TESTING OF THE IERS2000 SUB-DAILY EARTH ROTATION PARAMETER MODEL

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ABSTRACT

The differences between the new International Earth Rotation Service (IERS) 2000 and the previous IERS1996 sub-daily Earth rotation parameters (ERP) models can reach 0.1 mas (0.001 arc sec) and 0.1 mas/day. The largest differences are seen for the aliasing periods of 14.2 and 360 days, which correspond to the diurnal tidal waves of O1 and (K1, P1), respectively. Precise independent polar motion (PM) rate solutions effectively doubles the sampling rate and allows for effective testing of sub-daily ERP models and other periodical effects at the diurnal and semi-diurnal frequency bands. Since November 12, 2000, when the Jet Propulsion Laboratory (JPL) Analysis Center of International GPS Service (IGS) has switched to the conventional IERS1996 sub-daily ERP model, from the older model of Herring and Dog (1994), the JPL daily PM rate solutions show no, or greatly reduced 14.2 day amplitude (O1) peaks. This confirmed that the anomalistic amplitudes at 14.2 day period seen for JPL PM solutions prior November 12, 2000 was largely due to the effects of the older sub-daily ERP model on independent PM rate solutions. As indicated by the latest IGS PM rate solutions, which were corrected for the IERS1996 and 2000 model differences, the new IERS2000 sub-daily ERP model is expected to perform equally well as the conventional IERS1996 model.

Keywords: Earth rotation, polar motion, sub-daily earth rotation models

1. INTRODUCTION

Since June 30, 1996, in all IGS Analysis Center (AC) analyses (*Neilan et al., 1996*), the International GPS Service (IGS) has adopted the sub-daily ERP model (for PM and UI1-UTC), based on the International Earth Rotation Service (IERS) 1996 Conventions. All ACs have complied and have been using sub-daily ERP models, i.e. according to the IERS conventions the sub-daily ERP model is subtracted from all ERP solutions. However, early in 1999, while analyzing IGS and AC ERP rate solutions with respect to Atmospheric Angular Moment (AAM) data, a significant anomalistic, 14.2-day period spectral peaks were noticed for the Jet Propulsion Laboratory (JPL) ERP solutions (*Kouba et al., 2000*). Later on this was confirmed to be due to a different sub-daily ERP model

(*Herring and Dong, 1994)*, used by JPL up to November 12, 2000, (modified Julian day (MJD) 51860) (*Kouba, 2002*).

For completeness, the conventional sub-daily polar motion (PM) *Xp*, *Yp* model of *IERS (1996)* and the older model of *Herring and Dong (1994)* are compared in Table 1. The differences in mas (0.001 arc sec) of Table 1 indicate that the 14.2 and 180 day (aliasing period) anomalies noticed in 1999 are mainly due to the use of the older sub-daily ERP model. This is so, since the tidal waves O1 and K2, which have the retrograde aliasing periods (with exactly 24h UTC) of 14.2 and 181.3 days, also show the largest differences. An analysis of the most recent JPL PM solutions (after Nov. 12, 2000), which are based on the *IERS (1996)* conventions, confirmed this, since the apparent 14.2 day PM rate amplitudes were significantly decreased *(Kouba, 2002*), see also Fig. 7 below. This demonstrates not only the sensitivity of independent PM rate solutions to the sub-daily PM effects, but also the capability to detect possible sub-daily PM model deficiencies while using the existing *ERP* rate solutions with the standard sampling rate of 24-h.

2. IERS1996 AND IERS2000 SUB-DAILY ERP MODEL DIFFERENCES

Since January 2003 the IERS has adopted a new set of conventions (*IERS, 2000*), including a new sub-daily ERP model, which is still supposed to be consistent with the IERS1996 model, i.e. it is also based on the model of *Ray et al. (1994)*. However, the new IERS2000 model has been extended by a number small tidal waves derived by a standard admittance from a recent ocean tide model, so that it now includes 71, rather than the eight principal tidal waves of *IERS (1996)* listed in Table 1. The pertinent question now is how much better is the performance of the new sub-daily ERP model. The IERS1996 and IERS2000 sub-daily ERP model differences for the period of July 1996–September 2001 are plotted Fig. 1a–c. For comparison purposes the complete sub-daily ERP signal based on the IERS2000 model is also shown in each figure. In order to quantify the effect of the

Table 1. Differences between *Herring and Dong (1994)* and the conventional *IERS1996* sub-daily ERP models for X_P, Y_P pole positions (*Herring and Dong (1994)–IERS (1996)*) in milliarcsec (mas). The aliasing periods are the periods with which the tidal waves beat against the period of exactly 24-h UTC; prograde (+), retrograde(-).

Tide wave	Period (h)	Alias P (d)	X_P cos (mas)	X_P sin (mas)	Y_P cos (mas)	Y_P sin (mas)
M2	–12.42	14.75	0.0370	–0.0070	0.0117	0.0253
S2	–12.00	∞	0.0002	–0.0345	–0.0004	–0.0098
N2	–12.66	9.62	0.0107	0.0018	0.0018	–0.0103
K2	–11.97	–181.32	–0.0296	–0.0152	–0.0102	–0.0473
K1	23.94	368.23	0.0190	–0.0042	0.0042	0.0190
O1	25.82	–14.19	0.0449	–0.0404	0.0404	0.0449
P1	24.07	–364.64	–0.0013	–0.0099	0.0099	–0.0013
Q1	26.87	–9.37	0.0068	–0.0047	0.0047	0.0068

sub-daily ERP on independent ERP rate solutions, both the IERS2000 pole position corrections and the corresponding differences between the IERS2000 and IERS1996 models have been fitted for apparent 24-h ERP rates. The apparent 24-h polar motion (PM) X_p and Y_p rates are shown in Fig. 2a,b. The amplitude spectra corresponding to Figs. 1 and 2, expressed in the conventional prograde (counterclockwise +) and retrograde (clockwise –) components are shown in Figs. 3 and 4, respectively.

