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ORIGINAL ARTICLE

Jim Ray · Jan Kouba · Zuheir Altamimi

Is there utility in rigorous combinations of VLBI and GPS Earth orientation parameters?

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Abstract Combinations of station coordinates and velocities from independent space-geodetic techniques have long been the standard method to realize robust global terrestrial reference frames (TRFs). In principle, the particular strengths of one observing method can compensate for weaknesses in others if the combination is properly constructed, suitable weights are found, and accurate co-location ties are available. More recently, the methodology has been extended to combine time-series of results at the normal equation level. This allows Earth orientation parameters (EOPs) to be included and aligned in a fully consistent way with the TRF. While the utility of such multi-technique combinations is generally recognized for the reference frame, the benefits for the EOPs are yet to be quantitatively assessed. In this contribution, which is a sequel to a recent paper on co-location ties (Ray and Altamimi in J Geod 79(4–5):189–195, 2005), we have studied test combinations of very long baseline interferometry (VLBI) and Global Positioning System (GPS) time-series solutions to evaluate the effects on combined EOP measurements compared with geophysical excitations. One expects any effect to be small, considering that GPS dominates the polar motion estimates due to its relatively dense and uniform global network coverage, high precision, continuous daily sampling, and homogeneity, while VLBI alone observes UT1-UTC. Presently, although clearly desirable, we see no practical method to rigorously include the GPS estimates of length-of-day variations due to significant time-varying biases. Nevertheless, our results, which are the first of this type, indicate that more accurate polar motion from GPS contributes to improved UT1-UTC results from VLBI. The situation with combined polar motion is more complex. The VLBI data contribute directly only very slightly, if at all, with an impact that is probably affected by the weakness of the current VLBI networks (small size and sparseness) and the quality of local ties relating the VLBI and GPS frames. Instead, the VLBI polar motion information is used primarily in rotationally aligning the VLBI and GPS frames, thereby reducing the dependence on co-location tie information. Further research is needed to determine an optimal VLBI-GPS combination strategy that yields the highest quality EOP estimates. Improved local ties (including internal systematic effects within the techniques) will be critically important in such an effort.

Keywords Earth orientation · Reference frames · Multi-technique combinations · GPS · VLBI

1 Introduction

Conventional Earth orientation angles describe the time-varying position of the pole in the terrestrial reference frame (TRF) (X_p and y_p), rotation about the polar axis (UT1-UTC), and motion of the pole in the celestial frame (precession and nutation). Each angle changes continuously, with secular, broadband, seasonal, tidal, and stochastic components. The variations in the terrestrial frame are related to redistributions of fluid masses and momentum within the Earth system, whereas precession and nutation involve primarily gravitational interactions with external bodies as well as their couplings with internal mass redistributions within the Earth. Earth orientation parameter (EOP) measurements sample the variations over some discrete integration interval, typically 24 h, and usually report an offset value at a given epoch together with its rate of change. The conventional practice of the International Earth Rotation and Reference Systems Service (IERS) is to remove EOP tidal variations near 12- and 24-h

J. Ray (✉)
National Geodetic Survey& Bureau International des Poids et Mesures,
1315 East-West Hwy, Silver Spring, MD, 20910-3282, USA
E-mail: jimr@ngs.noaa.gov
Tel.: +1-301-713-2850
Fax: +1-301-713-4475

J. Kouba
Natural Resources Canada, 615 Booth Street,
Ottawa K1A 0E9, Canada
E-mail: kouba@geod.nrcan.gc.ca

Z. Altamimi
Institut Géographique National, Paris, France
E-mail: altamimi@ensg.ign.fr

periods from exchanged values using a prescribed model during the data analysis; see IERS Conventions (2003) (McCarthy and Petit 2004).

