J Geod (2005) 79: 189–195
DOI 10.1007/s00190-005-0456-z

ORIGINAL ARTICLE

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Evaluation of co-location ties relating the VLBI and GPS reference frames

Received: 14 October 2004 / Accepted: 21 March 2005 / Published online: 30 May 2005

Abstract We have compared the VLBI and GPS terrestrial reference frames, realized using 5 years of time-series observations of station positions and polar motion, with surveyed co-location tie vectors for 25 sites. The goal was to assess the overall quality of the ties and to determine whether a subset of co-location sites might be found with VLBI–GPS ties that are self-consistent within a few millimeters. Our procedure was designed to guard against internal distortion of the two space-geodetic networks and takes advantage of the reduction in tie information needed with the time-series combination method by using the very strong contribution due to co-location of the daily pole of rotation. The general quality of the available ties is somewhat discouraging in that most have residuals, compared to the space-geodetic frames, at the level of 1–2 cm. However, by a careful selection process, we have identified a subset of nine local VLBI–GPS ties that are consistent with each other and with space geodesy to better than 4 mm (RMS) in each component. While certainly promising, it is not possible to confidently assess the reliability of this particular subset without new information to verify the absolute accuracy of at least a few of the highest-quality ties. Particular care must be taken to demonstrate that possible systematic errors within the VLBI and GPS systems have been properly accounted for. A minimum of two (preferably three or four) ties must be measured with accuracies of 1 mm or better in each component, including any potential systematic effects. If this can be done, then the VLBI and GPS frames can be globally aligned to less than 1 mm in each Helmert component using our subset of nine ties. In any case, the *X* and *Y* rotations are better determined, to about 0.5 mm, due to the contribution of co-located polar motion.

Keywords International terrestrial reference frame (ITRF) · GPS · VLBI · Co-location sites · Local ties

1 Introduction

With only a few years of continuous GPS or regular (typically, 1 day every week or two) VLBI observations, individual terrestrial reference frames can be realized with sub-mm internal precision at their midpoint epoch. In order to relate independent frames in a multi-technique combination, such as the international terrestrial reference frame (ITRF), it is necessary to introduce tie vectors at a subset of co-location sites.

The currently available local ties used in the ITRF combination come from diverse sources and are usually without covariances, which prevents objective evaluation of their quality and any discrepancies with space-geodetic estimates. Typical discrepancies are usually much larger than the internal precisions of the space-geodetic long-term frames, often at the centimeter level or larger. Therefore, the overall accuracy of the combined frame and its internal consistency are normally determined by the quality of the ties, more so than by the space-geodetic data. Significant internal inconsistencies and some distortions are nearly unavoidable, at least in the current circumstance. It is very important to note that any local systematic errors in the space-geodetic frames, especially within the observational systems themselves (see Discussion below), must be considered when determining the co-location ties, not just the random measurement errors of the local surveys.

Improved co-location ties are important if a multi-technique frame is recognized as potentially superior in certain respects to frames from any single technique. For instance, in a VLBI-GPS combination, VLBI is expected to contribute predominantly to fixing the global scale due to unresolved

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complications in GPS related to non-ideal antenna beam patterns (Altamimi et al. 2002; Schmid and Rothacher 2003). GPS dominates in the overall combination of reference coordinates and polar motion due to its relatively dense and uniform global coverage, high precision, and homogeneity. Their combination, properly weighted, should enjoy the best attributes of each technique, but only if accurate ties are available.

In order to make a nearly undistorted comparison between VLBI-GPS differences and the corresponding local survey ties, we have developed a modified strategy from that used in previous ITRF combinations. For this study, we have focussed on VLBI and GPS ties because these techniques realize very precise frames with only a few years of data. This also permits us to simplify and test our methods. In principle, a similar approach might be useful to assess ties with other space-geodetic techniques.

