CONTRIBUTION OF THE GPS TO MONITOR EARTH ORIENTATION PARAMETERS

Weber Robert (1), Rothacher M. (2), Beutler G. (3)
(1) Institute of Geodesy and Geophysics, TU-Vienna
(2) Research Facility of Satellite Geodesy, TU-Munich
(3) Astronomical Institute, University of Berne

Abstract

In February 1994 CODE, one of the seven analysis centers of the IGS, started to derive nutation rates in addition to the routinely estimated polar motion and UT1-UTC rates. In 1999, a set of nutation amplitude corrections for 34 periods with respect to the IERS96 model as well as to the IAU80 model was presented in (*Rothacher et al., 1999*) based on 3.5 years of data. It has been demonstrated that GPS is especially sensitive to periods up to about 20 days. This paper deals with an update of the published amplitude corrections by taking into account the most recent observation data.
Additionally the quality of currently available subdaily polar motion series as well as the consequences of changes in processing and orbit modeling, which may impair the consistency of the series over time, will be discussed briefly.

Introduction

GPS data has proven to be a valuable source for the computation of accurate polar motion (PM) series. The series are of high quality mainly because of the uninterrupted coverage with observation data and the more or less regular distribution of the active IGS tracking sites (*Neilan, 1998*). In this context (*Kouba et al.,1999*) give a comprehensive description of IGS combined and contributed daily ERP solutions, considering in special AAM/ERP correlation studies and comparisons of combined OAM and AAM with excess PM rates.

Since 1995 the CODE Analysis Center produces besides the regular daily submissions PM- and LOD-estimates with a two hour time resolution. This sub-daily series, calculated from the same IGS observational data as the time series with one day resolution, are extremely suitable for studying half-daily and daily tidal signals. Based on about 3 years of data (*Rothacher et al., 2000*) have determined 57 tidal terms in PM and 41 in UT1 with an internal consistency of the estimated amplitudes in the order of 1μs in UT1 and 10μas in PM. The agreement of the GPS results with ocean tide models derived from altimeter data is at the same level. The chapter Subdaily Polar Motion below will focus on aspects related to the consistency of these series over the past years.

Nutation

In contrast to polar motion the estimation of corrections to the apriori nutation model ($\delta\Delta\varepsilon$, $\delta\Delta\psi$) was uniquely reserved to VLBI in the past. Satellite techniques used to determine UT1-UTC rates (LOD) at the most. (*Rothacher et al., 1999*) have shown, that there is no reason to discriminate between the estimation of the former and the latter quantities. Offsets in UT1-

UTC and in nutation are correlated with the orbital elements and unmodeled orbit perturbations lead to systematic errors in the rate estimates of both parameter types.

$$\begin{aligned} \Delta(UT1-UTC) &= -(\Delta\Omega + \cos i \cdot \Delta u_o)/k \\ \delta\Delta\varepsilon &= \cos\Omega\cdot\Delta i + \sin i\cdot\sin\Omega\cdot\Delta u_o \\ \delta\Delta\psi\cdot\sin\varepsilon_o &= -\sin\Omega\cdot\Delta i + \sin i\cdot\cos\Omega\cdot\Delta u_o \end{aligned} \qquad (1)$$

(Ω ...right ascension of the ascending node, u_o ...argument of latitude at the osculation epoch, i ... inclination of the orbit, k...ratio of universal time to sidereal time)

We may parameterize corrections in nutation, e.g. in obliquity, with respect to the reference model as piece-wise linear functions

$$\delta\Delta\varepsilon = \delta\Delta\varepsilon_0 + \dot{\delta\Delta\varepsilon}(t-t_0) \qquad (2)$$

enforcing continuity at the interval boundaries. Due to equations (1) $\delta\Delta\varepsilon_0$ has to be constrained to the reference model (IAU 1980, IERS96), but $\dot{\delta\Delta\varepsilon}$ may be freely estimated. To obtain corrections in the nutation amplitudes $A_{ij}^{\varepsilon}, A_{oj}^{\varepsilon}$, the quantity $\delta\Delta\varepsilon$ can be represented as

