On the selection of prospective sources for ICRF extension

Z. Malkin

Abstract Despite continuous increasing of the number of ICRF sources, their sky coverage is still not satisfactory. The goal of this study is to discuss some new considerations for extending the ICRF source list. Statistical analysis of the ICRF catalog allows us to identify less populated sky regions where new ICRF sources or additional observations of the current ICRF sources are most desirable to improve both the uniformity of the source distribution and the uniformity of the distribution of the position errors. It is also desirable to include more sources with high redshift in the ICRF list. These sources may be of interest for astrophysics. To select prospective new ICRF sources, the OCARS catalog is used. The number of sources in OCARS is about three times greater than in the ICRF list, which gives us an opportunity to select new ICRF sources that have already be tested and detected in astrometric and geodetic VLBI experiments.

Keywords ICRF, VLBI, OCARS, SREAG

1 Introduction

The International Celestial Reference Frame (ICRF) is the standard of the celestial reference frame recommended by the International Astronomical Union (IAU) for scientific researches and practical applications in various fields. The third ICRF realization, ICRF3 [Charlot et al., 2020] approved by the IAU in 2018 is currently in use. It contains positions of 4588 sources included in three catalogs ICRF3-SX, ICRF3-XKa, and ICRF3-K containing source positions determined from observations at three radio frequency bands. The ICRF3-SX catalog containing of 4536 sources observed at the S/X band is most complete and it is currently used to link ICRF and Gaia-CRF catalogs.

Although the number of sources in the ICRF catalog is continuously increased with time and the accuracy of their positions is continuously improved, the sky coverage by the ICRF sources, its density and uniformity, as well as the sky distribution of the source position errors, are still not satisfactory. For this reason, several institutions are considering new observing programs aimed at improving the ICRF. Statistical analysis of the ICRF catalog allows us to identify less populated sky regions where new ICRF sources or additional observations of the current ICRF sources are most desirable to improve both the uniformity of the source distribution and the uniformity of the distribution of the position errors. One more consideration for extending the ICRF list is including of sources with high redshift. These sources may be of interest for astrophysics.

The main goal of this work is to discuss new approaches for improving the source list for further ICRF extensions. Special attention will be given to formalization and quantification of some criteria (mostly known) for the selection of new sources for future ICRF extensions, as well as identification of the ICRF sources that need more observations to provide more uniform sky distribution of the position errors.

To select prospective new ICRF sources, the catalog OCARS (Optical Characteristics of Astrometric Radio Sources) [Malkin, 2018] is used. The current version of the OCARS catalog includes more
than 13 thousand sources which is about three times greater than the ICRF3 catalog. The OCARS non-ICRF sources mostly have lower position accuracy compared to ICRF, but these sources have already been tested and detected in VLBI experiments. This gives us an opportunity to select new ICRF sources from the OCARS list without resource consuming detection tests, which are necessary if new sources are pre-selected from general radio surveys.

2 Analysis of possibilities for improving ICRF source list

This study is based on the analysis of the sky distribution of the ICRF3 and Gaia catalogs, and position errors of the ICRF3 sources. To quantify the uniformity of the source sky distribution a method of pixelization of the spherical surface SREAG (Spherical Rectangular Equal-Area Grid) (Malkin, 2019, 2020) is used. It provides rectangular equal area cells with wide range of resolutions from $\sim 45^\circ$ to $\sim 16''$ (for 31-bit integer arithmetic). Fortran routines to perform basic operations with the SREAG pixelization are provided.

