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MILLIARCSECOND-ACCURATE ASTROMETRY OF 34 SOUTHERN HEMISPHERE RADIO SOURCES

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ABSTRACT

Milliarcsecond-accurate radio positions in the International Celestial Reference Frame for 34 southern hemisphere extragalactic sources are reported. The positions are derived from Mark III/IV very long baseline interferometry observations made between 2004 August and 2006 April using radio telescopes located in Australia, South Africa, and Hawaii. Positions for 7 of the 34 sources have been reported previously by us but are reported here with significantly improved accuracy. These results supplement an ongoing project to increase the sky density of southern hemisphere sources in order to better define the International Celestial Reference Frame and to provide additional phase reference sources with accurate positions for use in astrophysical observations. Positions for all 34 sources are south of $\delta = -20^\circ$ (positions for nine of the sources are south of $\delta = -60^\circ$) and have average formal uncertainties of 0.23 mas in $\alpha \cos \delta$ and 0.35 mas in δ.

Key words: astrometry — catalogs — quasars: general — radio continuum: galaxies — reference systems — techniques: interferometric

1. INTRODUCTION

The United States Naval Observatory (USNO) and the Australia Telescope National Facility are leading a collaboration in a very long baseline interferometry (VLBI) research program in southern hemisphere astrometry. The primary goal is to increase the sky density of International Celestial Reference Frame (ICRF; Ma et al. 1998; Fey et al. 2004c) sources in the southern hemisphere by adding new sources with milliarcsecond-accurate positions. The ICRF (Ma et al. 1998) is currently defined by the radio positions of 212 extragalactic objects obtained using the technique of VLBI at frequencies of 2.3 and 8.4 GHz over a period of ≈15 yr. The positional accuracy of the ICRF sources is estimated to be at the 0.25 mas level. The ICRF is the realization of the International Celestial Reference System (ICRS; Arias et al. 1995). There have been two extensions/updates of the ICRF (Fey et al. 2004c) since its initial definition by Ma et al. (1998). One of the primary objectives of extending the ICRF was to provide positions for an additional 109 extragalactic radio sources observed since the ICRF was defined. However, because the new observations concentrated primarily on northern hemisphere sources, only 4 of the 109 new sources reported by Fey et al. (2004c) have positions south of $\delta = -30^\circ$.

To increase the sky density of southern hemisphere sources in the ICRF, we are continuing a program of dedicated southern hemisphere VLBI observations with the specific intent of obtaining accurate positions for southern hemisphere sources not previously reported with coordinates in the ICRF. Our early southern hemisphere VLBI astrometry programs (Russell et al. 1992, 1994; Reynolds et al. 1994; Johnston et al. 1995) provided the fundamental basis for the ICRF in the southern hemisphere, as well as the basis for the southern component of the Australia Telescope Compact Array (ATCA) position calibrator list currently in use. Milliarcsecond-accurate radio positions for 22 new southern hemisphere extragalactic sources have been recently reported by Fey et al. (2004b). Additional positions accurate on the 2–3 mas level for 25 new southern hemisphere sources based on observations using the intra-Australia baseline connecting Hobart, Tasmania, and Parkes, New South Wales, have also been reported by Fey et al. (2004a).

In this paper we use astrometric VLBI data obtained between 2004 August and 2006 April to estimate milliarcsecond-accurate positions for 34 new southern hemisphere sources. Positions for these new sources are reported in the frame of the ICRF. These observations provide new sources for possible inclusion in the

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next realization of the ICRF, as well as additional ATCA calibrators for phase referencing use, thereby improving the science potential of this instrument.

2. OBSERVATIONS

In order to identify new extragalactic radio sources for possible inclusion in the next realization of the ICRF, survey VLBI observations of candidate sources were made as part of our southern hemisphere imaging program (Ojha et al. 2004, 2005) at a frequency of 8.4 GHz using the S2 VLBI recording system (Cannon et al. 1997). Candidate sources were identified from the gravitational lens survey of Lovell (1997) and the Parkes-MIT-NRAO[2] survey. Sources were selected for further astrometric observations based on positive detection on baselines either between Australia and South Africa or between Australia and Hawaii. These survey observations identified a total of 38 possible astrometric targets. Dedicated astrometric VLBI experiments were subsequently scheduled to determine accurate positions for these sources.