The model difference shown in Fig. 1a–c are fairly large, when considering that both models are supposed to be based on the same model of *Ray et al. (1994).* Although the model differences are exceeding the formal precision of IGS ERP solutions (< 0.1 mas), they do not affect the ERP solutions as they are largely averaged out over the 24-h interval sampling used for all IGS ERP solutions. (This may not be the case for other solution parameters, such as precise orbits). However, the apparent rate differences, shown in Fig. 2a,b, may be significant and should be a matter of concern, as they map directly into independent ERP rate solutions and since they are also approaching the solution precision level of 0.1 – 0.2 mas/day. In particular, the 14- and 360-day periods seem to be predominant for the model differences as seen in Figure 4, which show the apparent PM rate spectra.

3. TESTING METHODOLOGY

To test a sub-daily ERP model, it is necessary either to solve for ERP at intervals much shorter than the current IGS sampling of 24-h, or solving it directly by including significant diurnal and semidiurnal tidal terms amongst the solution parameters. In both cases, the retrograde (–) diurnal polar motion (PM) signal must be suppressed, as in GPS global analyses it is completely correlated with the orientation of the solved GPS satellite orbits (*Rothacher 1998; Rothacher at al., 2001*). However, both of these approaches require specialized processing and cannot take the advantage of the wealth of the existing, long and precise AC solutions as well as the IGS combined product series. An alternative approach used here is to analyze the existing series of long and precise AC and IGS ERP and ERP rate solutions with 24-h sampling and to examine the aliasing periods that are listed in the third column of Table 1. The independent 24-h ERP rate solutions are quite sensitive to the signals at the diurnal and semi-diurnal tidal frequency bands (see Fig. 2a,b and e.g., *Kouba, 2002*). However, continuity constraints applied by most ACs and up to mid 2002 in the official IGS Final ERP series (IGS00P02) completely suppress any such signals at the diurnal and semi-diurnal tidal frequency bands (see Fig. 5). *Kouba et al. (2000*) have successfully used the ERP rates derived from Atmospheric Angular Momentum (AAM) data to detect the JPL anomalistic periods at 14.2 and 181 days which were caused by using a sub-daily ERP model that did not conform to the *IERS (1996)* conventions. This kind of comparisons revealed the above aliasing periods as well as other, long period ERP rate signals that were not contained in the AAM and which correlated well with oceanic signals, even with some ionospheric effects (*Kouba et al., 2000*).

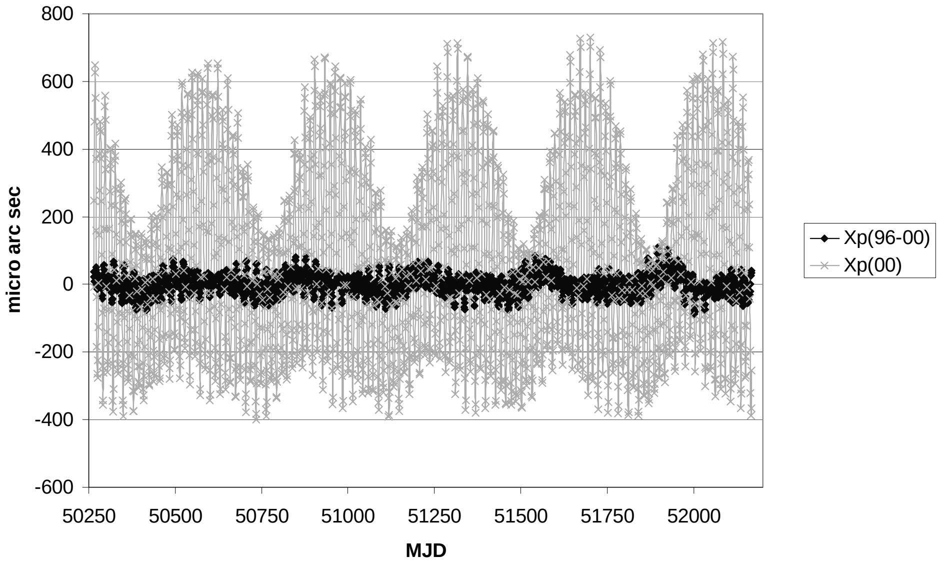

Fig. 1a. IERS1996 (96) and IERS2000 (00) conventional ERP model differences for the X_P PM component.

