# Revisiting the VLBA Calibrator Surveys for ICRF3

David Gordon

**Abstract** ICRF2 contains two classes of sources. Approximately 1/3 are sources observed in many sessions, and the other ∼2/3 are single epoch sources whose average formal errors are ∼5 times worse. About 300 of these single epoch sources have since been re-observed in RDV sessions, but around 1,900 remain. A second epoch VCS campaign is underway to re-observe these remaining single epoch sources. Results from the first of these sessions is shown to improve the position formal errors by factors of ∼5-10.

**Keywords** ICRF2, ICRF3, RDVs, VLBA, VCS, VCS-II

## 1 Introduction

ICRF2 [1] contained positions for 3,414 sources. However, two classes of sources were distinguished – those observed in many sessions (1,448 sources) and those observed in a single session (1,966 sources). If we look more closely though, we see that there are ∼2,200 sources that were observed in between one and three sessions over a short time period, which we will refer to as 'single epoch' sources. Most of these sources are from the original Very Long Baseline Array (VLBA) Calibrator Surveys (VCS) [2, 3, 4, 5, 6, 7]. These were a series of seven observing projects that used the National Radio Astronomy Observatory's (NRAO) VLBA to accurately measure the positions of as many compact radio sources as possible. The average formal position errors for the single epoch sources is approximately five times greater than that of the other ∼1,200 sources. Figure 1 shows the Right Ascension (RA) and Declination formal errors vs. the number of sessions for each source in ICRF2, using the original (unscaled) solution (gsf008a) that was used for ICRF2. The distinction between the two classes is quite clear.

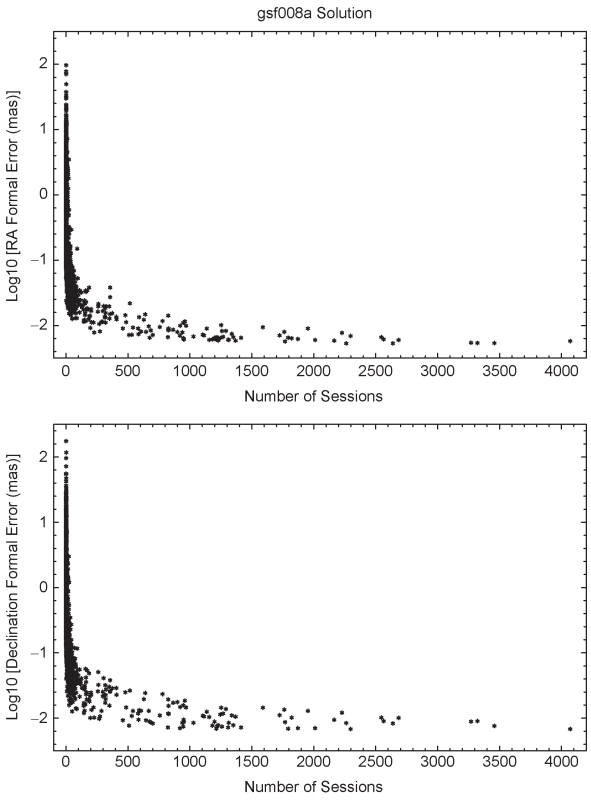


**Fig. 1** Unscaled ICRF2 formal errors in Right Ascension and Declination vs. number of sessions each source was observed in.

NVI, Inc.

Table 1 shows some statistics for the ICRF2 sources by the number of sessions in which they were observed for sources at the low end of Figure 1. ICRF2 had so many weak sources observed in three or fewer sessions that it has not been practical or possible to significantly reduce their numbers through the regular IVS observing program. If we look at the distribution of formal errors among the 1,903 one-session sources, we see a wide range, from around ∼100 mas for sources with the fewest number of observations, to ∼0.1 mas for sources with the largest number of observations. This is plotted in Figure 2, which shows a fairly smooth decrease in formal errors with an increasing number of observations. Table 2 gives the statistics of ICRF2 for sources with ten or fewer observations. There were 36 sources with only three observations, 31 with only four observations, etc. These were smaller numbers that could be addressed by re-observing these sources in the regular RDV sessions.

