TOWARD A UNIFIED TERRESTRIAL COORDINATE SYSTEM

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ABSTRACT. In order to obtain coordinate transformations between our CDP-VLBI terrestrial coordinate frame and the corresponding frames used by the Goddard Space Flight Center SLR group, the University of Texas Center for Space Research SLR group, and Deep Space Network, we obtained geocentric, Cartesian coordinates and formal errors of five locations in our system and those of the two SLR groups, and of three locations in our system and that of the Deep Space Network. After transformation we found that both SLR coordinate sets agree at the 20 to 30 mm level with our values. The Deep Space Network values, with higher formal errors than the other sets, agree at the half meter level.

1. INTRODUCTION

Our group at the Goddard Space Flight Center (GSFC) has had an interest in terrestrial reference frames since the inception of the NASA Crustal Dynamics Project (CDP). Members of our VLBI analysis team were investigators in a CDP investigation to compare station positions derived from satellite laser ranging (SLR) and very-long-baseline interferometry (VLBI) data. The task's main objective was to demonstrate that the VLBI and SLR techniques could obtain baseline lengths which agreed at the level of their stated errors. The result of this activity was documented in the special LAGEOS issue of the Journal of Geophysical Research (Kolenkiewicz _et_ _al_., 1985) where it was shown that the root-mean-square (RMS) agreement in baseline length for the twenty-two baselines investigated was 52 mm.

A second goal of the comparisons was to gain insight into the errors which affect the two observing techniques. We also hoped to understand the relationship between the two coordinate systems at the subcentimeter level so that it would be possible to define a common

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terrestrial frame for use by both techniques.

In this paper we discuss three-dimensional comparisons of coordinates in our CDP-VLBI frame with coordinates obtained by three other groups in their frames: the GSFC-SLR frame, the University of Texas - Center for Space Research (CfSR) frame, and the Jet Propulsion Laboratory Deep Space Network (DSN) frame. Such comparisons require three types of information: VLBI-derived coordinates and formal errors, coordinates and formal errors for the same locations derived with another technique, and, where needed, local survey information to tie the coordinates of different points at a given location to a common monument. Except as discussed below, local survey vectors were taken from the revised edition of the CDP: Catalogue of Site Information, January 1987 (in press).

2. CDP-VLBI/GSFC-SLR COMPARISON

The results presented in Kolenkiewicz et al. were limited to a discussion of baseline lengths because the authors were specifically interested in verifying the error budgets dealing with lengths. The authors subsequently attempted a three-dimensional comparison of station coordinates which produced unreasonably large (0.5 m) station height residuals. The study was discontinued when the members of each group felt their data could not be the source of the large disagreement. Early this year R. King, as a part of a Global Positioning System study, discovered an error in the local network survey at the Owens Valley Radio Telescope (personal communication). One effect of this error was a 50 cm discrepancy between the height of the VLBI reference point of the 40-m telescope and survey monument 7114, which was used as the common reference point of the VLBI-SLR comparisons. When this local survey error was corrected the comparison results became reasonable and it was possible to complete the three-dimensional VLBI-SLR comparison.

Five VLBI stations were used in the study: the 40-m telescope of the Owens Valley Radio Observatory (OVRO 130) and the 26-m telescope of the DSN Goldstone Venus station (GOLDVENU), both in California; the 26-m telescope of the George R. Agassiz station (HRAS 085) in Texas; the 37-m telescope of the Haystack Observatory (HAYSTACK) in Massachusetts; and the 20-m telescope of the Institute for Applied Geodesy (IFAG) at the Wettzell station (WETTZELL) in Germany. Other stations used in the comparison of baseline lengths were not used here because they were measured with mobile VLBI equipment, and our VLBI analysis software does not yet support the estimation of average positions of mobile antennas from several experiments. We obtained geocentric rectangular coordinates and their formal errors for these five stations from global solution GLB028, our most recent published global solution based on the ensemble of Mark III base station data (Ma and Ryan, 1986). We also obtained from R. Kolenkiewicz of Goddard's Geodynamics Branch coordinates and formal errors for these stations based on LAGEOS satellite laser ranging data from their solution SL6 (personal communication). We then estimated a seven-parameter fit to define the transformation between the two coordinate sets. In this fit we used weighted-least-squares to minimize the coordinate differences where the weight assigned to each coordinate residual was equal to the root-sum-square of the VLBI and SLR formal errors for that coordinate. The parameters of this fit are defined by the following matrix equation:

