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Densification of the International Celestial Reference Frame: Results of EVN+ Observations

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Abstract. The current realization of the International Celestial Reference Frame (ICRF) comprises a total of 717 extragalactic radio sources distributed over the entire sky. An observing program has been developed to densify the ICRF in the northern sky using the European VLBI network (EVN) and other radio telescopes in Spitsbergen, Canada and USA. Altogether, 150 new sources selected from the Jodrell Bank–VLBA Astrometric Survey were observed during three such EVN+ experiments conducted in 2000, 2002 and 2003. The sources were selected on the basis of their sky location in order to fill the "empty" regions of the frame. A secondary criterion was based on source compactness to limit structural effects in the astrometric measurements. All 150 selected new sources have been successfully detected and the precision of the estimated coordinates in right ascension and declination is better than 1 milliarcsecond (mas) for most of them. A comparison with the astrometric positions reported in the VLBA Calibrator Survey for 129 common sources indicates consistency within 2 mas for 80% of the sources.

1. Introduction

The International Celestial Reference Frame (ICRF), the most recent realization of the VLBI celestial frame, is currently defined by the radio positions of 212 extragalactic sources observed by VLBI between August 1979 and July 1995 (Ma et al. 1998). These *defining* sources, distributed over the entire sky, set the initial direction of the ICRF axes and were chosen based on their observing histories with the geodetic networks and the accuracy and stability of their position estimates. The accuracy of the individual source positions is as small as 0.25 milliarcsecond (mas) while the orientation of the frame is good to the 0.02 mas level. Positions for 294 less-observed *candidate* sources and 102 *other* sources with less-stable coordinates were also reported, primarily to densify the frame. Continued observations through May 2002 have provided positions for an additional 109 new sources and refined coordinates for candidate and "other" sources (Fey et al. 2004).

The current ICRF with a total of 717 sources has an average of one source per $8^\circ \times 8^\circ$ on the sky. While this density is sufficient for geodetic applications, it is clearly too sparse for differential-VLBI applications (spacecraft navigation, phase-referencing of weak targets), which require reference calibrators within a-few-degree angular separation, or for linking other reference frames (e.g. at optical wavelengths) to the ICRF. Additionally, the frame suffers from a inhomogeneous distribution of the sources. For example, the distance to the nearest ICRF source for any randomly-chosen sky location is up to 13° in the northern sky and 15° in the southern sky (Charlot et al. 2000). This non-uniform source distribution makes it difficult to assess and control any local deformations in the frame. Such deformations might be caused by tropospheric propagation effects and the apparent motions of the sources due to variable intrinsic structure (see Ma et al. 1998).

This paper reports results of astrometric VLBI observations of 150 new sources to densify the ICRF in the northern sky. These observations were carried out using the European VLBI Network (EVN) and additional geodetic antennas that joined the EVN for this project. The approach used in selecting the new potential ICRF sources was designed to improve the overall source distribution of the ICRF. Sources with no or limited extended emission were preferably selected to guarantee high astrometric suitably. Sections 2 and 3 below describe the source selection strategy in further details, the network and observing scheme used in these EVN+ experiments, and the data analysis. The astrometric results that have been obtained are discussed in Sect 4, including a comparison with the VLBA Calibrator Survey astrometric positions for 129 common sources.

2. Strategy for Selecting New ICRF Sources

The approach used for selecting new sources to densify the ICRF was to fill first the "empty" regions of the frame. The largest such region for the northern sky is located near α = 22 h 05 min, δ = 57°, where no ICRF source is to be found within 13°. A new source should thus be preferably added in that part of the sky. By using this approach again and repeating it many times, it is then possible to progressively fill the "empty" regions of the frame and improve the overall ICRF source distribution. The input catalog for selecting the new sources to observe was the Jodrell Bank–VLA Astrometric Survey (JVAS) which comprises a total 2118 compact radio sources distributed over all the northern sky (Patnaik et al. 1992, Browne et al. 1998, Wilkinson et al. 1998). Each JVAS source has a peak flux density at 8.4 GHz larger than

