THE VLBI CELESTIAL REFERENCE FRAME OF THE NASA CRUSTAL DYNAMICS PROJECT

C. Ma
Goddard Space Flight Center
Geodynamics Branch 621.9
Greenbelt, Maryland 20771
USA

ABSTRACT. A celestial reference frame can be defined by precise positions of extragalactic radio sources using Mark III VLBI data available to the NASA Crustal Dynamics Project for geodynamic research. Seven years of such data have been analyzed to generate a catalogue of 101 sources with formal statistical errors between 0.01 and 0.77 ms in right ascension and between 0.2 and 9.3 mas in declination. In order to achieve such precision it is necessary to adjust the standard IAU nutation model. The rotations and scatter of the positions from year to year are generally less than 1 mas. A comparison of this catalogue with a completely independent catalogue derived from Mark II data shows a weighted average position difference, after a rotation, of 1.9 mas.

1. INTRODUCTION

The Mark III VLBI (very-long-baseline interferometry) system was developed by the Crustal Dynamics Project (CDP) of the National Aeronautics and Space Administration (NASA) to support research in geodynamics. This system is described in Clark *et al*. (1985) and is also used in the IRIS network coordinated by the National Geodetic Survey (NGS). Since the quasi-inertial reference frame in which terrestrial motions are to be measured with centimeter precision is that defined by extragalactic radio sources, it is necessary to have correspondingly precise positions of these fiducial points.

An ideal observing schedule for geodetic VLBI would use a number of structureless radio sources in all parts of the mutually visible sky with many observations of each source in the course of a day. Given the actual constraints on telescope sensitivity and recording bandwidth, the CDP VLBI program uses a catalogue of 20-30 sources in its normal observing. This catalogue varies with time as sources change their character and different stations are used in the CDP network. In addition, other sources have been observed to test their suitability for geodetic measurements, to improve the distribution of sources over the sky, and to prepare for eventual replacement of current sources. From the data available to the CDP, which include

A. K. Babcock and G. A. Wilkins (eds.), The Earth's Rotation and Reference Frames for Geodesy and Geodynamics, 73–81.

data acquired with the POLARIS/IRIS networks, a limited but still useful set of precise source positions can be developed. This paper describes the current state of the celestial reference frame defined by such a catalogue.

2. DATA AND ANALYSIS

The data used for this catalogue comprise 147 569 dual-frequency Mark III observations, each observation consisting of a group delay and phase delay rate. The latter, however, do not contribute much to the estimates of celestial positions. The time interval spans August, 1979 through May, 1986. The data were acquired from the 21 fixed stations listed in Table I with a small number from three mobile VLBI sites: PENTICTN, Brit. Col.; PLATTVIL, Colo.; and YELLOWKN, Northwest Terr. Several stations are not normally available for Mark III geodetic measurements. HARTRAO, for example, required a special effort on the part of Axel Nothnagel and NGS with cooperation from the CDP. The total data set contains 106 observed baselines, WESTFORD-HRAS 085 alone having more than 34 000 observations.

TABLE I. Geodetic Mark III VLBI stations.

ALGOPARK, Ontario	HRAS 085, Texas	ONSALA60, Sweden
CHLBOLTN, UK	KASHIMA , Japan	OVRO 130, Calif.
EFLSBERG, FRG	KAUAI , Hawaii	RICHMOND, Florida
GILCREEK, Alaska	KWAJAL26, Marshalls	ROBLED32, Spain
HARTRAO , S. Afr.	MARPOINT, Maryland	VNDNBERG, Calif.
HATCREEK, Calif.	MOJAVE12, Calif.	WESTFORD, Mass.
HAYSTACK, Mass.	NRAO 140, W. Va.	WETTZELL, FRG

There are 411 sessions altogether, each covering approximately one day and using up to seven stations simultaneously. A large majority of the sessions are from the POLARIS/IRIS networks, but the observations are roughly equally divided between CDP and POLARIS/IRIS. Fifty-three sources have been used in geodetic measurements. In six survey sessions 48 other sources were observed in addition to the standard sources. There is wide variation in the number of observations for each source. 3C345, for example, has more than 14 000 observations while some sources observed only during survey sessions have fewer than ten.