$$\delta\Delta\varepsilon(t) = \sum_{j=1}^{n} A_{ij}^{\varepsilon}\cos\theta_j(t) + \sum_{j=1}^{n} A_{oj}^{\varepsilon}\sin\theta_j(t) \qquad (3)$$

and the first derivative as

$$\dot{\delta\Delta\varepsilon}(t) = -\sum_{j=1}^{n} A_{ij}^{\varepsilon}\sin\theta_j(t)\frac{\partial\theta_j}{\partial t} + \sum_{j=1}^{n} A_{oj}^{\varepsilon}\cos\theta_j(t)\frac{\partial\theta_j}{\partial t} \qquad (4a)$$

For the nutation in longitude, of course, a similar relation holds

$$\dot{\delta\Delta\psi}(t) = -\sum_{j=1}^{n} A_{oj}^{\psi}\sin\theta_j(t)\frac{\partial\theta_j}{\partial t} + \sum_{j=1}^{n} A_{ij}^{\psi}\cos\theta_j(t)\frac{\partial\theta_j}{\partial t} \qquad (4b)$$

The θ_j denote a linear combination of the Delaunay variables and n the number of waves in consideration. The A_i, A_o are usually called in-phase and out-of-phase components. Advantageously these numbers may be converted to prograde and retrograde circular amplitudes. For details see (*Defraigne et al., 1995*).

The results given below are based on 1765 daily trend-reduced nutation rate estimates covering the period from April 1994 till March 1999. The formal errors of these nutation rates were about $25\mu as/d$ ($\dot{\Delta\varepsilon}, \dot{\Delta\psi}\sin\varepsilon_o$). The orbit models in use during this time span characterize the satellite motion (3-day arcs) by a set of initial conditions, one set of radiation pressure coefficients and by pseudo-stochastic pulses once per revolution in radial and along track direction.

Till the end of 1996 solar radiation pressure has been parametrized only by a direct radiation pressure coefficient and the y-bias. Afterwards three constant terms (direct, y-bias, x-bias) and periodic terms in x-direction were included in the estimation process. (*Springer et al., 1998*) have shown, that the selection of such a parameter-subset optimizes the orbit quality and the quality of the UT1-UTC rate estimates. Tentatively we may deduce, that the effects of mismodeled radiation pressure parameters on the orbital elements are either short periodic perturbations (f(u_o); revolution period) or long term variations with annual and semi-annual character. These variations are not critical for monitoring nutation terms with periods below 30 days, but the former may be critical for LOD.

Due to the fact, that retrograde diurnal PM is geometrically equivalent to nutation, it is impossible to solve for both simultaneously. Thus, to overcome the singularity, amplitudes of PM terms within this frequency range were constrained to zero.