Very long baseline interferometry (VLBI) is the only technique able to determine all EOP components because it is the only current means to access the International Celestial Reference Frame (ICRF), which is realized by the coordinates of a set of astronomical radio sources [see McCarthy and Petit (2004) and references therein for a full description of the procedures]. VLBI observing sessions are nominally 24 h duration and scheduled at quasi-regular, non-continuous intervals. About six widely separated radio telescopes are used in standard VLBI sessions, but the networks vary among sessions. The EOP results are normally reported for the midpoint epoch of each observing session. Routine geodetic VLBI operations began in 1984; more limited data sets exist in earlier years. While there has been a general improvement in VLBI quality with time, results from individual sessions are highly inhomogeneous due to differences in geometry, numbers of stations, and data yields.

Observations of the GPS satellites have been collected continuously since about 1994 from a global network of stations, coordinated by the International GPS Service (IGS) [recently renamed International GNSS (Global Navigation Satellite System) Service]. More limited data exist in earlier years. The IGS tracking network has now grown to more than 350 stations. Not having direct access to the ICRF, GPS is unable to observe UT1-UTC or nutation offsets, but is sensitive to variations of these quantities. The excess length-of-day (LOD), equivalent to the discrete change of UT1-UTC over one day, is routinely reported by IGS analysis groups (Ray 1996). Rates of change of the nutation angles can be similarly determined (Rothacher et al. 1999), but these estimates are not commonly produced. On the other hand, the IGS excels in its continuous observations of polar motion (and rate of change) due to its robust global coverage, homogeneity, and use of combined analyses from up to eight independent groups (Mireault et al. 1999). IGS polar motion, polar motion rates, and LOD determinations are reported at UT noon epochs for integrations over the surrounding 24-h period.

Multi-technique EOP combinations are formed by the IERS, and others, using inputs from VLBI, GPS, and satellite laser ranging (SLR); see the series of annual reports of the IERS. All data analyses are assumed to follow the 2003 IERS Conventions (McCarthy and Petit 2004) as closely as possible so that common or equivalent models are applied. Until recently, individual EOP time-series have been separated from their associated reference frames, then calibrated in isolation for systematic biases (including those related to the reference frames), and combined using empirical weights. Without precise knowledge of the attached reference frames, bias calibration is inherently problematic.

While the shortcomings of this approach have been recognized for years, until recently the only rigorous joint EOP-TRF combination available operationally was that of the IGS using solutions from GPS only. Consistent with common usage, the term "rigorous" is applied here to solution methods using reduced, unconstrained normal equations, or equivalent, with full variance-covariance information for all TRF and EOP parameters (at least) simultaneously. Kouba et al. (1998) developed appropriate procedures used by the IGS; the IERS has since embraced a similar goal for its multi-technique combinations, as described by Richter et al. (2003).

Ponte and Ali (2002) showed that the IGS GPS-only polar motion series is considerably better correlated with an independent geophysical series of atmospheric and oceanic angular momenta (AAM+OAM) than is the IERS multi-technique polar motion, especially at most periods <5 days. Ray and Kouba (2003) and Kouba (2005) expanded the Ponte–Ali study to include additional multi-technique polar motion combinations. They found that all the non-rigorous (without TRF and covariance information) combinations either lost power in the highest frequencies (presumably due to smoothing), lost coherence with AAM+OAM, or both. Only a test multi-technique combination by Altamimi (2003) using rigorous methods with joint EOP-TRF solution files did as well as the GPS-only solution from the IGS.

This study, which is a sequel to earlier work dealing with VLBI-GPS co-location ties (Ray and Altamimi 2005), is the first attempt to clarify the relative EOP contributions of VLBI and GPS in a joint rigorous combination including their respective TRFs, polar motion, UT1-UTC (LOD), and full variance-covariance matrices. As the EOP errors from SLR are much larger than from GPS and VLBI (and even more so for DORIS), other techniques will be investigated in a future study.

