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ORIGINAL ARTICLE

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Comparison of length of day with oceanic and atmospheric angular momentum series

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Abstract This is a companion paper to earlier comparisons and study of operational polar motion series, published recently in the same journal. In this contribution, four operational, publicly available, length-of-day (LOD) time series have been compared to the atmospheric angular momentum (AAM) augmented with recent oceanic angular momentum (OAM) data during September 1997–July 2000, using several intervals ranging from 3 days to almost 3 years. Additionally, the LOD of the International GNSS Service (IGS) historical series and a new LOD combination (CMB) were also analyzed. All the six LOD series showed an overall correlation exceeding 0.99 for the complete interval of almost 3 years. Even for the shortest interval of only 3 days, the correlation was still higher than 0.60. The combined AAM + OAM series with inverted barometer corrections always gave the best correlation. The Rapid Service LOD of the International Earth Rotation and Reference Systems Service (IERS) compared the best at all intervals but the shortest one, where the CMB LOD was the best with a correlation of 0.73, followed by both IGS series with a correlation of about 0.71. Prior to all the correlation analyses, in addition to the removal of all the known (conventional) LOD tidal variations with periods ranging from 5.6 days to 18.6 years and lunar fortnightly and monthly oceanic tides, small corrections of lunar fortnightly and monthly tides, semi-annual, annual periodical signals, drift and scale had to be estimated with respect to the combined AAM + OAM series.

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1 Introduction

Earth rotation integrates temporal global mass and kinematic energy distribution, both inside and outside the Earth. It offers a unique tool for various global interdisciplinary geophysical studies of atmosphere, oceans and hydrology, as well as the Earth's interior. More specifically, the Earth continually changes its orientation in space due to well-known torques caused by celestial bodies (Moon, Sun and planets), as well as due to less-well-known torques of external and internal mass distribution changes, caused by the atmosphere, oceans and global geophysical processes.

Changes in Earth orientation are required for precise transformation between the conventional celestial and terrestrial reference frames. Conventionally, they are separated into the orientation changes of the Earth's spin axis in space, called precession and nutation, the wobble of the "solid Earth" around the axis of rotation – polar motion (PM), the rotation around the spin axis expressed as rotational phase angle (UT1) and its negatively taken time derivative, expressed as the length-of-day (LOD). These Earth orientation parameters (EOP) describe both spatial and terrestrial orientation of the conventional terrestrial coordinate system and they include precession-nutation, PM and UT1/LOD. The subset, consisting of PM, UT1 and LOD, usually referred to as the Earth rotation parameters (ERP), is required to relate the instantaneous Earth's spin axis to a conventional terrestrial coordinate system and the proper rotation. Similarly to LOD, which is related to the rate of change of UT1, the rate of change of PM, here called PM rates, can also be observed with ever-increasing precision by most space techniques. ERPs are monitored with respect to a stable and consistent reference frame, linked to very distant quasars, accessible only by very long baseline interferometry (VLBI). Thus, ERP observations also offer a unique calibration opportunity; i.e.,

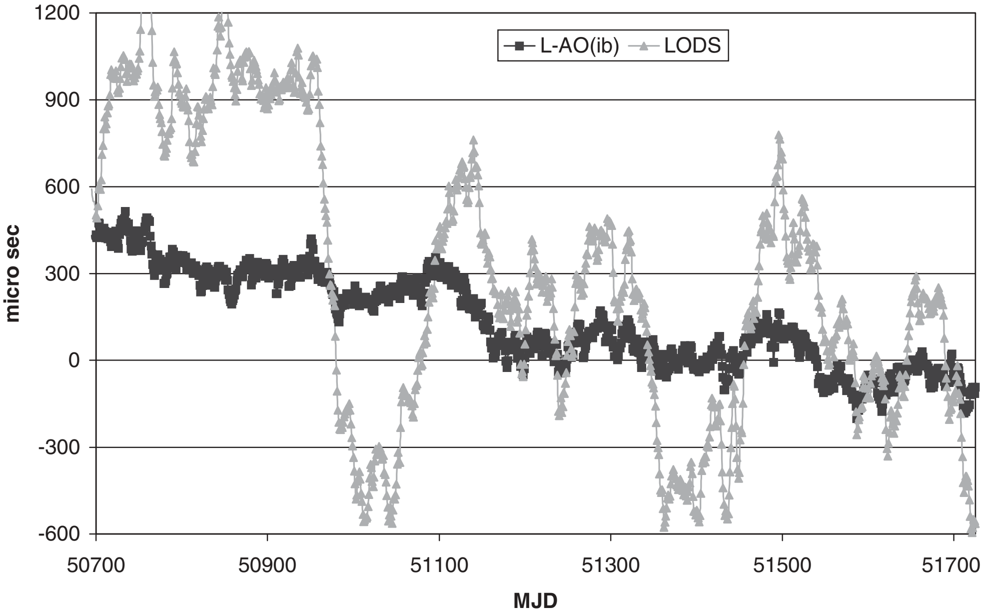

Fig. 1 IGS LODS (L) and IGS LODS – (AAM+OAM) (AO) residuals with inverted barometer (ib) corrections during September 1997 – July 2000

they could facilitate a stable, globally consistent reference frame for related disciplines of global geophysics, meteorology, oceanography and space navigation.

PM, which describes the small wobble variations in the Earth's rotational axis with respect to its crust and the small irregularities of rotational rate, which are expressed as LOD, have been monitored for about a century, but these variations have remained largely unexplained until a few decades ago. In the early 1980's a strong temporal correlation of newly generated atmospheric angular momentum (AAM) time series with LOD and PM variations, on a time scale of about 30 days, was observed by a number of authors (e.g., Langley et al. 1981; Barnes et al. 1983). Although the ocean contributions to PM and LOD were also expected to be significant, it has taken considerably longer to confirm the significance of the oceanic angular momentum (OAM) contributions to PM and LOD due to the complexity of global ocean modeling. A clear correlation between combined AAM and OAM with PM at seasonal to 10-day periods, during 1985 to April 1996, was found by Ponte et al. (1998). Here, only the PM from the C04 EOP combination series of IERS (International Earth Rotation and Reference Systems Service – http://www.iers.org/) was used along with the equatorial AAM and OAM data. The OAM data were based on (then) a state of the art, nearly global general ocean circulation model (Marshal et al. 1997), driven up to twice daily with wind, temperature and fresh water fluxes obtained from the U.S. National Center for Environment Prediction (NCEP). The study was limited only to PM and by the 5-day sampling of the OAM data, and no atmospheric pressure data were included in the ocean model. Kouba et al. (2000) compared the same OAM, linearly interpolated to match the daily NCEP AAM, with the new combined ERP solutions of IGS (International GNSS Service – http://igscb.jpl.nasa.gov/) (Mireault et al. 1999), which only became available in 1995. The comparisons revealed a significant correlation (∼0.6) between the OAM + AAM and PM for periods as short as 6 days. Since no axial component of OAM was available, the IGS combined LODR series, (i.e., LOD with all the solid Earth tide effects with periods up to 35 days removed, hereafter called LODR), was also compared, but only with the AAM axial component, both with and without the inverted barometer (IB) corrections. Here, the IGS LODR yielded an overall correlation of more than 0.92, and contrary to expectation, the IB-corrected AAM gave a slightly lower correlation than the uncorrected (non-IB) AAM (see below for more discussions on IB corrections).