**Table 1** Distribution of sources in gsf008a (ICRF2) by number of sessions.

| Sessions | Sources | Average RA-sigma (mas) | Average Dec-sigma (mas) |
|---|---|---|---|
| 1 | 1903 | 1.35 | 2.29 |
| 2 | 477 | 1.28 | 2.22 |
| 3 | 120 | 0.87 | 1.41 |
| 4 | 49 | 0.57 | 0.81 |
| 5 | 48 | 0.98 | 1.08 |
| 6 | 44 | 0.79 | 0.74 |
| 7 | 34 | 0.49 | 0.64 |
| 8 | 31 | 0.56 | 0.54 |
| 9 | 18 | 0.44 | 0.48 |
| 10 | 19 | 0.79 | 0.57 |
| 15 | 21 | 0.27 | 0.33 |
| 20 | 20 | 0.20 | 0.20 |
| 25 | 12 | 0.14 | 0.19 |
| 30 | 8 | 0.06 | 0.07 |
| 35 | 7 | 0.04 | 0.05 |
| 40 | 10 | 0.04 | 0.06 |
| 45 | 4 | 0.04 | 0.05 |
| 50 | 3 | 0.05 | 0.06 |

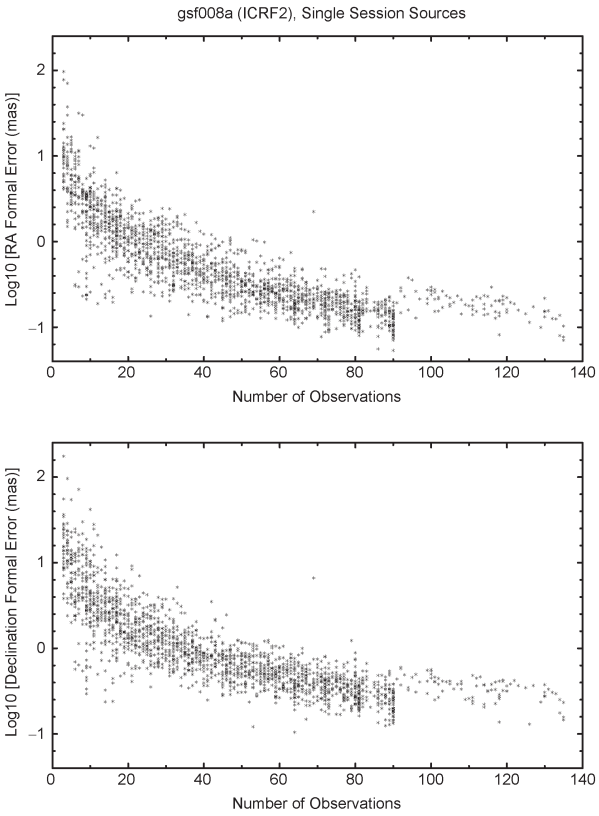


**Fig. 2** Unscaled ICRF2 formal errors in Right Ascension and Declination vs. number of observations, for single-session sources.

**Table 2** Distribution of sources in gsf008a (ICRF2) by number of observations for sources with ten or fewer observations.

| # Obs | # Sources | Average RA-sigma (mas) | Average Dec-sigma (mas) |
|---|---|---|---|
| 3 | 36 | 14.87 | 24.28 |
| 4 | 31 | 10.38 | 15.48 |
| 5 | 42 | 6.91 | 11.30 |
| 6 | 34 | 4.95 | 6.77 |
| 7 | 30 | 5.78 | 10.09 |
| 8 | 32 | 4.34 | 7.69 |
| 9 | 49 | 3.41 | 6.25 |
| 10 | 41 | 2.93 | 5.46 |