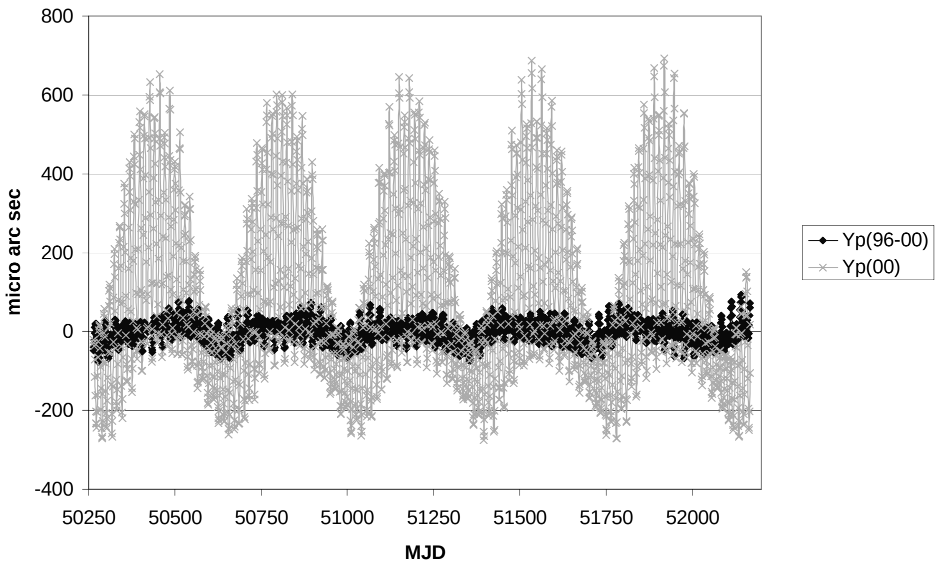

Fig. 1b. IERS1996 (96) and IERS2000 (00) conventional ERP model differences for the Y_P PM component.

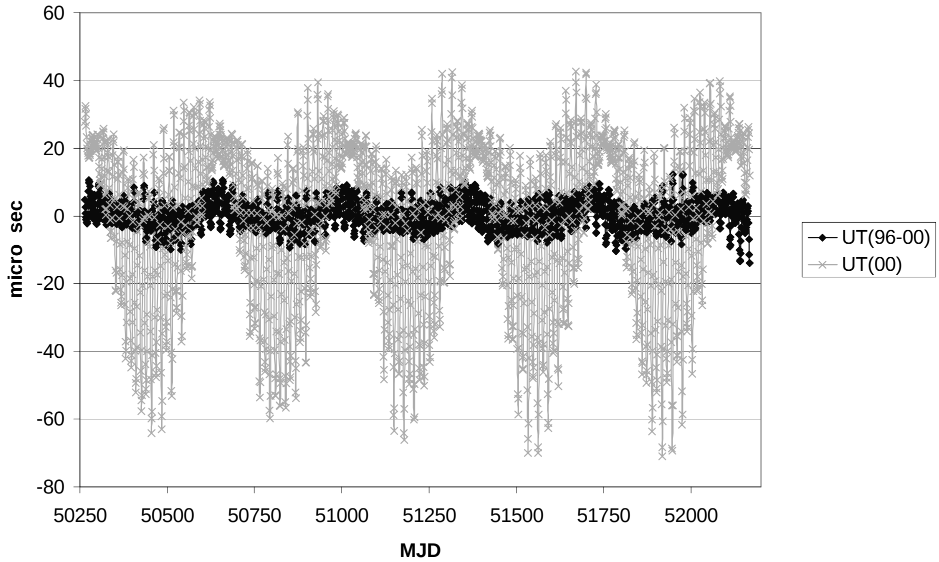

Fig. 1c. IERS1996 (96) and IERS2000 (00) conventional ERP model differences for UT1-UTC (UT).

For the tests here, a different comparison was used which was specifically designed to detect only the aliasing periodical signals at diurnal and sub-diurnal frequencies. Such signals can be real (e.g. due to the oceans, atmosphere), or only apparent (e.g. due to (orbit) modeling deficiencies). Since the UT rate, i.e. the length of day (LOD) is subjected to a number of zonal tidal terms, some of which have the same periods as the expected aliasing periods of the sub-daily ERP effects, here only PM rate solutions were used in this testing. More specifically, the following daily PM rate differences (*dX*) were used for this purpose:

$$dX\left(t_{i+0.5}\right) = X\left(t_{i+1}\right) - X\left(t_i\right) - \frac{X_{rt}\left(t_{i+1}\right) + X_{rt}\left(t_i\right)}{2}, \qquad (1)$$

where $X(t_{i+1})$, $X(t_i)$ and $X_{rt}(t_{i+1})$, $X_{rt}(t_i)$ are the pole position and pole rate solutions at the two adjacent daily epochs t_{i+1} and t_i, respectively. The quantity (1) can be interpreted as either the pole position difference at the mid points, interpolated either from the subsequent or preceding pole position using the pole rate solutions. Alternatively, it can also be viewed as the difference between the pole rates derived from the pole position and the pole rate solutions. Since the 24-h average pole position solutions, unlike the independent 24-h pole rate solutions, are insensitive to any diurnal and semi-diurnal signals, the rate difference (1) will fully reflect the real (e.g. due to ocean/atmosphere) and apparent signals (e.g . orbit model errors), but only at the aliasing frequencies of the diurnal/semi-diurnal tidal bands. The other, long period signals will cancel out in (1),