VLBI observations for geodesy and astrometry using Mark III compatible systems (Clark et al. 1985) have been conducted since about mid-1979. These observations are made in a bandwidth synthesis mode at standard frequencies of 2.3 and 8.4 GHz. The bandwidths over which the group delay is synthesized are typically 85 and 360 MHz, respectively. Dual-frequency observations allow for an accurate calibration of the frequency-dependent propagation delay introduced by the ionosphere, while the multiplicity of channels facilitates the determination of a precise group delay (Rogers 1970). Observing sessions are typically of 24 hr duration in order to recover (separate) parameters for nutation and polar motion.

Dedicated astrometric VLBI observations were scheduled on 2004 August 5 using a VLBI array consisting of the 26 m antenna at Hartebeesthoek, South Africa, and the 70 m Deep Space Network (DSN) antenna at Tidbinbilla, Australia. Observations on 2005 January 11 and March 16 used a VLBI array consisting of the 64 m antenna at Parkes,[3] Australia, and the 26 m antenna at Hartebeesthoek. Observations on 2005 May 29 and 2005 July 17 used a VLBI array consisting of the 26 m antenna at Hartebeesthoek, the 70 m DSN antenna at Tidbinbilla, and the 26 m antenna at Hobart, Australia. Observations on 2006 April 25 used a VLBI array consisting of the 70 m DSN antenna at Tidbinbilla, and the 20 m antenna at Kokee Park, Hawaii. All observations were correlated at the Washington Correlator (Kingham 2003). Additional astrometric observations for several of the 34 sources were also obtained from the International VLBI Service astrometric/geodetic database.

3. ANALYSIS

3.1. *The Software*

Accurate astrometric positions were estimated at the USNO using the Goddard Space Flight Center (GSFC) analysis system. The GSFC analysis system (Ryan et al. 1980, 1993; Ma et al. 1986; Caprette et al. 1990) consists of the astrometric and geodetic VLBI reduction software CALC and SOLVE. The data analysis methods using the GSFC system are covered in detail in Ma et al. (1986). A typical analysis combines data from many different observing sessions, allowing some parameters (e.g., source positions) to be estimated from a combination of many data sets. Application of the analysis methods to the ICRF are described in detail in Ma et al. (1998). Application of the analysis methods to the two ICRF extensions are described in Fey et al. (2004c).

To obtain a solution, the individual observing sessions are combined sequentially using "arc" parameter elimination (Ma et al. 1990). All solutions give weighted least-squares estimates for parameters. Time-invariant or "global" parameters, i.e., parameters dependent on all data sets, are carried from step to step, resulting in a single estimate derived from the combined data of all experiments in the solution. Depending on the problem at hand, these global parameters may include station positions, station velocities, source positions, source velocities (proper motions), nutation series coefficients, the precession constant, Love numbers for the solid Earth tides, and the relativistic gamma factor. Local or arc parameters depend only on the data from an individual experiment and are estimated separately for each epoch of observation. Arc parameters include those for the station clocks and atmospheric delay, the Earth's orientation, and nutation offsets in obliquity and longitude. Station positions and source positions can also be arc parameters if the solution is to follow changes over time.

3.2. *Radio Position Estimation*

The ICRF radio positions (Ma et al. 1998) were based on a general solution for all applicable dual frequency 2.3 and 8.4 GHz Mark III VLBI data available through the middle of 1995 consisting of 1.6 million pairs of group delay and phase delay rate observations. The two ICRF extension/update solutions (Fey et al. 2004c) were parameterized similarly to the ICRF solution but differed primarily in that more recent data were added to the previous data set.

