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ACCURATE ASTROMETRY OF 22 SOUTHERN HEMISPHERE RADIO SOURCES

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ABSTRACT

Milliarcsecond-accurate radio positions for 22 southern hemisphere extragalactic sources are reported. These positions are derived from Mark III very long baseline interferometry observations made between 2003 February and 2003 August. The results presented here 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. The positions for all 22 sources are south of $\delta = -30°$ (positions for 10 of the sources are south of $\delta = -60°$) and represent the largest group of new milliarcsecond-accurate astrometric positions for sources in this declination range since the initial definition of the International Celestial Reference Frame. The reported positions have average formal uncertainties of 0.5 mas in right ascension and 0.6 mas in declination.

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

1. INTRODUCTION

The US Naval Observatory (USNO) and the Australia Telescope National Facility are leading a collaboration in a continuing very long baseline interferometry (VLBI) research program in southern hemisphere astrometry and source imaging. The goals of this program are to increase the sky density of International Celestial Reference Frame (ICRF; Ma et al. 1998) sources in the southern hemisphere by adding new sources with milliarcsecond-accurate positions and to image all southern hemisphere ICRF sources at least twice for structure monitoring. Initial results of the precise astrometry are reported here. Results of the imaging will be reported elsewhere.

The ICRF 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 the past ≈20 years. The positional accuracy of the ICRF sources is better than about 1 milliarcsecond (mas) in both coordinates. The ICRF is the realization of the International Celestial Reference System (ICRS; Arias et al. 1995).

Despite its significance and stated accuracy, the ICRF suffers from a deficit of sources (Ma et al. 1998; Fey et al. 2004), particularly in the southern hemisphere. Of the 212 ICRF defining sources, less than about 30% are in the southern hemisphere. This nonuniform distribution between the northern and southern skies is due primarily to the fact that most VLBI arrays are physically located in the Northern Hemisphere. As a result, astrometric and geodetic observations have historically concentrated on northern hemisphere sources.

Extragalactic radio sources are generally very distant and thus should exhibit little or no detectable motion. For this reason, systematic effects should be greatly reduced in frames derived from such sources. However, there is no a priori reason to assume that the radio frame will be completely free of systematic errors. For example, deformations of the ICRF might be caused by tropospheric propagation effects (MacMillan & Ma 1997). In order to help control such local deformations, it is crucial to increase the sky density of ICRF sources, particularly in the southern hemisphere.

It should also be noted that the deficit and nonuniform distribution of ICRF sources precludes the use of the ICRF as a catalog of calibrators serving as fiducial points to determine the relative positions of weaker nearby objects (radio stars, pulsars, weak quasars) with the phase-referencing technique. The separation between the calibrator and target source should be a few degrees at most in such observations.

There have been two extensions/updates (Fey et al. 2004) of the ICRF 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 four of the 109 new sources reported in Fey et al. (2004) have positions south of $\delta = -30°$.

To increase the sky density of southern hemisphere sources in the ICRF, we have initiated a program of dedicated southern hemisphere VLBI observations with the specific intent of obtaining accurate positions for new southern hemisphere sources, that is, sources not previously reported with coordinates in the ICRF. In this paper, we use astrometric VLBI data obtained between 2003 February and 2003 August to estimate milliarcsecond-accurate positions for 22 new southern hemisphere sources. Positions for these new sources are reported in the frame of the ICRF.

2. OBSERVATIONS

In order to identify new extragalactic radio sources to be added to the ICRF, survey observations of selected Australia

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Telescope Compact Array (ATCA) calibrator sources were interspersed among our VLBI imaging observations. At the time of these observations, the ATCA calibrator list consisted of 240 extragalactic radio sources. Of these, 133 already had ICRF coordinates listed in Ma et al. (1998). This left a total of 107 candidate sources for the survey observations. The survey observations were made at a frequency of 8.4 GHz and used the S2 VLBI recording system (Cannon et al. 1997). Candidate sources were selected based upon positive detection on transoceanic baselines (i.e., baselines either between Australia and South Africa or between Australia and Hawaii). These survey observations identified a total of 29 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 hours' duration in order to recover (separate) parameters for nutation and polar motion.

Dedicated astrometric Mark III VLBI observations were scheduled on 2003 February 5 using a VLBI array consisting of the 64 m antenna at Parkes,[6] New South Wales, Australia, the 26 m antenna at Hobart, Tasmania, Australia, the 34 m antenna at Kashima, Japan, and the 20 m antenna at Kokee Park, Hawaii, USA. Observations on 2003 May 20 used a VLBI array consisting of the 26 m antenna at Hartebeesthoek, South Africa, the 26 m antenna at Hobart, and the 64 m antenna at Parkes. Observations on 2003 August 9 and 20 used a VLBI array consisting of the 26 m antenna at Hartebeesthoek and the 70 m Deep Space Network antenna at Tidbinbilla, Australia. All observations were correlated at the Washington Correlator (Kingham 2003). Additional astrometric observations for several of the 29 sources were also obtained from the International VLBI Service astrometric/geodetic database.