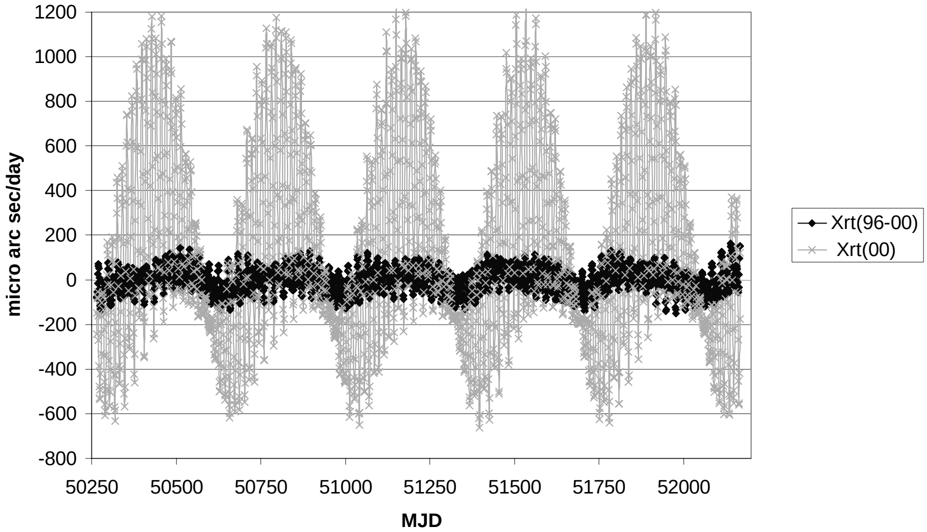

Fig. 2a. Apparent PM X_P rate differences of IERS1996 (96) and IERS2000 (00) conventional models.

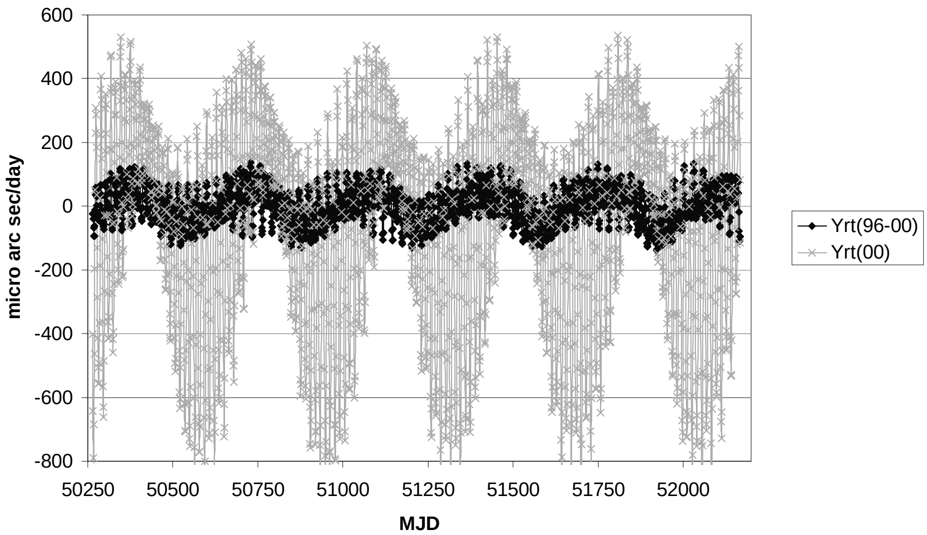

Fig. 2b. Apparent PM Y_P rate differences of IERS1996 (96) and IERS2000 (00) conventional models.

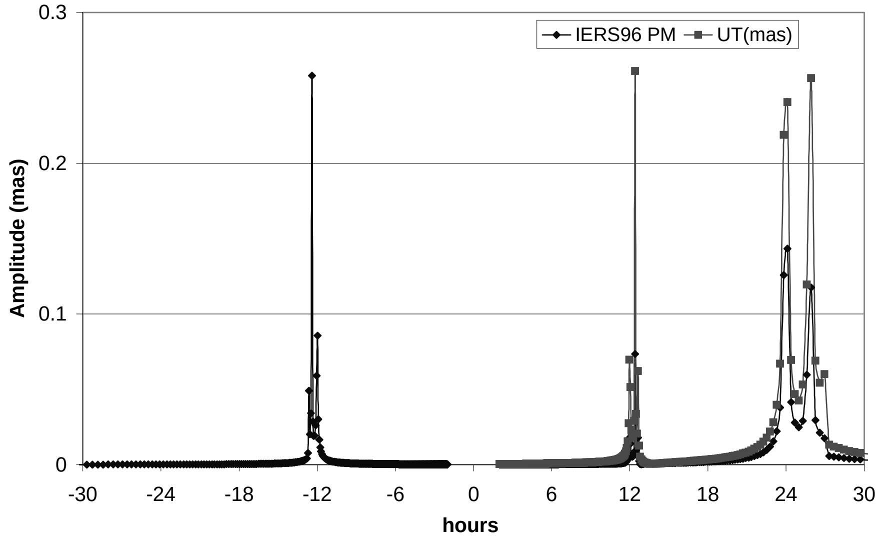

Fig. 3. Prograde (+) and retrograde (–) spectra of IERS1996 conventional sub-daily ERP model, note that for compatibility the UT component is expressed also in mas units.

since they are contained in both the pole position and pole rate solutions. Note that the expression (1) is quite suitable for a detection of the (aliasing) periods that are much longer than two days, since the random noise of the rate solutions is reduced by $\sqrt{2}$ (due to the averaging over the two adjacent days). Yet the long period signals ($\gg 2$ days) are not affected by this averaging. Furthermore, the error contributions of the pole position difference in (1) is relatively small, since the 24-h average pole position solutions are more precise, by at least a factor of 2, than the corresponding rate solutions. Subsequently, the error contribution of the pole position difference in (1) is typically smaller than the averaged rate solution errors in (1). Expression (1) also demonstrates that by solving for independent pole rate, the sampling rate of pole rate series effectively doubles, i.e. the observed pole rate series and the one computed from the corresponding pole position solutions are offset by 0.5 day in this case. However, when the ERP continuity constraints are enforced in the pole rate solutions, both the computed and observed pole rate series become equivalent and the rate differences of (1) becomes equal to zero, and cannot be used for such sub-daily ERP tests. This can be seen in Fig. 5, which shows a segment of the rate differences (1), evaluated from the official IGS Final ERP combined series (IGS00P02) which clearly contains continuity constraints during each week. Note that since mid 2002 the IGS00P02 series does not contain any such continuity constraints (*Ferland, NRCan, personal communication, 2002*).