2 Intra-technique combinations

Initially, time-series of GPS and VLBI solutions were combined (rigorously stacked) separately, which requires no local ties. The GPS solutions were the weekly terrestrial frames and EOPs, produced by the IGS from a weighted combination of submissions from as many as eight independent analysis centers (Ferland 2004). The IGS weekly SINEX (solution-independent exchange format) files for the period 28 February 1999 through 28 February 2004, containing parameters for 346 station coordinates and daily polar motion and polar motion rates, were combined into a single consistent frame estimating coordinates and linear velocities at the mean epoch of 29 August 2001. The LOD values reported by the IGS were ignored altogether. These estimates are not strictly based on GPS observations alone since external calibrations were already applied (Mireault et al. 1999) to mitigate time-varying biases (Ray 1996). The polar motion (and rates) series consists of 1827 continuous epochs reported at each daily UT noon. (For specifications of the SINEX format, see http://tau.fesg.tu-muenchen.de/∼iers/)

The VLBI solutions were from the analysis of the NASA Goddard Space Flight Center (GSFC) group of individual 24-h observing sessions, reduced to SINEX format (IVS 2004), since there was no corresponding SINEX combination of separate VLBI solutions available at the time. Only recently has such a project begun. Prior comparisons have shown that the NASA solution was among the highest quality and was the most complete. However, in principle, future combined VLBI solutions should be equally precise and more robust than the best individual analysis solutions, as already demonstrated for IGS combinations. Data for a total of 62 stations were combined, together with polar motion, polar motion rates, UT1-UTC, and LOD values for 677 non-continuous days during the same 5-year span as for the GPS data. The mean reference epoch was also 29 August 2001. The reported VLBI nutation offsets and the corresponding parts of the variance-covariance matrix were ignored in this study, which has no impact on the results presented since this is equivalent to an algebraic elimination of the nutation parameters. The GPS and VLBI combined frames were each minimally aligned to match ITRF2000 as closely as possible without internal distortion (Altamimi et al. 2002).

For both of these SINEX combinations, as well as all the others discussed here, the CATREF software developed at the Institut Géographique National of France (Altamimi and Boucher 2003), was used. The CATREF package contains modules for handling constraints, comparisons, and combination and analysis of individual TRF realizations provided in SINEX format. Using a least-squares approach, the combination model simultaneously adjusts station positions, velocities, and the sets of 14 Helmert transformation parameters relating each individual solution to the combined frame. It also allows EOPs to be included in a fully consistent way to rigorously enforce EOP alignment to the combined frame; see Altamimi and Boucher (2003) for details. The output EOP values are always reported at the nearest UT noon epochs. CATREF permits accurate datum specification, using the well-established geodetic approach of minimum constraints, so ensuring full internal consistency within the combined frame.

Overall, the internal consistency of the global station positions within each combined frame is at the sub-mm level for stations that observed for the full 5-year period. The average formal errors for x_p and y_p, using the reported unscaled covariances, are 27.3 and 28.5 μas for the IGS and 205.3 and 186.7 μas for the VLBI series, respectively. The IGS errors are highly uniform throughout the study period (standard deviations of about 8 μas) but the VLBI errors are not (standard deviations of 53 μas) due to varying networks and data quality. Median formal errors for the VLBI polar motion are about 120 and 103 μas, respectively. The considerably larger VLBI formal errors and their variations are commensurate with the much smaller, sparser VLBI networks that observe at any particular epoch. Weighted RMS differences between our homogeneous combination of the IGS data and their operational polar motion values are 29.1 and 41.1 μas, respectively.

The operational IGS series suffers from the effects of several reference frame changes, not entirely compensated: from ITRF96 realized by 47 stations to ITRF97 realized by 51 stations on 1 August 1999; from ITRF97 to the IGS internal realization of ITRF97 (IGS97) on 5 March 2000 (which has the largest EOP impact); from IGS97 realized by 51 stations to the IGS realization of ITRF2000 (IGS00) using 54 stations on 2 December 2001; from IGS00 to an updated version using 99 stations on 11 January 2004. The consistent GPS reference frame applied in our reduction over the full 5-year period is an important advantage for this study. Note that the VLBI errors are inflated by propagation (using the observed polar motion rates) from session midpoints to regular noon epochs; the average formal errors for the VLBI rates are roughly 500 μas/day (with large scatters).

