented in this Information System (accessible though internet `http://igscb.jpl.nasa.gov/`) where, *e.g.*, a general description of all IGS components, all participating agencies, the currently valid Terms of Reference, *etc.*, may be found. Additional information concerning the development of the service may be found, *e.g.*, in Beutler *et al.* (1996).

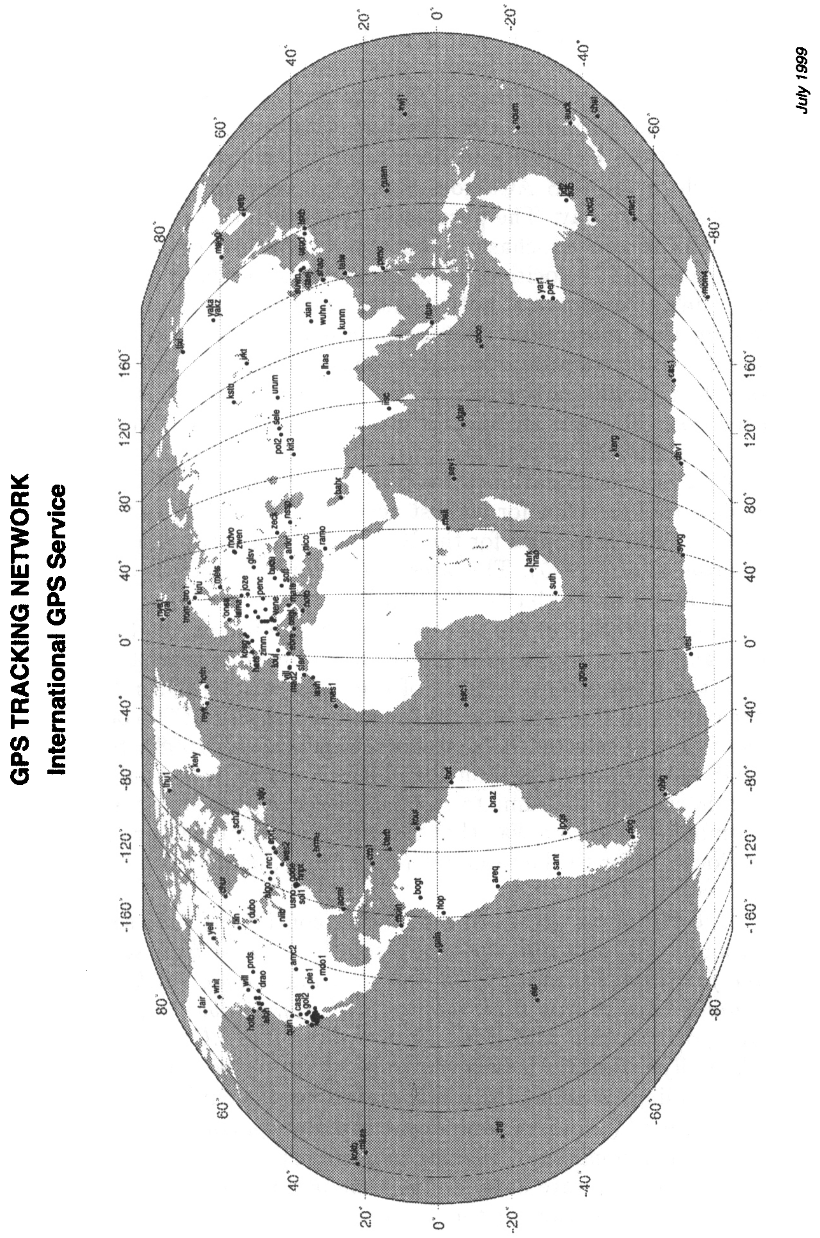


Figure 1. The IGS Global Tracking Network (July 1999).

2.2. Polar Motion Analysis within the IGS

Seven analysis centers (AC) deliver so-called final products and eight deliver so-called rapid products. The final products are available after 10 days, the rapid products after about 17 hours. The work of the IGS ACs is coordinated by the *IGS Analysis Coordinator.* Till the end of 1998 Natural Resources Canada (NRCan) was acting as Coordinating Center for the IGS. The Astronomical Institute of the University of Bern assumed this role starting January 1, 1999.

