STABILITY OF THE EXTRAGALACTIC REFERENCE FRAME REALIZED BY VLBI

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ABSTRACT. The 318 compact extragalactic radio sources with positions derived from dual frequency Mark III VLBI data acquired by the geodetic and astrometric programs of NASA, NOAA, NRL and USNO form a celestial reference frame with stability in orientation and relative position at the 1 mas level. This paper examines the reference frame realized using 461,000 observations from 1021 observing sessions between 1979 August and 1990 August in the NASA Crustal Dynamics Project VLBI data base. Catalogs of positions estimated from subsets of data (annual, seasonal, network) show differences in orientation typically less than 1 mas provided precession and nutation are adjusted using a reference day. For 17 sources with >5 year time span and >200 one-day position estimates, the rates of change of right ascension and declination are generally less than 5 mas/century, giving upper limits on real motion.

1. Introduction

A kinematically fixed celestial reference frame can be realized from VLBI (Very Long Baseline Interferometry) observations of compact extragalactic radio sources. Since most of these radio sources have optical counterparts (albeit faint) that can be measured in the conventional FK5 frame, this radio reference frame can anchor the stellar frame. The level of stability of the radio reference frame is thus of considerable importance. This paper discusses two aspects of stability: the global orientation of the frame and individual source positions relative to the frame. The current distribution of the data and progress in analysis are briefly reviewed.

This paper is an extension of the work described in Robertson *et al.* (1986), Ma *et al.* (1986), Ma *et al.* (1990), Ma (1990) and Russell *et al.* (in press). A parallel and completely independent effort is described in Fanselow *et al.* (1984), Sovers *et al.* (1988), Sovers (1990), and Sovers (this volume). The comparison and convergence of these independent catalogs indicate that milliarcsecond (mas) accuracy has been achieved.

2. Data

The 461,000 dual frequency Mark III observations used for this work can be divided into four categories from three geodetic programs and the combined astrometric effort: 1) 206,000 observations from the Crustal Dynamics Project (CDP) of the National Aeronautics and Space Administration (NASA) acquired at irregular intervals beginning in 1979 and using many networks around the globe, 2) 210,000 observations from the IRIS program of the National Oceanic and Atmospheric Administration (NOAA) acquired at regular intervals beginning in 1980 using a small number of networks, 3) 29,000 observations from the

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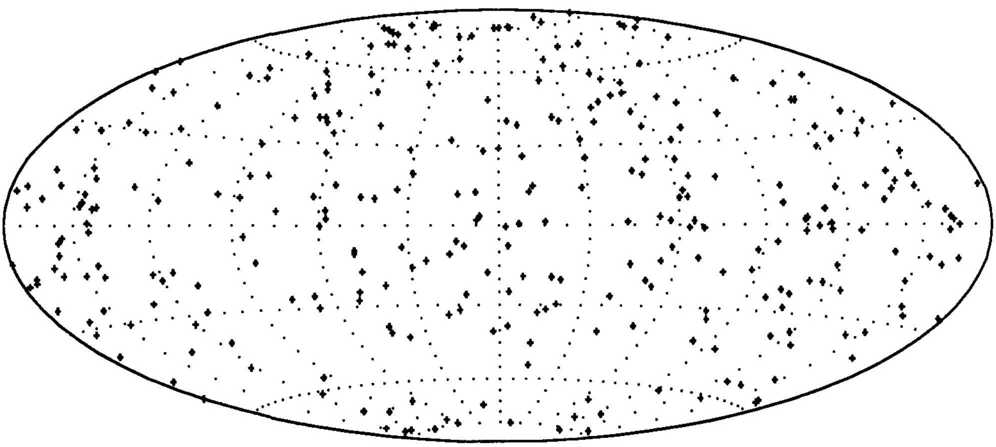

Figure 1. GLB677 sources on an Aitoff projection. 0 hr at right.