The radio positions reported here are based on a general solution similar to that for the ICRF and its extensions except that all applicable dual-frequency 2.3 and 8.4 GHz Mark III/IV VLBI data available through the end of 2006 April, including the six dedicated experiments described in § 2, were used. This data set consisted of 4,668,573 group delay measurements from 3985 24 hr observing sessions. The weighting of the data followed the ICRF solution. For each session a pair of added noise values was computed for delays on a station-by-station basis, which caused the reduced χ_ν^2 (the χ^2 per degree of freedom) to be close to unity when added to the variance of the observations derived from the correlation and fringe-finding process, as well as the calibration of the ionosphere. The postfit weighted rms residuals of the solution were 23.36 ps (80.42 fs s^{-1}) for delay (rate) with a combined reduced χ_ν^2 of 0.96. There were 1538 global parameters, 2,167,454 arc parameters, 849,134 constraints, and 8,017,288 degrees of freedom.

Similar to the ICRF solution, the primary geodetic parameters, the station positions, were estimated separately for each session in the solution. In this way, any nonlinear motion of the stations (e.g., unmodeled tectonic motion, long-term antenna motion, or earthquake displacements) does not affect the integrity of the invariant source positions. Station motions within a day, from solid Earth tides and ocean loading, were derived from unadjusted a priori models (McCarthy 1996). The adjusted arc parameters included the following: positions of sources with identified excessive apparent motion or random variation; celestial pole offsets in ecliptic longitude and obliquity to account for errors in the standard precession/nutation models; positions of the stations; the rate of UT1 relative to a good a priori time series; 20 minute piecewise linear continuous troposphere parameters; tropospheric gradients in the east-west and north-south directions, linear in time,

[2] See http://www.parkes.atnf.csiro.au/research/surveys/pmn/pmn.html.

[3] The Parkes telescope is part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