Each of the IGS ACs goes through a very complex parameter estimation procedure every day. The parameter types include orbit parameters (deterministic and (pseudo-)stochastic), Earth rotation and orientation parameters, site coordinates and "velocities," satellite and receiver clock parameters, troposphere zenith delay parameters, initial phase ambiguity parameters, *etc.* It is not uncommon that more than 2000 parameters are estimated in a daily estimation process — not counting the initial phase ambiguity parameters (there may be more than 10,000 parameters of this type per process). There are by definition correlations between all parameters, and it is not a trivial affair to guarantee full consistency of all results.

Analysis coordination proved to be a vital stimulus for IGS analysts and the ideal tool to strive for highest accuracy, reliability, and compatibility of IGS products. The principles for the IGS Analysis Coordination were first presented in Beutler *et al.* (1995). The latest review of IGS analysis coordination activities may be found in Kouba *et al.* (1998).

The realization of the terrestrial reference frame, the Earth rotation parameters, and the orbits in principle have to be fully consistent. It is IGS policy to use the most recent versions of the ITRF as the IGS reference frame. Since March 1998 all IGS products were based on the ITRF96 coordinates and velocities of 47 well-selected IGS stations (Kouba *et al.* 1998). Since August 1, 1999 all IGS analyses are based on the ITRF97. As all IGS Analysis Centers are now using, in essence, the same terrestrial reference frame their orbits and EOPs may be combined in such a way that the resulting combined products (orbits, EOPs, and clocks) refer to the same reference frame, namely the IGS realization of the most recent ITRF.

The IGS gives access to the longest continuous time series of polar motion (x, y and LOD) with one-day time resolution. *These time series are of the highest value for the years since 1992 and they are unique in the sense that no other technique coverer this time interval with comparable time resolution.* Figure 2 shows polar motion as derived by one of the IGS ACs since 1993. The accuracy of the daily estimates is believed to be of the order of 0.1 mas (milliarcseconds) corresponding to about three millimeters on the surface of the Earth.

Figure 3 (χ_1 and χ_2 component top row, χ_3 component bottom, left) shows the three components of angular momentum computed from IGS polar motion and polar motion rate data for the time period December 1997–November 1998 and a power spectrum of the χ_3 component (bottom, right, periods up to 40 days). The usual dimensionless representation in units of 10^{-7} are used in Figures 3. In the same figures we see the corresponding angular momentum time series as retrieved from the IERS Sub-bureau for atmospheric angular momentum (AAM). The high degree of correlation between the two time series is obvious.

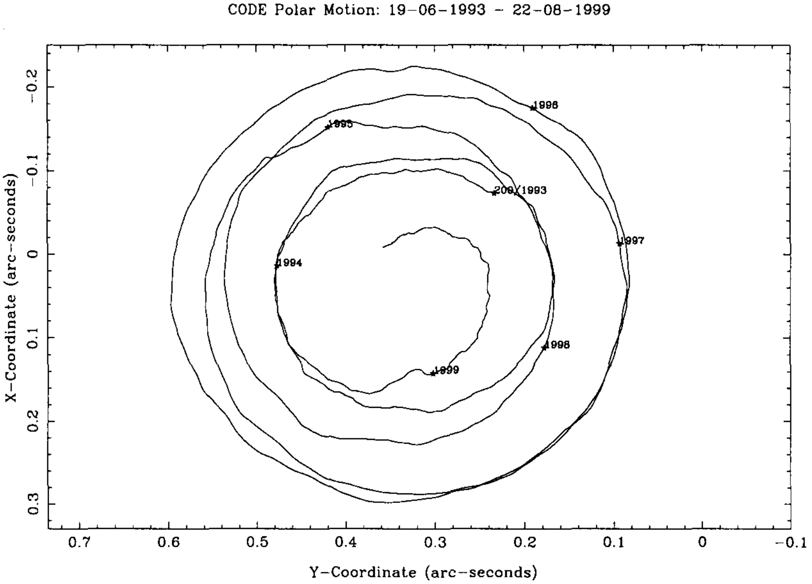


Figure 2. Polar Motion as recorded by the IGS since 1993.