The average x_p and y_p formal errors at session midpoints, from the original GSFC analysis, are about 106.4 and 90.6 μas, respectively. Regularization of the EOP epochs is a standard and necessary part of any multi-technique combination intended for general use. However, the increased VLBI errors due to regularization also demonstrate the value of using common observation epochs for all EOP solutions and techniques.

3 Inter-technique combinations

Four VLBI-GPS test combinations have been made. In each case, CATREF was used to form a homogeneous 5-year solution combining the station coordinates and selected EOP information. A 14-parameter Helmert transformation was adjusted to align the VLBI and GPS frames, including velocities. The GPS covariances were scaled by a factor of $(1.5)^2$ while those of the VLBI solution were scaled by $(3.2)^2$, based on past experience with ITRF2000 (Altamimi et al. 2002) [For comparison, Gross (2004) found scale factors for VLBI polar motion, relative to unity for the IGS, of $(1.844)^2$ and $(1.692)^2$ for x_p and y_p, respectively].

In test solutions 1 and 2, the included EOPs were polar motion and rates from the IGS and VLBI, as well as UT1-UTC and LOD from VLBI only. The LOD values reported by the IGS were omitted due to time-varying biases (Ray 1996) and lack of independence. In principle, the GPS-derived LOD values should be useful if a satisfactory method can be found to mitigate or model the biases in the combination. We suggest that GPS-based LOD and rigorously adjusted UT1-UTC/LOD from VLBI could be combined in a secondary step using a Kalman filter, for instance.

Test solutions 1V and 2V were the same as above, except that IGS polar motion and rate observations were rejected, so EOP output values are only available for days with VLBI sessions (677 non-continuous epochs). These latter two combinations were designed to study whether the strong IGS TRF is able to reinforce the much less robust VLBI frame.

The difference between solutions 1/1V and 2/2V concerns the handling of the VLBI-GPS co-location ties. In the former case, nominal weights are used for all 25 available co-location ties based on the formula:

$$\sigma_{\text{nominal}} = \sqrt{(\sigma_1^2 + \sigma_2^2)} \tag{1}$$

where $\sigma_1 = 3$ mm, $\sigma_2 = 10^{-6} \times D$, and D is the length of the tie vector in kilometers. The ties are given in Ray and Altamimi

Table 1 Summary of test combinations. All solutions cover the period from 28 February 1999 through 28 February 2004, for a total of 1827 days if continuously sampled

Code	Data used	EOPs used	Tie weights	# PM epochs	# UT1 epochs
I	GPS only	G:PM,PM-rates	n/a	1827	None
V	VLBI only	V:PM,PM-rates, UT1-UTC/LOD	n/a	677	677
1	GPS+VLBI	G:PM,PM-rates V:PM,PM-rates, UT1-UTC/LOD	Nominal	1827	677
1V	GPS+VLBI	V:PM,PM-rates, UT1-UTC/LOD	Nominal	677	677
2	GPS+VLBI	G:PM,PM-rates V:PM,PM-rates, UT1-UTC/LOD	8 down-weighted	1827	677
2V	GPS+VLBI	V:PM,PM-rates, UT1-UTC/LOD	8 down-weighted	677	677

All output EOP estimates [polar motion (PM), PM-rates, UT1-UTC, LOD] are generated at UT noon epochs. For a description of the down-weighted local ties, see the text

(2005). In addition, velocity parameters are constrained to be the same at the co-location sites and at those GPS sites with multiple receivers.

Based on co-location residuals from prior test combinations, some of the less reliable ties have been down-weighted in solutions 2/2V: FAIR-Gilcreek and HOB2-Hobart to 5 mm; NOT1-Noto, ALGO-Algonquin, WES2-Westford, and FORT-Fortaleza to 1 cm; PIE1-PieTown to 1.5 cm; and GOLD-Goldstone to 2 cm. In addition, velocity constraints were dropped for the pairs TROM-TRO1 (both GPS), NYAL-NYA1 (both GPS), YAKA-YAKT (both GPS), and WES2-Westford (GPS-VLBI). In all the combinations, any position discontinuities (due to earthquakes or equipment changes, for instance) were handled by selecting the longest homogenous data segments.