The stations and sources are almost entirely in the northern hemisphere, and the observing baselines have predominantly east-west orientation. HARTRAO in South Africa is the sole station in the southern hemisphere and participated in only six sessions. There is, however, relatively wide latitude range for observations that include GILCREEK (65 deg N) and southerly stations like KWAJAL26 (9 deg N), which contributes to better determination of the declination of the sources used.

The data were analyzed in a single, sequential least-squares solution as described in Ma *et al*. (1986). The astronomical and geophysical models followed the MERIT standards with the following departures: 1) no ocean loading model was applied; 2) a pole tide model was used in observing geometry; 3) the solar light deflection algorithm of Shapiro (1967) was used instead of the MERIT formula; and 4) the IAU 1980 nutation model was adjusted. The last has the largest effect on the estimated source positions. The MERIT standards do not specify the theoretical model for the VLBI observables. In this analysis, as in all Mark I and Mark III geodetic work described and published by the VLBI groups at Goddard, NGS, and the Center for Astrophysics, the theoretical model was that of Robertson (1975).

To estimate the source positions given in Table II, 10 529 parameters were adjusted, consuming 15 hours on the HP A900 minicomputer at the CDP VLBI analysis facility. The parameters included source positions (except for the right ascension of 3C273B following customary VLBI practice), station positions for each session, troposphere and clock parameters, and an offset in obliquity and longitude for each session except the reference day. See Himwich and Harder (this volume) for a further discussion of nutation adjustments. The reference day was Oct. 17, 1980, carried over from the date normally used to define earth orientation in VLBI. The weighted root-mean-square post-fit residual of the solution was 89 picosec in delay and 75 femtosec/sec in rate.

TABLE II. CDP radio source positions from Mark III VLBI data with nutation offsets adjusted relative to 80/10/17. Sigmas are formal statistical errors from the solution. The right ascension of 3C273B defines the origin.

Source	Right Ascension			sigma	Declination			sigma
	hr	min	sec	0.01 ms	deg	'	"	0.1 mas
0016+731	0	19	45.78654	19	73	27	30.0191	12
0048-097	0	50	41.31746	5	- 9	29	05.2237	40
0106+013	1	08	38.77108	0	1	35	00.3198	4
0133+476	1	36	58.59490	5	47	51	29.1025	9
0212+735	2	17	30.81370	5	73	49	32.6223	3
4C67.05	2	28	50.05175	4	67	21	03.0299	3
0229+131	2	31	45.89409	1	13	22	54.7178	3
0234+285	2	37	52.40574	1	28	48	08.9908	3
0235+164	2	38	38.93013	1	16	36	59.2761	4
0300+470	3	03	35.24234	2	47	16	16.2762	3
3C84	3	19	48.16018	2	41	30	42.1038	4
NRAO140	3	36	30.10763	5	32	18	29.3430	12
CTA26	3	39	30.93778	4	- 1	46	35.8040	27
NRAO150	3	59	29.74737	2	50	57	50.1616	3
0420-014	4	23	15.80071	1	- 1	20	33.0644	4
3C120	4	33	11.09558	3	5	21	15.6158	16
0454-234	4	57	03.17929	3	-23	24	52.0181	5
0458-020	5	01	12.80979	4	- 1	59	14.2518	26
0454+844	5	08	42.36321	77	84	32	04.5425	12
0528+134	5	30	56.41677	1	13	31	55.1493	3
0552+398	5	55	30.80566	2	39	48	49.1643	2

https://doi.org/10.1017/S0074180900119308 Published online by Cambridge University Press