2 Intra-technique combinations

In a first step, time-series of GPS and VLBI solutions have been combined (rigorously stacked using full variance–covariance information) separately, which requires no local ties. The GPS solutions were the weekly reference frames produced by the international GPS service (IGS) from a weighted combination of submissions from as many as eight independent analysis centers (Ferland 2004a). The IGS weekly SINEX files for the period 28 February 1999 (GPS week 999) to 28 February 2004 (GPS week 1259), containing parameters for 346 station coordinates and daily polar motion and polar motion rates, were combined into a single consistent frame while estimating coordinates and linear velocities at the mean epoch of 29 August 2001. (For specifications of the SINEX format, see http://tau.fesg.tu-muenchen.de/∼iers/.)

The VLBI solutions used here resulted from the analysis of the NASA Goddard Space Flight Center group of individual 24-h observing sessions, reduced to SINEX format (IVS 2004). Data for a total of 62 stations were combined, together with polar motion, polar motion rates, UT1–UTC, and length of day values for 677 days during the same 5-year span as for the GPS data. The mean reference epoch was also 29 August 2001. For convenience, the GPS and VLBI combined frames were aligned closely to ITRF2000 (Altamimi et al. 2002), although this does not affect our results concerning the ability to link the two frames using local ties.

For both of these SINEX combinations, as well as all others discussed herein, the CATREF software (Altamimi and Boucher 2003), developed at the Institut Géographique National of France, was used. The CATREF package contains several modules for handling constraints, comparisons, and combination and analysis of individual terrestrial reference frame 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 Earth orientation parameters (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. CATREF permits accurate datum specification, using the well-known geodetic approach of minimum constraints, thus ensuring full internal consistency within the combined frame.

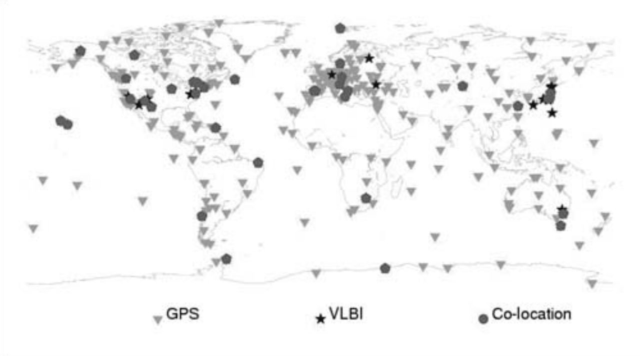

Fig. 1 Map showing the distribution of VLBI (*stars*) and GPS (*triangles*) stations during the period 1999–2004. All possible co-locations are indicated by *solid circles*

The set of co-located VLBI and GPS stations is shown in Fig. 1. Of these, 25 have usable local tie vectors and sufficiently long observing histories (see Table 1). The average uncertainty for the co-located GPS coordinates at the combined midpoint epoch is 0.3 mm, with a standard deviation of 0.7 mm. The errors for YEBE (Yebes, Spain), which has a relatively short observing history, are an order of magnitude larger. Excluding YEBE, the average coordinate error is 0.2 mm, with a standard deviation of 0.1 mm. The combined VLBI frame has somewhat larger internal errors and they are more heterogeneous. For the full set of 25 co-located VLBI stations, the average coordinate uncertainty is 0.9 mm with a standard deviation of 1.3 mm. Excluding the three with the largest errors (at Washington, Tidbinbilla, and Goldstone), the average error drops to 0.6 mm with a standard deviation of 0.4 mm. Overall, the internal consistency of each frame is at the sub-mm level.

3 Local ties

A co-location site is defined by the presence of two or more space-geodetic instruments occupying very nearby locations, which have observed simultaneously or at different times. To be useful, their differential geometric relationship must be surveyed in three dimensions using classical surveying or GPS techniques. Classical surveys consist of direction angles, distances, and spirit-levelling measurements between the instrument reference points or associated geodetic markers. Adjustments of local survey data are usually performed by national geodetic agencies or operators of the space-geodetic observatories.