TABLE 1
COORDINATES OF SOURCES

Source	α (J2000.0)	δ (J2000.0)	σ_α (s)	σ_δ (arcsec)	$C_{\alpha-\delta}$	Epoch of Observation (MJD) Mean	First	Last	N_{exp}	N_{obs}
0110−668	01 12 18.912936	−66 34 45.18735	0.000046	0.00042	0.268	53435.5	53223.4	53569.1	5	17
0116−219[a]	01 18 57.262167	−21 41 30.14042	0.000019	0.00033	−0.338	53580.6	53223.4	53851.5	6	27
0122−514	01 24 57.391458	−51 13 16.16803	0.000025	0.00031	−0.105	53568.6	53223.4	53851.5	6	19
0234−301[b]	02 36 31.169435	−29 53 55.54090	0.000016	0.00027	−0.278	53576.3	53223.4	53851.5	6	26
0254−334[c]	02 56 42.602737	−33 15 21.27737	0.000017	0.00035	−0.122	53550.0	53223.4	53851.5	6	25
0524−485	05 26 16.671290	−48 30 36.79120	0.000018	0.00026	−0.095	53505.7	53223.4	53851.5	6	41
0549−575	05 50 09.580131	−57 32 24.39644	0.000022	0.00030	0.221	53432.2	53223.4	53569.1	5	41
1034−374[d]	10 36 53.439601	−37 44 15.06513	0.000016	0.00023	−0.197	53525.6	53223.4	53851.5	6	34
1055−301[b]	10 58 00.427418	−30 24 55.02701	0.000019	0.00024	−0.377	53546.2	53223.4	53851.5	6	32
1143−287[a]	11 46 26.188566	−28 59 18.50423	0.000020	0.00023	−0.409	53535.3	53223.4	53851.5	6	33
1143−696[e]	11 45 53.624183	−69 54 01.79777	0.000042	0.00029	0.237	53206.0	52872.9	53569.1	10	45
1156−663[e]	11 59 18.305522	−66 35 39.42688	0.000052	0.00034	0.338	53163.3	52872.9	53569.1	10	38
1245−454[e]	12 48 28.495138	−45 59 47.17966	0.000020	0.00032	0.095	53384.7	53018.7	53851.5	8	49
1420−679[e]	14 24 55.557408	−68 07 58.09430	0.000042	0.00037	0.204	53198.9	52872.9	53569.1	10	42
1448−648[e]	14 52 39.679254	−65 02 03.43323	0.000046	0.00036	0.156	53275.7	52887.6	53569.1	9	38
1454−354[b]	14 57 26.711708	−35 39 09.97114	0.000019	0.00042	0.181	53536.9	53223.4	53851.5	6	34
1519−294[a]	15 22 25.486336	−29 36 25.23020	0.000019	0.00044	0.041	53507.6	53223.4	53851.5	6	32
1556−245[a]	15 59 41.409089	−24 42 38.83086	0.000019	0.00054	0.008	53499.9	53223.4	53851.5	6	30
1611−710[e]	16 16 30.641519	−71 08 31.45435	0.000066	0.00039	0.337	53251.8	52887.6	53569.1	9	33
1725−795[e]	17 33 40.700248	−79 35 55.71649	0.000093	0.00034	0.090	53305.1	52887.6	53569.1	9	43
1824−582	18 29 12.402364	−58 13 55.16165	0.000031	0.00034	0.233	53444.9	53223.4	53569.1	5	27
1929−457	19 32 44.887762	−45 36 37.92911	0.000020	0.00032	−0.065	53523.5	53223.4	53851.5	6	31
2002−375[c]	20 05 55.070919	−37 23 41.47819	0.000017	0.00029	−0.144	53536.7	53223.4	53851.5	6	33
2030−689	20 35 48.876518	−68 46 33.84104	0.000050	0.00033	0.014	53428.1	53223.4	53569.1	5	26
2058−297[a]	21 01 01.659976	−29 33 27.83612	0.000019	0.00065	0.200	53484.6	53223.4	53851.5	6	26
2123−463	21 26 30.704261	−46 05 47.89225	0.000017	0.00032	0.102	53535.2	53223.4	53851.5	9	37
2138−377[b]	21 41 52.448982	−37 29 12.99146	0.000022	0.00039	0.096	53553.1	53223.4	53851.5	9	22
2220−351[d]	22 23 05.930586	−34 55 47.17672	0.000014	0.00036	0.028	53535.7	53223.4	53851.5	9	35
2236−572	22 39 12.075921	−57 01 00.83955	0.000025	0.00035	0.284	53447.3	53223.4	53569.1	5	25
2239−631	22 43 07.839317	−62 50 57.32250	0.000036	0.00040	0.226	53485.2	53223.4	53605.5	8	25
2306−312[b]	23 09 14.331414	−30 59 12.58466	0.000018	0.00037	−0.142	53569.1	53223.4	53851.5	8	25
2333−415	23 36 33.985096	−41 15 21.98460	0.000017	0.00033	−0.155	53553.6	53223.4	53851.5	9	30
2344−514	23 47 19.864088	−51 10 36.06584	0.000018	0.00028	0.192	53555.2	53223.4	53851.5	9	41
2351−309[b]	23 53 47.458856	−30 37 48.50360	0.000017	0.00035	−0.121	53597.4	53223.4	53851.5	8	30

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] Astrometric position can also be found in the First VLBA Calibrator Survey (Beasley et al. 2002).
[b] Astrometric position can also be found in the Third VLBA Calibrator Survey (Petrov et al. 2005).
[c] Astrometric position can also be found in the Second VLBA Calibrator Survey (Fomalont et al. 2003).
[d] Astrometric position can also be found in the Fourth VLBA Calibrator Survey (Petrov et al. 2006).
[e] Astrometric position can also be found in the VLBI short-baseline survey of Fey et al. (2004a).

estimated once per session; quadratic clock polynomials for the gross clock behavior; 60 minute piecewise linear continuous clock parameters; and necessary nuisance parameters such as clock jumps and baseline clock offsets (i.e., separate bias parameters for each VLBI baseline to accommodate small, constant, baseline-dependent instrumental and correlator errors). The same set of sources was treated as arc parameters as in the ICRF solution with the exception of the following ICRF defining sources that were downgraded in the ICRF extension solutions (Fey et al. 2004c) to arc parameters due to excessive apparent motion: 0804+499, 1308+326, 1606+106, 2037+511 (3C 418), and 2145+067. One additional source (1718−649) was downgraded to arc parameter in this solution for the same reason. The remaining parameters, including source positions, were adjusted as invariant, or "global," quantities from the entire data set.