0605-085	6	07	59.69906	6	- 8	34	49.9789	43
0642+449	6	46	32.02604	5	44	51	16.5885	5
0707+476	7	10	46.10491	14	47	32	11.1426	23
0716+714	7	21	53.44835	26	71	20	36.3636	13
0723-008	7	25	50.64009	6	- 0	54	56.5793	36
0727-115	7	30	19.11251	1	-11	41	12.6001	4
0735+178	7	38	07.39380	5	17	42	18.9946	27
0736+017	7	39	18.03391	7	1	37	04.6145	62
0742+103	7	45	33.05946	2	10	11	12.6915	7
0748+126	7	50	52.04568	6	12	31	04.8302	39
0749+540	7	53	01.38457	13	53	52	59.6374	13
0754+100	7	57	06.64292	5	9	56	34.8515	7
0804+499	8	08	39.66633	9	49	50	36.5270	13
0812+367	8	15	25.94486	10	36	35	15.1462	21
0814+425	8	18	15.99969	3	42	22	45.4123	4
0828+493	8	32	23.21679	11	49	13	21.0356	14
OJ287	8	54	48.87490	1	20	06	30.6397	2
0917+624	9	21	36.23098	13	62	15	52.1795	10
4C39.25	9	27	03.01383	1	39	02	20.8507	2
OK290	9	56	49.87539	2	25	15	16.0476	8
0954+658	9	58	47.24495	27	65	33	54.8130	21
1034-293	10	37	16.07995	4	-29	34	02.8099	7
1055+018	10	58	29.60506	4	1	33	58.8246	10
1128+385	11	30	53.28221	33	38	15	18.5452	75
1144+402	11	46	58.29780	1	39	58	34.3043	3
1150+812	11	53	12.49790	54	80	58	29.1528	18
1219+285	12	21	31.69048	2	28	13	58.4993	8
1222+037	12	24	52.42177	9	3	30	50.2930	11
3C273B	12	29	06.69970	*	2	03	08.5992	4
3C274	12	30	49.42314	11	12	23	28.0445	12
3C279	12	56	11.16659	4	- 5	47	21.5285	24
1308+326	13	10	28.66375	2	32	20	43.7823	4
1342+663	13	44	08.67935	64	66	06	11.6652	68
1354+195	13	57	04.43658	1	19	19	07.3728	4
OQ208	14	07	00.39430	1	28	27	14.6902	3
1418+546	14	19	46.59718	3	54	23	14.7875	3
1502+106	15	04	24.97973	1	10	29	39.2004	4
1510-089	15	12	50.53290	4	- 9	05	59.8250	27
1538+149	15	40	49.49160	6	14	47	45.8845	24
1548+056	15	50	35.26918	1	5	27	10.4509	3
1555+001	15	57	51.43391	9	- 0	01	50.4119	82
1606+106	16	08	46.20315	8	10	29	07.7739	42
CTD93	16	09	13.32023	35	26	41	28.9583	93
1611+343	16	13	41.06415	5	34	12	47.9092	11
1633+38	16	35	15.49284	3	38	08	04.5023	5
1637+574	16	38	13.45612	3	57	20	23.9809	3
NRAO512	16	40	29.63262	9	39	46	46.0276	18
1642+690	16	42	07.84823	5	68	56	39.7577	2
3C345	16	42	58.80984	2	39	48	36.9956	2
1656+053	16	58	33.44731	6	5	15	16.4487	35
NRAO530	17	33	02.70580	1	-13	04	49.5444	4

https://doi.org/10.1017/S0074180900119308 Published online by Cambridge University Press

1739+522	17	40	36.97764	10	52	11	43.4076	10
1741-038	17	43	58.85610	1	- 3	50	04.6125	5
1749+701	17	48	32.84029	17	70	05	50.7683	6
1749+096	17	51	32.81854	1	9	39	00.7315	3
1803+784	18	00	45.68345	10	78	28	04.0198	2
3C371	18	06	50.68065	22	69	49	28.1070	10
1823+568	18	24	07.06811	7	56	51	01.4919	8
3C390.3	18	42	08.98961	43	79	46	17.1286	8
1842+681	18	42	33.64153	24	68	09	25.2295	11
1921-293	19	24	51.05603	3	-29	14	30.1155	6
1923+210	19	25	59.60533	2	21	06	26.1632	9
1928+738	19	27	48.49486	13	73	58	01.5712	6
1954+513	19	55	42.73820	16	51	31	48.5492	17
2007+777	20	05	30.99852	18	77	52	43.2487	5
2005+403	20	07	44.94485	21	40	29	48.6104	24
2021+614	20	22	06.68196	11	61	36	58.8085	8
2021+317	20	23	19.01719	11	31	53	02.3096	22
3C418	20	38	37.03474	4	51	19	12.6644	4
2121+053	21	23	44.51742	2	5	35	22.0964	6
2134+00	21	36	38.58632	0	0	41	54.2171	3
2145+067	21	48	05.45866	1	6	57	38.6072	3
VR422201	22	02	43.29137	2	42	16	39.9824	3
2201+315	22	03	14.97574	2	31	45	38.2722	5
2216-038	22	18	52.03773	1	- 3	35	36.8755	4
3C446	22	25	47.25940	4	- 4	57	01.3916	33
2234+282	22	36	22.47083	1	28	28	57.4154	3
2243-123	22	46	18.23203	4	-12	06	51.2798	31
3C454.3	22	53	57.74796	1	16	08	53.5636	3
2345-167	23	48	02.60851	2	-16	31	12.0178	5