Some groups have started to use SINEX files to exchange local tie vectors with the full variance–covariance information

Table 1 Vectors relating co-located VLBI and GPS reference points in the geocentric ITRF Cartesian frame (units = m). The DOMES directory of sites and space geodetic reference points is available at http://lareg.ensg.ign.fr/ITRF/

DOMES	GPS->VLBI		dX	dY	dZ	Ref.	Site name
Europe							
10317	M003	S003	28.7940	102.1620	−6.4700	1	Ny Alesund
10402	M004	S002	−52.6310	40.4640	43.8650	2	Onsala
12711	M003	S001	−30.9149	3.4023	54.5170	3	Medicina
12717	M004	S001	16.7420	−63.5990	28.5140	1	Noto
12734	M008	S005	−10.9460	−42.2460	38.2030	2	Matera
13407	S012	S010	134.2460	−159.6640	−164.2750	1	Madrid
13420	M001	S001	55.5220	−69.7130	−58.2990	2	Yebes
14201	M010	S004	−40.8020	−118.3980	61.3170	2	Wettzell
Asia							
21730	S005	S007	−209.5453	29.7219	−216.8837	5	Tskuba
Africa							
30302	M004	S001	90.2990	−132.1884	34.6547	1	Hartebeesthoek
North America							
40104	M002	S001	−94.7560	−61.0210	−6.6650	2	Algonquin
40127	M003	M004	52.9330	−57.1550	−17.9960	2	Yellowknife
40405	S031	S019	75.3330	−264.1070	−306.4530	1,2	Goldstone
40408	M001	S002	74.1260	−49.2880	31.2610	1,2	Fairbanks
40440	S020	S003	−26.7960	−41.0220	−30.4760	2	Westford
40442	M012	S017	5989.5518	−3788.5737	−4541.7251	2	McDonald
40451	M123	M125	20.8950	19.7530	16.6470	2	Washington
40456	M001	S001	−36.9160	−34.8270	−35.2550	2	Pie Town
40465	M001	S001	62.2280	−25.3870	−3.6260	2	North Liberty
Pacific							
40424	M004	S007	0.4960	19.4002	42.2362	2	Kokee Park
40477	M001	S001	30.1321	−82.2265	5.9084	2	Mauna Kea
South America & Caribbean							
41602	M001	S001	−16.5980	−21.7320	−45.8050	2	Fortaleza
43201	M001	S001	77.3621	7.0895	−28.1538	2	St.Croix
Australia							
50103	M108	S010	60.7284	208.6318	62.4956	4	Tidbinbilla
50116	M004	S002	−165.3730	−67.6194	75.8229	4	Hobart

References:
1. IGN data base at http://lareg.ensg.ign.fr/local_surveys.php
2. IGS site logs at http://igscb.jpl.nasa.gov/igscb/station/log
3. Sarti et al. (2004)
4. Johnston et al. (2000)
5. Matsuzaka et al. (2004)

(e.g., Johnston et al. 2000; Sarti et al. 2004). Except for the few cases where local tie SINEX files are available, most of the limited information available regarding local tie quality is from the reported standard deviations (SD) for the three components of each tie vector. In the usual case where SD estimates are not reported by their sources, a default formulation is used based on the distance of the tie vector:

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

where $\sigma_1 = 3\,\text{mm}$, $\sigma_2 = 10^{-6} \times D$, and D is the length of the tie vector.

The 25 VLBI–GPS ties used in this study are listed in Table 1, together with the source for each. Ties are also available for O'Higgins and Syowa (both in Antarctica) but previous comparisons indicate errors approaching the 10-cm level for these, so they are not included here. A few other co-location sites are not used because of short observing histories. Full variance–covariance information was available for only three sites (Medicina, Hobart, and Tidbinbilla) and so was not used.

4 Inter-technique combination

An initial test was made to establish the minimum tie information needed to relate the VLBI and GPS frames. For a combination of global position and velocity frames (not time-series of station position solutions), ties would be needed to resolve the usual 14 degrees of freedom corresponding to the Helmert transformation parameters between the two frames: three orthogonal translations of origin, radial scale, three rotations of orientation, and their time derivatives. This is the approach that has been used for all past ITRF realizations (e.g., Altamimi et al. 2002). If it is assumed that the VLBI and GPS velocities are the same at the tie sites, then a minimum of seven components of tie vectors are needed.