According to our opinion these IGS time series are not yet fully exploited for geodynamics purposes. We refer to (Kouba *et al.* 1999) for more information.

2.3. The IGS as an Interdisciplinary Service

In recent years the IGS, and in particular its network, were more and more (ab)used for purposes which were no longer purely geodesy or geodynamics related. Let us mention the use of the IGS network for ionosphere monitoring, for troposphere calibration, for GLONASS orbit determination, and for time transfer. Activities related to these topics were set up or organized in IGS working groups or pilot projects, some of them being joint groups with other organizations such as BIPM (Bureau International des Poids et Mesures) or CSTG (IAG Commission VIII on the International Coordination of Space Techniques for Geodesy and Geodynamics). It is thus fair to state that the IGS moved into the direction of an interdisciplinary service. For an overview of (almost) all IGS activities we refer to Beutler *et al.*, (1999).

3. Analysis of the CODE Polar Motion Time Series with 2-Hour Time Resolution

In March 1996, the Center for Orbit Determination CODE (a cooperation of the Astronomical Institute, University of Berne (Switzerland), the Swiss Federal Office of Topography, Wabern (Switzerland), the Bundesamt für Kartographie und Geodäsie, Frankfurt (Germany), and the Institut Géographique National, Paris

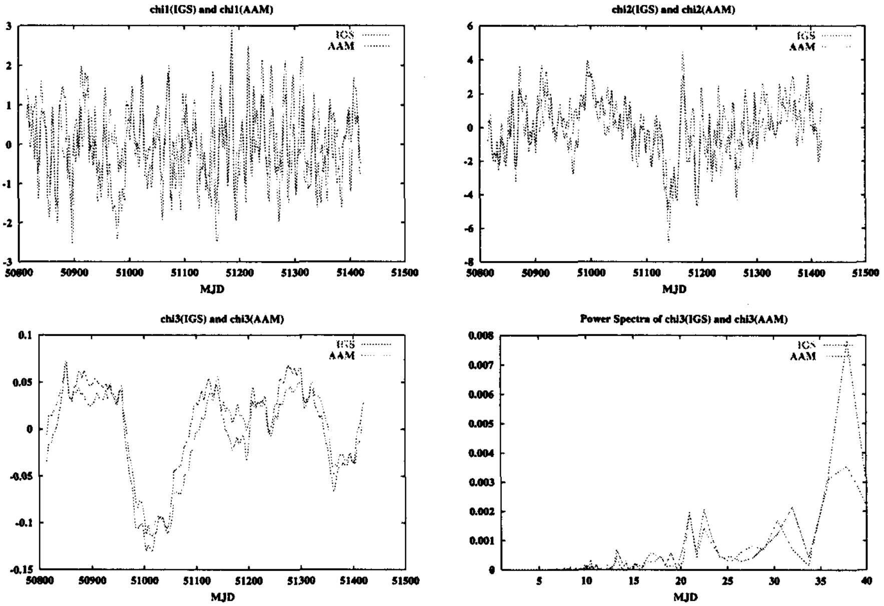


Figure 3. Angular momentum computed from IGS Polar Motion (and PM rate) compared to the Atmospheric Angular Momentum (AAM).

(France)) started to estimate sub-daily (2-hourly) Earth rotation parameters (ERPs) on a routine basis, using the GPS data of the global IGS network.

With a reprocessing effort the series was extended backwards in time to January 1995, which means, that by now an uninterrupted ERP series with a time resolution of two hours is available that covers about four years. So far, these series are unique. At present, VLBI and SLR cannot produce comparable series because of the limited amount of observations. In the case of VLBI, continuous 24-hour observation session covering many consecutive days are available from a few special experiments like, *e.g.*, CONT94, CONT95, and CONT96.