3. ANALYSIS

3.1. *Software*

Accurate astrometric positions were estimated at USNO using the Goddard Space Flight Center analysis system. This system (Ryan, Ma, & Vandenberg 1980; Ma et al. 1986; Caprette, Ma, & Ryan 1990; Ryan, Ma, & Caprette 1993) consists of the astrometric and geodetic VLBI reduction software CALC and SOLVE. Data analysis methods using the GSFC system are covered in detail by 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. (2004).

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, that is, 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, 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 upon 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. 2004) 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 upon 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 VLBI data available through the end of 2003 August, including the four dedicated experiments described in § 2, were used. This data set consisted of 3,899,468 group-delay measurements from 3562 observing sessions of 24 hours' duration. 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^2_ν (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.

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 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, estimated once per hour; 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 were treated as arc parameters as in the ICRF solution with the exception of the following sources, which were downgraded to

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[6] 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.

arc parameters: 0804+499, 1308+326, 1606+106, 2037+511 (3C 418), and 2145+067. The remaining parameters, including source positions, were adjusted as invariant, or "global," quantities from the entire data set. The post-fit weighted rms residuals of the final solution were 22.23 ps for delay, with a reduced χ^2_ν of 0.923.

The entire database of available observations, rather than just the four dedicated experiments, was used in the solution because these data, when combined, constitute the foundation upon which the reference frame is built. The resulting set of over 800 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 using their published positions from Ma et al. (1998). If only the four 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 and extension solutions in that the delay-rate observable was not used; only the group-delay observable was used. The delay-rate observable was deemed to make a negligible contribution to the solution and was used in the ICRF solution only as a supplement to make up for the paucity of data on several poorly observed sources. In addition, 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 29 sources, no successful observations (group-delay measurements) were obtained for the source PKS 0201−440. The sources PKS 1045−620, PKS 1109−567, PKS 1505−496, PKS 1600−489, PKS 1646−506, and PKS 2205−636 had too few successful observations to be useful at the present time. The remaining 22 sources were observed with 10 or more successful observations obtained during at least two or more 24 hr observing sessions. Positions for these sources are listed in Table 1. The column labeled $C_{\alpha\text{-}\delta}$ lists the correlation between right ascension and declination. The column labeled $N_{\rm exp}$ lists the number of 24 hr observing sessions, and column $N_{\rm obs}$ 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.

The distribution on the sky of the new sources is shown in Figure 1. Note that the positions for all 22 sources are south of $\delta = -30°$. In addition, the positions for 10 of the sources are south of $\delta = -60°$. The distribution of the formal uncertainties in position 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. 2004). The estimated positions have average formal uncertainties of 0.5 mas in right ascension and 0.6 mas in declination.

Optical information from the literature, including identification, visual magnitude, and redshift (where known), for all 22 sources is listed in Table 2. A. L. F. has proposed additional observations of these sources to obtain precise optical positions for use in linking the radio and optical reference frames. Multiwavelength observations of these sources will help to significantly strengthen the radio-optical frame link, particularly in the southern hemisphere.

5. SUMMARY

We have used new Mark III astrometric VLBI observations to estimate the radio positions of 22 southern hemisphere extragalactic sources. These results are part of an ongoing program to increase the sky density of southern hemisphere