Table 1 shows basic parameters of several grids that looks most relevant for ICRF studies. In this paper, the grid with $N_{\text{ring}}=10$ (128 cells) has been used for plots of the sky distribution of the ICRF3-SX, Gaia, and OCARS sources, and the grid with $N_{\text{ring}}=18$ (412 cells) has been used for plots of the sky distribution of the ICRF3 defining sources.

| $N_{\text{ring}}$ | $N_{\text{cell}}$ | Cell area [sq. deg] |
|-------------------|-------------------|---------------------|
| 4                 | 20                | 2063                |
| 6                 | 46                | 897                 |
| 8                 | 82                | 503                 |
| 10                | 128               | 322                 |
| 12                | 184               | 224                 |
| 14                | 250               | 165                 |
| 16                | 326               | 127                 |
| 18                | 412               | 100                 |
| 20                | 508               | 81                  |

Table 1 SREAG grid parameters as a function of the number of rings $N_{\text{ring}}$.

Similar situation can be observed when analyzing the sky distribution of common ICRF3-SX and Gaia sources (Fig. 1). In this work, the Gaia EDR3 astrometric catalog (Lindegren et al., 2020) was used. One can see again the source deficiency in the south and near the Galactic plane. The number of cross-identified sources between the Gaia EDR3 and OCARS catalogs is more than twice as much as the number of cross-identified sources between the Gaia EDR3 and ICRF3-SX catalogs. Therefore, the selection of new ICRF sources from the list of cross-identified Gaia/OCARS sources will allow us to improve the uniformity of the source distribution of common ICRF/Gaia sources and thus

Figure 1 shows the sky distribution of the ICRF3-SX and OCARS sources. The upper panel of this plot allows us not only to see the well-known weakness of the ICRF3 catalog in the south, but also to identify the sky regions where the ICRF list should be enriched with new sources to obtain more even source distribution over the sky, in particular, the region of the Galactic plane. It can be seen that the number of sources in the poorly populated cells in the OCARS catalog is two-four times larger than in the ICRF3-SX catalog, which opens a new opportunity to select new ICRF sources from the OCARS source list.
improve the accuracy, both systematic and stochastic, of the ICRF/Gaia link. It should be noted that uneven distribution of common sources may cause problems with analysis of the coordinate differences ICRF minus Gaia by means of spherical harmonics.

![Sky distribution of sources cross-identified with Gaia EDR3 for ICRF3-SX (top, 3485 sources) and OCARS (bottom, 8707 sources) catalogs.](image)

It is important for ICRF not only to have even source distribution over the sky but also even sky distribution of the position error. Figure 3 shows the sky distribution of the ICRF3-SX sources with the position errors less than 1 mas (top, 4177 sources) and less than 0.2 mas (bottom, 2023 sources).

![Sky distribution of the ICRF3-SX sources with the position errors less than 1 mas (top, 4177 sources) and less than 0.2 mas (bottom, 2023 sources).](image)

Another consideration which is worth bearing in mind is having more ICRF sources with high redshift. These sources are important for astrophysical and cosmological studies [Coppejans et al. (2017)]. Therefore this makes sense to include the redshift as a criterion for source selection for the ICRF extension. OCARS provides redshift info for about 58% of the sources. Table 2 shows the number of sources with high redshift in the ICRF3 and OCARS catalogs. The number of high-z sources in the OCARS catalog is about two-four times larger than in the ICRF3 catalog. So, inclusion of additional high-z sources from OCARS will make the future ICRF releases more useful for non-astrometric astronomical studies.
Table 2  Number of sources with high redshift in the ICRF3 and OCARS catalogs.

| Catalog | Redshift | all | ≤ 3 | ≤ 4 | ≤ 5 |
|---------|----------|-----|-----|-----|-----|
| ICRF3   |          | 3382| 106 | 15  | 3   |
| OCARS   |          | 7967| 213 | 58  | 13  |

Increasing the number of observations of prospective ICRF sources requires either to involve supplement network resources, which is not always possible, or to improve the scheduling strategy. A possible way to make more observations of CRF sources was discussed and tested in [Malkin et al. 2013].