Authors deriving sub-daily Earth rotation parameters from GPS data were concentrating on intensive campaigns of one or two weeks (*e.g.*, from GIG'91 (Lichten *et al.* 1992), Epoch'92 (Freedman *et al.* 1994), CONT'94 (Weber 1996)). Such investigations showed that the high-frequency variations of Earth rotation due to ocean tides indeed may be monitored by GPS. The time spans analyzed were, however, much too short to allow for the estimation of ocean tide amplitudes or a model for sub-daily ERP variations from GPS data.

Let us briefly review the analysis performed by (Rothacher 1998) based on three years of the CODE 2-hour series. More information and an extension of this analysis may be found in (Weber *et al.* 2000) in this volume.

3.1. The GPS Observations

The GPS data used in this analysis are from the global IGS network and include 40 to 90 sites of the global network in Figure 1. The sites are well-distributed and form a very stable reference frame for the determination of Earth Rotation Parameters (ERPs).

The time interval considered starts on January 2, 1995 and ends on February 14, 1998, covering a period of 1140 days. Using Version 4 of the Bernese GPS Software (Rothacher and Mervart 1996) and double-difference phase observations, global 3-day solutions were computed for each day in this time interval. By computing overlapping 3-day solutions, 3-day satellite arcs (only one set of initial conditions per satellite for three days) could be set up. The results (ERP and other parameters) from the middle days of each 3-day solution were extracted to form a continuous series of ERPs, satellite positions, *etc.*

With a considerable increase in the number of sites and observations since the start of the series, with lowering the satellite elevation cut-off angle from 20° to 10° in October 1997, and with many software improvements, one may expect a significant quality gain of the CODE ERPs series as a function of time.

The routine processing scheme at CODE saves the normal equation systems (NEQS) of the 3-day solutions. The NEQS contain (among other) site coordinates, ERPs with a two-hour time resolution, and geocenter coordinates. The ERP series could therefore be generated starting from NEQ files without reprocessing actual observations.

3.2. The Analysis Strategy

Earth Rotation Parameters. For the entire set of 1140 3-day solutions the normal equation files were saved with a 2-hour temporal resolution for EOPs by the normal CODE processing scheme. Offsets and rates for all five components of Earth orientation, namely the x- and y-pole coordinates, the difference $UT1-$

UTC, and the nutation corrections $\Delta\epsilon$ and $\Delta\Psi$ in obliquity and longitude, were set up for each 2-hour time interval.

Starting from these normal equations, different solution types may be produced depending on the constraints put on the Earth orientation components. To generate the sub-daily ERP series, continuity was enforced at the boundaries of the 2-hour intervals, *i.e.*, the components of Earth rotation were represented as piece-wise linear functions over three days. Nutation parameters were not considered in this analysis.

PM may be determined in an absolute sense using GPS data. Because $UT1$ is fully correlated with the orbital elements of the satellites, the $UT1 - UTC$ offset referring to the start of the first 2-hour interval of each 3-day solution had to be constrained to an *a priori* value (taken, *e.g.*, from one of the IERS series). The rate of change of $UT1$, or length of day (LOD) variation, is accessible to GPS. All results and computations concerning $UT1$ are thus based on LOD (or $UT1 - UTC$ drifts).

Due to correlations of the GPS orbital elements with the retrograde diurnal PM terms, the retrograde diurnal part of the PM spectrum is not accessible to the GPS. Using a special technique described in (Hefty *et al.* 1999) the retrograde diurnal band was constrained to the *a priori* setting.

Other Parameters. Each 3-day satellite arc is represented by one set of initial conditions (position and velocity vector at the start of the interval), by one set of radiation pressure parameters, and by pseudo-stochastic pulses (small changes in the satellite's velocity) (Beutler *et al.* 1996). Such pulses were introduced in the along track and radial direction every 12 hours, *i.e.*, five times in a 3-day interval. For satellites that were difficult to model on specific days, the 3-day arc was split up at the day boundaries into 2 or even 3 arcs).