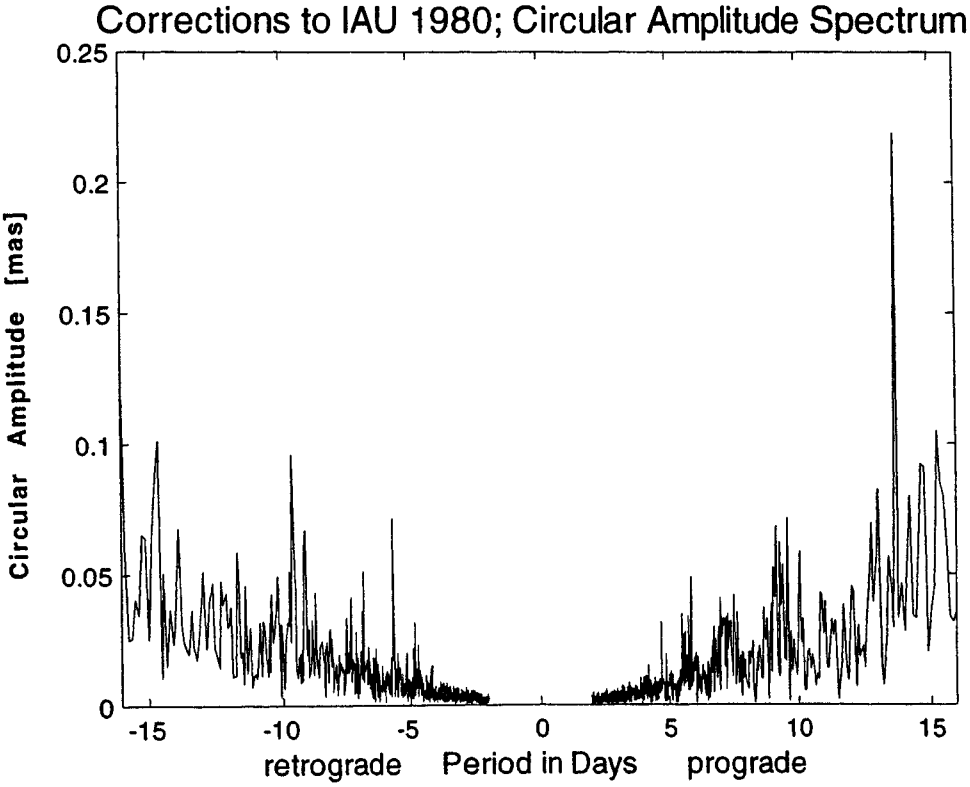

Figure 1

Figure 1 shows the spectrum of circular nutation amplitude corrections with respect to the IAU 1980 model obtained from the rate amplitude spectrum by using the conversion factor $1/\omega_j = T_j/2\pi$. Afterwards, amplitude corrections were determined by a least square algorithm for 20 periods and listed in Tables 1a,b below (label CODE99). The weighted rms of the resulting post-fit residuals of the nutation rate corrections ($\Delta\dot{\alpha} \hat{=} \Delta\dot{\varepsilon}; \Delta\dot{\psi}\sin\varepsilon$) of $\sigma_{\Delta\dot{\alpha}} = 0.3\, mas/d$ indicates that the formal errors of the GPS estimation (see above) are not really representative.

For comparison the IERS96 model and CODE98 solution are given as well. CODE98 refers to (*Rothacher et al., 1999*) who presented amplitude corrections both in obliquity and in longitude for 34 terms based on 3.5 years of data.

Table 1a: Nutation Amplitude Corrections in $\Delta\varepsilon$ relative to the IAU 1980 Model
(units: 0.001 mas)

Argument	Period	CODE99		CODE98		IERS 96
	days	cos / sin	stdev	cos / sin	stdev	cos / sin
2 0 2 2 2	4.68	+31/ *	8	+34/ 0	8	+47/ 0
0 0 2 4 2	4.79	+24/ *	8	+28/ 0	8	+29/ 0
3 0 2 0 1	5.49	*/ *	9	+21/ 0	9	+24/ 0
1 0 2 2 2	5.64	+49/ *	9	+14/ 0	10	+25/ 0
1 -1 2 2 2	5.73	+28/ *	10	+27/ 0	10	+25/ 0
-1 0 2 4 2	5.80	-27/ *	10	-10/ 0	10	-34/ 0
0 0 2 2 2	7.10	+21/ *	12	+62/ 0	12	+43/ 0
-2 0 2 4 2	7.35	-44/ *	12	-31/ 0	13	-48/ 0
3 0 2 -2 2	8.75	-46/ *	15	-48/+18	15	-40/ 0
-1 0 4 0 2	9.06	-23/ *	16	-34/+19	16	-49/ 0
1 0 2 0 1	9.12	-85/ *	16	n.e.		-65/+8
1 0 2 0 2	9.13**	0 / +35	16	+20/+34	16	0 /+35
-1 0 2 2 2	9.56	-41/ +18	16	-36/+20	17	-46/+7
1 0 0 2 1	9.63	+73/+28	17	+32/+27	17	+49/ 0
0 0 2 0 1	13.63	+89/+33	34	n.e.		+76/+32
0 0 2 0 2	13.66**	+164/+136	27	+125/+115	24	+164/+136
0 -1 2 0 2	14.19	-34/ +67	24	0 /+60	25	0 / 0
-2 0 2 2 2	14.63	+65/ -62	25	+52/ -39	26	+40/ 0
0 0 0 2 2	14.77	+94/ *	25	+80/ *	26	+75/ 0*