Ponte and Ali (2002) have reported significant correlation even at the 3-day period between the IGS PM data, COM2000 LOD (Gross 2001) and their new daily OAM series combined with the IB-corrected NCEP AAM. The new OAM data included all the three components and were based on a new barotropic ocean model, driven four times daily with the NCEP/National Center for Atmospheric Research (NCAR) reanalysis data (including atmospheric pressure) and optimized to explain sea level variations observed by TOPEX/POSEIDON (T/P) altimetry. The interval used (July 1996 – July 2000) was dictated by the availability of the IGS PM and OAM data. In the preceding paper, Kouba (2005) used the above OAM data and only the PM of the new, rigorously combined IGS ERP series (IGS00P02) (Ferland et al. 2000). He reported a high overall correlation (>0.8) with the combined, IB-corrected, (AAM + OAM) series, with significant correlation already starting at periods as short as

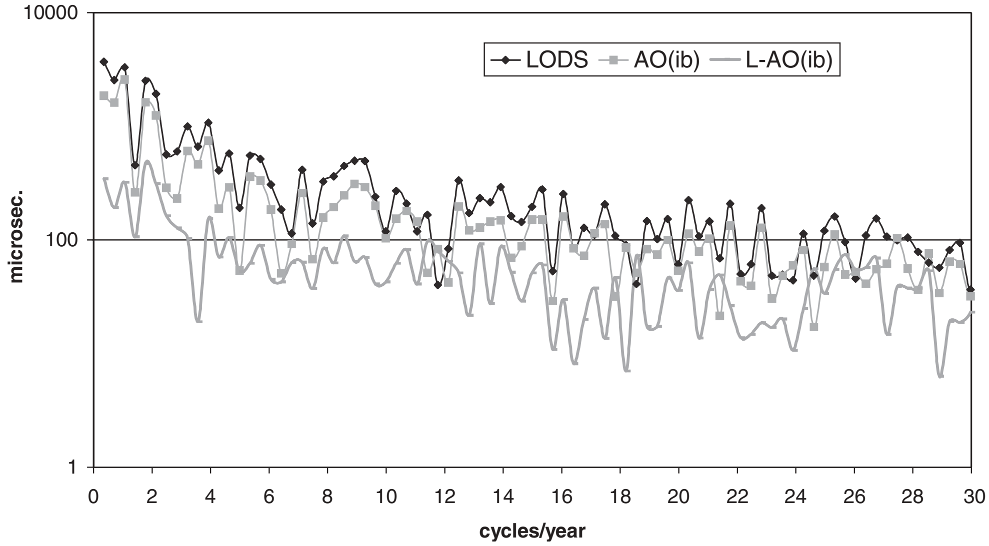

Fig. 2 Amplitude spectra for slope-corrected IGS LODS, IB-corrected (AAM + OAM) (AO) and their difference (L-AO), during September 1997 – July 2000

2.2 days. For additional recent studies of atmospheric and oceanic effects in PM and LOD, see e.g., Gross (2000), Brzezinski and Nastula (2002), Gross et al. (2003, 2004), Chen et al. (2004) and Brzezinski et al. (2004).

Although the oceanic effects on LOD are several times smaller than for PM, they have already been well established (e.g., Ponte and Ali 2002; Gross et al. 2004). Unlike PM, the daily mean LOD observations are affected by significant tidal effects, with periods ranging from 5.6 days to 18.6 years (McCarthy and Petit 2004). Furthermore, the daily LOD solutions, which are mainly based on satellite solutions, are usually biased and typically require at least monthly calibrations by very long baseline interferometry (VLBI) observations (Ray 1996). These aspects also bring an additional degree of uncertainty that should be assessed first before a proper AAM/OAM comparison with LOD is undertaken. For these reasons, the comparisons of Kouba (2005) concentrated only on PM and did not include LOD. This work is a continuation of Kouba (2005), but concentrates solely on LOD, while using the same methodology, AAM and OAM data series.

2 Data

Length-of-day data from four operational daily EOP or ERP series were used in this study. Two were the daily IERS EOP, multi-technique combinations, namely the final combination C04 (a continuous version of the monthly Bulletin B) and the Bulletin A, a rapid combination, largely based on the same input data as C04, but generated by the IERS Rapid Service Product Center at the U.S. Naval Observatory (USNO). After 1996, both C04 and Bulletin A series should contain only minimum smoothing (Dick and Richter 2001). The third LOD series, SPACE2003, was taken from a 2003 issue of the SPACE/COMB multi-technique EOP combinations, which are based on a Kalman filter and routinely generated by jet propulsion laboratory (JPL) (Gross 2004). The fourth operational series, which uses only GPS ERP solutions, though with LOD regularly calibrated by VLBI (see below), is the IGS Final ERP combinations (Beutler et al. 1995; Kouba et al. 1998a; Kouba 2003a). The IGS PM and LOD combinations start on June 30, 1996 and February 23, 1997, respectively. However, the IGS LOD combinations have achieved the current level of accuracy only in the second half of 1997, when most analysis center (AC) improvements and AC LOD bias calibrations have been implemented. Prior to combinations, all the AC LOD solutions are subjected to a calibration with respect to the VLBI-based Bull. A LOD, which is typically based on a 3-week-old 21-day interval (Mireault et al. 1999). Note that since February 27, 2000, the IGS ERP Final series (IGS00P02) is based on a rigorous combination, based on the normal equations of seven AC solutions of ERP, ERP rates and station coordinates (Kouba et al. 1998a,b; Ferland et al. 2000). However, even here, unlike for PM, before the rigorous combinations, the AC LOD solutions still have to be calibrated with respect to Bull A/VLBI as described by Mireault et al. (1999). Two additional LOD series were also compared, the first is the former IGS Final ERP series, IGS95P02 (Mireault et al. 1999), which uses the same LOD calibration and an empirical weighting. The second (CMB) is a new combination of VLBI UT, generated by IVS (International VLBI Service – http://ivscc.gsfc.nasa.gov/) and the IGS LOD (IGS00P02), designed in such a way that the satellite LOD contributions are diminished for periods above 30 days (Vondrák and Čepek 2000; Vondrák et al. 2002; Vondrák and Ron 2005). All the PM/LOD series considered here, according to the IERS conventions, are 24-h averages of the instantaneous ERP signal, corrected for the sub-daily, tidally induced, ERP effects that are at the 1-ms (0.001 arc sec) and 0.1-ms level for PM and

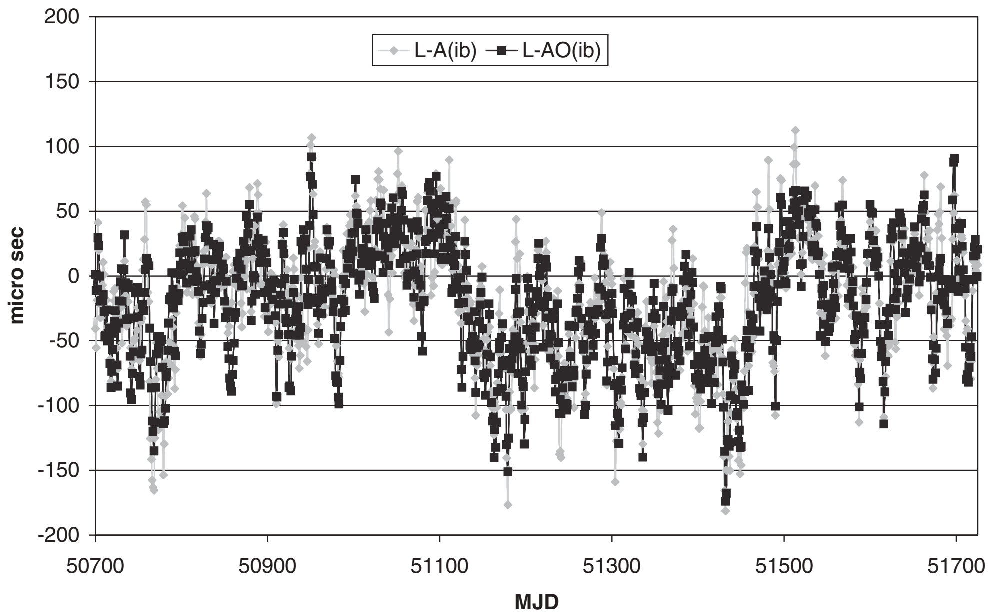

Fig. 3 IGS LODS residuals with respect to AAM (L-A) and (AAM+OAM) (L-AO), with IB corrections, after fitting annual, semi-annual, monthly and fortnightly periodic signals, rates and scales (see Table 2). (September 1997–July 2000)

LOD, respectively. The two IERS and SPACE 2003 daily data series are given at 0-h UT, while IGS ERP and the CMB combinations use the middle epoch of 12-h UT (the middle of the IGS data/solution intervals). The IGS ERP combinations also include PM rate solutions, which are needed for OAM and AAM comparisons. Since the OAM series is given only for 0-h UT epochs, the well-proven natural cubic spline interpolation was used to generate the IGS and CMB LOD values for the standard epoch of 0-h UT.