The ERP rate continuity within each week of the IGS00P02 series was the consequence of unremoved/unreported continuity constraints in at least one of the submitted AC weekly solutions in the standard SINEX format. Since, as long as even

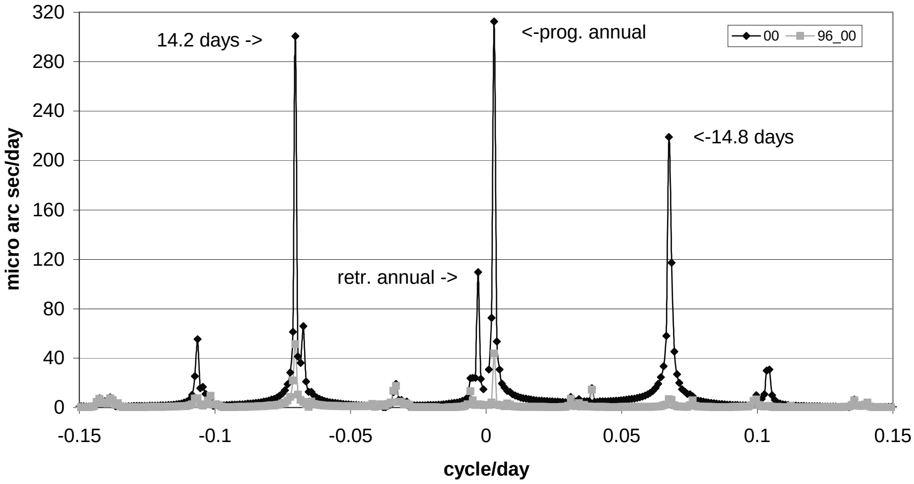

Fig 4. Prograde (+) and retrograde (–) aliasing period spectra of apparent daily PM rates computed from the IERS2000 (00) and the difference with respect to IERS1996 (96_00) sub-daily ERP model (during March 2000 – January 2003).

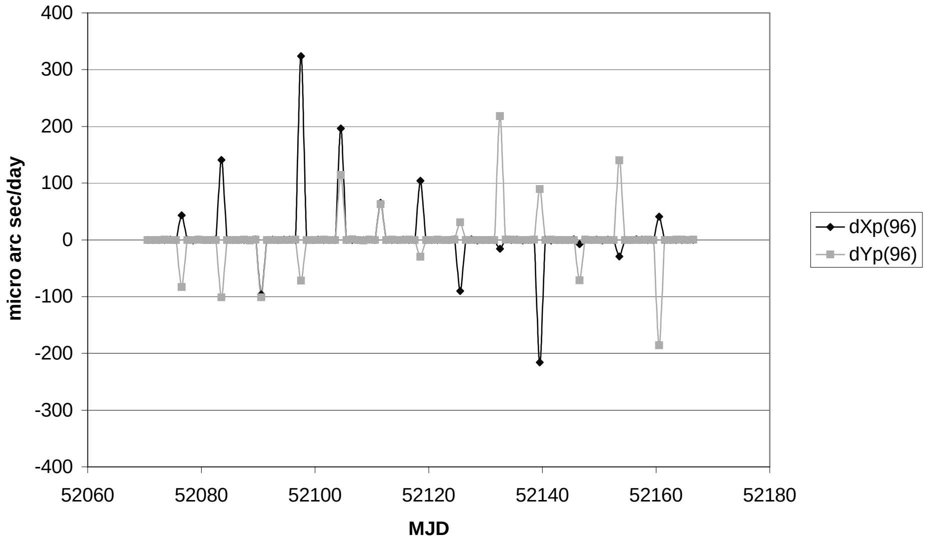

Fig. 5. PM rate continuity differences (*dXp*, *dYp*) evaluated according to (1) for the IGS Final ERP combination series (IGS00P02.erp) prior July, 2002.

a single AC SINEX solution contains the unremoved ERP continuity constraints within its weekly SINEX variance-covariance matrix, then the rigorously combined IGS SINEX solutions (which includes the corresponding variance-covariance matrices) for IGS00P02 ERP will also include the ERP rate continuity constraints within the current week. There is no ERP continuity between subsequent weeks, as the AC weekly SINEX submissions are considered independent from week to week within the IGS SINEX combinations. Thus the weekly ERP rate discrepancies are clearly visible in Fig. 5.

Unfortunately, most ACs have chosen to apply the continuity constraints in their ERP rate solutions, so that the rate differences (1) are largely suppressed also in the original, independently combined, IGS ERP series (IGS95P02). This original IGS combined series, which was superceded by the SINEX combination (IGS00P02) in early 2000, is generated independently within the orbit/clock Final combinations, while also utilizing for the ERP combinations the objectively determined, orbit weights (*Beutler et al., 1995*). Since only two ACs (JPL and EMR) are confirmed to solve for independent ERP rates (*Kouba et al., 2000*), then the IGS95P02 signal of (1) is expected to be attenuated by a factor of about 0.25, which should correspond to an average proportional combined weight of the two AC solutions within the orbit/ERP combination process (*Mireault, NRCan, personal communication, 2001*). Furthermore, as already noticed prior MJD 51860, the JPL AC solutions, which up to November 12, 2000 were based on a different sub-daily ERP model, are also included within the IGS95P02 series. For completeness, Fig. 6 shows the PM difference (1) for a recomputed SINEX combination (IGS02) with no continuity constraints (*Ferland, NRCan, personal communication, 2002*), the Fig. 6 should be representative of the current IGS00P02 PM rate solutions, which after July 2002 do not employ any continuity constraints.