Navnet program of the US Naval Observatory (USNO) acquired at weekly intervals beginning in 1988 on a network normally including Hawaii, Alaska, West Virginia and Florida, and 4) 16,000 observations acquired by the CDP, Naval Research Laboratory (NRL), and NOAA astrometric programs from various northern and southern hemisphere networks in 48 sessions since 1980. Geodetic data from small (< 2000 km) networks were not included. The distribution of the 318 sources with useful data in both observing frequencies is shown on an equal area projection in Figure 1. While the spatial distribution is quite uniform (see Ma, 1990), Table 1 shows that the distribution of the number of observations, the number of observing sessions and time spans is very uneven. Some sources used since the beginning of the geodetic programs have tens of thousands of observations from hundreds of sessions over many years while the majority of sources, which come from the astrometric programs, have very few observations from a small number of sessions. It is the intention of the NRL/USNO astrometric program, however, to observe each source on a continuing basis as scheduling permits. All these data are now contained in the CDP VLBI data base and can easily be re-analyzed.

Table 1. Data Distribution

observations	1-99	100-999	1000-9999	> 10000
sources	231	39	34	14
sessions	1-2	3-9	10-99	> 100
sources	130	96	53	39
span (days)	1-99	100-999	> 1000	
sources	78	113	127	

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3. Analysis

The data from the 1021 one-day sessions were analyzed as a whole and in subsets using the CALC/GLOBL software developed at Goddard. Details of the parametrization and estimation algorithm are given in Ma *et al.* (1990) and Ma *et al.* (in press). The *a priori* models generally follow the IERS (International Earth Rotation Service) standards although our theoretical VLBI delay model departs from the alternative IERS algorithm (McCarthy, 1989) at the few picosecond rms level. It should be noted that the development of the relativistic effects on VLBI observations is more complete than in the past. Adjusted parameters included source positions from the ensemble of data and station positions, celestial pole offsets in longitude and obliquity, and nuisance parameters (station clocks and residual atmospheres) for each session. The parametrization of the residual atmosphere (after calibration from real-time information) permitted better compensation for atmospheric fluctuations than previous astrometric work. The post-fit weighted rms residual from the GLB677 solution that generated the full catalog was 45 ps and the reduced χ^2 was 1.01. The standard errors of 261 sources are less than 1 mas in both right ascension and declination while another 39 sources have standard errors less than 3 mas.

Sovers (this volume) discusses different methods of adjusting the conventional precession/nutation (P/N) models. While the direct adjustment of the precession constant, nutation coefficients and free core nutation is possible from these data, this method requires the full time span to give a useful separation of the longer periods. In addition, it cannot handle variations which may not be at the modeled frequencies. Since this paper uses catalogs formed from short subsets of data, it is necessary to adopt the method of estimating daily pole offsets from the pole of a reference day. The position of the celestial ephemeris pole of the reference day, evaluated from the conventional P/N models, and an arbitrary choice of right ascension zero point (in this case the *a priori* right ascension of one source) define the orientation of the catalog axes with respect to the observed objects. The strength of the catalog, *i.e.*, the precision of the angles between sources, is improved as more days of data are added. All the sources observed on each day need not be the same but the full catalog must be constructed from days with overlapping source lists. A day with no sources in common with any other day cannot be included since the pole offset cannot be determined. It should be noted that the precision of source positions, as opposed to the precision of relative angles, depends on the precision with which the pole of the reference day can be determined from the data of the reference day. It is most desirable to use as the reference day one which has a large network and high intrinsic data quality. For this work the CDP observing session of 86 Nov 5 was arbitrarily chosen. The network included stations in Japan, Alaska, California, Massachusetts and Germany, and the pole determination had a standard error of 0.17 mas. There are, however, other CDP days with even better networks and data distribution.

4. Stability of Orientation

Tables 2 through 4 show the comparison of catalogs derived from subsets of data with the catalog constructed using all the data. It is important to understand that each subset also included the data from the reference day. The numbers of sources and observations refer to the subset catalog. The three angles A_1, A_2, and A_3 follow the conventions of Arias *et al.* (1988) and represent small, rigid rotations about the coordinate axes between catalogs. Sinδ is a systematic variation of declination with declination and $\Delta\delta$ is a declination offset. The large variation of source numbers in Table 2 and 3 arises from the irregular scheduling of astrometry sessions. A difference in observing strategy is reflected in the disparity of numbers for IRIS compared to Navnet. The slight drop in the number of observations for 1990 is caused by having data only through August.