It should be noted that including the polar motion and polar motion rate parameters in a time-series combination effectively acts as a daily two-dimensional co-location point that is free of any tie error (Ray and Altamimi 2005). This eliminates the need for two local tie components and two co-located velocity component links for the Helmert rotations about X and Y and their rates. In this case, only five components of the tie vectors are needed, at minimum, significantly reducing the effect of local tie errors in test combinations 1 and 2.

Table 1 summarizes the characteristics of the six test combinations, including the two intra-technique solutions.

4 Geophysical excitations

To provide an independent "ground truth" series for comparison, we have used geophysical polar motion and LOD excitations derived by adding AAM, from the National Centers for Environmental Prediction (NCEP) reanalysis Kalnay et al. (1996), to OAM, from Ponte and Ali (2002). The AAM values include winds up to 10 mbar, with pressure corrected for the inverted-barometer (IB) effect (which assumes the ocean level compensates instantaneously for any atmospheric pressure changes). The OAM values were derived from a barotropic model (Ponte 1993) driven by NCEP reanalysis winds four times daily, and are consistent with the IB assumption of the AAM series. The OAM series has been provided to us for midnight epochs so the four-times daily AAM values have been averaged to the same epochs. The OAM series is only available from 2 October 1992 through 1 July 2000, so the overlap of AAM+OAM and geodetic data is limited to about 1.5 years (28 February 1999 until 1 July 2000).

Using a 4-year comparison period, Ponte and Ali (2002) showed that the cross-coherency amplitude of AAM+OAM and geodetic excitations for polar motion and LOD is about 80% or more for periods longer than 7 days, but drops steadily at shorter periods. The oceanic contribution is considerably more important for polar motion excitation than for LOD changes, varying between about 30 and 100% of the AAM power depending on the spectral band. Therefore, for polar motion comparisons, we are restricted to the 1.5-year overlap period with OAM. However, for LOD comparisons, where OAM excitation is much smaller and AAM alone is useful, the full 5-year period has been used.

Effective excitation functions (χ_1 and χ_2) have been computed from the geodetic measurements using the formulation of Barnes et al. (1983). In order to aid interpretation, the equatorial functions (proportional to polar motion rates of change) have been scaled to meaningful units (mas/d) by multiplication with the Chandler rotational frequency ($2\pi/434$ days). For the continuous polar motion time-series (where IGS data have been included), the polar motion rates at midnight epochs have been determined by a natural cubic spline fit to the polar motion offsets (at noon epochs). This procedure gives better, less smoothed polar motion rate determinations than does an average of the two nearest noon polar motion rates (Kouba 2005).

For the non-continuous series, where only VLBI EOP data contribute, such a method cannot be used. In these cases, the observed polar motion rates were used directly (a somewhat noisier procedure than using spline-fitted GPS rates) and AAM+OAM excitations were averaged to noon, rather than midnight, epochs. Very poor EOP determinations have been rejected from the following comparisons based on having formal errors >1 mas/day for polar motion rates and >0.1 ms for LOD. After editing, 610 polar motion rate and 623 LOD values were usable in the VLBI-only solutions.