All the LOD series were first corrected for the solid Earth tide effects, which have periods ranging from 5.6 days to 18.6 years and they were computed according to Yoder et al. (1981). Additionally, before comparisons, two out-of-phase (UT/LOD) components of the lunar fortnightly and monthly oceanic tides, with periods of 13.66 days and 27.56 days (called the Mf and Mm tides), generated according to Kantha et al. (1998), have also been removed from all the LOD series. The two in-phase components of the Mf and Mm oceanic tides are already included in the UT tidal model (Yoder et al. 1981), so the in-phase Mf and Mm oceanic components of Kantha et al. (1998) were not used. Such regularized LOD series, with all the conventional tidal effects removed, though using a slightly different LOD tidal model than that used here, has been referred to as LODS (McCarthy 1996). For the sake of brevity, an LOD series, corrected for the complete Yoder et al. (1981) tidal model and augmented with Kantha et al. (1998) oceanic tides as described above, will be also referred to here and after as an LODS series. Such LODS then should, apart from much smaller neglected effects, reflect mainly atmospheric and oceanic LOD excitations with periods up to a few years. For time scales upwards of a few years, the angular momentum transfer between the Earth's liquid core and solid mantle effects will become significant or even predominant in LODS (e.g., Barnes et al. 1983).

The IERS Special Bureau for Atmosphere (SBA) makes the AAM data readily available (http://www.iers.org/iers/pc/ggfc/sba/). From the four AAM data sets, made available by SBA, based on different global atmospheric models generated in Europe, Japan, U.K. and U.S.A, only the AAM series of the U.S. NCEP/NCAR reanalysis project (hereafter called NCEP AAM) is complete (in terms of the 6-h epochs) and fairly current (with a delay of several weeks). The other data series, which are based on operational analyses, rather than on postprocessing of atmospheric data, may not be as current and often have missing, or duplicate epochs, or even long periods with no data. For these reasons, the NCEP AAM series was used in Kouba (2005) and in this study. However, since the Japanese Meteorological Agency (JMA) data set is also relatively current and complete, it was also tested here. The number of missing epochs and gaps within the JMA operational AAM data was filled with the corresponding NCEP values, while correcting for the respective means within the longest chosen period (April 1993 – July 2000), in order to mitigate possible discontinuities. NCEP and JMA AAM series have been compared by Aoyama and Naito (2000) where a good agreement (correlation up to 0.9) has been reported for the NCEP and JMA mass (pressure) AAM components, but much worse comparison (correlation ∼0.4) was noted for the wind (motion) components. Note that in LOD excitations the wind contributions are overwhelming, about 90% of the total AAM effects (e.g., Barnes et al. 1983). In order to be consistent with the OAM (see below), only IB-corrected

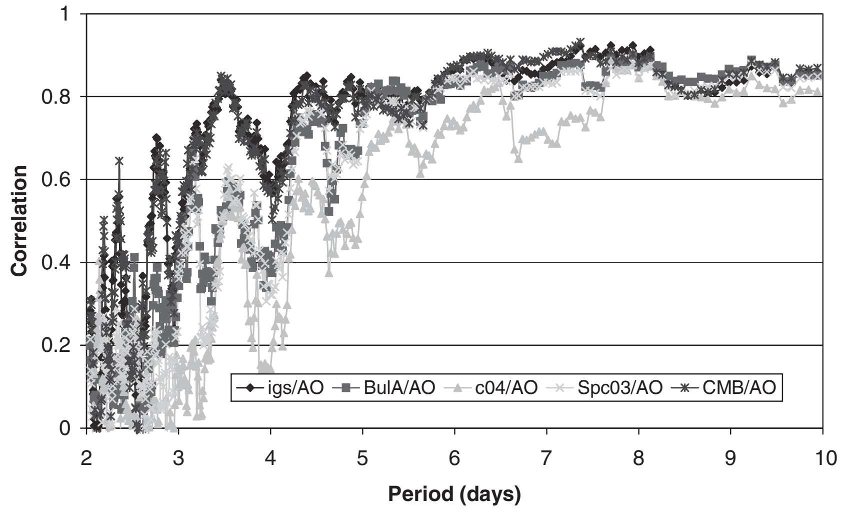

Fig. 4 LODS Correlation with IB-corrected AAM+OAM (AO), averaged within a moving window of 20 FFT bins, during September 1997 – July 2000 (igs- IGS00P02 shown only)

Table 1 IGS LODS (L) correlation with AAM (A) and (AAM+OAM) (AO), without (nib) and with (ib) inverted barometer (IB) corrections (September 1997 – July 2000)

Interval	L/A nib	L/A ib	L/AOnib	L/AOib
∼3 year	0.955	0.952	0.957	0.956
30 day	0.894	0.915	0.890	0.934
15 day	0.842	0.852	0.849	0.887
10 day	0.802	0.803	0.819	0.852
3 day	0.649	0.629	0.682	0.702

AAM data should be used. For more information on AAM data and the SBA of IERS, see Salstein et al. (1993), Salstein and Rosen (1997) and Salstein (2003).

The daily OAM series of Ponte and Ali (2002) is based on a barotropic ocean model (Ponte 1993), optimized to explain the observed TOPEX/POSEIDON (T/P) altimeter data, with improved topography and friction representations. It is driven with 6-h wind and pressure fields of the NCEP/NCAR reanalysis, corrected for the IB effects. The hourly OAM values were averaged within 24-h bins centered at 0-h UT to obtain the daily OAM series for the period of October 1992 to July 2000 (Ponte and Ali 2002). Thus, this new daily OAM data series used here should be highly consistent with 24-h averages centered at 0-h UT and the IB-corrected NCEP AAM series.

3 Comparison of LOD with oceanic (OAM) and atmospheric (AAM) angular momentum series

For proper calculation of the 24-h means ($\tilde{\chi}$) from the 6-h AAM (χ) values, it is essential to know the smoothness of the epoch values. Several 24-h averaging schemes were investigated in Kouba (2005), after some testing, the following simple averaging was selected:

$$\tilde{\chi} = (0.5\,\chi_{-12h} + \chi_{-6h} + \chi_{0h} + \chi_{6h} + 0.5\chi_{12h})\,/4, \quad (1)$$

where the subscripts of -12 h and -6 h denote the AAM values of the preceding day at 12- and 18-h UT. For the sake of consistency with Kouba (2005), the same AAM averaging scheme was also adopted here for all (OAM + AAM) comparisons with LODS. The standard effective excitation functions of Barnes et al. (1983) have been used here, i.e. subject to an integration constant and scaled,

$$LODS = \Omega_0\ \tilde{\chi}_3 + \text{const.}, \quad (2)$$

where LODS are the LOD observations, corrected for all the known tidal effects and the long-period oceanic tides, according to Yoder et al. (1981) and Kantha et al. (1998); Ω_0 is the nominal rate of the Earth's rotation and $\tilde{\chi}_3$ is the axial excitation component (OAM + AAM). Consistent with Barnes et al. (1983), the AAM $\tilde{\chi}_3$ series, archived at the SBA, are based on effective transfer coefficients of .70 and 1.00 for the pressure and motion components, respectively. The OAM of Ponte and Ali (2002) used the same transfer coefficients for the ocean pressure and current components, respectively (Ponte 2003, personal comm.). However, note that there is no conventional agreement for the coefficients; consequently some authors use different transfer coefficients, e.g., Gross et al. (2004) used 0.756 for the pressure transfer coefficient.