3. RESULTS

3.1. The CDP VLBI source catalogue

Table II shows the positions and associated errors of 101 extragalactic radio sources. Nine other sources have been observed but failed to give more than one usable observation. The sigmas are formal statistical errors from the solution. These errors include raw observation uncertainties derived from measurement signal-to-noise ratio and augmented variance for each baseline subset for each session to bring the normalized post-fit residuals for each subset to unity. See Ma et al. for a more detailed discussion. Since the reduced chi-square of the solution is 0.96, the overall fit is in agreement with the uncertainties applied to the data. There are 75 sources with formal errors in right ascension less than 0.1 milliseconds (ms) and 58 with formal errors in declination less than 1 milliarcsecond (mas).

The formal errors are probably optimistic and the true uncertainties are likely to be a factor of two higher based on previous studies. Systematic errors such as source structure may affect a number of positions. There is a geometric correlation between the z-components of the observing baselines and source declinations which may have a small systematic effect on the declinations of this catalogue because of the predominance of east-west baselines.

It is important to remember that the VLBI celestial reference frame is defined by the relative positions of the sources rather than by their absolute positions. The numerical value of the reference right ascension is arbitrary and is only fortuitously in excellent agreement with the optical reference frame. Changing the reference position or the reference source merely changes all right ascensions by the same amount. Changing the reference day rotates the positions.

3.2. Reference Frame Stability

TABLE III. Reference frame stability with nutation coefficients adjusted. The subset solution positions are compared to the master set, all solutions having coefficients for annual, semi-annual, 122-day and 13.7-day periods adjusted. The rotation takes the master positions to the subset positions (x - 0 hr RA, z - celestial pole, y - right-handed). The average arclength discrepancy after rotation (delarc) is computed from the common sources.

	R(x) mas		R(y) mas		R(z) mas		delarc mas	# src
1986+	-2.69	± .13	-1.05	± .10	.63	± .04	1.0	41
1985	.16	.02	.11	.01	-.16	.02	.7	30
1984	.08	.03	-.10	.02	.14	.03	.7	32
1983	-.54	.06	-.16	.05	-.33	.06	1.4	23
1982	-.32	.07	-.31	.07	-.36	.07	1.1	18
1979-81	-1.69	.05	-2.51	.05	-1.42	.05	2.1	26

TABLE IV. Reference frame stability with nutation offsets adjusted. The subset solution positions are compared to the master set, all solutions having offsets adjusted for each session except the reference day, Oct. 17, 1980. The rotation takes the master positions to the subset positions (x - 0 hr RA, z - celestial pole, y - right-handed). The average arclength discrepancy after rotation (delarc) is computed from the common sources.

	R(x) mas		R(y) mas		R(z) mas		delarc mas	# src
1986+	-.12	± .07	.14	± .06	.55	± .03	1.2	44
1985	.04	.07	.36	.06	-.16	.03	.5	33
1984	.10	.07	-.08	.06	.10	.04	.8	35
1983	.20	.09	-.77	.07	-.54	.07	1.4	26
1982	.24	.10	-.58	.10	-.15	.07	1.1	21
1979-81	.49	.09	-.65	.09	-1.44	.06	1.8	26

To examine the stability of the VLBI reference frame over time, the available data except for the six survey sessions were divided into subsets: one-year subsets for 1982 through 1985, 1979-81 as one subset, and January through July, 1986 as one subset (designated 1986+). Source positions were estimated from each subset and compared with positions derived from the master data set described above. Two types of solutions were made, one estimating in-phase and out-of-phase corrections to nutation coefficients for the four largest terms with periods less than 366 days and one estimating nutation offsets for each day except the reference day. In the first case, presented in Table III, the subsets are completely disjoint. In the second case, shown in Table IV, the same reference day is included in each subset. The tables give the rotation transforming the master positions to the subset positions, the average arclength discrepancy after rotation, and the number of sources compared. The rotational x-axis points towards 0 hr right ascension, the z-axis is the celestial pole and the y-axis completes a right-handed coordinate system.