5 Comparison of geodetic and geophysical polar motion excitations

Table 2 gives the correlation coefficients between geodetic and geophysical polar motion excitations for three continuous

Table 2 Correlation coefficients between geodetic polar motion rates and geophysical AAM+OAM excitations for three continuous test solutions over the period from 28 February 1999 to 1 July 2000

Interval	χ_2 (x_p–rate)			χ_1 (y_p-rate)		
	PM_I	PM_1	PM_2	PM_I	PM_1	PM_2
All	0.910	0.910	0.910	0.825	0.825	0.825
30 days	0.870	0.869	0.870	0.837	0.837	0.837
15 days	0.872	0.871	0.871	0.830	0.830	0.830
10 days	0.854	0.852	0.853	0.793	0.792	0.793
5 days	0.794	0.792	0.793	0.718	0.718	0.718
3 days	0.696	0.698	0.697	0.624	0.623	0.623

Correlations are computed for various sliding-window intervals. Solution PM_I used only GPS data whereas PM_1 and PM_2 included GPS+VLBI data, with different weights for the co-location ties

test solutions over the period from 28 February 1999 to 1 July 2000. Sliding-window intervals of various lengths are considered. There is almost no difference whether data from the IGS are used alone (PM_I) or VLBI data included (PM_1 and PM_2), regardless of the tie weights. Clearly, the GPS data overwhelmingly dominate the combined polar motion time-series.

The correlation coefficients in Table 3, where only VLBI polar motion data were used, confirm its smaller contribution relative to GPS. (Some of the difference, compared to Table 2, is due to the use of directly observed VLBI polar motion rates and geophysical excitations at noon epochs, as described previously, but this affects only the highest frequencies.) When GPS network, but not polar motion, data are added with different tie weights (solutions PM_1V and PM_2V), the correlations generally decrease further, especially for χ_2. This seems to point more clearly (than Table 2) to inconsistencies in the two frames and the ties that relate them. Note that the VLBI-GPS co-locations are weaker in these test cases than in solutions PM_1 and PM_2 because the joint combination of polar motion data is itself a very important frame tie (Ray and Altamimi 2005). Down-weighting the suspect ties (solutions PM_2 and PM_2V) appears to perform marginally better than using nominal weights for all VLBI-GPS ties.

Adding the VLBI data without compromising the GPS quality, however slightly, seems to require an accurate understanding of the quality of the co-location ties. A fully optimal combination of GPS and VLBI polar motion data, with no degradation of the IGS-only results, may not be feasible until at least two VLBI-GPS ties are shown to be accurate to the 1 mm level (Ray and Altamimi 2005). Note that the local ties must account for any systematic bias effects within the VLBI and GPS observing systems, which is particularly challenging.

Table 3 Correlation coefficients between geodetic polar motion rates and geophysical AAM+OAM excitations for three non-continuous test solutions over the period from 28 February 1999 to 1 July 2000

Interval	χ_2 (x_p–rate)			χ_1 (y_p-rate)		
	PM_V	PM_1V	PM_2V	PM_V	PM_1V	PM_2V
All	0.648	0.641	0.648	0.579	0.562	0.568
30 days	0.574	0.567	0.569	0.547	0.544	0.545
15 days	0.530	0.519	0.523	0.499	0.501	0.503
10 days	0.412	0.402	0.404	0.433	0.437	0.437

Correlations are computed for various sliding-window intervals. Solution PM_V used only VLBI data whereas PM_1V and PM_2V included GPS+VLBI station data but no GPS polar motion. Epochs with polar motion rate sigmas >1 mas/day were omitted

6 Comparison of geodetic and geophysical LOD excitations

Table 4 shows the correlation coefficients between geodetic LOD and geophysical AAM excitations for the five non-continuous test solutions containing UT1-UTC/LOD over the 5-year period between February 1999 and December 2003. The LOD values have been corrected for well-known tidal signals (Yoder et al. 1981), denoted as LODR. The highest correlations are for GPS+VLBI solutions that included GPS polar motion and the differences are greatest at the shortest time periods. Adding the GPS TRF without polar motion causes only a very tiny improvement, implying that the GPS pole is a much more important contributor to improved LOD than the GPS network.

There are two ways that GPS-derived polar motion improves VLBI UT1-UTC/LOD in a joint combination. More accurate GPS polar motion reduces the effect of larger VLBI polar motion errors through the direct parameter correlations. In addition, joint combination of poles from both techniques will greatly strengthen the alignment of the two frames.