The entire database of available observations, rather than just the six dedicated experiments, were used in the solution because these data, when combined, comprise the foundation on which the reference frame is built. The resulting set of over 850 source positions defines a rigid frame that requires only a rotation into the system of the ICRS. This frame alignment was achieved through a no-net-rotation constraint imposed on the positions of the 212 ICRF defining sources (minus the six defining sources as described above) using their published positions from Ma et al. (1998). If only the six dedicated experiments were used, there would be insufficient positional information to construct a rigid frame, and no frame alignment would be possible.

The solution described here also differed from that of the ICRF solution in that the troposphere was modeled using the NMF mapping function (Niell 1996), estimating the zenith troposphere effects in the form of 20 minute piecewise linear continuous functions with a constraint of 50 ps hr^{-1} on the rate of variations.

4. RESULTS

The primary result obtained from the least-squares solution is the set of invariant source positions and their formal uncertainties. Of the initial 38 sources, no successful observations (group delay measurements) were obtained for the sources PKS 0802−276, PKS 1049−650, and PKS 1303−827. The source

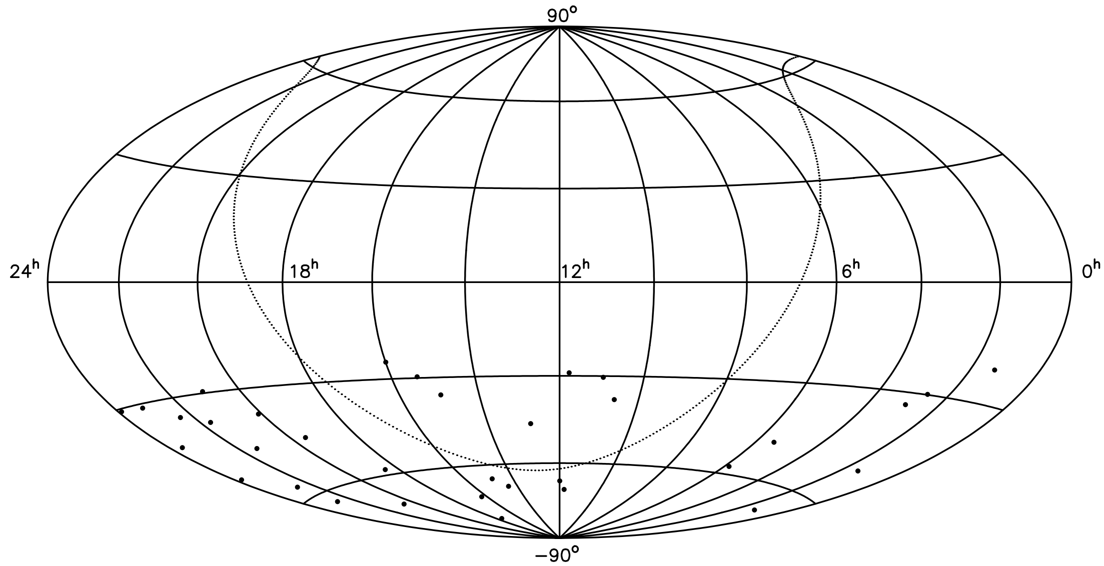

FIG. 1.—Distribution of sources on an Aitoff equal-area projection of the celestial sphere. The dotted line represents the Galactic equator.

PKS 1928−698 had too few successful observations to be useful at the present time. The remaining 34 sources were observed with 17 or more successful observations obtained during at least two 24 hr observing sessions. Positions for these sources are listed in Table 1. The column headed $C_{\alpha-\delta}$ lists the correlation between right ascension and declination. The column head $N_{\rm exp}$ lists the number of 24 hr observing sessions, and that headed $N_{\rm obs}$ lists the number of observations. As a direct result of the no-net-rotation constraint described in § 3.2, the positions listed in Table 1 are given directly in the frame of the ICRF.