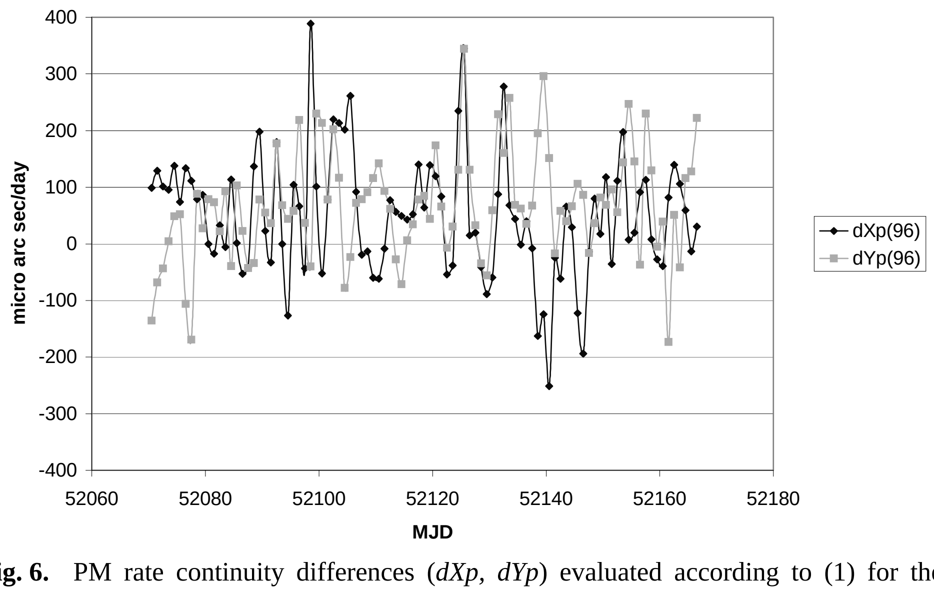

Fig. 6. PM rate continuity differences (*dXp, dYp*) evaluated according to (1) for the recomputed IGS ERP series (igs02).

4. RESULTS

Since only JPL and EMR ACs are known to submit independent ERP rate solutions, they were chosen for the testing. Two IGS Final ERP series were also used, i.e. the official IGS Final ERP (IGS00P02.erp), which is combined rigorously within SINEX station/ERP combinations, and which appears to have continuity constraints (see Fig. 5) and the recomputed SINEX IGS02 combinations with no continuity constraints (Fig. 6). Furthermore, since JPL has used the *Herring and Dong (1994)* sub-daily ERP model prior November 12, 2000 (MJD 51860), the JPL solutions were subdivided into two equal sets of 8.5 months, one before (JPL1) and one after (JPL2) the model change. For the second set (JPL2) and EMR and IGS solutions, which are based on the IERS1996 model, the corresponding ERP solutions also have been obtained with the proposed IERS2000 model. This was accomplished by simply adding the IERS1996-IERS2000 apparent (X_P, Y_P) rate differences (see Fig. 2a,b) to the ERP rate solutions based on the IERS1996 sub-daily ERP model. This should be a legitimate approximation of an actual processing with the new IERS2000 model, since the apparent rates caused by the sub-daily ERP effects are expected to map directly into the independent ERP rate solutions.

The resulting periods and amplitudes for the JPL PM (prograde and retrograde) rate solutions are shown in Fig. 7, with the vertical scale twice larger than in Fig. 4. One can readily notice the significant improvements after the change from the *Herring and Dong (1994)* to the IERS1996 model. This is true in particular for the noted 14.2-day period for which the retrograde amplitude of about 160 μarcsec practically vanished. This is quite consistent with the Table 1, which shows the largest differences for the tidal wave O1 with the aliasing period of −14.19 days. Furthermore, most amplitudes for longer periods, in particular for retrograde ones (Fig. 7), are smaller for the IERS1996 than for the

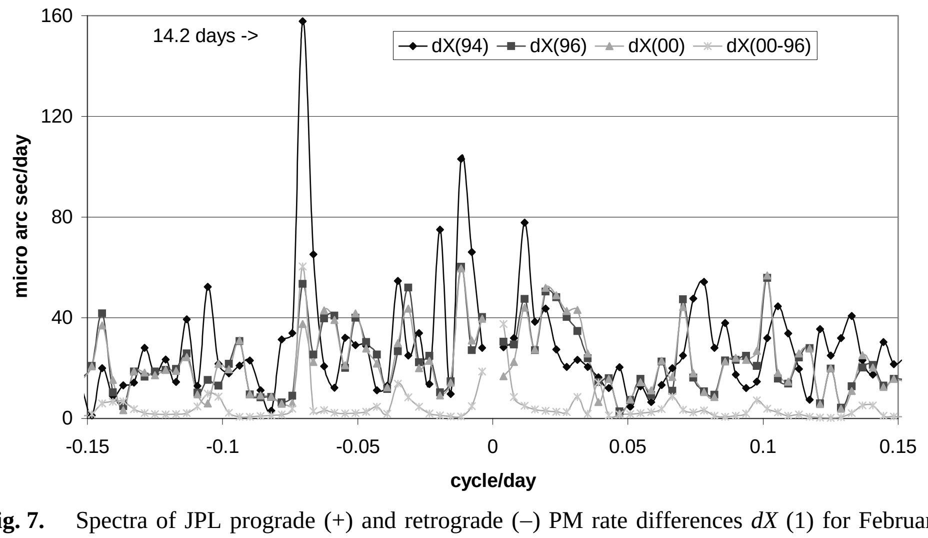

Fig. 7. Spectra of JPL prograde (+) and retrograde (−) PM rate differences *dX* (1) for February 2000 to July 2001. (Sub-daily ERP models: *Herring and Dong, 1994,* (94) used prior November 12, 2000; IERS1996 (96) and IERS2000 after November 12, 2000).