$$\begin{vmatrix} X(new) \\ \\ Y(new) \\ \\ Z(new) \end{vmatrix} = \begin{vmatrix} Delta\text{-}X \\ \\ Delta\text{-}Y \\ \\ Delta\text{-}Z \end{vmatrix} + \begin{vmatrix} 1+Scale & -Sin(R3) & Sin(R2) \\ \\ Sin(R3) & 1+Scale & -Sin(R1) \\ \\ -Sin(R2) & Sin(R1) & 1+Scale \end{vmatrix} * \begin{vmatrix} X(old) \\ \\ Y(old) \\ \\ Z(old) \end{vmatrix}$$

where *old* and *new* designate the rectangular coordinates before and after transformation, *Delta-X*, *Y*, and *Z* translate the origin of the coordinate system, *R1*, *R2*, and *R3* rotate the coordinate system about the X, Y, and Z axes, respectively, and *Scale* changes the scale of the coordinate system.

Table I presents the coordinates and formal errors from the CDP-VLBI and GSFC-SLR solutions. These are coordinates of the reference monuments at these locations; for both the SLR and VLBI systems the coordinates actually determined by the systems have been transformed to coordinates of the monuments using local survey information. In our VLBI solution we did not recover the position of GOLDVENU; rather we estimated the coordinates of MOJAVE12, an antenna in the Goldstone complex 13 km distant from GOLDVENU. We then obtained the coordinates of GOLDVENU by adding to the coordinates of MOJAVE12 an offset vector determined with the VLBI phase delay technique (J. Ray, private communication). Finally we obtained the coordinates of monument 7115 by adding the GOLDVENU-to-7115 local survey. Table III presents the seven transformation parameters obtained from the adjustment and Table IV presents the post-fit coordinate residuals in the X, Y, and Z components and the derived monument heights. The unweighted RMS errors of the component residuals are 2-3 cm, which is consistent with the formal errors of the VLBI values and much smaller than the formal errors supplied with the SLR values. A note of caution: we have used fifteen coordinate residuals to estimate a seven-parameter fit and are thus in the unreliable regime of small number statistics. Table V presents the derived baseline length post-fit residuals, and their unweighted RMS is 4.0 cm. This is a more convincing indicator of accuracy since of the seven parameters estimated only scale affects baseline lengths. Moreover, the scale difference of 2 parts in 1 billion is insignificant.

3. CDP-VLBI/CfSR-SLR COMPARISON

We obtained from the CDP Data Information System the coordinates of the same five locations estimated from LAGEOS SLR data at the University of Texas Center for Space Research. These values were produced in their solution, LAGEOS Long Arc Solution 8511. We then estimated a seven-parameter transformation between our values and the CfSR values in an identical fashion to the GSFC-SLR values. Tables I, III, IV, and V also present information for the CfSR-SLR comparison. The translation of the origin is nearly identical to that for the GSFC-SLR solution. This is reasonable since both SLR coordinate frames should be true center-of-mass coordinate frames. VLBI data has no sensitivity to the Earth's center of mass and so its origin is arbitrary. The rotation between the two frames is very small and as such is somewhat puzzling. VLBI has no absolute orientation reference about any axis; the orientation of our VLBI frame depends directly on our adopted values of the coordinates of the HAYSTACK telescope. Those values were selected in an *ad hoc* fashion in 1975. The scale difference of -12 parts in 1 billion is larger than for the GSFC-SLR transformation, but its significance is unclear. It could be caused by an error in the value of the Earth's GM used in the CfSR solution, by an error in our handling of general relativity, or by some as yet unknown effect. The fit of the VLBI and CfSR coordinates after transformation is insignificantly different from that of the GSFC-SLR comparison.