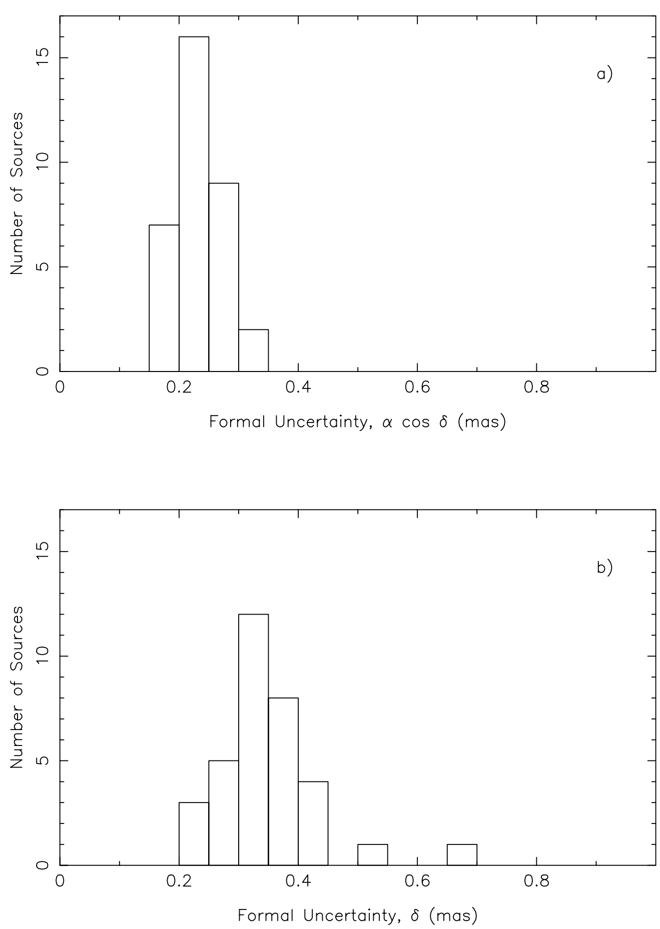

FIG. 2.—Distribution of position formal uncertainty in (*a*) α cos δ and (*b*) δ. Note that the distribution of errors in α cos δ is slightly better than that in δ due to the predominance of east-west baselines in the VLBI arrays used for these observations.

The distribution on the sky of the new sources is shown in Figure 1. Note that the positions for all 34 sources are south of $\delta = -20°$. In addition, the positions for nine of the sources are south of $\delta = -60°$. The distribution of the position formal uncertainties is shown in Figure 2. The formal uncertainties of the positions were *not inflated* as was done for the ICRF and its extensions (Ma et al. 1998; Fey et al. 2004c). The estimated positions have average formal uncertainties of 0.23 mas in right ascension and 0.35 mas in declination. Note that the distribution of errors in α cos δ is slightly better than that in δ due to the predominance of east-west baselines in the VLBI arrays used for these observations.

5. DISCUSSION

Positions for a large fraction (≈44%) of the sources listed in Table 1 can be found in the VLBA Calibrator Survey (VCS; Beasley et al. 2002; Fomalont et al. 2003; Petrov et al. 2005, 2006). However, the observing methodology of the VCS was significantly different from that used here. The VCS target sources were observed in declination strips, leading to significantly less uniform sky coverage, with observations of calibrator sources (usually high-quality geodetic sources whose positions are assumed to be well known) at both low and high elevation for each station to estimate fluctuations in the troposphere path delays interspersed only once every hour. The methodology used for the observations reported here was that of traditional astrometric VLBI experiments, i.e., optimizing all observations for sky coverage with the estimation of fluctuations in the troposphere path delays derived directly from observations of all sources. The potential also exists for systematic errors in the VCS positions of these southern hemisphere sources due to the fact that the Very Long Baseline Array is a northern hemisphere instrument (with the VLBA antenna at St. Croix, US Virgin Islands, being the furthest south in the array at a geographic latitude of 18° north). The rms scatter between the positions reported here and their associated VCS values is 0.5 mas in α cos δ and 1.4 mas in δ. As expected, the rms scatter