Table 1b: Nutation Amplitude Corrections in $\Delta\psi$ relative to the IAU 1980 Model
(units: 0.001 mas)

Argument	Period	CODE99		CODE98		IERS 96
	days	sin / cos	stdev	sin / cos	stdev	sin / cos
0 0 2 4 2	4.79	+49/*	14	+42/+25	20	+ 29/ 0
3 0 2 0 1	5.49	-31/ *	15	-31/ *	23	+ 24/ 0
1 0 2 2 2	5.64	+89/*	17	+67/ *	24	+ 32/ 0
1 -1 2 2 2	5.73	-52/+31	18	-49/+38	25	- 59/ 0
-1 0 2 4 2	5.80	+75/*	18	+27/ *	25	+ 49/ 0
2 1 2 0 2	6.73	+22/+29	21	* / *	29	+ 40/ 0
0 1 2 2 2	6.96	+41/+29	21	+44/ *	30	+ 54/ 0
0 0 2 2 2	7.10	-69/ *	22	-83/ *	31	- 54/ 0
0 -1 2 2 1	7.23	-40/ *	22	n.e.		- 44/ 0
1 0 2 0 1	9.12**	-65/*		n.e.		- 65/ 0
1 0 2 0 2	9.13	-26/+58	38	-31/+51	40	- 37/+77
-1 0 2 2 2	9.56	-60/ *	29	-61/ *	42	- 65/ 0
0 1 2 0 2	13.17	+97/*	40	+66/ *	57	+ 57/ 0
0 0 2 0 1	13.63	-171/+48	50	n.e.		-152/+37
0 0 2 0 2	13.66**	-320/+269		-284/+272	61	-320/+269
-2 0 2 2 2	14.63	+70/-162	45	+223/-124	65	+ 39/ 0

* ... estimates below one sigma uncertainty
** ... constrained to IERS 1996 value
n.e. ... not estimated

Discussion

We find no drastic differences in the amplitudes of the CODE solutions (except in the 14.63 term in $\Delta\psi$, which is still unsatisfactory). This implies that the solution becomes more and more stable due to the extended time interval. The formal errors of the coefficients in Tables 1a and 1b basically follow the rule

$$\sigma_G = \sigma_{\Delta\dot{\alpha}} \cdot \sqrt{\frac{2}{m}} \cdot \frac{1}{\omega_j} \qquad (5)$$

$\sigma_{\Delta\dot{\alpha}}$ ... rms of post-fit residuals of the nutation rate corrections

m ... number of nutation rate estimates

With m=1765 and $\sigma_{\Delta\dot{\alpha}} = 0.3\,mas/d$ we find $\sigma_G = 0.0016 \cdot T_j\ mas$. In contrast to equation (5) the formal errors of amplitude corrections computed from VLBI data (σ_V) do not show this dependence on the frequency (see Figure 2).