Beginning in May 2009, while ICRF2 was still being finalized, we began to add a few of these poorly observed, one-session sources to each RDV session. We also re-observed some VCS sources that were originally detected in X-band only, as well as many sources whose positions were requested by members of the astronomical community for use in phase calibrating or other purposes. In RDVs 75–102, (May 2009—Dec. 2013), some 341 ICRF2 few-observation and X-only sources have been successfully re-observed. 118 new requested sources have also been observed and detected. Table 3 gives the current numbers for sources

observed ten times or less, to be compared with Table 2. Most of the sources with six or fewer observations in ICRF2 have been re-observed. Those remaining are sources that are too far south to be observed with the VLBA. These RDV re-observations are more sensitive than the original VCS sessions because we use longer integration times, 2-bit sampling (since October 2009), and fourfit fringing (since February 2011). We currently have 3,670 sources with three or more X/S observations (256 more than ICRF2). But there are still ∼1,900 single epoch sources remaining.

**Table 3** Distribution of sources by number of observations after RDV75—RDV102, for comparison with Table 2.

| # Obs | # Sources | Average RA-sigma (mas) | Average Dec-sigma (mas) |
|---|---|---|---|
| 3 | 7 | 37.59 | 31.03 |
| 4 | 5 | 8.96 | 7.34 |
| 5 | 5 | 3.64 | 4.46 |
| 6 | 7 | 3.02 | 3.03 |
| 7 | 23 | 3.76 | 6.37 |
| 8 | 30 | 3.62 | 6.14 |
| 9 | 48 | 2.82 | 5.06 |
| 10 | 40 | 2.52 | 4.30 |

## 2 The VCS-II Proposal

To address the many single epoch sources that remain, a group was formed to request VLBA time to re-observe them in a second epoch VCS campaign. The VLBA can now observe at 2 Gbps with 2-bit sampling, which is a vast improvement over the original VCS sessions (64 and 128 Mbps, 1-bit sampling). It was estimated that ∼300 sources could be observed twice in a 24-hr session. A request was made for eight 24-hr sessions to observe ∼2,400 sources. This also included several hundred sources observed but not detected in the original VCS sessions. This proposal was approved.

The primary goals of the VCS-II campaign are: to improve or obtain the positions of ∼2,400 sources for ICRF3; improve the VLBA calibrator list; produce images of all the sources; and obtain many more apparent proper motions for secular aberration drift studies. The members of the VCS-II campaign are: D. Gordon/PI, A. Beasley (NRAO), C. Jacobs (JPL), A. Fey (USNO), R. Gaume (USNO), C. Ma (GSFC), O. Titov (Geosciences Australia), D. Boboltz (USNO/NSF), A. Peck (NRAO/ALMA), and P. Charlot (Bordeaux Observatory). The observations will use the RDBE/Mark 5C system with 16 32-Mhz channels, 12 in X-band and four in S-band. Each session will make two scans each of ∼300 single epoch sources. Slewing times will be minimized by observing a troposphere calibrator (∼20-30 seconds) and six nearby single epoch sources (∼60-120 seconds each). Scheduling will be done with the NRAO SCHED program.

## 3 VCS-II Observations and Analysis

Only one VCS-II session, BG219A, has been run so far, on January 4/5, 2014. Six of the VLBA antennas were used successfully for the full 24 hours, and a seventh (FD-VLBA) for ∼six hours. We did not get any BR-VLBA or HN-VLBA data, so the declination formal errors are somewhat larger than expected. However, all 300 target sources were detected, most with 20-30 observations.

Figures 3 and 4 compare the formal errors for these 300 sources, before and after this first VCS-II session. Before, the formal errors for these sources were in the range of .2–15 mas. Afterwards, the formal errors are all below 1.7 mas, and most are below 0.5 mas in RA and 1.0 mas in Declination.