TABLE 2
OPTICAL IDENTIFICATION OF SOURCES

Name	ID[a]	Magnitude	Redshift	Reference
0110−668	Q	17.7	. . .	1
0116−219	Q	19.0	1.161	2
0122−514	Q	19.2	. . .	1
0234−301	Q	18.0	2.1034	3
0254−334	Q	17.0	1.915	4
0524−485	Q?	20.0B	. . .	1
0549−575	Q	19.5	. . .	5
1034−374	Q	19.5	1.821	6
1055−301	Q	19.5	2.523	7
1143−287	Q	20.0	0.45?	8
1143−696	Q	17.7	. . .	9
1156−663	. . .	. . .	. . .	. . .
1245−454	. . .	. . .	. . .	. . .
1420−679	Q	22.2	. . .	9
1448−648	G	22.0	. . .	9
1454−354	Q	19.5B	1.424	10
1519−294	Q	24.3B	2.126	10
1556−245	Q	19.0	2.813	11
1611−710	Q	20.7	. . .	9
1725−795	Q	19.7	. . .	9
1824−582	. . .	. . .	. . .	. . .
1929−457	Q	19.5	0.652	12
2002−375	. . .	. . .	. . .	. . .
2030−689	Q	18.8	. . .	13
2058−297	Q	18.0	1.492	2
2123−463	Q	18.0	1.67	14
2138−377	B	18.0	0.4228	1
2220−351	G	. . .	0.298	15
2236−572	Q?	18.5	. . .	1
2239−631	Q?	18.5	. . .	1
2306−312	Q	19.7	1.38	10
2333−415	Q	20.0	1.406	10
2344−514	Q	20.1	. . .	1
2351−309	B	18.0	. . .	1

[a] Q, quasar; G, galaxy; B, BL Lac object.
REFERENCES.—(1) Jackson et al. 2002; (2) Drinkwater et al. 1997; (3) Croom et al. 2004; (4) Peterson et al. 1976; (5) NASA/IPAC Extragalactic Database; (6) Jauncey et al. 1984; (7) Ellison et al. 2001; (8) Wilkes et al. 1983; (9) White et al. 1987; (10) Hook et al. 2003; (11) Wright et al. 1979; (12) Jauncey et al. 1978; (13) Savage et al. 1977; (14) Savage & Wright 1981; (15) Bade et al. 1995.

is larger for δ due to the difference between the geographic latitude of the VLBI arrays used here and that for the VCS. The mean position differences are not significant, with values of 0.3 mas in $\alpha \cos \delta$ and -0.2 mas in δ. Conceptually, the data from these two sets of observations, when combined in a future realization of the ICRF, will complement each other. No VCS data were used in the solution to derive the positions reported here.

Also note that positions for seven of the sources listed in Table 1 can be found in Fey et al. (2004c) but with much less accuracy than those reported here. The positions reported by Fey et al. (2004a) for these seven sources were based solely on observations using the intra-Australia baseline connecting Hobart and Parkes and were estimated to be accurate only on the 2–3 mas level. Data from these short-baseline observations are included in the solution to derive the positions reported here.

Optical information from the literature, including identification, visual magnitude, and redshift (where known) for all 34 sources, is listed in Table 2. We include these data in the hopes that precise optical positions of these sources will be obtained in the future for use in linking the radio and optical reference frames. Multiwavelength observations of these sources will help significantly strengthen the radio/optical frame link, particularly in the southern hemisphere.

6. SUMMARY

We use new Mark III/IV astrometric VLBI observations to estimate the radio positions of 34 southern hemisphere extragalactic sources. Positions for seven of these sources have been reported previously by us but are reported here with significantly improved accuracy. These results are part of an ongoing program to increase the sky density of southern hemisphere sources in the ICRF and to provide additional phase reference sources with accurate positions for use in astrophysical observations. The reported positions are in the frame of the ICRF, and all sources are located south of $\delta = -20°$. All sources have position estimates with formal uncertainties less than 0.7 mas in both coordinates. These results, together with those previously reported by us, represent a significant increase in the number of new sources with milliarcsecond-accurate astrometric positions in this declination range since the initial definition of the ICRF.

We would like to thank the staffs of the participating observatories for the time and effort required to make these observations. In addition, we would like to thank the staff of the Washington Correlator for their hard work and dedication. We would also like to thank the NASA/JPL Deep Space Network for MEGA support and for use of the 70 m antenna at Tidbinbilla, ACT, Australia. This research has made use of the NASA/IPAC Extragalactic Database, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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