The rotations are all small, less than 1 mas except for six angles out of 36. All the large values involve either the 1986+ subset, a short interval from which nutation coefficients are poorly determined, or the 1979-81 subset, where the data are sparse. For these subsets, the rotations are generally smaller when nutation offsets are estimated, probably because data from the reference day are included in the solutions. The rotation angles and arclength discrepancies are particularly small for 1984 and 1985, which have extensive multibaseline sessions from both CDP and IRIS. The arclength discrepancies are not strongly affected by the mode of adjusting nutation. These results indicate that the Mark III reference frame should be stable as the observed sources are gradually changed.

3.3. Catalogue Comparisons

TABLE V. Comparison of different catalogues. The rotation takes the positions of the first catalogue to those of the second (x - 0 hr RA, z - celestial pole, y - right-handed). The average arclength difference after rotation (delarc) is computed from the common sources.

A: Nutation offsets (reference day 80/10/17) - nutation coefficients (annual, semi-annual, 122-day, 13.7-day).
B: Table II (53 standard sources) - Sovers 1986-2.
C: Table II (all sources) - Sovers 1986-2.

	R(x) mas		R(y) mas		R(z) mas		delarc mas	# src
A	2.03 ±	.04	.98 ±	.04	-.12 ±	.02	.7	41
B	2.30	.12	-.36	.12	.36	.07	2.3	36
C	2.15	.11	-.84	.10	.37	.06	3.0	57

Table V shows three comparisons between source positions derived from different methods. Comparison A is between positions derived from the master Mark III data set, in the first solution adjusting nutation offsets and in the second adjusting nutation coefficients. Not all the

https://doi.org/10.1017/S0074180900119308 Published online by Cambridge University Press

sources are included because of current software limitations. The average arclength difference is less than 1 mas. The rotation reflects the error in the nutation model on the reference day. The second and third comparisons are between the CDP Mark III catalogue in Table II and the 1986-2 catalogue derived from Mark II data acquired with the Deep Space Network (DSN) stations in California, Spain and Australia (O. Sovers, private communication). There is no commonality whatsoever in VLBI instrumentation, baselines, or software. Comparison B uses only the 53 sources found in Mark III geodetic schedules and hence generally having many observations. Comparison C uses all the common sources except for 0723+008, which has a large discrepancy in declination. In both cases the weighted average arclength difference is less than 2 mas. The magnitude of the discrepancy does not represent the ultimate limit for the accuracy of the VLBI reference frame. Improvements can be made, for example, which would vastly improve the uncertainties of the raw measurements. In particular, the planned installation of Mark III systems and wide-band receivers at all DSN stations and greater use of HARTRAO should make it possible to extend the sky coverage southward and to improve the overall precision of the source positions.

4. CONCLUSIONS

The celestial reference frame defined by the positions of extragalactic radio sources derived from Mark III VLBI data available through the CDP is internally consistent and stable over time at the 1 mas level. While currently limited largely to the northern sky, it can provide a quasi-inertial frame for fundamental studies.

5. ACKNOWLEDGEMENTS

The author wishes to thank O. Sovers of the Jet Propulsion Laboratory for providing his 1986-2 catalogue prior to publication and A. Mallama for assistance in computing the celestial reference frame rotations.

6. REFERENCES

Clark, T. A. *et al*. (1985). *IEEE Trans. Geosci. Remote Sensing* **GE-23**, 438.

Himwich, W. E. and Harder, E. J. (this volume).

Ma, C. *et al*. (1986). *Astron. J.* **92**, 1020.

Robertson, D. S. (1975). Ph.D. thesis, Massachusetts Institute of Technology.

Shapiro, I. I. (1967). *Science* **157**, 806.

DISCUSSION

Herring: Some of the rotation between the solutions treating nutation corrections as daily angle corrections or as nutation series coefficients is probably due to the correction to the nutation angles on the reference day.

Reply by Ma: That is undoubtedly correct.

Dickey: There is considerable overlap in the Goddard and NGS catalog for e.g. antennas and software. It would be useful to describe the differences between their frames.

Reply by Ma: The GSFC catalog used NGS data, but the NGS catalog did not use GSFC data.