$$\sigma_V = \sigma_{\Delta\alpha} \cdot \sqrt{\frac{2}{m}} \qquad (6)$$

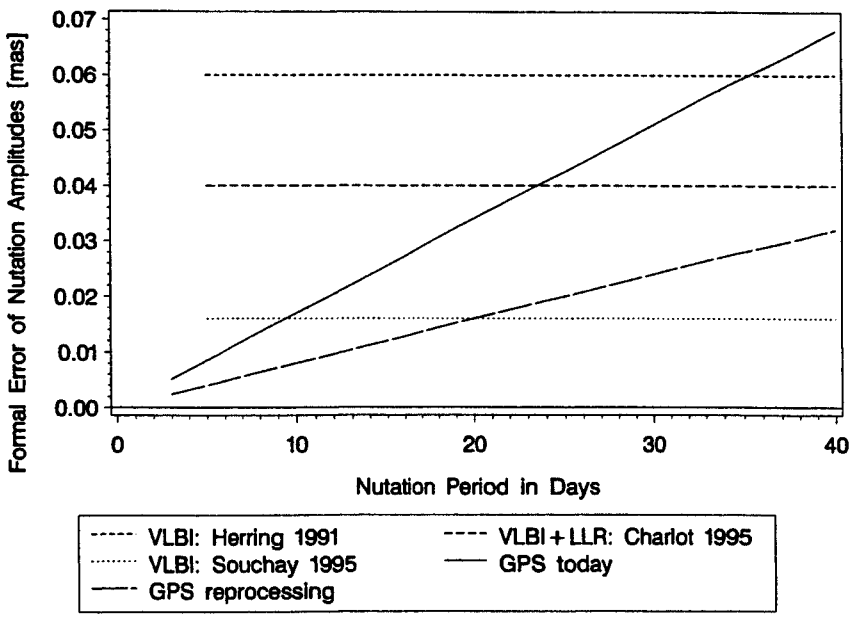

Figure 2

Thus assuming again for instance m = 1765, $\sigma_{\Delta\alpha} = 0.6$mas (*Herring et al., 1991*) results in $\sigma_V = 0.020 mas$. More recent publications (*Souchay et al., 1995, Charlot et al., 1995*) show smaller numbers, indicating further improvements in modeling.

The comparison of (5) and (6) immediately leads to the conclusion that GPS is able to deliver unique contributions to the nutation spectrum in the high frequency range (up to 14 days). Moreover, amplitude corrections for terms with periods ranging from 14 to 28 days may be

used in comparisons as independent determinations (although they are less accurate than the VLBI estimates). Both techniques are still improving in terms of data modelling as well as in data acquisition, which will decrease the error bars of the observed nutation series significantly in the future.

Subdaily Polar Motion

Due to ongoing attempts aiming to improve the processing strategy, the resulting series sometimes suffer from inhomogeneity and are subsequently difficult to interpret (see e.g. *Rothacher et al., 1999*). At the CODE Analysis Center, for example, several model changes concerning the force field, the weighting of the observations (elevation dependence), the time resolution of the estimates or the realization of the reference frame can be reported between 1993 and 1998. Thus, the homogeneous recalculation of ERP-series with the most recent (and best available) strategy promises a remarkable reduction of inherent systematic errors. Test calculations were carried out, focusing on the period from Sept.1, 1996 till Dec. 31 the same year. Data sets and models basically differ from the original computation due to the inclusion of more low-elevation data, the consideration of ocean loading effects, an improved modeling of solar radiation pressure and last but not least due to an increased time resolution of the ERPs of one hour.

The series were computed with respect to the model by Ray (*Ray, 1996*). Because of the well-known effect, that satellite techniques are restricted to estimate UT-rates, the difference UT-UTC has to be recovered by integration. Nutation offset drift parameters were constrained to reflect the IERS 1996 empirical model given in (*Mc Carthy, 1996*).

A short look at the residual ‚amplitude spectrum' in PM shows us large, still remaining differences in the prograde diurnal band (Figure 3a). Due to the short series a more detailed assignment to special waves is not possible at the moment. But it might be assumed, that the differences stem from tides with periods very close to 24 hours ($S1, \psi 1$) and therefore within the 2:1 resonance of the orbit period and the sidereal day.