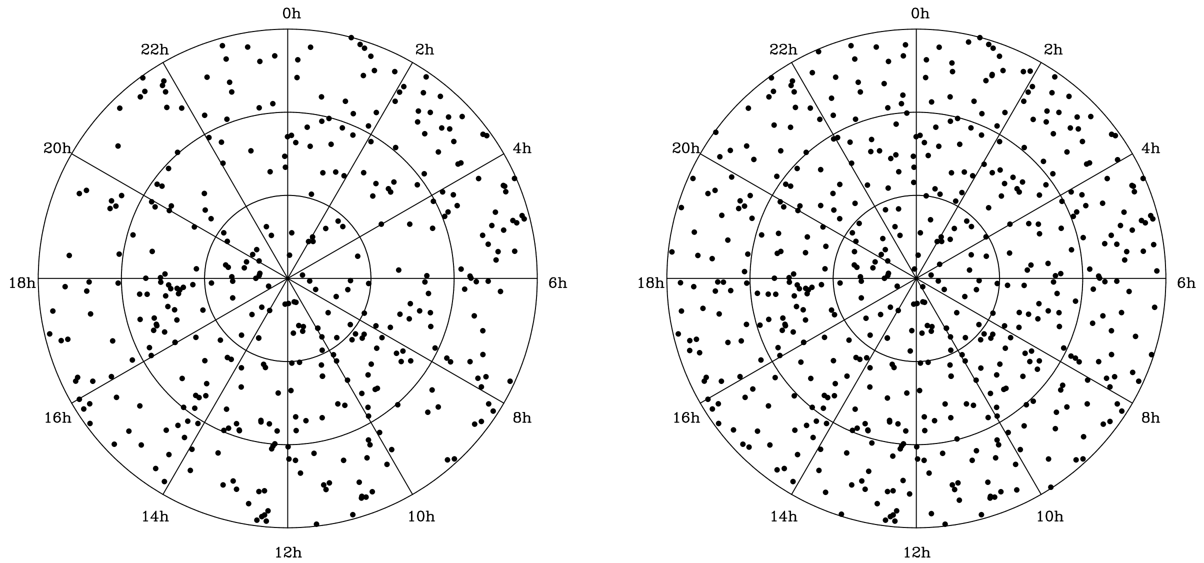

Fig. 1. Northern-sky source distribution in polar coordinates. *Left:* for the current ICRF, including defining, candidate, and "other" sources plus the additional sources published in ICRF-Ext.1 (see Fey et al. 2004). *Right:* same plot after adding the 150 new sources identified to fill the "empty" regions of the frame. The outer circle corresponds to a declination of 0° while the inner central point is for 90° declination. The intermediate circles correspond to declinations of 30° and 60°.

50 mJy at a resolution of 200 mas, contains 80% or more of the total source flux density, and has a position known to an rms accuracy of 12–55 mas. For every "empty" ICRF region, all JVAS sources within a radius of 6° (about 10 sources on average) were initially considered. These sources were then filtered out using the VLBA Calibrator Survey, which includes VLBI images of most JVAS sources (Beasley et al. 2002), to eventually select the source with the most compact structure in each region.

The results of this iterative source selection scheme show that 30 new sources are required to reduce the distance to the nearest ICRF source from up to 13° to up to 8°. Another 40 new sources would further reduce this distance to a maximum of 7° while for a maximum distance of 6°, approximately 150 new sources should be added. Carrying this procedure further, it is found that the number of required new sources doubles for any further decrease of this distance of 1° (approximately 300 new sources for a maximum distance of 5° and 600 new sources for a maximum distance of 4°) with the limitation that the JVAS catalog is not uniform enough to fill all the regions below a distance of 6°. Based on this analysis, we have selected the first 150 sources identified through this procedure for observation with the EVN+ network described below. As shown in Fig. 1, the overall source distribution is potentially much improved with these additional 150 sources in the northern sky.

3. Observations and Data Analysis

The observations were carried out in a standard geodetic mode during three 24-hour dual-frequency (2.3 and 8.4 GHz) VLBI experiments conducted in May 31, 2000, June 5, 2002, and October 27, 2003, using the EVN (including the Chinese and South African telescopes) and up to four additional geodetic radio telescopes (Algonquin Park in Canada, Goldstone/DSS 13 and Greenbank/NRAO20 in USA, and Ny-Alesund in Spitsbergen). There were between 10 and 12 telescopes scheduled for each experiment. Such a large network permits a geometrically-strong schedule based on sub-netting which allows tropospheric gradient effects to be estimated from the data. The inclusion of large radio telescopes (Effelsberg, Algonquin Park) in this network was essential because the new sources are much weaker than the ICRF ones (median total flux of 0.26 Jy against 0.83 Jy for the ICRF sources, see Charlot et al. 2000). Each experiment observed a total of 50 new sources along with 10 highly-accurate ICRF sources so that the positions of the new sources can be linked directly to ICRF.

The data were correlated with the Bonn Mark 4 correlator, fringe-fitted using the Haystack software fourfit, and exported in the standard way to geodetic data base files. All subsequent analysis employed the models implemented in the VLBI modeling and analysis software MODEST (Sovers & Jacobs 1996). Standard geodetic VLBI parameters (station clock offsets and rates with breaks when needed, zenith wet tropospheric delays every 3 hours, and Earth orientation) were estimated in each experiment along with the astrometric positions (right ascension and declination) of the new sources. The positions of the 10 ICRF link sources were held fixed as were station coordinates. Observable weighting included added baseline-dependent noise adjusted for each baseline in each experiment in order to make χ^2 per degree of freedom approximately equal to 1.