We started with actual schedule for IVS session R1591 that involved the 11-station network. In the original (actual) IVS schedule for the R1541 session, 60 sources were observed including 7 southern sources with declination less than −40°. For comparisons, the supplementary southern sources were added to the original source list and three experimental schedules were obtained to evaluate the trade-off between the number of southern sources and the accuracy of geodetic products. Schedule ‘R1’ was obtained with the original R1591 source list. Schedule ‘R1+’ includes three more southern sources, and schedule ‘R1++’ includes six more southern sources as compared with the original R1541 schedule. The three schedules for 24-hour continuous observations were generated with VieVS scheduling package (Sun et al., 2011).

For Monte Carlo simulation, 50 sessions were generated using the same 24-hour schedule but different realizations of noise delays, each time creating new values for wet zenith delay, clocks and white noise to simulate observations as realistic as possible. The simulated NGS data files were entered into the software package VieVS (Böhm et al. 2012), which computes a classical least squares solution. The source coordinates were fixed to the ICRF2 positions, and only Earth orientation parameters (EOP) and station positions were estimated. The standard deviation of the 50 EOP estimates and mean formal uncertainties obtained in our computations are listed in Table 3. One can see that we found no overall degradation of the EOP accuracy after the inclusion of supplement southern sources. Errors in some EOP became even smaller with inclusion of more southern sources, and some EOP showed minor degradation in the accuracy.

Table 3  Repeatability and standard deviation of EOP for the IVS R1541 and two experimental schedules R1+ and R1++ (Malkin et al. 2013).

| Parameter | R1 | R1+ | R1++ |
|-----------|----|-----|------|
| Number of scans | 1258 | 1351 | 1375 |
| Number of observations | 3905 | 3813 | 3997 |
| EOP repeatability | Xp 143.2 Yp 98.2 UT1 5.6 dX 36.2 dY 45.0 | 125.5 98.2 4.6 42.8 39.5 | 98.2 79.1 5.9 39.1 37.2 |
| Mean EOP uncertainty | Xp 94.8 Yp 77.2 UT1 4.4 dX 29.8 dY 29.1 | 95.6 77.3 4.6 30.9 29.6 | 93.4 74.8 4.7 29.5 28.1 |

As to the baseline length repeatability, it was found that for the baselines shorter than ~5,000 km the R1 schedule shows the best result, and R1+ and R1++ schedules shows worse repeatability, whereas for longer baselines the R1++ schedule is the best, and R1 is the worst. However, in fact, the results obtained with the three schedules are close to each other. The mean baseline length repeatability derived from R1, R1+, and R1++ schedules are 13.5 mm, 12.4 mm, and 11.9 mm, respectively. In other words, increasing of the number of southern sources (cf. R++ and R+ schedules) leads to a small degradation of baseline length repeatability for short baselines, and small improvement for long baselines. However, an overall improvement in the baseline length repeatability was found after inclusion more southern sources in the schedule.

Summarizing the results of this simulation experiment, one can conclude that the inclusion of targeted southern sources in regular IVS sessions such as R1 and R4 can help to increase substantially the number of ICRF southern sources with accurate positions. Suppose, we want to add 100 new sources in the south observed each 100 times (to obtain sub-mas position error) during one year. Then we need to make ~200 observations of these sources per week (cf. current ~10K observations in R1+R4 weekly schedule), which would not significantly influence the normal IVS operations, and might even provide some improvement in obtained geodetic parameters.
3 Conclusion

In this paper, an approach is discussed to select new sources for ICRF extension and identify sources already included in the ICRF that preferably need more observations to improve their position. It is suggested that the OCARS catalog (Malkin, 2018) can be used as an initial (candidate) list of already VLBI-detected sources to enrich ICRF.

Of course, some sources selected from OCARS using sky coverage criterion discussed in this paper may be too weak and/or may have a bad structure index (SI) to be used in the regular geodetic observing programs aimed at EOP and TRF monitoring. However, both source SI and flux are often variable and change with time (Charlot, 2008; Charlot et al., 2010). So, currently “bad” source can become a “good” one and vice versa.