Adding the polar motion and polar motion rate parameters in a time-series combination effectively acts as a daily two-dimensional co-location point, which is free of any tie error, and therefore eliminates the need for two tie components and two co-located velocity component links, for the rotations about X and Y and their rates. In this case, only five components of the tie vectors should be needed. We verified this by forming a VLBI–GPS time-series combination using just two local site ties (with the assumption of equal velocities), a slightly over-determined system. The North Liberty and Hartebeesthoek tie sites were picked on account of being geometrically well separated. For this exercise, the ties were assigned errors of 1 mm in each component. The GPS formal errors were scaled by a factor of 1.5, while those of the VLBI solution were scaled by 3.2, based on our past experience with ITRF2000.

Demonstrating how powerful the polar motion frame co-location is, we found formal uncertainties for the Helmert *X* and *Y* rotations of 0.015 mas (0.47 mm) compared with sigmas of about 1 mm for the other five parameters; see Table 2. Thus, a joint VLBI-GPS frame can be formed with 1-mm datum consistency given only two co-location ties, provided that the accuracy of the two tie vectors is also at the 1-mm level in all components. With 5 years of data, the long-term stability of the combined frame is at the 0.1 mm/year level, a value which does not depend on the tie accuracy but rather on the data span.

Table 2 Formal errors of VLBI–GPS Helmert parameters using two local ties with assumed errors of 1 mm per component and including daily polar motion and polar motion rates over the 5-year span 1999–2003

Helmert parameter	Uncertainty in offset at midpoint epoch	Uncertainty in rate
Translation in *X*	1.0 mm	0.1 mm/year
Translation in *Y*	1.1 mm	0.1 mm/year
Translation in *Z*	0.9 mm	0.1 mm/year
Scale	0.21 ppb	0.02 ppb/year
	1.3 mm	0.13 mm/year
Rotation about *X*	0.015 mas	0.003 mas/year
	0.47 mm	0.09 mm/year
Rotation about *Y*	0.015 mas	0.002 mas/year
	0.47 mm	0.06 mm/year
Rotation about *Z*	0.035 mas	0.002 mas/year
	1.09 mm	0.06 mm/year

The co-location ties for North Liberty and Hartebeesthoek were used for this example

5 Comparison of space-geodetic and survey ties

At the moment, we have no ties with established accuracies of 1 mm. If two such ties existed, then a VLBI–GPS combination including them could be used to identify the errors in all other ties. Instead, we make no a priori assumptions about the relative reliability of the ties in Table 1. A VLBI–GPS combination of the type above, using just two local ties, was made to derive discrepancies between $(\text{VLBI–GPS})_{\text{SPACE}}$ and $(\text{VLBI–GPS})_{\text{TIE}}$ determinations for the 25 co-location sites. By using nearly the minimal tie information necessary, internal distortions in the VLBI and GPS frames should be greatly reduced in this comparison compared to the usual approaches. The tie discrepancy values themselves are not very meaningful since any errors in either of the two ties are redistributed into all the other site residuals and the non-rotational Helmert parameters. This step was only intended to produce a set of local tie discrepancies nearly free of any reference frame distortions. The "datum" for these discrepancy vectors is, however, ill-specified at this stage.

Taking the framework of globally distributed (space-tie) discrepancies, we then applied a series of secondary Helmert transformations to minimize the datum defects and search for a set of ties that are as consistent with each other as possible. The search considered, in part, the Helmert transformation residuals as a basis for rejection. However, this is not an adequate criterion by itself because it will always lead to a large number of ties being rejected and a geometrically robust distribution is not ensured. In the first cut, all ties with normalized residuals (using the default error formula) greater than 3.0 were removed: Algonquin, Fairbanks, Fortaleza, Goldstone, Hobart, Noto, Pie Town, and Westford. Fairbanks is also questionable because the nearby Denali earthquake on 3 November 2002 probably introduced non-linear components to its motion. In the next iterations, ties were dropped successively due to having the largest vertical residuals: Washington (>3.0 cm); Yellowknife (>1.5 cm); McDonald, North Liberty, and Ny Alesund (>1.0 cm).

The latter three sites also have GPS antennas covered by radomes. We view all GPS sites using radomes with suspicion since their use can affect the apparent GPS positions by as much as a few centimeters. For instance, when the JPLA radome at KOKB was removed on 24 September 2002, the IGS coordinates shifted by about 27, 24, and 11 mm in the local N,E,U frame (Ferland 2002). The KOKB data used in our tie comparisons is therefore only for the period before the radome change. At TROM (not included in our study), the coordinates shifted by about 6, 10, and 12 mm in N,E,U when the ASH701073.1 antenna with radome was replaced by a AOAD/M_T with no radome on 13 July 2004 (Ferland 2004b).