TABLE 1

COORDINATES OF SOURCES

SOURCE	α (J2000.0)	δ (J2000.0)	σ_α (s)	σ_δ (arcsec)	$C_{\alpha\text{-}\delta}$	EPOCH OF OBSERVATION (MJD)			$N_{\rm exp}$	$N_{\rm obs}$
						Mean	First	Last		
0048−427[a]	00 51 09.501817	−42 26 33.29302	0.000028	0.00053	0.1286	52,781.2	52,676.7	52,872.9	6	35
0107−610	01 09 15.475244	−60 49 48.45992	0.000078	0.00073	0.0298	52,857.8	52,780.7	52,872.9	3	10
0235−618	02 36 53.245762	−61 36 15.18351	0.000072	0.00053	0.2749	52,865.2	52,780.7	52,872.9	4	15
0355−669	03 55 47.883412	−66 45 33.81688	0.000088	0.00054	0.3535	52,867.8	52,780.7	52,872.9	3	16
0534−340[a]	05 36 28.432382	−34 01 11.46825	0.000028	0.00049	0.2256	52,795.9	52,676.7	52,878.7	7	27
1012−448[a]	10 14 50.354931	−45 08 41.15435	0.000037	0.00037	−0.3030	52,790.1	52,676.7	52,878.7	6	36
1016−311[a]	10 18 28.753476	−31 23 53.84983	0.000026	0.00035	0.0609	52,777.5	52,676.7	52,872.9	6	37
1022−665	10 23 43.533113	−66 46 48.71825	0.000090	0.00065	−0.1287	52,862.5	52,780.7	52,872.9	3	19
1325−558	13 29 01.144911	−56 08 02.66635	0.000067	0.00066	−0.0140	52,804.4	52,676.7	52,872.9	5	19
1412−368[a]	14 15 26.016348	−37 05 26.97028	0.000030	0.00032	−0.2535	52,786.6	52,676.7	52,872.9	6	38
1511−476........	15 14 40.024595	−47 48 29.85811	0.000050	0.00076	0.3774	52,813.6	52,676.7	52,872.9	6	18
1554−643	15 58 50.284359	−64 32 29.63755	0.000088	0.00059	0.1348	52,866.7	52,780.7	52,872.9	3	19
1606−398[a]	16 10 21.879121	−39 58 58.32895	0.000056	0.00056	−0.1860	52,798.6	52,676.7	52,878.7	7	14
1624−617	16 28 54.689843	−61 52 36.39843	0.000081	0.00071	0.2428	52,861.3	52,780.7	52,872.9	3	13
1633−810	16 42 57.345671	−81 08 35.07065	0.000259	0.00060	0.0879	52,867.1	52,780.7	52,872.9	3	12
1657−562	17 01 44.858118	−56 21 55.90214	0.000061	0.00061	0.2737	52,834.9	52,676.7	52,878.7	7	23
1659−621	17 03 36.541291	−62 12 40.00846	0.000079	0.00063	0.3129	52,854.5	52,780.7	52,872.9	4	15
2102−659	21 06 59.721974	−65 47 43.58553	0.000090	0.00075	0.2078	52,866.5	52,780.7	52,872.9	3	11
2117−614........	21 21 04.074204	−61 11 24.62420	0.000081	0.00074	0.2828	52,865.1	52,780.7	52,872.9	3	12
2244−372	22 47 03.917338	−36 57 46.30357	0.000022	0.00027	0.0201	52,788.0	52,676.7	52,878.7	8	50
2314−340[a]	23 16 43.386298	−33 49 12.48495	0.000044	0.00060	−0.0505	52,773.9	52,676.7	52,872.9	5	17
2321−375[a]	23 24 07.111819	−37 14 22.45480	0.000034	0.00047	0.2232	52,772.3	52,676.7	52,872.9	4	14

[a] Astrometric position can also be found in the Second VLBA Calibrator Survey (Fomalont et al. 2003).