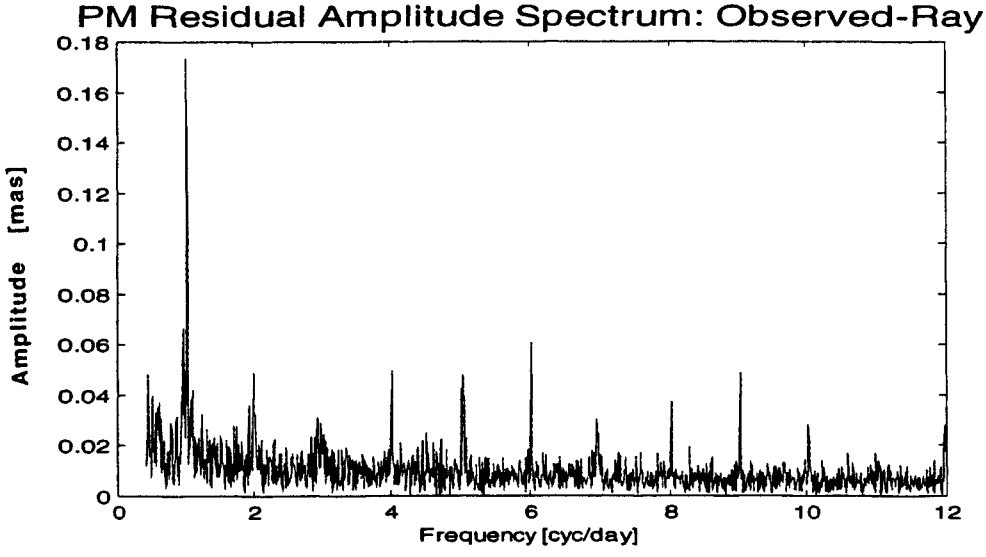

Figure 3a: Prograde Polar Motion

Similar to the UT-series there are small peaks at the higher harmonics of one cycle/day, which have to be investigated in the near future. Figure 3b shows the corresponding retrograde spectrum (same scale) giving evidence that terms at the nutation frequency have been suppressed succesfully. Moreover, both plots tell us that GPS results and the Ray-Model correspond fairly good in the semidiurnal band. Compared to the original series the 'new' series show a more smooth behaviour. Remaining differences are dominated by a 14-days period both in PM and in UT1.

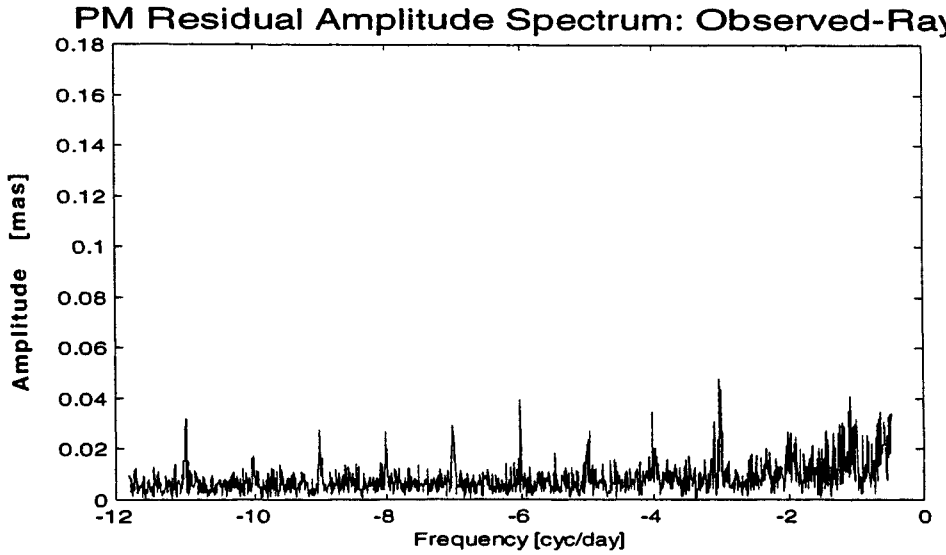

Figure 3b: Retrograde Polar Motion

Summary

GPS is able to determine a number of coefficients in the nutation series with a precision of about +/-15 micro-arcseconds growing linearly with the associated period. As expected, the contributions concentrate in the first place on terms with short periods (up to 14 days). Nevertheless, there is some residual power at periods up to a month or more. Due to correlations of the orbit force parameters with other parameter types, improving the orbit model can cause inconsistencies in the nutation rate series. Therefore reprocessing efforts and correlation studies are encouraged.

The nutation amplitude corrections computed from the GPS series provide a significant contribution to the comparison of analytic and semi-empirical nutation models. In future the combined analysis of VLBI, LLR and GPS series in order to estimate nutation amplitudes will be a worthwhile undertaking.