It should be emphasized that the ICRF is not only needed for geodesy. Many other scientific and practical applications, from navigation to astrophysics and cosmology, will appreciate a dense and highly accurate catalog of radio source positions evenly distributed over the sky. Low flux radio sources are also important for astronomy, especially those sources that are cross-identified with objects in other wave bands such as optics, X-ray or gamma-ray. Such cross-identification is also provided by OCARS.

It should be also noted that increasing the number of ICRF sources evenly distributed over the sky is important for improving the link between ICRF and Gaia-CRF. Therefore, inclusion of radio weak but optically bright sources in ICRF will be of mutual benefit. OCARS provides optical and NIR magnitudes for about 78% of the sources, which can be used for source selection. The selection of candidate sources for ICRF extension that can be used for the ICRF–Gaia link can be made even simpler because OCARS provides the cross-identification table with the Gaia catalog.

Therefore it is worth spending efforts to enrich the next ICRF catalogs not only with sources “convenient” for solving say IERS- and GGOS-related tasks, but also with other sources that would improve general ICRF quality. In particular, observations of weak radio sources for ICRF can be performed in cooperation with other VLBI networks, which include large antennas.

4 Acknowledgments

This research has made use of the SAO/NASA Astrophysics Data System (ADS). The figures were prepared using gnuplot.

References

Basu S, de Witt A, Quick J, Malkin Z (2018) Multi-epoch VLBI images to study the ICRF-3 Defining Sources in the Southern Hemisphere. In: 14th European VLBI Network Symposium & Users Meeting. 8-11 October. Granada, Spain, PoS(EVN2018)135, doi: 10.22323/1.344.0135
Charlot P (2008) Astrophysical Stability of Radio Sources and Implication for the Realization of the Next ICRF. In: A. Finkelstein and D. Behrend (eds.) 5th IVS General Meeting Proceedings, St. Petersburg, Russia, 2008, 345–354
Charlot P, Boboltz DA, Fey AL, et al. (2010) The celestial reference frame at 24 and 43 GHz. II. Imaging. AJ, 139, 1713, doi: 10.1088/0004-6256/139/5/1713
Charlot P, Jacobs CS, Gordon D, et al. (2020) The third realization of the International Celestial Reference Frame by very long baseline interferometry. A&A, 644, 159, doi: 10.1051/0004-6361/202038368
Coppejans R, van Velzen S; Intema HT, et al. (2020) Radio spectra of bright compact sources at z > 4.5. MNRAS, 467, 2039 doi: 10.1093/mnras/stx215
Lindegren L, Klioner SA, Hernandez J, et al. (2020) Gaia Early Data Release 3: The astrometric solution. A&A, doi: 10.1051/0004-6361/202039709
Malkin Z, Sun J, Böhm J, Böhm S, Krásná H (2013) Searching for an Optimal Strategy to Intensify Observations of the Southern ICRF sources in the framework of the regular IVS observing programs. In: N. Zubko and M. Poutanen (eds.) 21st Meeting of the European VLBI Group for Geodesy and Astronomy, Espoo, Finland, March 5–8, 2013, 199–204
Malkin Z (2020) A New Version of the OCARS Catalog of Optical Characteristics of Astrometric Radio Sources. AJ, 239, 20, doi: 10.3847/1538-4365/aac777
Malkin Z (2019) A New Equal-area Isolatitudinal Grid on a Spherical Surface. AJ, 158, 158, doi: 10.3847/1538-3881/ab3a44
Malkin Z (2020) Spherical Rectangular Equal-Area Grid (SREAG)–Some features. In: C. Bizouard (ed.) Proc. Journees 2019 Astrometry, Earth Rotation, and Reference Systems in the GAIA era, 55–59

2 https://ui.adsabs.harvard.edu/
3 http://www.gnuplot.info/