The CODE radiation pressure model in its general form is defined in Beutler *et al.* (1994). It consists of a total of 9 parameters. Different combinations of parameters were estimated in the three years time interval considered. The inhomogeneity of the orbit modeling is thus an important issue of our detailed analysis (Rothacher 1998).

The realization of the reference frame (either by constraining a number of stations to their ITRF positions or by imposing no-net rotation conditions on a set of station coordinates) and the models used for solid Earth tides and ocean loading may influence the estimated ERPs. The impact of these modeling issues on ERPs is discussed by Rothacher (1998).

The amplitude spectra generated from the entire series are given in Figures 4 for the diurnal and semidiurnal, prograde and retrograde frequency bands. The main tidal constituents (labeled in the usual way) are easily seen and lead us to expect that coefficients of excellent quality may be derived from the CODE 2-hour data set. The $UT1$ rate spectra were converted into $UT1$ spectra by dividing the spectral rate amplitudes by the corresponding circular frequency as described by Rothacher *et al.* (1999).

The polar motion spectra exhibit a noise level of about 5–10 μas, those of $UT1$ a level of 0.5–1.0 μs. This gives a first indication of the achievable precision when estimating tidal amplitudes. The series is still far too short, however, to give insight into the problem of the sidebands of the major tides.

The retrograde diurnal part of the polar motion spectrum has only been added for completeness and will not be discussed below. We observe that the retrograde diurnal band was successfully suppressed.

3.3. Tidal Analysis

The driving force behind ocean tides and thus behind most of the high-frequency variations in Earth orientation is the gravitational attraction exerted by the Sun and Moon. The tidal potential generated by the Sun and Moon deforms the Earth and changes ocean heights and ocean currents, which, in turn, cause variations in polar motion and $UT1$. In the frequency domain the tidal potential may be expressed as a series of discrete tides:

$$\begin{aligned} \Delta X(t) &= \sum_{j=1}^{n} \left(-p_j^c \cos\phi_j(t) + p_j^s \sin\phi_j(t)\right), \\ \Delta Y(t) &= \sum_{j=1}^{n} \left(p_j^c \sin\phi_j(t) + p_j^s \cos\phi_j(t)\right), \\ \Delta UT1(t) &= \sum_{j=1}^{n} \left(u_j^c \cos\phi_j(t) + u_j^s \sin\phi_j(t)\right), \end{aligned} \tag{1}$$

where ΔX, ΔY, and $\Delta\ UT1$ are the tidal variations in the x- and y-component of polar motion and in $UT1$, respectively. n is the number of tidal constituents considered. p_j^c and p_j^s are the cosine and sine amplitudes of the tidal variations in polar motion, u_j^c and u_j^s the corresponding amplitudes in $UT1$. The angular argument $\phi_j(t)$ denotes a linear combination of the five fundamental astronomical arguments F_i $(i = 1, 2, \ldots, 5)$ and of $F_6 = \theta + \pi$ (θ stands for the Greenwich mean sidereal time).

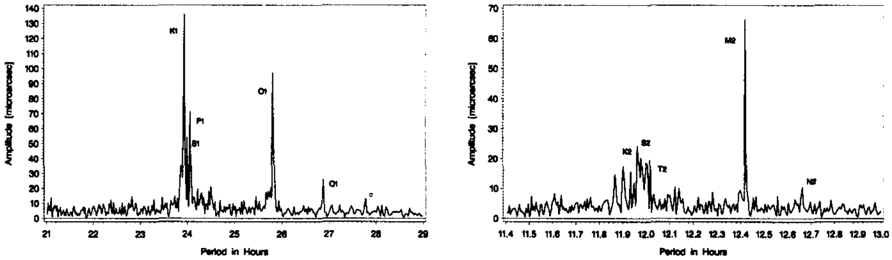
We decided to estimate the same set of tidal amplitudes from the 2-hour ERP series as the one selected and determined by Gipson (1996) using VLBI data from 17 years. It includes all tides with an amplitude larger than 5 mm in the tidal potential.