3.1 IGS combined solution of LOD

IGS LOD combinations matured only in the second half of 1997 (Mireault et al. 1999), so an interval of September 1997 to the end of the OAM series, June 30, 2000, was chosen for the AAM + OAM comparisons with the six LOD series (the four operational ones, the new combination (CMB) and the IGS historical ERP series). The official IGS LODS series was first compared to the combined OAM and AAM, both with and without the IB AAM corrections, since the validity of correcting the AAM pressure component with IB model is sometimes questioned, in particular for intervals shorter

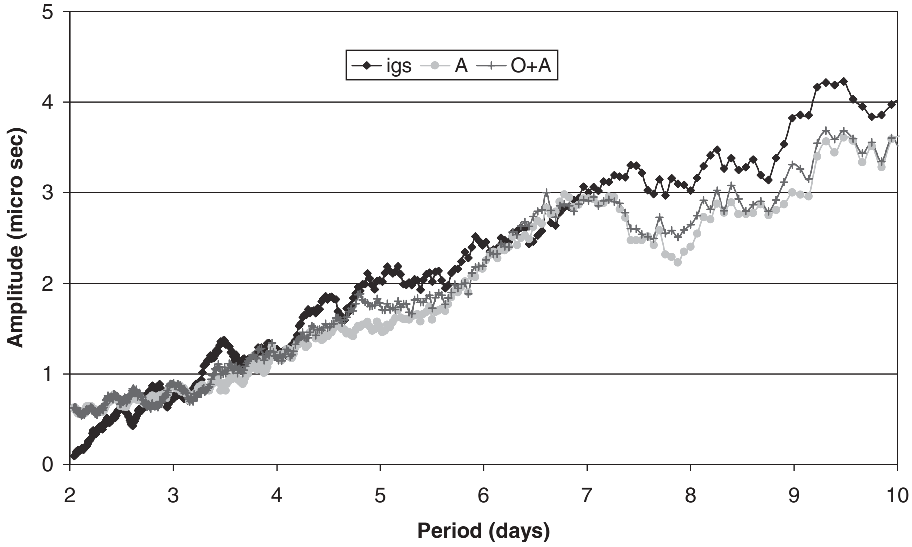

Fig. 5 High-frequency IGS00P02 LODS, AAM (A) and AAM+OAM (A+O) amplitudes, averaged within a moving window of 20 FFT bins, during September 1997 – July 2000

Table 2 Estimated annual and semi-annual period amplitudes (with respect to J2000), monthly and fortnightly LODS tidal amplitude corrections (with respect to the Yoder et al. (1981) model), rate and AAM/OAM scaling, for IGS LODS, residuals LODS-AAM (L-A) and LODS-(AAM+OAM) (L-AO) in microseconds (µs), without (nib) and with IB (ib) AAM corrections. (September 1997–July 2000)

Period(days)	Comp/unit	LODS	L-A nib	L-A ib	L-AO nib	L-AO ib
365.2d	cos	318	−25	−47	−1	−28
	sin	182	−15	−53	−2	−44
182.6d	cos	−131	−43	−34	−39	−28
	sin	−304	−33	−22	−41	−24
Mm 27.56d	cos	188.3*	11	7	14	8
Mf 13.66d	cos	356.8*	−1	−5	−1	−4
13.63d	cos	147.9*	−7	−7	−7	−6
k/C		0.940*	0.935	0.933	0.935	0.937
Rate	µs/y	−373	−125	−116	−130	−119
A/AO scale		n/a	1.028	1.083	1.003	1.077
Mean	µs	792.0	−33.2	−19.5	−36.0	−20.6
RMS	µs	211.2	51.7	49.4	54.2	45.8

*The Yoder et al. (1981) a priori model; the LOD amplitudes were multiplied by k/C = 0.940

than 7 days (e.g., Gross et al. 2004). Note that the IB correction model assumes an ocean surface isostatic yield to atmospheric pressure variations as an "inverted barometer".

The resulting correlations for AAM and AAM+OAM with the IGS LODS are listed in Table 1, which summarizes the correlation for intervals ranging from almost 3 years down to 3 days. Here, the interval values were computed as arithmetic averages of correlation coefficients for sliding interval windows (of 3 – 30 days) within the September 1997 to July 2000 interval. The shortest interval of 3 days is based on rather small samples (of 3), which for a single interval determination cannot be considered significant. However, when averaged over many samples (>1000), the average correlation becomes quite precise and statistically meaningful. The sliding window correlation coefficients were assumed to be statistically independent (uncorrelated) for the interval averaging. When looking only at the correlation for the complete interval (the first line of Table 1), one is tempted to conclude that the IB corrections did not help, or even made the LODS correlation slightly worse. However, the situation is quite different for the shorter intervals, where in all but one case (the 3-day AAM/LODS correlation) the IB corrections increased correlation. The decrease for the 3-day, IB-corrected AAM correlation is likely due to the nonisostatic (non-IB) behavior of the sea surface for such short periods, but as seen in Table 1, this is fully compensated by OAM that accounts for these non-IB effects (Ponte and Ali 2002).

Table 1 also indicates only a relatively small increase in correlation when going from the 30-day to the complete interval of almost 3 years, which could indicate some long-period systematic differences. This is confirmed by Fig. 1, which shows IGS LODS and its residuals with respect to the OAM combined with IB-corrected AAM, which happened to begin with the very strong El Niño season of 1997–1998. Note that since OAM is consistent with the IB AAM corrections, only the IB corrected AAM should be used for the combined OAM + AAM; this is apparent from both Fig. 1 and Table 1. Figure 1 also shows that the combined OAM + AAM indeed

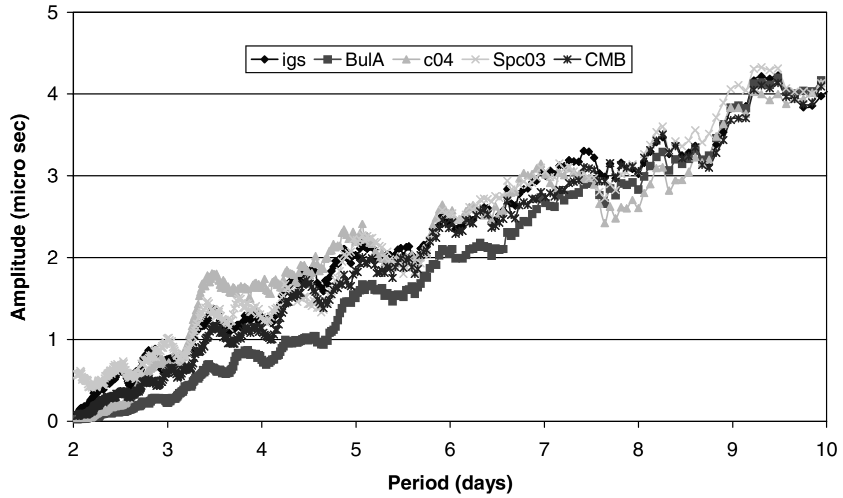

Fig. 6 High-frequency LODS amplitudes averaged within a moving window of 20 FFT bins, during September 1997 – July 2000

Table 3 IGS LODS (L) correlation with AAM (A) and (AAM+OAM) (AO), without (nib) and with (ib) IB AAM corrections, after the fitted parameters of Table 2 were removed, during September 1997–July 2000.

Interval	L/A nib	L/A ib	L/AO nib	L/AO ib
∼3 year	0.994	0.995	0.994	0.996
30 day	0.900	0.922	0.894	0.937
15 day	0.848	0.858	0.852	0.888
10 day	0.807	0.809	0.822	0.851
3 day	0.656	0.636	0.688	0.706

removed all the large (mostly seasonal) variations of LODS, in spite of the strong El Niño event, which caused some of the most extreme variations of AAM (Salstein 2003).

A significant drift as well as some variations at seasonal and shorter periods (mainly semi-annual and fortnightly) has also remained in LODS (Fig. 1). This is also indicated by the amplitude spectra of the LODS residuals (L-OA) shown in Fig. 2, where the semi-annual period (2 cycles/years) has the largest peak with smaller peaks near 1, and 26 cycles/year, which correspond to the annual and lunar fortnightly periods, respectively. The remaining drift and long-period (<1 cycle/year) variations could be caused by sources other than the atmosphere and oceans (e.g., by Earth's core/mantle interface). Figures 1 and 2 gave an impetus to remove (i.e., to solve for) some reasonable (bias) parameters, prior to any comparisons at seasonal and shorter periods. All the three series types (LODS, AAM and OAM) could be subjected to small drifts as well as seasonal and semi-seasonal periodical signals, which may or may not be real (e.g., the neglected hydrological effects, possible stability problems of AAM and/or OAM). Furthermore, there are additional scale uncertainties: e.g., the tidal LODS corrections are scaled by a relatively poorly known value (0.94) of the coefficient *k/C* (e.g., McCarthy and Petit 2004); there are uncertainties in the transfer coefficients for AAM and OAM; atmospheric numerical models and wind integration limits (Aoyama and Naito 2000) may cause an implicit smoothing and/or a small-scale change of AAM. Additionally, there are also (small) uncertainties with the fortnight and monthly LODS tidal model amplitudes (e.g., Kantha et al. 1998; McCarthy and Petit 2004). Consequently, the following parameters were chosen for unweighted least-square estimations with respect to the AAM, or AAM+OAM: a drift, semi-annual, annual amplitudes, the scale of (AAM+OAM), the coefficient *k/C*, the lunar fortnightly and monthly amplitude corrections to the a priori tidal model (Yoder et al. 1981).