In terms of PM and LOD the processing of the remaining 1993-1996 GPS data is still under way and the results will be used to replace the corresponding parts of the elder series, e.g. in order to evaluate an improved set of ocean tide coefficients.

References

Beutler G., R. Weber, E. Brockmann, M. Rothacher, St. Schaer, A. Verdun, 1998,
The GPS as a Tool in Global Geodynamics,
in 'GPS for Geodesy',Teunissen, Kleusberg (eds.)
pp. 569-598, Springer-Verlag, Berlin/Heidelberg.

Beutler G., J.Kouba, M. Rothacher, R. Weber, 1999,
Polar Motion with Daily and Subdaily Time Resolution,
Proceedings of the IAU Colloquium No.178, Cagliari.

Brzezinski A., 1994,
Atmospheric Excitation of Nutation estimated from the 4-times daily Effective Angular Momentum Data,
Paper presented at the 22nd General Assembly of the IAU , The Hague.

Charlot P., O.J. Sovers, J.G. Williams, X.X. Newhall, 1995,
Precession and Nutation from joint analysis of radio interferometric and lunar laser ranging observations, Astron.J., 109(1), pp. 418-427.

Defraigne P., V. Dehant, 1995,
Towards new non-rigid Earth Nutations,
Proceedings to the Journees 1995, pp. 45-52, Space Research Centre Warsaw, Poland.

Defraigne P., V. Dehant, P. Paquet, 1995,
Link between the retrograde-prograde nutations and nutations in obliquity and longitude,
in 'Celestial Mechanics and Dynamical Astronomy', Vol. 62, pp. 363-375.

Herring T.A., B.A. Buffett, P.M. Mathews and I.I. Shapiro, 1991,
Forced Nutations of the Earth; Influence of Inner Core Dynamics;
3. Very Long Interferometry Data Analysis,
Journal of Geophysical Research, Vol. 96, No. B5, pp. 8259-8273.

Kouba J., G. Beutler, M. Rothacher, 1999,
IGS Combined and Contributed ERP Solutions,
Proceedings of the IAU Colloquium No.178, Cagliari.

McCarthy D.D. (editor), 1996,
IERS Conventions,
IERS Technical Note 21, Observatoire de Paris.

Neilan, R.E. (editor), 1998,
International GPS Service; IGS Directory,
IGS Central Bureau, JPL.

Ray R.D., 1996,
Tidal Variations in the Earth's Rotation,
in 'IERS Conventions', McCarthy D.D. (editor)
IERS Technical Note 21, pp. 76-77, Observatoire de Paris.

Rothacher M., G. Beutler, T.A. Herring, R. Weber, 1999,
Estimation of Nutation Using the Global Positioning System,
Journal of Geophysical Research (JGR),Vol. 104, No. B3, pp. 4835-4859.

Rothacher M., G. Beutler, R. Weber, J. Hefty, 2000,
High Frequency Earth Rotation Variations from three Years of Global Positioning System Data,
Submitted to the Journal of Geophysical Research.

Souchay J., M. Feissel, C. Bizouard, N. Capitaine and M. Bougard, 1995,
Precession and Nutation for a Non-Rigid Earth; Comparison between Theory and VLBI Observations, Astronomy and Astrophysics, Vol. 299, pp. 277-287.

Springer T., G. Beutler, M. Rothacher, 1998,
A new Radiation Pressure Model for the GPS Satellites, in Proceedings of the IGS 1998 Analysis Center Workshop, edited by J.Dow, J.Kouba and T. Springer, pp. 89-106, ESOC, Darmstadt.

Weber R., 1996,
Monitoring Earth Orientation Variations at the Center for Orbit Determination in Europe
ÖZf Vermessung & Geoinformation; Heft 3/1996 ; pp. 269-275, Vienna.

Weber R., 1999,
The Ability of the GPS to Monitor Earth Rotation Variation
in 'Acta Geodaetica et Geophysica Hungarica',
Volume 34, Number 4, pp. 457 – 473, Akademiai Kiado, Budapest.