It can be seen that the catalogs made from individual years, from different seasons, and from separate networks differ in orientation from the full catalog by less than 1 mas. The larger declination differences in the early years are probably caused by poor network distribution, predominantly single baseline sessions.

It is clear, however, that the observations of the reference day determine the orientation of a catalog even if the vast majority of the data are removed in time or use different networks. Similarly, incrementing a catalog with additional data will not significantly change its orientation. Errors in the P/N models which would cause spurious changes in position with time are entirely absorbed in the estimated pole offsets.

Table 2. Comparison with annual catalogs

Year	sources	obs	A_1 mas	A_2 mas	A_3 mas	$\sin\delta$ mas	$\Delta\delta$ mas
80	28	12000	.1	-.2	-.1	-1.7	1.8
81	52	10000	.1	-.2	-.2	-1.4	1.5
82	35	13000	.1	-.2	-.1	-1.5	1.6
83	45	15000	.1	-.4	-.4	- .2	.4
84	50	34000	.4	.2	.3	.1	.0
85	32	48000	.2	.4	.3	- .5	.4
86	43	52000	-.3	-.0	.2	- .1	- .1
87	166	68000	.3	.1	-.1	- .6	.6
88	213	72000	-.0	-.1	-.2	- .1	.1
89	185	73000	.2	.3	-.1	- .3	.0
90	146	66000	-.1	-.3	-.1	.1	- .1

Table 3. Comparison with seasonal catalogs

	sources	A_1 mas	A_2 mas	A_3 mas	$\sin\delta$ mas	$\Delta\delta$ mas
Winter	194	-.1	.1	.1	-.0	.1
Spring	243	-.0	-.1	.0	.2	-.2
Summer	230	-.0	-.1	-.1	-.3	.1
Autumn	101	.2	.2	.1	-.3	.3

Table 4. Comparison with network catalogs

	sources	A_1 mas	A_2 mas	A_3 mas	$\sin\delta$ mas	$\Delta\delta$ mas
IRIS	44	-.1	.0	-.0	-.1	.1
Navnet	80	-.0	-.3	.1	.3	-.4

If the conventional P/N model is not adjusted, both the orientation and the relative positions of the catalogs are compromised. Table 5 shows annual catalogs constructed using only the conventional P/N model compared to the full catalog with P/N adjusted. There are large variations in A_1 and A_2. The right ascension zero point constraint forces the much smaller variation in A_3. The column labeled fit is the post-fit weighted rms residual of the annual solution, to the left with only the conventional model and to the right with adjustment of P/N. Within the one-year interval the error in nutation causes considerable spurious variation in the source positions and a poor fit. The column labeled χ^2 gives the reduced χ^2 of the catalog comparison after the rotation has been applied. The larger value to the left from the comparison with annual solutions lacking P/N adjustment reflects distortions caused by P/N model errors and nonuniform temporal distribution of data for each source. The smaller value to the right shows that the difference between catalogs derived with adjusted P/N models is entirely a rotation.

Table 5. Comparison with annual catalogs lacking adjustment of precession/nutation

Year	A_1 mas	A_2 mas	A_3 mas	fit ps	χ^2
80	-3.1	-3.8	-.5	61/58	.95/.92
81	-1.6	-2.8	-.9	52/50	.98/.93
82	-1.0	-3.0	.0	55/53	1.01/.93
83	-1.1	-2.5	-.7	61/57	1.07/.97
84	- .9	-1.0	-.1	66/60	1.13/.97
85	- .8	-1.7	-.0	55/48	1.22/.94
86	- .2	-1.6	.3	51/45	1.18/.93
87	- .2	-1.0	.0	51/45	1.22/.94
88	-1.4	- .6	-.2	47/40	1.33/.97
89	-2.2	.3	.1	50/39	1.61/1.02
90	-4.4	- .3	-.2	54/44	1.63/1.09