Table 2 summarizes the estimation of all the adopted parameters for IGS LODS with respect to AAM and the combined OAM and AAM, both with and without IB AAM corrections. For comparisons, a comparable parameter solution for LODS is also listed here; only here the fortnight, monthly tidal amplitudes and *k/C* were not estimated. The fortnight, monthly amplitudes and *k/C* of the a priori Yoder et al. (1981) model, used for LODS, are listed in this column. Note that the LOD model amplitudes were obtained by scaling the corresponding UT amplitudes of Yoder et al. (1981) by a factor of (2π/Period (days)). Table 2 shows an increase in the estimated annual amplitudes for the IB-corrected AAM, which is somewhat decreased when OAM is added. This may be due to data and/or model errors, or it may be real, e.g., due to the neglected hydrology and/or the neglected stratospheric winds above the 10-mbar upper integration limit of AAM, both of which can be expected to be significant at this level (Gross et al. 2004). Also, the IB corrections could cause a small annual bias signal, e.g., when they are based on a single reference pressure, rather than annual means, they can

Table 4 Estimated annual, semi-annual period amplitudes (with respect to J2000), monthly and fortnightly LODS tidal amplitude corrections (to the Yoder et al. 1981 model) in μs, rate and AAM/OAM scaling for IGS00P02 (igs00), the IERS Bull. A and C04, SPACE2003 (Spc03), CMB and IGS95P02 (igs95) LOD combinations, and IB-corrected (NCEP AAM + OAM) during September 1997–July 2000. Also shown is the Bull. A solution (A/JMA), with JMA AAM rather than NCEP AAM

P(days)	Comp/unit	igs00	Bull A	C04	Spc03	CMB	igs95	A/JMA
365.2d	cos	−28	−28	−28	−29	−29	−28	16
	sin	−44	−42	−42	−42	−42	−42	−15
182.6d	cos	−28	−30	−30	−31	−30	−29	−45
	sin	−24	−24	−25	−23	−24	−25	−47
Mm 27.56d	cos	8	8	8	9	7	8	1
Mf 13.66d	cos	−4	−4	−5	1	−6	−6	−2
13.63d	cos	−6	−4	−5	0	−6	−7	−6
k/C		0.937	0.938	0.942	0.932	0.940	0.937	0.937
Rate	μs/y	−119	−118	−118	−118	−118	−118	−123
AO Scale		1.077	1.075	1.074	1.077	1.080	1.076	0.969
sigma	μs	45.8	45.6	48.4	47.1	45.6	46.2	48.4

introduce a small annual signal (Dorandeu and Le Traton 1999). Since the data interval used in Table 2 is not even 3 years long, the estimated parameters have little practical significance. However, they are still useful to observe how much different AAM and OAM configurations can influence the estimations of some physically meaningful parameters. This parameter estimation is also useful for comparisons of different LODS series, as it could also show differences in terms of some physically meaningful parameters. It is encouraging to see that, after accounting for atmosphere and ocean, and the above parameter estimation, the RMS residuals have decreased from more than 200 μs for LODS, down to the 50-μs level for LODS – (AAM+OAM). This is already approaching the IGS LOD observational noise of about 30 μs (Mireault et al. 1999).

Figure 3 and Table 3 show the IGS LODS residuals and correlation after correcting for the estimated parameters of Table 2. As expected, the combined AAM and OAM with IB corrections gave the best RMS (Table 2) and correlation for all the intervals, with a very high overall correlation of 0.996. This time, both IB and OAM significantly increased correlation at all intervals, except for the 3-day AAM/LODS (L/A ib) correlation, which was already discussed above.

3.2 Other combined LOD solutions

In order to compare different LOD series, the same estimation and correlation comparisons were performed for the six LOD series, but only for IB corrected combined (AAM+OAM) series. The results are listed in Tables 4 and 5. All the LODS series performed well and for the same AAM (i.e. NCEP AAM), all gave statistically the same solutions when the formal sigmas are considered, which were about 2 μs for the amplitudes, 0.01 for the scales and about 1 μs/year for the drift. However, there are some exceptions, such as the fortnightly tide amplitude solutions for the SPACE 2003 LODS series. Furthermore, for most parameters the Bull. A solutions utilizing JMA AAM (A/JMA) show statistically significant differences with respect to all the remaining NCEP AAM-based solutions of Table 4. This demonstrates, rather convincingly, the danger of any physical interpretation of solutions from such a short data interval of a few years, which are quite sensitive to any biases and inconsistencies of AAM, OAM and LOD data.

In Table 5, all the LODS series gave high correlation coefficients, though the JMA AAM-based values are the lowest for most intervals, in spite of the fact that with the NCEP AAM, Bull. A LODS had the best correlation in all intervals but the shortest one of 3 days. This indicates that during this interval, the NCEP AAM corresponded better to the observed LODS than JMA AAM. This is likely due to the relatively poor agreement of NCEP and JMA motion (wind) components (Aoyama and Naito 2000), which are predominant (∼90%) in the AAM excitations of LOD. The new CMB and both IGS LOD series gave the highest correlation for the shortest interval of 3 days, but when compared to the Bull A, they both experienced some correlation decrease for the intervals between 10 days and 30 days. It is not surprising that the CMB series behaved similarly to IGS, since the IGS00P02 LOD series was combined with VLBI UT observations. Furthermore, this spectral domain combination is designed, for the periods below 30 days, to rely with increasing frequency on the satellite LOD observations, while UT observations facilitate the stability and de facto a calibration of the biased satellite LOD at lower frequencies with periods >30 days (Vondrák and Čepek 2000). The decrease in the 3-day correlation (relative to the best ones), seen in particular for both IERS series, is likely due to an implicit or explicit smoothing.

Figure 4 shows the correlation with IB-corrected OAM+AAM for all the LODS series, except the historical IGS95P02, which was quite similar to the official IGS00P02 series and thus is not shown hereafter. Mean correlation values plotted in Fig. 4 were generated from respective spectra as averages within 20-frequency bin sliding windows for the high-frequency portion of the LOD spectrum (periods < 10 days). Like the time-domain correlation (Table 5), the frequency-domain one is also sensitive to LODS/(AAM+OAM) phase coherence. The corresponding amplitudes are shown in Figs. 5 and 6. All LODS, except for C04, reach high correlation values for periods above the 3 days. However, the IGS and

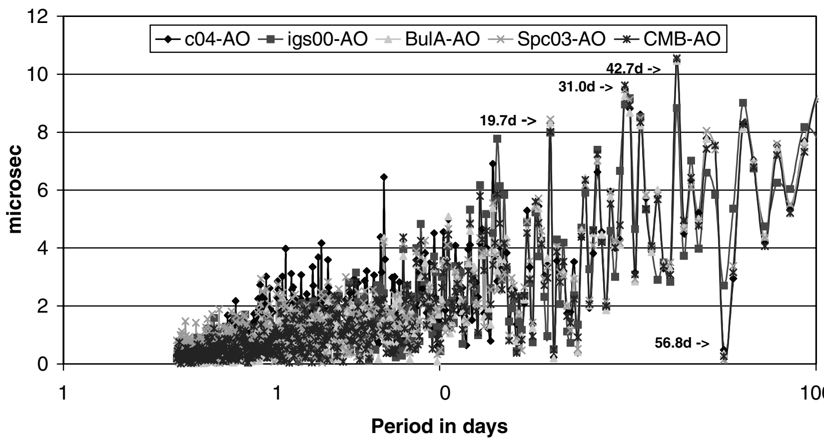

Fig. 7 LODS residual amplitudes with respect to IB-corrected (AAM+OAM), during September 1997 – July 2000