The estimation of the coefficients p_j^c, p_j^s, u_j^c, and u_j^s in Eqn. (1) for the selected tides was performed using a least-squares algorithm introducing the 2-hour polar motion and $UT1$ rate estimates of the global ERP series (after removing the low-frequency part). In order to estimate the $UT1$ amplitudes directly from $UT1$ rates the time derivative of the third of Eqns. (1) was used in the least squares procedure:

$$\frac{d}{dt}\Delta UT1(t) = \sum_{j=1}^{n} \omega_j \cdot \left(-u_j^c \sin\phi_j(t) + u_j^s \cos\phi_j(t)\right). \tag{2}$$

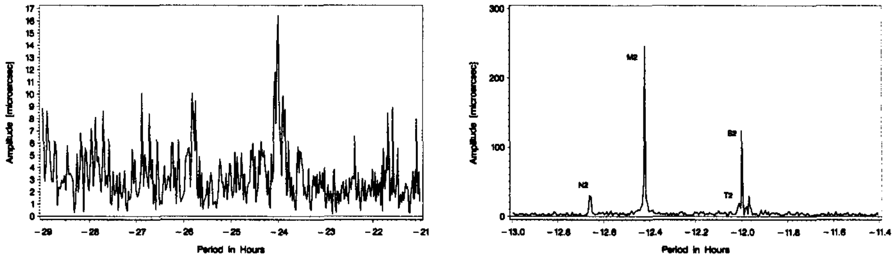
We use the $UT1$ rates because only these may be determined by GPS measurements, but not $UT1$ itself. We thus avoid the problem of having to remove a random walk from a GPS-derived $UT1$ series. Simultaneously with the tidal amplitudes we always determined an offset and drift for all three ERP components over the entire series analyzed to remove systematic offsets or drifts present in the sub-daily ERP series.

Because the sub-daily ERP series currently available from GPS are much too short to estimate the major tides together with their sidebands (*e.g.*, K_1,



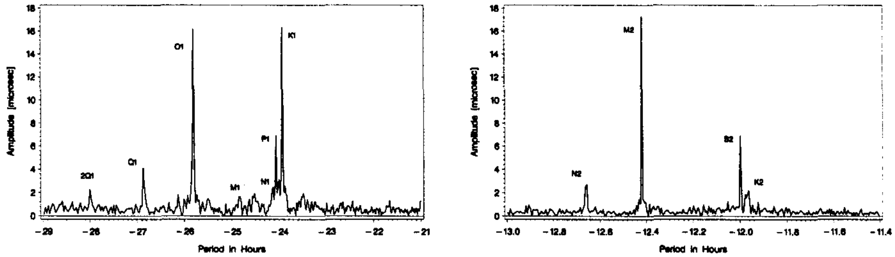
(a) Diurnal prograde polar motion

(b) Semidiurnal prograde polar motion.



(c) Diurnal retrograde polar motion (nutation).

(d) Semidiurnal retrograde polar motion.



(e) Diurnal $UT1$.

(f) Semidiurnal $UT1$.

Figure 4. Amplitude spectra of the diurnal and semidiurnal tidal frequency bands generated from the entire sub-daily ERP series. The $UT1$ spectra were computed from the $UT1$ rate estimates and subsequently converted to spectra in $UT1$. (Note that the spectra are drawn with different scales.)

K_1', and K_1''), we implemented the option to constrain the ratio of the sideband amplitude and the amplitude of the major tide as described in Gipson (1996).

The formal errors $\sigma(p_j^c)$, $\sigma(p_j^s)$, $\sigma(u_j^c)$, and $\sigma(u_j^s)$ of the tidal coefficients to be expected from a least-squares algorithm may be estimated by using the simple formulas developed in Rothacher *et al.* (1999). It is important to note that the expected formal errors are inversely proportional to the square root of the length of the series and that in the case of $\Delta\ UT1$ the formal error is also proportional to the period of the estimated terms. Short period terms are thus better established than long period terms. When only considering daily or half daily terms the issue is not important (in view of the length of the series).