5. Stability of Individual Source Positions

A small number of sources have been observed repeatedly in the geodetic programs. These include strong (> 1 Jy) radio sources with structure on the few mas scale that were used in the early years when the VLBI systems had less sensitivity. These sources have now been largely relegated to observations using small mobile antennas where sensitivity is still a problem but only on short baselines where structure is less important. Seventeen sources observed for more than 5 years in more than 200 sessions were used to study possible changes in position. Since some of these sources are now no longer used in long baseline networks, a catalog was constructed using both long baseline fixed antenna and short baseline mobile antenna data. The position of each test source was estimated relative to all the other sources for each day in which the test source was observed. Typical standard errors for these one-day estimates of position are < 1 mas from days with large networks. The time series of positions of two of these sources are shown

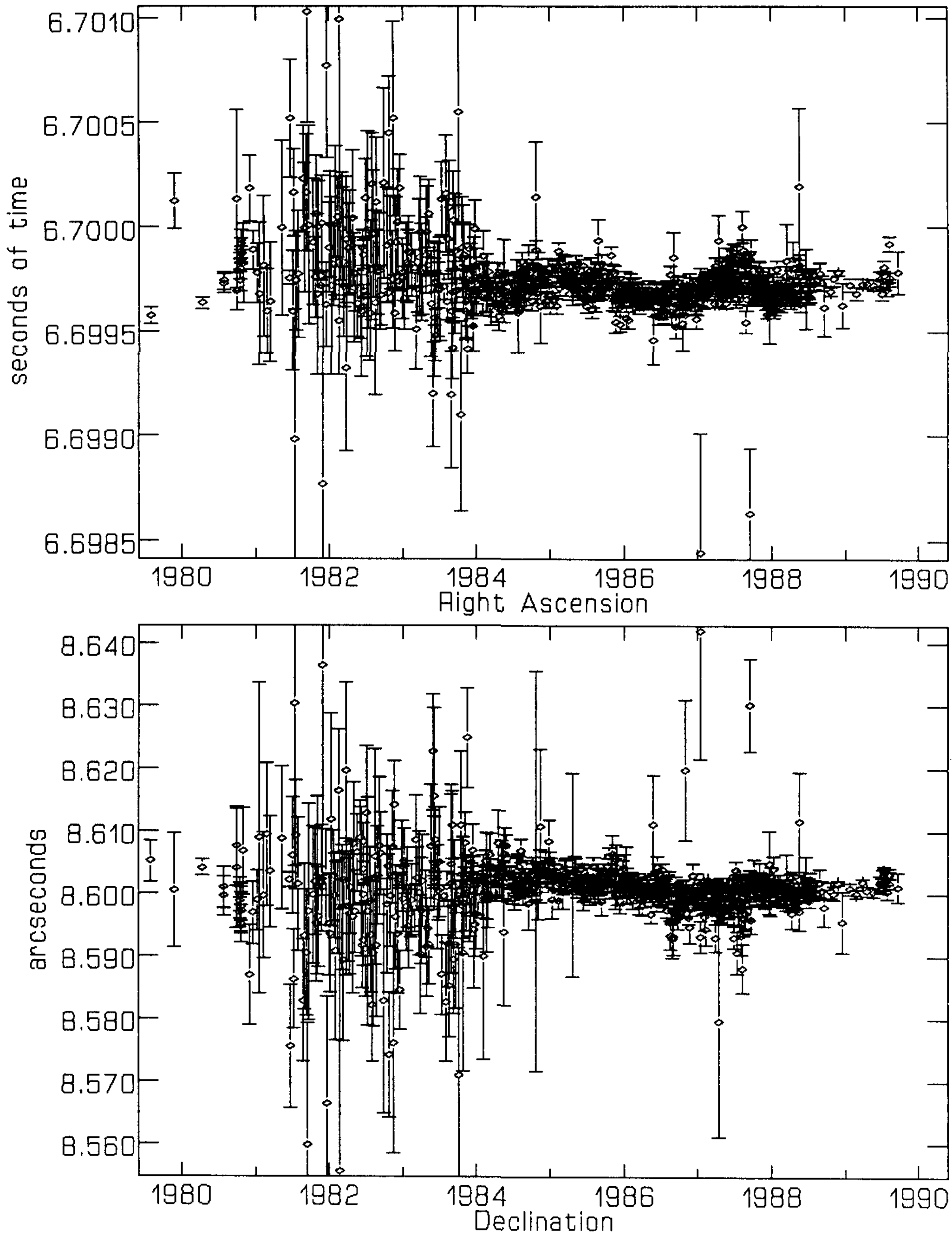

Figure 2. Estimated positions of 3C273B

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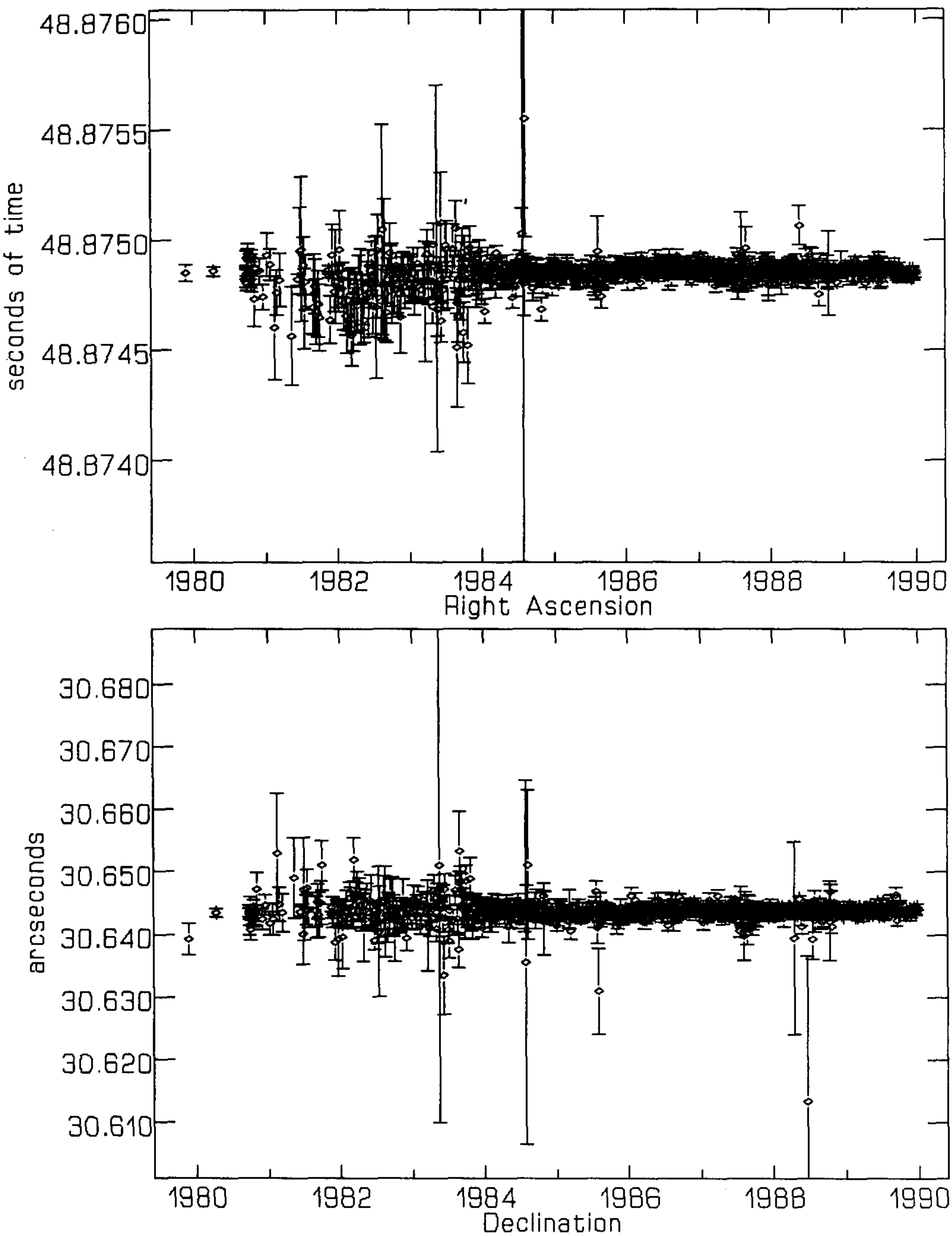