Table 5 LODS correlation with IB-corrected (NCEP AAM + OAM), after removing the fitted annual, semi-annual, monthly and fortnightly periodic signals, rates and scales from the LODS series (see Table 4), during September 1997–July 2000. A/JMA is the correlation of Bull. A LODS and (JMA AAM+OAM)

Interval	igs00	Bull A	C04	Spc03	CMB	igs95	A/JMA
∼3 year	0.996	0.996	0.995	0.995	0.996	0.996	0.995
30 day	0.937	0.944	0.926	0.936	0.941	0.937	0.924
15 day	0.888	0.905	0.869	0.892	0.898	0.890	0.862
10 day	0.851	0.868	0.815	0.847	0.864	0.854	0.813
3 day	0.706	0.699	0.600	0.642	0.731	0.711	0.629

CMB series, which look almost identical here, reached fairly high correlation values below 3 days, though with some rapid and sharp variations. These sharp variations for periods up to 4 days are puzzling, and they are likely caused by the corresponding, often sharp, LODS amplitude lows seen in Fig. 5. The AAM+OAM spectra in this frequency band (with periods < 4 days) do not have such structures and at times are even asymmetric with respect to the LODS amplitudes (see the IGS LODS amplitude lows just below the 3-day period in Fig. 5). Figure 6 also shows implicit or explicit smoothing for some LOD series. Note that the sharp amplitude drop just above 2 days, seen for IGS and CMB (Figs. 5, 6), is caused by the cubic spline interpolation used for both series to interpolate them from the 12-h to 0-h epoch sampling (Kouba 2005).

The amplitude spectra of AAM+OAM residuals for the five LODS series, corrected for estimated parameters of Table 4, are shown in Figs. 7–9. Figure 7 includes all periods up to 100 days. For periods longer than 19 days and for all LODS, it shows several peaks, which exceed the 3-sigma significance level (∼6 μs). Most LODS series are fairly similar in this low-frequency window, which is not surprising as all rely heavily on the same VLBI (UT) observations and differ mainly in combination approaches, though IGS still shows a somewhat different behavior. Note that CMB, which is designed to retain the high frequency of GPS LOD and the low frequency of VLBI UT, starts to behave more like the rest of the LOD series, which are based on VLBI UT observations (see e.g., the 56.8-day amplitude low in Fig. 7).

Figure 8 shows the high-frequency part of the LODS – (AAM + OAM) residual spectrum. Here, there are four peaks exceeding the 3-sigma significance level. One is at the weekly period and three are near the fortnightly period. The first, the most conspicuous one, is the largest for C04, and though smaller, it is also present for Bull. A and SPACE 2003, but it is almost non-existent (∼2 μs) for IGS and CMB. This 7-day periodic signal has already been noticed for PM and LOD differences between Bull. A and C04 in 1999 (Kouba et al. 2000). Subsequently, it was practically eliminated by USNO simply by changing the treatment of the two, weekly alternating VLBI contributions within the Bull. A combinations.

Within the fortnightly frequency, there is considerably more variation amongst the five LOD series, as seen in Fig. 9, which shows an enlarged portion of the frequency bands shown in Fig. 8, approximately centered at the lunar fortnightly period. Amongst the three statistically significant amplitude peaks, the one at 14.22 is present only for the IGS (∼8 μs) and to a smaller extent also in the CMB series (∼6 μs), while the other LOD series here show even a local minimum of about (∼2 μs) only. These 14.2-day PM rate/LOD peaks have already been identified in 1999 for IGS and some AC ERP contributions (Kouba et al. 2000). Subsequently, it has been shown for the PM rates that they were caused by the sensitivity of unconstrained PM rate solutions to a small error in the O1 (25.82-h) period component of an older sub-daily PM model used by some IGS ACs (Kouba 2003b). Note that this sub-daily tidal wave has a beat period (against exactly 24-h period) of 14.19 days, so when in error,

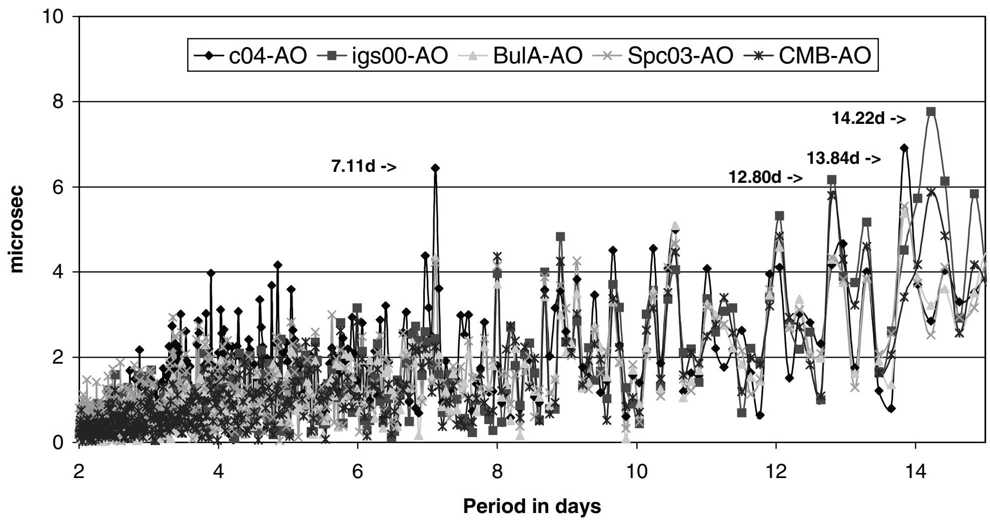

Fig. 8 High-frequency amplitudes of LODS residual with respect to IB-corrected (AAM+OAM), during September 1997 – July 2000

Table 6 Fitted LODS tidal amplitude corrections (μs) and scaling (k/C) of the Yoder et al. (1981) a prori model, LOD rate (μs/year) and AAM/OAM (AO) scaling solutions for the IERS Bull. A with respect to IB-corrected NCEP and JMA AAM, combined with OAM, during April 1993–July 2000. Also shown are Yoder et al. (1981) UT model amplitudes (scaled by 0.940) and Kantha et al. (1998) UT amplitudes that were multiplied by (2π/Period(days)), to obtain the LOD amplitudes, corresponding to the IERS 2003 model (Defraigne and Smits 1999)

Period(d/y)	Yd 81	Kha 98	IERS2003		A/NCEP		A/JMA	
	cos	sin	cos	sin	cos	sin	cos	sin
13.63d	147.9	0	148.6	0.9	−0.8	0	−1.2	0
13.66d	356.8	11.2	358.4	2.2	−1.5	0	0.4	0
27.56d	188.4	2.2	189.9	1.3	0.2	0	−0.2	0
182.6d	166.6	0	168.8	1.5	22	78	22	74
365 d.	28.1	0	26.9	0.3	50	17	51	18
18.6 y	159.8	0	−156.2	2.3	−294	0	−257	0
k/C	0.940		0.940		0.963		0.955	
Rate					−240		−233	
AO Scale					0.880		0.862	
sigma					98.4μs		93.8μs	

it will produce significant 14.2-day period errors, even for 24-h mean ERP rate or LOD solutions. This property was used for testing the IERS2000 sub-daily PM model against the unconstrained IGS PM rate solutions (Kouba 2003b). For a mathematical treatment of this approach and its applications to estimations of sub-daily periodical parameters, see Brzezinski et al. (2004). This 14.2-day period signal should disappear when using the conventional or a more precise sub-daily ERP model. The fact that the VLBI-based LOD series do not show this anomalistic period indicates that they were computed as the rate of change of the combined UT series, which is largely insensitive to sub-daily ERP errors when averaged over 24 h (Kouba 2003b). The other two significant peaks at 13.8 days, seen mainly for the VLBI-based LOD series, and the 12.8-day one seen only for IGS and CMB are more puzzling and not understood. However, it is encouraging to see that there is practically no signal left at the Mf tidal bands with periods of 13.63 and 13.66 days, indicating that the out-of- phase component of the long-period oceanic (Mf) tides, which were modeled according to Kantha et al. (1998), agree quite well with all LOD observations.