4. CDP-VLBI/DSN COMPARISON

The NASA Deep Space Network operated by the Jet Propulsion Laboratory has radio telescopes in California, Spain, and Australia, and formerly operated a telescope in South Africa. The coordinates of the active DSN telescopes have been determined with high accuracy from both deep space range and doppler tracking data and Mark II VLBI data. Three of the telescopes have been used in Mark III geodetic VLBI. They are DSS-13 at Goldstone, CA; DSS-61 in Spain; and DSS-51 in South Africa. We will refer to these telescopes by their CDP designations: GOLDVENU, ROBLED32, and HARTRAO, respectively. The GOLDVENU telescope was used in early Mark III mobile experiments, but of greater importance it can be connected very accurately to the CDP-VLBI reference via the nearby MOJAVE12 telescope as discussed above. ROBLED32 participated in one Mark III experiment in May 1983 carried out by J. Campbell of the Geodetic Institute of the University of Bonn (Germany) and his colleagues. Data directly connecting ROBLED32 with four other sites in the CDP-VLBI catalog were obtained. In January and February 1986 the HARTRAO telescope participated in a series of six Mark III geodetic experiments arranged by W. Carter of the National Geodetic Survey and carried out by Axel Nothnagel of the Hartebeesthoek Radio Astronomy Observatory. In these experiments HARTRAO was directly connected to four sites in the CDP-VLBI catalog. Given the locations of these three DSN telescopes in our VLBI frame it became possible to define a transformation between our frame and that of the DSN. We obtained coordinates of these telescopes and their formal errors from O. Sovers of the Jet Propulsion Laboratory (personal communication). Table II presents our coordinates and formal errors for these telescopes and the DSN values and formal errors from Sovers. Note the large (nearly meter level) formal errors of HARTRAO. This station has not been a DSN station for some years and the coordinates are based on relatively poor data. Table III presents the transformation and Table IV presents the rectangular coordinate and height residuals. Because of the very different formal errors applicable to the DSN coordinates the transformation is dominated by GOLDVENU; as Table IV shows GOLDVENU essentially defines the translation of the origin. The HARTRAO residuals are very large, but only factors of 2 to 3 larger than the formal errors. This transformation is at best a preliminary definition of the relationship between the CDP-VLBI and DSN reference frames. There are plans to instrument DSN stations with Mark III VLBI terminals, but it will be a few years before such plans are complete. At that time it will be possible to acquire data on all DSN telescopes and to define the CDP-VLBI to DSN transformation with extremely high accuracy.

5. CONCLUSIONS

The limited comparisons we have done between the CDP-VLBI and SLR coordinate frames indicate that we understand the relationships between these coordinate frames at the level of 5 cm or better. Moreover, these new results confirm the previously published baseline length results.

Both the GSFC-SLR and CfSR-SLR to CDP-VLBI comparisons show a height residual at GOLDVENU of approximately 7 cm and at OVRO 130 of approximately -6 cm. This is a relative height discrepancy of 13 cm between two sites separated by only 258 km. We do not believe that the relative VLBI height is in error by more than a few centimeters. There may yet remain local survey errors at the 10 cm level; the surveys at the Goldstone and Owens Valley facilities should be repeated.

In the future we will add to our CDP-VLBI site catalog the monuments at Platteville, CO; Quincy, CA; Monument Peak, CA; and Pasadena, CA. These sites were used in the earlier baseline length comparison and there are coordinates for them in the SLR frame. Also, Global Positioning System observations already acquired between a monument near the SLR system in Hawaii on the island of Maui and a monument near the VLBI antenna on Kauai should provide a sufficiently accurate local connection so that we can add Hawaii to our frame tie. Finally, as discussed above, the DSN has plans to implement Mark III capability. This should make it possible to connect the SLR monuments in Australia to CDP-VLBI coordinates of a DSN antenna in Australia. The inclusion of these additional locations should make the connections between the CDP-VLBI frame, the two SLR frames, and the DSN frame much more robust.

6. REFERENCES

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Ma, C., and J. W. Ryan, Crustal Dynamics Project Data Analysis: Fixed Station VLBI Geodetic Results, NASA TM-87806, NASA/GSFC, Greenbelt, MD, 1986.

Crustal Dynamics Project: Catalogue of Site Information, January 1987, NASA/GSFC, Greenbelt, MD, in press. Also available online from the CDP Data Information System.

TABLE I. Station Coordinates in the CDP-VLBI, GSFC-SLR, and CfSR-SLR Coordinate Frames

		Values (mm)			Formal Errors (mm)		
		X	Y	Z	X	Y	Z
CDP-VLBI							
HAYSTACK	7091	1492455475	-4457279595	4296816297	0	0	0
HRAS 085	7086	-1330123558	-5328527423	3236150812	2	6	7
OVRO 130	7114	-2410420567	-4477803506	3838687313	2	7	9
GOLDVENU	7115	-2350859763	-4655547090	3660998426	2	8	6
WETTZELL	7834	4075531962	931780350	4801618337	8	5	14
GSFC-SLR							
HAYSTACK	7091	1492450563	-4457280163	4296815393	67	59	47
HRAS 085	7086	-1330129074	-5328525801	3236149858	104	163	212
OVRO 130	7114	-2410425476	-4477801214	3838686384	52	239	261
GOLDVENU	7115	-2350864858	-4655544868	3660997580	55	231	261
WETTZELL	7834	4075530876	931777838	4801618134	379	132	316
CfSR-SLR							
HAYSTACK	7091	1492453583	-4457278685	4296815868	27	20	20
HRAS 085	7086	-1330125459	-5328526457	3236150403	26	14	21
OVRO 130	7114	-2410422491	-4477802528	3838686814	25	20	21
GOLDVENU	7115	-2350861729	-4655546139	3660998018	25	19	21
WETTZELL	7834	4075530321	931781133	4801618124	19	25	17