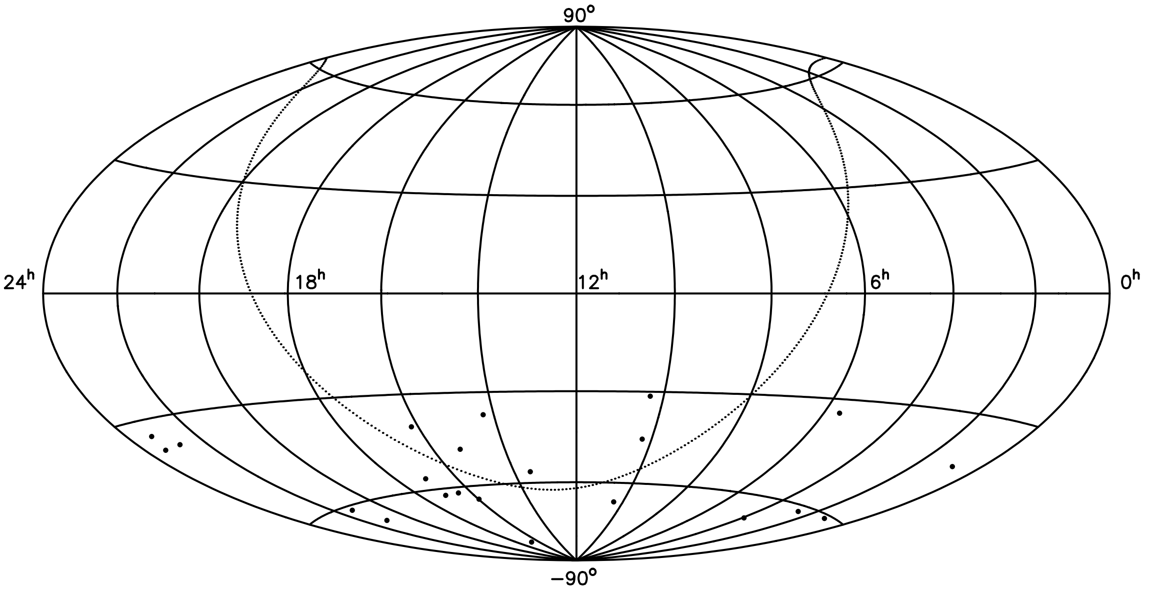

Fig. 1.—Distribution of sources on an Aitoff equal-area projection of the celestial sphere. The dotted line represents the Galactic equator.

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 $\delta = -30°$. All sources have position estimates with formal uncertainties less than 1 mas in both coordinates. These results represent the largest group of new milliarcsecond-accurate astrometric positions for sources in this declination range since the initial definition of the ICRF.

TABLE 2

Optical Identification of Sources

Source	ID[a]	Magnitude	Redshift	Ref.
0048−427	Q	19.98	1.749	1
0107−610	Q	21.4	. . .	2
0235−618	Q	17.8	. . .	2
0355−669	Q	18.7	. . .	2
0534−340	G	18.3	0.684	3
1012−448	. . .	. . .	. . .	
1016−311................	Q	17.58	0.794	1
1022−665	. . .	. . .	. . .	
1325−558	. . .	. . .	. . .	
1412−368	G	22.5	. . .	2
1511−476................	. . .	. . .	. . .	
1554−643	G	17.0	. . .	2
1606−398	Q	20.9	0.518	4
1624−617	. . .	. . .	. . .	
1633−810	Q	18.0	. . .	2
1657−562	. . .	. . .	. . .	
1659−621	. . .	. . .	. . .	
2102−659	G	21.0	. . .	2
2117−614................	. . .	. . .	. . .	
2244−372	Q	19.0	2.252	2
2314−340	Q	18.5	3.1	5
2321−375	Q	18.9	0.37	6

References.—(1) Drinkwater et al. 1997; (2) NASA/IPAC Extragalactic Database; (3) Caccianiga et al. 2000; (4) Landt et al. 2001; (5) Maza et al. 1993; (6) Osmer & Smith 1980.

[a] (Q) QSO; (G) galaxy.

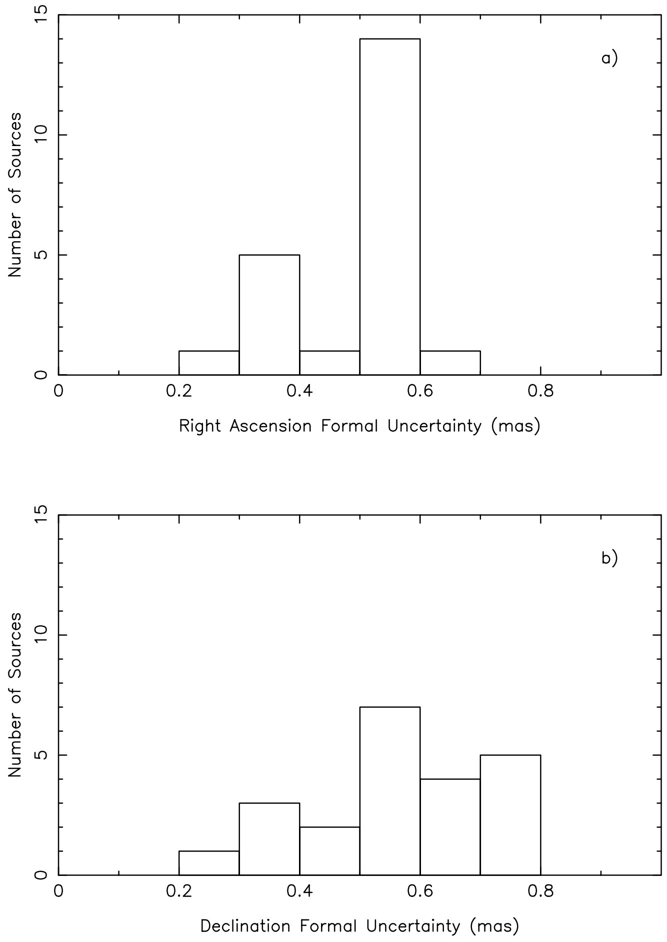

Fig. 2.—Distribution of formal uncertainty in (*a*) right ascension and (*b*) declination.

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