The result of the tidal analysis may be summarized as follows:

- A maximum of 57 tidal terms in PM and 41 in $UT1$ could be determined. Various tests (sampling of the 2-hour series, weighting the ERP estimates according to their formal errors, different orbit models, *etc.*) have shown that the GPS-internal consistency of the estimated tidal amplitudes is of the order of 1 μs in $UT1$ and 10 μas in PM, with maximum differences between GPS solutions of about 3 μs and 25 μas.

- Comparing the best tidal amplitude estimates from GPS with the best estimates from VLBI and SLR (based on about 17 years of data), we find an agreement of all three space-geodetic techniques on the level of about 1 μs in $UT1$ and 10 μas in PM rms differences in the tidal coefficients.

- The agreement of the GPS results with ocean tide models derived from altimeter data is 9–12 μas in PM and 0.7–0.9 μs in $UT1$.

- One can thus safely conclude that GPS is capable of contributing with comparable quality as VLBI and SLR to the establishment of high-frequency variations in the Earth's rotation.

- The impact of orbit modeling biases on the sub-daily ERP series is a crucial issue and is one of the accuracy limiting factors for the determination of diurnal and semidiurnal tidal amplitudes with GPS. Periods close to 12 and 24 hours are particularly critical, because the satellites revolve around the Earth in 12 sidereal hours and orbit errors typically vary periodically with the revolution period.

- The GPS sub-daily ERP series analyzed are still far from being perfect. The increase in the quality of the series over time due to significant changes in processing and modeling (orbit model extension, inclusion of low-elevation data, *etc.*) makes it clear that a reprocessing of the earlier GPS data using the most recent processing strategy would be extremely beneficial and should be undertaken as soon as possible.

- Further improvements of the series may be expected from a higher time resolution of, *e.g.*, one hour for the ERP estimates, the use of an ocean loading model for the stations' motion, and the estimation of a larger number of troposphere zenith delays per site and day than the four parameters presently set up at CODE.

3.4. Non-Tidal Variations in Earth Rotation

Because the GPS series consist of continuous 2-hour values since the beginning of 1995, it is easily possible to generate detailed spectra of the series (like those shown in Figure 4) and to look for non-tidal signals. It is of course preferable to remove the estimated tidal model first in Figures 4 and to analyze the residual spectrum. This was done in Rothacher (1998). The findings may be summarized as follows:

- There is a considerable amount of power left in the spectra close to one and two cycles per day (cpd). A peak of about 55 μas is present at a period of 23.92 hours, just below the K_1' sideband. The resolution of the spectrum at these periods is about 0.02 days.
- Similar peaks may also be seen in the semidiurnal band, in particular around the large M_2 tide. The power near these major tides is just too far away to be absorbed by either the tides or the sidebands estimated. Possible explanations for the residual signals are atmospheric tides and ocean normal modes. The true reason for these "lines" is not clear yet.
- Much care has to be taken when interpreting these non-tidal residual effects. We have seen in particular that orbital effects (typically with a period of 12 hours) might be responsible for the signals seen in the immediate vicinity of the 12- and 24-hour periods.
- There is also additional power near the M_2 tide with a period neither commensurate with the orbital period nor with the 1-day solution sampling nor with the 2-hour ERP or 6-hour troposphere binning intervals. This may be seen as an argument that the signals are real.

4. Summary and Conclusions

In Section 2. we briefly summarized the regular contributions of the IGS to Earth rotation. Daily estimates of polar motion and of length of day are a very important input to the IERS.

In Section 3. we outlined an analysis based on a three years time series of PM and LOD. This time series could be used to estimate the sub-daily tidal motion of the pole and the sub-daily variations of LOD. We have seen some indications for non-tidal constituents in these time series.

Time series with 1–2 hour temporal resolution for Earth rotation monitoring could in principle be "easily" set up by IGS and other Analysis Centers. We believe that there is a wealth of information in such time series. We hope that the IERS will encourage the establishment of such series and will start exploiting the existing material in the near future.

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Barbara Kołaczek