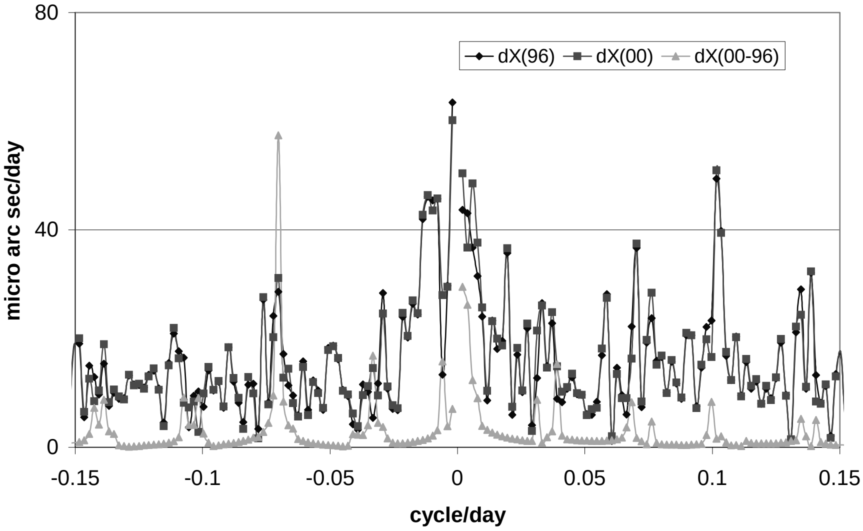

Fig. 8. Spectra of EMR prograde (+)and retrograde (–) PM rate differences *dX* (1) for April 2000 to September 2001. (Sub-daily ERP Models: IERS1996 (96) and IERS2000 (00)).

Herring and Dong (1994) model. The IERS2000 model, for most periods, gives practically the same amplitudes for the recent JPL solutions, as can be observed in Fig. 7.

Note that the corresponding spectra of the IERS2000-IERS1996 pole rate differences, abbreviated here as (00–96), are also shown in Fig. 7 for a reference. A more complete spectra of the IERS2000–IERS1996 pole rate differences, based on a longer period of about 3 years, were already shown in Fig. 4. Note that for the two 8.5 month solution intervals of Fig. 7, it was not possible to get any meaningful results for the seasonal and semi-seasonal terms.

For the EMR solutions, a different interval, covering about 17 months of the most recent EMR ERP solutions, was used. During this period the EMR solutions should be fairly homogenous and were based only on the IERS1996 model. Similarly as above, the IERS2000 EMR solutions were simulated by adding the corresponding IERS1996–IERS2000 apparent rate difference of Fig. 2. The results are shown in Fig. 8. Like for JPL, the EMR results based on the IERS2000 model did not seem to improve with respect to the IERS1996 model results. Note that EMR ERP rate solutions are considerably noisier (by a factor of about 2) than the JPL PM rate solutions and thus may be affected by larger solution biases. In particular, the large amplitude in seasonal and semi-seasonal bands are disturbing and should be investigated by using solution intervals much longer than 17 months used here.

Fig. 9, which show the official IGS ERP series (IGS00P02) that appears to include the ERP continuity constraints (see Fig. 5), is included for completeness only and to show how any apparent ERP rate signal is suppressed, nearly down to zero in this case. Consequently, the model IERS2000 – IERS1996 differences and the reconstructed series based on *IERS (2000)* show much larger amplitudes at the 14.2-day period. This

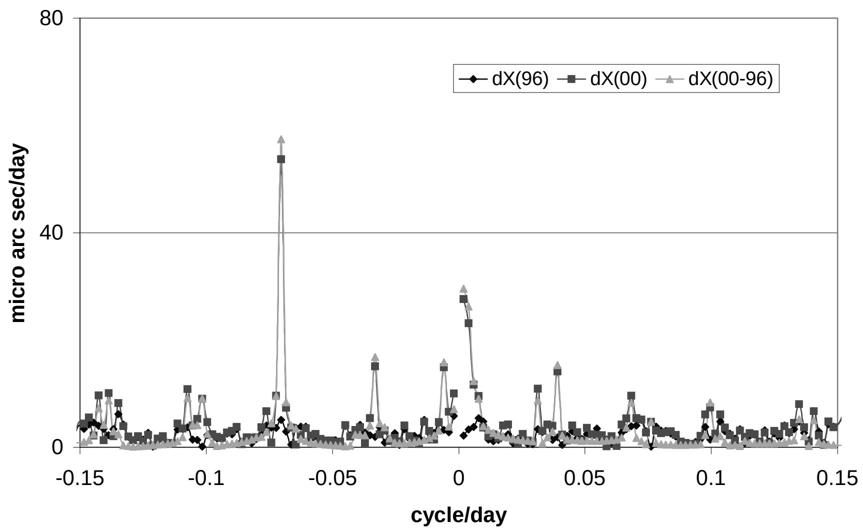

Fig. 9. Spectra of IGS00P02 retrograde and prograde PM rate differences *dX* (1) for April 2000 to September 2001. (Sub-daily ERP models: IERS1996 (96) and IERS2000 (00).

demonstrates the relative size of the model difference signal with respect to the continuity-imposed series, which gives nearly zero amplitudes for all periods. Finally, Fig. 10 show the newly recomputed IGS series, which does not contained any continuity constraints and should thus be representative of the currently official IGS00P02 series after July 2002. Note that for clarity, Figs. 8–10 used the same vertical scale that is twice larger than in Fig. 7 and four times larger than the one used in Fig. 4.