Even larger vertical shifts, up to about 5 cm, have been observed with some radome types, so the general advice has been to avoid their use whenever possible (Braun et al. 1997). A fundamental problem is that the IGS conventionally ignores the effect of any antenna radomes in its tables of phase center variations (PCVs); all antennas are treated as though radome-free even in those cases where the appropriate PCVs have been measured. This means that conventional surveys to the physical antenna reference point will not necessarily correspond to the same reference point determined from global IGS solutions for such stations.

In the next iteration, the nearby Madrid and Yebes ties were both dropped because of a relative vertical inconsistency between them of more than 17 mm. Finally, Matera was rejected because it had the largest residual in the relatively well-covered European region.

The nine tie sites not eliminated were: St. Croix, Hartebeesthoek, Kokee, Medicina, Mauna Kea, Onsala, Tidbinbilla, Tsukuba, and Wettzell. Using these nine ties (with default uncertainties) in a final combination to relate the VLBI and GPS frames, including daily polar motion, gives an

Table 3 Formal errors of VLBI–GPS Helmert parameters using nine selected local ties with default errors and including daily polar motion over the 5-year span 1999–2003

Helmert parameter	Uncertainty in offset at midpoint epoch	Uncertainty in rate
Translation in X	0.8 mm	0.1 mm/year
Translation in Y	0.8 mm	0.1 mm/year
Translation in Z	0.8 mm	0.1 mm/year
Scale	0.14 ppb	0.02 ppb/year
	0.9 mm	0.13 mm/year
Rotation about X	0.014 mas	0.003 mas/year
	0.43 mm	0.09 mm/year
Rotation about Y	0.014 mas	0.002 mas/year
	0.43 mm	0.06 mm/year
Rotation about Z	0.028 mas	0.002 mas/year
	0.87 mm	0.06 mm/year

overall alignment that is formally better than 1 mm in all components; see Table 3. The X and Y rotations have half the error due to the contribution of polar motion co-location. Despite the larger individual tie uncertainties, the frame alignment is somewhat better than using only two ties of hypothetical 1-mm accuracy (cf. Table 2).

Table 4 shows the tie residuals from the combination using the nine selected VLBI–GPS co-location sites out of the 25 available. The overall level of self-consistency among the nine selected ties and with the space geodetic frames is impressive, around 3 mm (RMS) per component. The largest residual among the ties included in the combination is the east component for Medicina, −7.3 mm. To some extent, the residuals of the included ties are biased slightly to smaller values because the VLBI and GPS frames are invariably distorted to accommodate any mismatch. However, since the tie formal uncertainties are always greater than 3 mm and the coordinate errors for these sites in the VLBI and GPS frames are much smaller, the effect of such distortions is minor, up to about 1 mm mostly in the local verticals.

As stated, four of the included ties involve GPS antennas with radomes: KOKB, ONSA, TIDB, and TSKB. While this practice is certainly problematic in some cases, we have no specific knowledge whether these particular radomes might cause positional shifts or whether their presence might have been accounted for in the local surveys. Since these four sites are globally consistent with the others and since two agree well with regionally close non-radome sites (KOKB/MKEA and ONSA/WTZR), we do not exclude them from the combination.

The level of discrepancy among the excluded ties is naturally larger, by selection. The overall differences are at the level of about 7 mm (RMS) in the horizontal and about 15 mm (RMS) in the vertical. Perhaps more worrisome are the fairly large net biases of about 5 mm in the north and vertical components. If real, these could have the effect of skewing the VLBI frame, or subnetworks of it, relative to the GPS frame when the full set of ties is used. The large vertical difference at the Washington (GODE) site is probably related to the fact that this involves the most poorly determined VLBI station, with formal errors at the centimeter level.