Table 5 reports the RMS residuals of tidally corrected LODR minus AAM and AAM+OAM. The non-inverted barometer (NB) correction – wherein the ocean level is not assumed to compensate instantaneously for changes in atmospheric pressure – gives lower residuals in both cases. Because the overlap period with OAM data is limited, the AAM comparison is much more robustly determined. In fact, the

Table 4 Correlation coefficients between geodetic LOD and geophysical AAM (no IB correction applied) excitations for five non-continuous test solutions over the period from 28 February 1999 to 30 December 2003

Interval	LODR (tidally corrected)				
	UT_V	UT_1	UT_2	UT_1V	UT_2V
All	0.977	**0.979**	**0.979**	0.977	0.977
30 days	0.883	**0.894**	**0.894**	0.884	0.884
15 days	0.813	**0.828**	**0.828**	0.814	0.814
10 days	0.715	0.735	**0.736**	0.718	0.718

Correlations are computed for various sliding-window intervals. Geodetic LOD observations have been corrected for tidal signals with periods between 5 days and 18.6 years (Yoder et al. 1981). Solution UT_V used only VLBI data whereas UT_1 and UT_2 included GPS+VLBI station data with GPS polar motion and UT_1V and UT_2V included GPS+VLBI station data but no GPS polar motion. Epochs with LOD sigmas >0.1 ms were omitted. The highest values for each interval are shown in boldface

Table 5 RMS residuals (units = μs) of geodetic LODR minus geophysical AAM or AAM+OAM. In both cases, inverted barometer (IB) and non-inverted barometer (NB) corrections have been tested. For the residuals with AAM, the period from 28 February 1999 to 30 December 2003 has been compared, whereas for AAM+OAM only 28 February 1999 to 1 July 2000 can be used

Solution	LODR – AAM		LODR – (AAM+OAM)	
	NB	IB	NB	IB
UT_V	75.4	78.6	72.4	75.0
UT_1	**71.7**	76.7	**68.8**	74.4
UT_2	**71.7**	76.3	**68.8**	74.2

Solution UT_V used only VLBI data whereas UT_1 and UT_2 included GPS+VLBI station data with GPS polar motion. Epochs with LOD sigmas >0.1 ms were omitted. The smallest values in each excitation case are shown in boldface

RMS reduction from 75.4 to 71.7 μs (4.9%) is significant at almost the 95% confidence level (5.5%).

7 Discussion and conclusions

Our tests of rigorous combinations, including EOPs, fail to find any direct utility in adding current VLBI polar motion data to the better determined GPS polar motion measurements, except in improving the rotational alignment of the two frames (cf. Ray and Altamimi 2005). Presumably, the VLBI pole information is preferentially used for alignment with the GPS frame because the co-location ties are not sufficiently accurate. There is evidence for a possible, very slight, degradation in the combined x_p values at intervals between about 5 and 15 days when VLBI results are included. While VLBI measurement noise could be partially responsible, errors in the co-location ties linking the VLBI and GPS frames are definitely implicated.

With a better understanding of the accuracies of the co-location ties (including components within the VLBI and GPS systems), it is likely that the combined polar motion series would be as accurate as the GPS-only solution. If the ties were significantly more accurate than the VLBI polar motion measurements, then the latter could be expected to contribute more relative to the GPS data. In order for VLBI to have any major impact, however, it will probably be necessary for the observing networks to be strengthened in terms of number and distribution of stations.

On the other hand, the addition of GPS-derived polar motion improves the VLBI UT1-UTC/LOD comparison with AAM by several percent. The beneficial effect could operate through direct parameter correlations and indirectly through improved alignment of the frames. In the former case, we expect that there should also be similar improvements in VLBI nutation estimates when combined with GPS polar motion, as well as in UT1-UTC determinations from the 1-h single-baseline VLBI "intensive" sessions (Robertson et al. 1985); effects we have not yet tested. Further improvements can be expected when GPS-based LOD measurements are integrated into the multi-technique combination, though we see no suitable rigorous method for doing so.

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