Figure 3. Estimated positions of OJ287

in Figures 2 and 3 with similar vertical scales. The source 3C273B is well known for variable structure while the source OJ287 is pointlike when mapped. Variations in position might arise from changes in structure, different networks from day to day, changes in observing schedules and geometry, *etc.* The actual changes are small. Tables 6 and 7 show the sources, the number of observing sessions, the total time span, the rate of change, the weighted rms scatter about the best-fit line, and the reduced χ^2 for right ascension and declination, respectively. The fit and χ^2 are generally worse for sources with much structure. While the rates are significantly different from zero in some cases, these should not be interpreted as actual proper motions of the real objects. Differential measurements of a pair of unrelated quasars separated by a small angular distance (Bartel *et al.*, 1986) place the upper limit on proper motion of the main components at 2 mas/century using essentially 2.5 years of data. More recent measurements reduce the upper limit by a factor of 4 (Bartel, 1990, personal communication). The rates given here should be viewed as upper limits of possible changes in this particular realization of the extragalactic frame and are illustrative of the stability of the positions of these sources, many of which have measurable, varying structure. Since the sources observed in the astrometric programs are generally fainter, it is expected that they are intrinsically smaller. Many have been selected because they have little or no structure visible on the long baselines.

Table 6. Rates of right ascension change

Source	sessions	span years	rate 0.1 ms/century	fit 0.1 ms	χ^2
0106+013	783	9	4.9 ± 0.8	.40	1.49
0212+735	678	8	-0.3 ± 1.7	.77	1.08
0229+131	539	5	-3.6 ± 0.7	.27	1.39
0234+285	276	9	-1.0 ± 0.8	.30	1.52
0420-014	233	5	5.4 ± 1.9	.32	2.48
0528+134	556	8	-2.7 ± 0.7	.28	1.37
0552+398	1068	10	-1.2 ± 0.4	.28	1.16
OJ287	811	10	0.7 ± 0.5	.26	1.52
4C39.25	771	10	3.2 ± 0.5	.28	1.40
3C273B	675	9	-4.6 ± 1.4	.56	3.13
OQ208	685	9	3.8 ± 0.6	.34	1.51
3C345	911	10	-9.1 ± 0.8	.46	2.12
1741-038	251	8	2.0 ± 2.0	.38	2.15
1803+784	629	6	5.8 ± 2.8	1.07	1.63
2134+004	504	10	2.3 ± 1.4	.50	1.86
VR422201	671	10	5.3 ± 0.6	.33	1.43
3C454.3	679	10	-5.7 ± 0.8	.35	2.39

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Table 7. Rates of declination change

Source	sessions	span years	rate mas/century	fit mas	χ^2
0106+013	783	9	3.8 ± 2.7	1.13	1.09
0212+735	678	8	2.5 ± 0.7	.32	1.16
0229+131	539	5	1.2 ± 1.9	.70	1.21
0234+285	276	9	6.7 ± 1.6	.46	1.18
0420-014	233	5	9.1 ± 4.0	.68	1.26
0528+134	556	8	0.1 ± 2.3	.82	1.19
0552+398	1068	10	-3.4 ± 0.7	.45	1.16
OJ287	811	10	2.5 ± 1.1	.55	1.05
4C39.25	771	10	0.7 ± 0.9	.49	1.44
3C273B	675	9	-8.8 ± 4.0	1.33	2.33
OQ208	685	9	8.7 ± 1.6	.83	1.24
3C345	911	10	-6.2 ± 1.1	.60	1.31
1741-038	251	8	8.5 ± 5.5	.94	1.58
1803+784	629	6	3.4 ± 0.7	.28	1.17
2134+004	504	10	19.1 ± 5.2	1.76	1.65
VR422201	671	10	0.1 ± 1.1	.57	1.35
3C454.3	679	10	-2.7 ± 1.7	.63	1.20

6. Conclusions and Possibilities

The existing VLBI data can be used to realize an extragalactic radio reference frame with overall orientation stability at the mas level over periods of decades if not longer. Individual sources should be useful over similar intervals in terms of both position stability and continued visibility to VLBI. The current number of radio sources is limited by system sensitivity rather than by intrinsic number. Since the number of radio sources is proportional to (source flux density)$^{-1.5}$, the number can be considerably expanded with more sensitive instruments such as the VLBA or QUASAR. With 800 second observations on the VLBA, it could be possible to extend the radio reference frame to one source per square degree.

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