4 Discussions

All the investigated LOD series, though using unique and different combination approaches, and sometimes unique LOD observations, look quite similar when compared to the combined AAM and OAM. Some combinations, such as the Bull. A, are regularly reprocessed, taking advantage of yearly reprocessing of the complete VLBI UT series. On the other hand, the IGS combinations, which utilize only GPS solutions (though calibrated by VLBI) of seven (currently eight) IGS ACs, are not reprocessed and should be gradually improving with improved GPS data (both quality and distribution) and with continuously improving AC analysis approaches and modeling (e.g., Kouba 2003a). Only the IGS00P02 ERP combinations use a simultaneous adjustment of PM, LOD and station coordinates along with the corresponding variance-covariance matrices (Kouba et al. 1998b). In particular, a simultaneous adjustment of PM and LOD benefits the LOD solutions as the PM solution parameters, through the corresponding variance-covariance matrices,

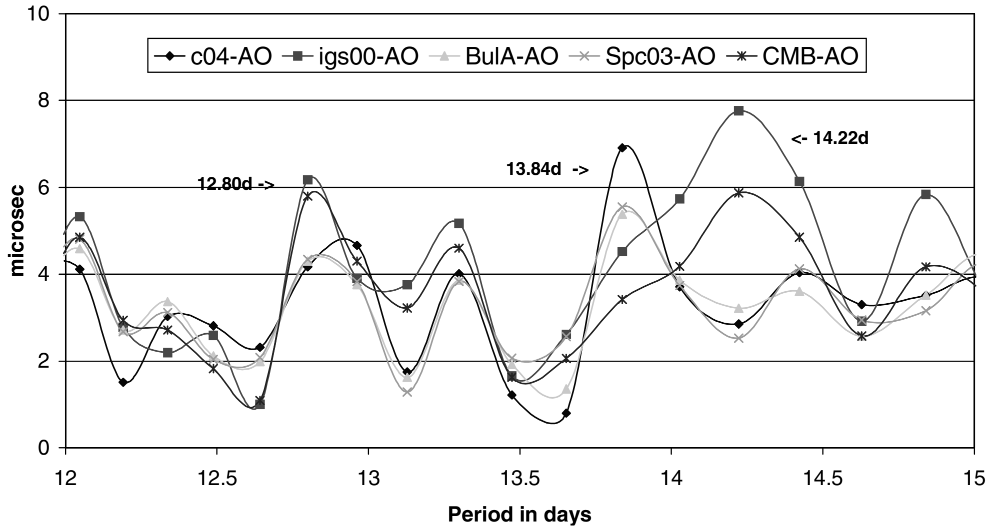

Fig. 9 Fortnightly band amplitudes of LODS residual with respect to IB-corrected (AAM+OAM), during September 1997 – July 2000

provide an effective link between different solution contributions (Ray et al. 2005). Consequently, IGS LOD should be gradually improving, which is also likely the case for most of the investigated series. A noticeable improvement in IGS PM correlation with the same OAM + AAM series was noticed when the second half of the interval (February 1999–July 2000) was used (Kouba 2005). However, for LOD, practically no significant improvement was observed when using this shorter, more recent interval. The LOD/(OAM + AAM) correlation values for all LOD series at all interval windows were similar to the ones shown in Table 5.

There are noticeable differences between the LOD series seen in both correlation and residual spectra (e.g., Table 5 and Fig. 5). Often they resemble smoothing (see e.g., Fig. 6, Bull A), which usually tends to help the correlation, particularly in the high-frequency band, since it also tends to suppress some anomalous high-frequency noise signals. In particular, the C04 series (and to a smaller extent also SPACE2003) exhibits a strange behavior, having a large number of spectral spikes for periods within 3–5 days (Fig. 8), causing a significant and abrupt amplitude increase and correlation decrease at these periods (see Figs. 4, 6, 8). The IGS series also has some sharp anomalous spikes, and rather strange and erratic correlation variations for periods below 3 days, which may be caused by some implicit smoothing within the contributed AC analyses. For example, 3-day orbit arcs, used by some ACs, may have introduced some implicit smoothing. The two sharp IGS amplitude lows seen in Fig. 5 at about 2.5 days and 3 days, which cause the corresponding sharp correlation decreases in Fig. 4, resemble 2.5-day and 3-day smoothing curves, though heavily attenuated by contributions of other, unsmoothed AC contributions, which used daily orbit arc solutions only. For more detailed discussions on explicit and implicit smoothing effects, see Rothacher et al. (1999) and Kouba (2005).

Encouraged by the solutions of the fortnightly and monthly tides shown in Table 5, which were based on a rather short interval of less than 3 years, a similar solution was tested, but for a longer interval of April 1993–July 2000, for which both the NCEP and JMA AAM data were available. The new solutions are summarized in Table 6. Unlike in Table 4, here the semi-annual and annual amplitudes are solved with respect to the corresponding tidal phase angles, and thus are expressed as tidal components. Both cosine (in-phase) and sine (out-of-phase) components were solved for these two fundamental tidal frequencies, as well as the cosine amplitude for the longest 18.6-year lunar tidal period. For convenience and consistently with the IERS2003, Table 6 also shows the LOD cosine amplitudes of the Yoder et al. (1981) model (scaled by $k/C = 0.94$), which was used as an a priori model, as well as the IERS2003 model amplitudes (Defraigne and Smits 1999). No sine amplitudes are given by Yoder et al. (1981) for the Mf (13.66-day) and Mm (27.56-day) tides, so the corresponding UT values, derived by Kantha et al. 1998, multiplied by a factor of (2π/Period(days)) to obtain the LOD amplitudes were used and are listed in Table 6. Note that both Yoder et al. (1981) and IERS2003 model amplitudes already include in-phase fortnightly and monthly oceanic tides, and also that the IERS model also includes small out-of-phase (sine) LODS amplitudes, as listed in Table 6 (see McCarthy and Petit 2004).

In Table 6, the fortnightly and monthly tide solutions are very close: they agree within 1.5 μs with the a priori for both AAM data series, which is remarkable considering that the formal sigmas are only about 1 μs. However, the remaining parameter solutions for semi-annual, annual and 18.6-year periods differ greatly from both tidal models and likely are of little or no significance. They simply demonstrate that AAM + OAM LODS residuals cannot be used for such long- period tidal estimation, since at these periods the LODS AAM/OAM residuals are significantly affected by possible AAM and OAM model errors, the neglected effects (e.g., stratospheric winds above 10 mbar), or simply caused by processes other than the atmosphere, ocean and the Earth tides. Rather discouraging and puzzling are the solutions of the (AAM + OAM) scale. They are too small and inconsistent with previous results for the equatorial (OAM + AAM) component scaling computed from PM rates, which tended to be 10% larger than unity (Kouba 2005). Nevertheless, it is encouraging to see a relatively good agreement between the two AAM series, except for the 18.6-year amplitude, which should be expected, since the 18.6-year period is too long for the data span used in the parameter estimation. Note the different, likely wrong sign of the IERS2003 18.6-year LOD amplitude, since this LODS amplitude, given in McCarthy and Petit (2004), is inconsistent with the corresponding UT amplitudes of both models listed in Table 6. For similar UT tidal amplitude solutions for tidal periods up to 35 days, and based on a 9-year long VLBI UT series, see Robertson et al. (1994)

5 Conclusions and recommendations

The precise, daily OAM data series of Ponte and Ali (2002), when combined with standard AAM series, appears to serve as an independent reference ("ground truth") to assess the quality of different LOD series at the spectral periods starting from 2 days up to a few months. Based on this OAM + AAM reference, the IERS Bull. A LOD series, which is a multi-technique combination, appeared to perform the best for all but the shortest interval of 3 days. However, one is cautioned that such comparisons are sensitive to inconsistencies of implicit and explicit smoothing employed in LOD solutions/ combinations, OAM and AAM analyses. AAM and OAM may also, apart from the 24-h averaging, be subjected to some implicit smoothing (Kouba 2005). Furthermore, we caution that the analyzed LOD series are more than 4 years old and the current combinations and the contributed solutions and modeling have probably improved significantly.