6 Discussion and conclusions

The process we have used here to evaluate VLBI–GPS co-location ties is unavoidably subjective to some extent and cannot lead to a unique identification of tie errors. It is possible that alternate subsets of co-location sites could be found with similar levels of residuals. It could also be that our iterative selection procedure has been skewed by fortuitously small residuals for a few sites. To extend such an exercise to a definitive assessment of actual tie errors requires additional, confident information regarding the accuracy of at least two high-quality ties (errors preferably no greater than 1 mm in each component). Nonetheless, our tests show that with such information it is possible to relate the VLBI and GPS frames to better than 1 mm globally. The X and Y rotations can be fixed, by including time-series observations of polar motion, to about 0.5 mm.

Furthermore, despite the excellent self-consistency of the nine selected co-locations, these might not be optimal for an operational VLBI–GPS frame combination. The VLBI frame is constructed from a series of 24-h networks, each of which usually contains only about five or six stations. While some VLBI stations are used very regularly, a few observe only occasionally. For a useful combined frame, all stations and sub-networks must be connected either by observational data or by local ties. Therefore, at least some of the seemingly less well-determined ties may be needed to ensure adequate inter-connectivity within the joint reference frame. This could be done, for instance, by assigning lower weights to suspect ties rather than excluding them altogether. A better approach, though, would be to improve the quality of the needed ties and to enhance the internal robustness of the VLBI frame by using larger, more global networks.

As we have already stressed, in order to further improve the combination of VLBI and GPS frames it is vital to improve the accuracy of ties at a few co-location sites. It is reasonable to suspect that local tie differences comprise combined effects of systematic errors in the GPS, VLBI, and local survey measurements plus random errors in the surveys; random GPS and VLBI errors are probably negligible.

Within GPS, probably the most important systematic effects deal with the phase patterns of the antennas and their relationship with the local environment, including multipath signatures. This problem area has been partially addressed by the IGS in its adoption of antenna-specific PCV corrections (Schupler et al. 1994; Mader 1999). However, radomes have been neglected even though their effects on apparent position have been shown to be large in certain cases (e.g., Ferland 2002). While methods may be adopted to explicitly handle radomes in the future, this will take some time. Meanwhile, the established IGS frame must be used cautiously when GPS stations equipped with radomes are involved.

For local tie surveys at all GPS sites, the IGS data should be included in the survey, something not usually done. Failing to do so makes it impossible to check for local tie closure to the GPS phase reference point between the global and

Table 4 Residuals for local ties from VLBI–GPS combination (units = mm). The radome type is indicated for those GPS stations equipped with them

DOMES	GPS->VLBI	(Space geodesy – Tie)			IGS	
		dE	dN	dU	Name	Radome type, if used
Ties included in combination (9)						
10402	M004 S002	0.5	0.4	0.2	ONSA	OSOD
12711	M003 S001	−7.3	−1.2	2.0	MEDI	
14201	M010 S004	0.5	−5.4	0.2	WTZR	
21730	S005 S007	−0.5	−3.2	−3.7	TSKB	Type unknown
30302	M004 S001	3.7	1.0	−1.6	HRAO	
40424	M004 S007	−1.6	0.5	4.3	KOKB	JPLA till 24.09.2002
40477	M001 S001	−1.7	−1.0	0.9	MKEA	
43201	M001 S001	2.9	3.0	−1.5	CRO1	
50103	M108 S010	2.6	1.6	−0.8	TIDB	JPLA
Mean		−0.1	−0.5	0.0		
SD		3.3	2.6	2.3		
Ties not included in combination (16)						
10317	M003 S003	6.8	−4.1	−11.7	NYA1	SNOW since 02.06.1999
12717	M004 S001	−11.1	−19.3	−6.1	NOT1	
12734	M008 S005	−11.8	−9.7	1.9	MATE	
13407	S012 S010	−4.6	0.1	7.4	MADR	
13420	M001 S001	1.9	3.2	−9.9	YEBE	
40104	M002 S001	−1.7	−3.4	12.6	ALGO	
40127	M003 M004	−5.4	−6.7	−19.0	YELL	
40405	S031 S019	−5.2	−10.3	−25.3	GOLD	
40408	M001 S002	−0.9	−9.4	2.4	FAIR	JPLA (quake 03.11.2002)
40440	S020 S003	8.0	−0.7	9.8	WES2	
40442	M012 S017	−1.0	−5.2	10.3	MDO1	JPLA
40451	M123 M125	2.8	−4.4	−36.6	GODE	JPLA
40456	M001 S001	−12.4	−8.6	−16.2	PIE1	JPLA till 01.06.1999
40465	M001 S001	−1.4	0.8	−11.1	NLIB	JPLA
41602	M001 S001	0.6	3.0	22.7	FORT	Type unknown
50116	M004 S002	11.5	−2.9	−10.5	HOB2	
Mean		−1.5	−4.9	−4.9		
SD		6.9	5.8	15.6		