The time domain statistics (means and RMS about the means) for the original IGS ERP combinations (IGS95P02) and the ERP solutions shown in Figs. 7–10 are summarized in Table 2. Note that the derived *IERS2000* statistics for IGS95 (IGS95P02), used only 25% of the IERS (1996-2000) model difference, in order to approximate the relative weighting of AC solutions within the IGS ERP combinations (IGS95P02). The JPL solutions were split here into two parts (JPL1, JPL2), before November 12, 2000, which used the *Herring and Dong (1994)* model and after November 12, 2000, based on the IERS1996 model. The JPL1 IERS1996 results here were obtained by simply adding the differences between *Herring and Dong (1994)* and IERS1996 models. The IERS2000 solutions in Table 1 were derived in a completely analogous way, while using the *IERS (1994)* and *IERS (2000)* model differences. As one can see, the conventional IERS1996 performed significantly better than the older *Herring and Dong (1994)* model and the proposed new convention *IERS (2000)* performed equally well as the IERS1996 sub-daily ERP model.

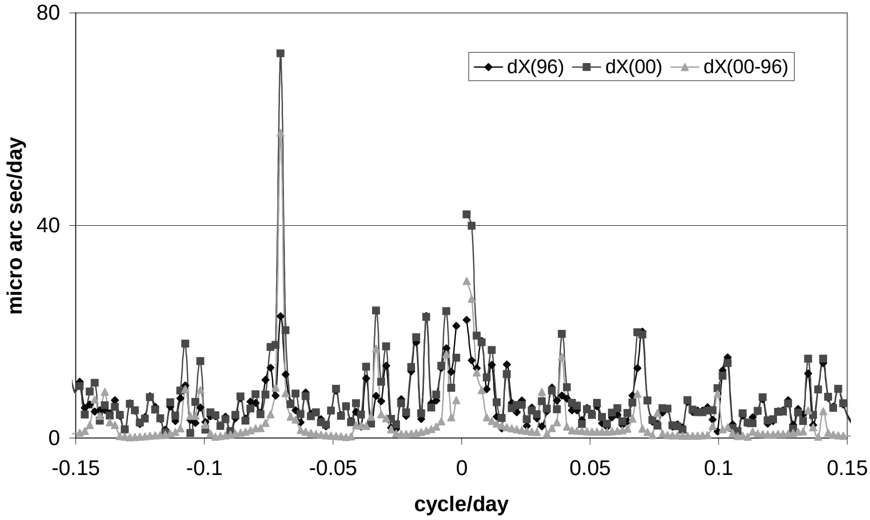

Fig. 10. Spectra of the recomputed IGS02 retrograde and prograde PM rate differences *dX* (1) for Nov. 1998 to Sep. 2001. (Sub-daily ERP models: IERS1996 (96) and IERS2000 (00).

Table 2. Pole Rate RMS for Tested EMR, JPL2 and IGS ERP Rate Solutions (in μarcsec/day); during November 12, 2000 to September 15, 2001; JPL1-*Herring and Dong (1994)* model for February 20, 2000 – November 11, 2000.

AC/IGS		*Herring and Dong (1994)*		IERS1996		IERS2000		IERS(1996–2000)	
		X_{rt}	Y_{rt}	X_{rt}	Y_{rt}	X_{rt}	Y_{rt}	X_{rt}	Y_{rt}
JPL1	mean	–11	–69	–5	–77	–8	–64	7	3
	RMS	250	286	233	260	244	262	60	62
JPL2	mean			6	–44	–2	–47	7	3
	RMS			188	202	189	195	60	62
EMR	mean			–59	21	–66	18	7	3
	RMS			246	276	250	277	60	62
IGS95*	mean			–3	–1	–4	–2	7	3
	RMS			69	80	67	79	60	62
IGS00	mean			3	–2	–4	–5	7	3
	RMS			41	40	68	75	60	62
IGS02	mean			–30	–20	23	17	7	3
	RMS			89	91	91	115	60	62

* Used 0.25×IERS(1996–2000) to reflect the relative weights of JPL and EMR solutions within IGS95P02.

5. CONCLUSIONS

An efficient test of the sub-diurnal ERP effects was developed and successfully tested with precise independent ERP rate solutions. Such tests, involving the continuity conditions of ERP and ERP rate solutions, are non zero and meaningful only for independent ERP rate solutions. Furthermore, they are sensitive only to sub-diurnal effects caused e. g. by the oceans, atmosphere or solution model inadequacies, since the other, long period effects, are the same for both the ERP and ERP rate solutions, thus they completely cancel out. However, this continuity testing is not possible for the official IGS Final ERP series (up to July 2002) and most of the AC ERP rate solutions, for which ERP rate continuities are enforced during each week.

The continuity tests, using the independent JPL ERP rate solutions, were able to confirm the differences between two sub-daily ERP models. The tests also indicated that the new conventional IERS2000 model is performing equally well as the old conventional model of IERS1996. The largest model difference of about 60 μarcsec/day is seen for the O1 tidal frequency (i.e. at the corresponding 14.2-day aliasing period).

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