The performance of the new LOD series CMB of Vondrák and Ron (2005) is encouraging, since it gave the best 3-day correlation and behaved exactly as designed, i.e. retained the high-frequency content (periods <30 days) of the satellite (IGS) LOD, typically subjected to significant biases with long periods (>30 days). It has outperformed the input IGS LOD, yet gradually letting the stable and strong VLBI UT observations to take over for longer periods (periods > 30 days). This new UT/LOD combination may be well suited to replace empirical LOD calibrations, such as those currently employed by IGS, or as a preprocessing, or calibrations of the biased satellite LOD solutions, before attempting rigorous, multi-technique combinations of ERP, EOP and station coordinates (e.g., Richter et al. 2002).

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References

Aoyama Y, Naito I (2000) Wind contributions to the Earth's angular momentum budgets in seasonal variation. J Geophys Res 105(D10:12417–12432

Barnes RTH, Hide R, White AA, Wilson CA (1983) Atmospheric angular momentum fluctuations, length-of-day changes and polar motion. Proc R Soc Lond, Ser A 387:31–73

Beutler G, Kouba J, Springer T (1995) Combining the Orbits of the IGS Analysis centers. Bull Geod 69:200–222

Brzezinski A, Nastula J (2002) Oceanic excitation of Chandler wobble. Adv Space Res 30(2):195–200

Brzezinski A, Ponte RM, Ali AH (2004) Nontidal oceanic excitation of nutation and diurnal/semi diurnal polar motion revisited. J Geophys Res 109:B11407, doi:10.1029/2003JB003054

Chen JL, Wilson CR, Hu XG, Zhou YH, Tapley BD (2004) Oceanic effects on polar motion determined from an ocean model and satellite altimetry: 1993–2001. J Geophys Res 109:B02411, doi:10.1029/2003JB002664

Defraigne P, Smits I (1999) Length of day variations due to zonal tides for elastic Earth in non-hydrostatic equilibrium. Geophys J Int 139:563–572

Dick WR, Richter B (eds) (2001) IERS annual report 2000. International Earth Rotation Service, Central Bureau. Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, p 152, ISBN 3-89888-862-2

Dorandeu J, Le Traton PY (1999) Effects of global mean atmospheric pressure variations on mean sea level changes from TOPEX/Poseidon. J Atm Oceanic Technol 16:1279–1283

Ferland R, Kouba J, Hutchison D (2000) Analysis methodology and recent results of the IGS network combination. Earth Planets Space 52:953–957

Gross R S (2000) The excitation of the Chandler wobble. Geophys Res Lett 27(15):2329–2333

Gross RS (2001) Combinations of Earth orientation measurements: SPACE2000, COMB2000, and POLE2000, JPL Pub. 01–2, p 25, Jet Propulsion Lab., Pasadena, Calif

Gross RS (2004) Combinations of Earth orientation measurements: SPACE2003, COMB2003, and POLE2003, JPL Pub. 04–12, p 28, Jet Propulsion Lab., Pasadena, Calif., 2004. ftp://euler.jpl.nasa.gov/keof/combinations/2003/ SpaceCombPole2003.pdf

Gross RS, Fukumori I, Menemenlis D, Gegout P (2003) Atmospheric and oceanic excitation of Earth's wobble during 1980–2000. J Geophys Res 108(B80):2370, doi:10.1029/2002JB002143

Gross RS, Fukumori I, Menemenlis D, Gegout P (2004) Atmospheric and oceanic excitation of length-of day variations during 1980–2000, J Geophys Res 109:B01406, doi:10.1029/2003JB002432

Kantha LH,. Steward JS, Desai SD (1998) Long-period lunar fortnightly and monthly oceanic tides. J Geophys Res 103:12639–12647

Kouba J, Mireault Y, Beutler G, Springer T, Gendt G (1998a) A Discussion of IGS Solutions and their impact on geodetic and geophysical applications. GPS Solut 2(2):3–15

Kouba J, Ray J, Watkins MM (1998b) IGS reference frame realization. In: Dow JM, Kouba J, Springer T (eds) The 1998 IGS Analysis Center proceedings, European Space Operations Centre, Darmstadt, Germany, Feb. 9–11, pp 139–171

Kouba J, Beutler G, Rothacher M (2000) IGS combined and contributed ERP solutions. In: Dick S, McCarthy DD, Luzum B (eds) Polar motion historical and scientific problems, IAU colloquium 178, Astronomical Society of Pacific, conference series 208, pp 277–302

Kouba J (2003a) A Guide to Using International GPS Service (IGS) products. A report prepared for IGS. February, available at ftp://igscb.jpl.nasa.gov/igscb/resource/pubs/GuidetoUsingIGS-Products.pdf

Kouba J (2003b) Testing of the proposed IERS 2000 convention subdaily earth rotation parameter model. Stud Geophys Geod 47:725–740

Kouba J (2005) Comparison of polar motion with oceanic and atmospheric angular momentum time series for 2-day to Chandler periods. J Geod Doi:10.1007/s00190-005-0440-7

Langley RB, King RE, Shapiro I I, Rosen RD, Salstein DA (1981) Atmospheric angular momentum and length of the day: a common fluctuation with periods near 50 days. Nat Lond 294:730–732

Marshall J, Hill C, Perelman I, Adcroft A (1997) Hydrostatic, quasi-hydrostatic and non-hydrostatic ocean modeling. J Geophys Res 102:5733–5752

McCarthy DD (ed) (1996) IERS conventions (1996). IERS technical Note 21, IERS central bureau, (http://maia.usno.navy.mil/conventions.html)

McCarthy DD, Petit G (eds) (2004) IERS conventions (2003). IERS technical note no. 32, BKG Frankfurt a/M. (http://maia.usno.navy.mil/conv2003.html)

Mireault Y, Kouba J, Ray J (1999) IGS Earth rotation parameters. GPS Solut 3(1):59–72

Ponte RM (1993) Variability in a homogenous global ocean forced by barometric pressure. Dyn Atmos Oceans 18:209–234

Ponte RM, Stammer D, Marshall J (1998) Oceanic signals in observed motions of the Earth's pole of rotation. Nature 391:476–479

Ponte RM, Ali AH (2002) Rapid ocean signal in polar motion and length of day. Geoph Res Lett 29(15): 10.1029/2002GL015312

Ray JR, Kouba J, Altamimi Z (2005) Is there utility in rigorous combinations of VLBI and GPS EOPs ? (Sumbmitted)

Ray JR (1996) Measurements of length of day using the global positioning system. J Geophys Res 101:20141–20149

Richter B, Schwegman W, Dick WR (eds) (2002) Proceedings of the IERS workshop on geophysical fluids, held in Munich, Germany, Nov. 20–21, IERS Technical Note No. 30

Robertson DS, Ray JR, Carter WE (1994) Tidal variations in UT1 observed with very long baseline interferometry. J Geophys Res 99:621–636

Rothacher M, Beutler G, Herring TA, Weber R (1999) Estimation of nutation using the global positioning system. J Geophys Res 104:4835–4859

Salstein DA, Kann DM, Miller AJ, Rosen RD (1993) The sub-Bureau for Atmospheric Angular Momentum of the International Earth Rotation Service: a Meteorological Data Center with geodetic applications. Bull Am Meteorol Soc 71(1):67–80

Salstein DA, Rosen RD (1997) Global momentum and energy signals from reanalysis systems, 7th conference on climate variations. American Meteorological Society, Boston pp 344–348

Salstein DA (2003) The GGFC Special Bureau for the Atmosphere of the international Earth Rotation and Reference System Service. In: Richter B, Schwegman W, and Dick WR (eds) Proceedings of the IERS workshop on geophysical fluids, held in Munich, Germany, Nov. 20–21, 2002, IERS Technical note no. 30

Vondrák J, Čepek A (2000) Combined smoothing method and its use in combining Earth orientation parameters measured by space techniques. Astron Astrophys 147:347–359

Vondrák J, Weber R, Ron C (2002) Earth orientation parameters – combination of results obtained by different techniques. In: Ádám J, Schwarz KP (eds) Vistas for geodesy in the new millennium, Proceedings of the IAG Symposium 125. Springer, Berlin Heidelberg New York, pp 24–29

Vondrák J, Ron C (2005) Combining GPS and VLBI measurements of celestial motion of the Earth's spin axis and Universal Time. Acta Geodynamica et geomaterialia (in press)

Yoder CF, Williams JG, Parke ME (1981) Tidal variations of Earth rotation. J Geophys Res 86:4835–4859