4. Results

The three EVN+ experiments described above have been very successful in observing our 150 new sources. Indeed, all 150 targets have been detected, hence indicating that the source selection strategy and observing scheme set up for these ex-

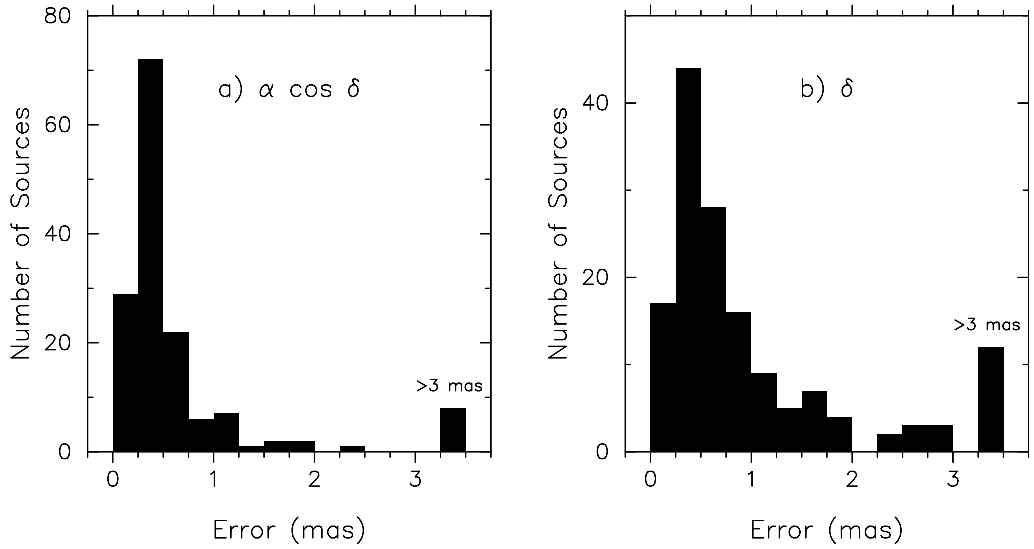

Fig. 2. Astrometric precision of the estimated ccordinates in *a)* right ascension and *b)* declination for the 150 newly-observed sources. All errors larger than 3 mas are placed in a single bin marked with the label "> 3 mas" on each plot.

periments were appropriate. In the first two experiments (2000 May 31 and 2002 June 5), there were generally between 20 and 60 pairs of delay and delay rates usable for each source to estimate its astrometric position. Conversely, more than half of the sources observed in the third experiment (2003 October 27) had less than 20 pairs of usable delay and delay rates because of the failure of three telescopes in that experiment.

Figure 2 shows the error distribution in right ascension and declination for the 150 newly-observed sources. The distribution indicates that about 70% of the sources have position errors smaller than 1 mas, consistent with the high quality level of ICRF. The median coordinate uncertainty is 0.37 mas in right ascension and 0.63 mas in declination. The larger declination errors are most probably caused by the predominantly East-West network used for these observations. Figure 2 also shows that a dozen sources have very large errors (> 3 mas). Most of these sources were observed during the 2003 October 27 experiment and have only a few available observations or data only on short intra-Europe baselines. Such sources should be re-observed to obtain improved coordinates if these are to be considered for inclusion in the next ICRF realization.

Among our 150 selected targets, 129 sources were found to have astrometric positions available in the VLBA Calibrator Survey (Beasley et al. 2002). A comparison of these positions with those estimated from our analysis shows agreement within 1 mas for half of the sources and within 2 mas for 80% of the sources. While the magnitude of the differences is consistent with the reported astrometric accuracy of the VLBA Calibrator Survey, further investigation is necessary to determine whether these differences are of random nature or show systematic trends. Such trends may be caused by the limited geometry used in observing the VLBA Calibrator Survey (see Beasley et al. 2002).

5. Conclusion

A total of 150 new potential ICRF sources have been successfully detected using the EVN and additional geodetic radio telescopes located in USA, Canada and Spitsbergen. About two-third of the sources observed with this EVN+ network have coordinate uncertainties better than 1 mas, and thus constitute valuable candidates for extending the ICRF. The inclusion of these sources would largely improve the ICRF sky distribution by naturally filling the "empty" regions of the current celestial frame.

Extending further the ICRF will require observing weaker and weaker sources as the celestial frame fills up and hence will depend closely on how fast the sensitivity of VLBI arrays improves in the future. Charlot (2004) estimates that an extragalactic VLBI celestial frame comprising 10 000 sources may be possible by 2010 considering foreseen improvements in recording data rates (disk-based recording, modern digital videoconverters) and new radio telescopes of the 40–60 meter class that are being built, especially in Spain, Italy and China. In the even longer term, increasing the source density beyond that order of magnitude is likely to require new instruments such as the Square Kilometer Array envisioned by 2015–2020.

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