Table 5 New vector VLBI-GPS ties that recently became available (units = m)

Domes	GPS->VLBI	dX	dY	dZ	Ref.	Site name
12711	M003 S001	−30.9120	3.3982	54.5189	1	Medicina (epoch 23.06.2001)
12711	M003 S001	−30.9118	3.3977	54.5219	1	Medicina (epoch 09.09.2002)
12711	M003 S001	−30.9094	3.3963	54.5212	1	Medicina (epoch 01.10.2003)
50116	M004 S002	−165.3740	−67.6263	75.8209	2	Hobart

References:
1. P Sarti (private communication 2004)
2. Johnston and Dawson (2004)

Table 6 Comparison of local tie residuals when using new (from Table 5) and old determinations (units = mm)

DOMES	GPS->VLBI	(Space geodesy – Tie)			IGS	
		dE	dN	dU	Name	Remarks
12711	M003 S001	−7.3	−1.2	2.0	MEDI	Old tie (in combination)
		−2.7	−1.1	−0.8		New tie (epoch 23.06.2001)
		−2.2	−3.2	−2.9		New tie (epoch 09.09.2002)
		−0.3	−1.3	−3.9		New tie (epoch 01.10.2003)
50116	M004 S002	11.5	−2.9	−10.5	HOB2	Old tie
		5.2	0.5	−9.8		New tie

local frames. The IGS data should be used, together with simultaneous GPS survey data from nearby control markers, and the reduction of that data should follow the same conventions adopted by the IGS.

Within the VLBI systems, physical deformations of the radio antennas must be evaluated in each case. Local tie surveys involving VLBI antennas should include sufficient measurements to determine the possible non-ideal motions of the antenna due to gravity and construction defects. It is particularly important to check for the level of gravitational sag of the feed or subreflector structure and useful also to monitor flexure of the primary reflector (Rogers et al. 1978; Carter et al. 1980). Effects of this type will tend to bias the apparent VLBI positions and are generally expected to scale roughly with antenna size.

A complete and comprehensive co-location survey must include all such systematic effects in addition to random measurement errors. Only when results are available for at least two co-location sites (preferably more) will it be possible to confidently isolate tie errors throughout the global network.

7 Postscript

After this work was completed, we learned of new VLBI–GPS tie determinations for two sites. These are given in Table 5 for three different measurement campaigns at Medicina (Italy) and for Hobart (Australia). The older Medicina tie in Table 1 corresponds to the epoch 2001 survey but the values in Table 5 applied a different local-to-geocentric transformation (P Sarti, private communication 2004). Accounting for the changes in the tie vectors but without actually replacing the old Medicina tie in the combination, the residuals in Table 4 for these two sites would change to the values given in Table 6.

These new ties provide an independent check of our nine-tie combination described above. All three new Medicina ties reduce the previous east discrepancy significantly, demonstrating the importance of local-to-geocentric reference frame alignment. If any of the new Medicina ties had been used in the combination, the RMS residuals for the nine co-locations would be less than 3 mm in all three components. The new Hobart tie also has a much smaller east residual than the older vector. However, its vertical discrepancy remains nearly unchanged at -10 mm. At least a few millimeters of this difference could be caused by gravitational sag at Hobart (J Dawson, private communication 2004).

Acknowledgements J. Ray thanks the Bureau International des Poids et Mesures (Sèvres, France) for their gracious hospitality during the year he had the pleasure to spend there as a visiting scientist. We appreciate the very helpful comments from P. Sarti, J. Dawson, and P. Sillard.

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