## 4 Conclusions

Position uncertainties for many of the noisiest sources in ICRF2 have been greatly improved through re-observation in the RDV sessions since 2009, and many new sources were also added to the current catalog. The first session of the VCS-II campaign has shown that formal position errors of the single epoch sources can be improved by factors of ∼5—10. The VCS-II campaign could potentially eliminate the second class of ICRF2 sources with large formal errors. The VCS-II campaign is also expected to add several hundred additional sources to ICRF3.

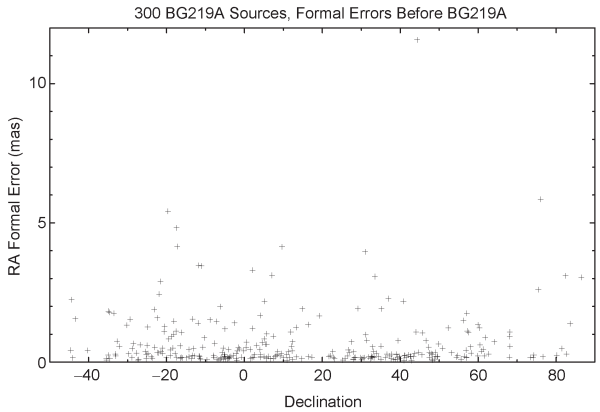


**Fig. 3** Formal errors of the 300 sources in BG219A before re-observations.

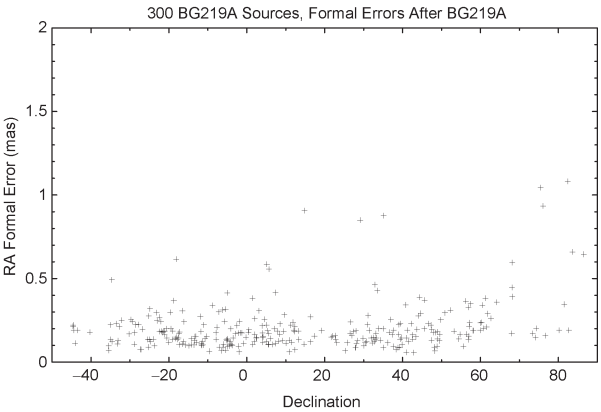


**Fig. 4** Formal errors of the 300 sources in BG219A after re-observations. Note the change in scales.

## Acknowledgements

The VLBA is operated by the National Radio Astronomy Observatory (NRAO) from the Pete V. Domenici Science Operations Center (SOC) in Socorro, New Mexico. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

## References

1. "The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry", IERS Technical Note No. 35, A.L. Fey, D. Gordon, C.S. Jacobs (editors), 2009. http://www.iers.org/TN35.
2. "The VLBA Calibrator Survey - VCS1", Beasley, A. J., D. Gordon, A. B. Peck, L. Petrov, D. S. McMillan, E. B. Fomalont, C. Ma, Asrophys. J., Supp., vol. 141, p. 13-21, 2002.
3. "The Second VLBA Calibrator Survey - VCS2", E. Fomalont, L. Petrov, D. S. McMillan, D. Gordon, C. Ma, Astronomical Journal, vol. 126 (N5), p. 2562-2566, 2003.
4. "The Third VLBA Calibrator Survey - VCS3", L. Petrov, Y. Y. Kovalev, E. Fomalont, D. Gordon, Astronomical Journal, vol. 129, p. 1163-1170, 2005.
5. "The Fourth VLBA Calibrator Survey - VCS4", L. Petrov, Y. Y. Kovalev, E. Fomalont, D. Gordon, Astronomical Journal, vol. 131, p. 1872-1879, 2006.
6. "The Fifth VLBA Calibrator Survey - VCS5", Y. Y. Kovalev, L. Petrov, E. Fomalont, D. Gordon, Astronomical Journal, Vol. 133, p. 1236-1242, 2007.
7. "The Sixth VLBA Calibrator Survey - VCS6", L. Petrov, Y. Y. Kovalev, E. Fomalont, D. Gordon, Astronomical Journal, vol. 136, p. 580-585, 2008.