TABLE II. Station Coordinates in the CDP-VLBI and DSN Reference Frames

	Values (mm) X	Y	Z	Formal Errors (mm) X	Y	Z
CDP-VLBI						
GOLDVENU	-2351127256	-4655477911	3660957483	20	7	9
ROBLED32	4849247141	-360279298	4114884520	45	14	41
HARTRAO	5085444338	2668262197	-2768697207	38	23	25
DSN-LS111A-860708						
GOLDVENU	-2351128816	-4655477051	3660956572	10	10	10
ROBLED32	4849245561	-360278746	4114883578	100	100	100
HARTRAO	508544261	2668261939	-2768701800	700	400	250

TABLE III. Coordinate Frame Transformation Parameters into the CDP-VLBI Coordinate Frame.

	Translation (meters) Delta-X	Delta-Y	Delta-Z	Rotation (0".001) R1	R2	R3	Scale
GSFC-SLR	1.78	-1.08	0.26	-28.	-2.	148.	0.2E-8
	±0.25	±0.26	±0.32	±13.	±9.	±6.	±1.6E-8
CfSR-SLR	1.72	-1.08	0.33	-6.	1.	7.	-1.2E-8
	±0.03	±0.03	±0.03	±2.	±1.	±1.	±0.3E-8
DSN-LS111A	0.66	0.65	2.46	84.	38.	9.	-2. E-8
-860708	±0.14	±0.19	±0.15	±10.	±7.	±3.	±1. E-8

TABLE IV. Rectangular Coordinate and Height Residuals (mm)

Station	Residual in: X	Y	Z	Height
CDP-VLBI to GSFC-SLR				
HAYSTACK	5	2	0	0
HRAS 085	33	24	30	-12
OVRO 130	21	5	-75	-57
GOLDVENU	-35	-47	32	67
WETTZELL	-28	-13	0	-23
RMS	27	24	22	41
CDP-VLBI to CfSR-SLR				
HAYSTACK	-19	62	-24	-64
HRAS 085	29	4	50	15
OVRO 130	-5	-12	-67	-30
GOLDVENU	-43	-40	31	63
WETTZELL	25	-31	12	21
RMS	27	31	41	43
CDP-VLBI to DSN-LS111A-860708				
GOLDVENU(DSS11)	12	2	0	0
ROBLER32(DSS61)	-245	-272	391	81
HARTRAO (DSS51)	-1789	1689	-1928	117

TABLE V. Baseline Length Residuals (mm)

	GSFC-VLBI to GSFC-SLR	GSFC-VLBI to CfSR-SLR
GOLDVENU TO HRAS 085	18	28
HAYSTACK TO HRAS 085	-42	-53
HAYSTACK TO GOLDVENU	36	19
OVRO 130 TO HRAS 085	-44	-31
OVRO 130 TO GOLDVENU	-51	-57
OVRO 130 TO HAYSTACK	-7	-8
WETTZELL TO HRAS 085	-74	-35
WETTZELL TO GOLDVENU	22	54
WETTZELL TO HAYSTACK	-28	-61
WELTZELL TO OVRO 130	-41	21
RMS	40	41

DISCUSSION

Dickey: There is a great deal of discussion concerning the Ft.Davis-Westford baseline and the observed discrepancies between the NGS and NASA Crustal Dynamics measurements. Your SLR and VLBI agree so well, could you not examine the SLR results on this baseline to help resolve this question?

Reply by Ryan: The monthly GSFC SLR results for MacDonald are too noisy to resolve the VLBI Ft.Davis results. The SLR scatter is ~ 5 cm compared to ~ 2 cm for the VLBI.

Carter: NGS does plan to do a GPS survey in Hawaii which is to include a connection between the VLBI and LURE observatories during 1987 — probably during the spring.