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Astrophysical Stability of Radio Sources and Implication for the Realization of the Next ICRF

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Abstract. The intrinsic radio structure of the extragalactic sources is one of the limiting errors in the definition of the International Celestial Reference Frame (ICRF). This paper reports about the ongoing work to monitor the structural evolution of the ICRF sources by using the Very Long Baseline Array and other VLBI telescopes around the world. Based on more than 6000 VLBI images produced from such observations, we assess the astrometric suitability and compactness of the ICRF sources at 2 GHz, 8 GHz, 24 GHz and 43 GHz. The number of VLBI images available for a given source varies from 1 for the least-observed sources to 28 for the most intensively-observed sources at the standard 8 GHz geodetic frequency. Overall, about one-third of the ICRF sources are found to be astrometrically suitable at 8 GHz, while the corresponding fraction at the higher frequencies (24 and 43 GHz) is above 80%. Conversely, only marginal differences in source compactness is found between the four frequencies. The astrometric suitability and compactness of the sources vary with time because of evolution in the astrophysical source morphology.

1. Introduction

The International Celestial Reference Frame (ICRF), which has been the official IAU reference frame in use since 1 January 1998, is currently based on the VLBI positions of 717 extragalactic radio sources. Of these, 608 sources are from the original ICRF built in 1995, with a categorization that comprised 212 well-observed *defining* sources (which served to orient the axes of the frame), 294 less-observed *candidate* sources, and 102 *other* sources showing coordinate instabilities [1]. The accuracy in the individual ICRF source positions has a floor of 250 μas, while the axes of the frame are stable to about 20 μas in orientation. Since then the positions have been improved for the non-defining sources and the frame has been extended by 109 *new* sources in ICRF-Ext.1 and ICRF-Ext.2 using additional data acquired in the period 1995–2002 [2].

At the IAU XXVI$^{\text{th}}$ General Assembly in Prague (August 2006), the community decided to engage in the realization of the successor of the ICRF, to be presented at the next IAU General Assembly in 2009. The motivation for generating this new celestial frame is to benefit from recent improvements in VLBI modeling (e.g. for the troposphere) and to take advantage of the wealth of VLBI data that have been acquired since the time the ICRF was built. A major issue to be addressed in this new realization is the revision of the source categorization, in particular the choice of the defining sources. Such a revision is necessary because some of the original ICRF defining sources were found to have extended structures [3] or position instabilities (e.g. [4]), and are therefore improper for defining the celestial frame with the highest accuracy.

The selection criteria that are considered by the working group in charge of the realization of the next ICRF for the identification of proper defining sources are based either on structure information (VLBI images), to evaluate the astrometric suitability of the sources, or on time series of source coordinates, to assess their position stability. In this paper, we discuss only the former. There are now more than 6000 VLBI images available at multiple epochs and several frequency bands (2 GHz, 8 GHz, 24 GHz and 43 GHz) to evaluate the source quality, whereas these were less than a hundred at the time the ICRF was built, thereby permitting considerable progress. In Sect. 2, we present the observational data used in this work, while our results are discussed in Sects. 3 and 4. These are presented in terms of astrometric suitability and source compactness, with specific emphasis on the time variability of such indicators.

2. Observational data

The VLBI maps used in our analysis were produced from a total of 46 VLBI sessions conducted between 1994 and 2007, which were imaged either at USNO or at Bordeaux Observatory. These comprise:

- 8 dedicated dual-frequency (8 GHz/2 GHz) imaging sessions conducted with the Very Long Baseline Array (VLBA) between July 1994 and January 1997 [3, 5, 6];
- 23 dual-frequency (8 GHz/2 GHz) Research & Development VLBA (RDV) sessions conducted between January 1997 and June 2007; these sessions were carried out with the 10 VLBA stations and up to 10 additional geodetic telescopes;
- 5 dedicated southern-hemisphere 8 GHz imaging sessions conducted between July 2002 and April 2004 with the Australian Long baseline Array, augmented by radio telescopes in South-Africa, Hawaii, and Japan [7, 8];
- 10 VLBA sessions conducted at either 24 GHz or 24/43 GHz between May 2002 and March 2007 for the purpose of extending the ICRF to higher frequencies [9]; data at 8 GHz/2 GHz were also obtained during one of these sessions while another session acquired data at 8 GHz.

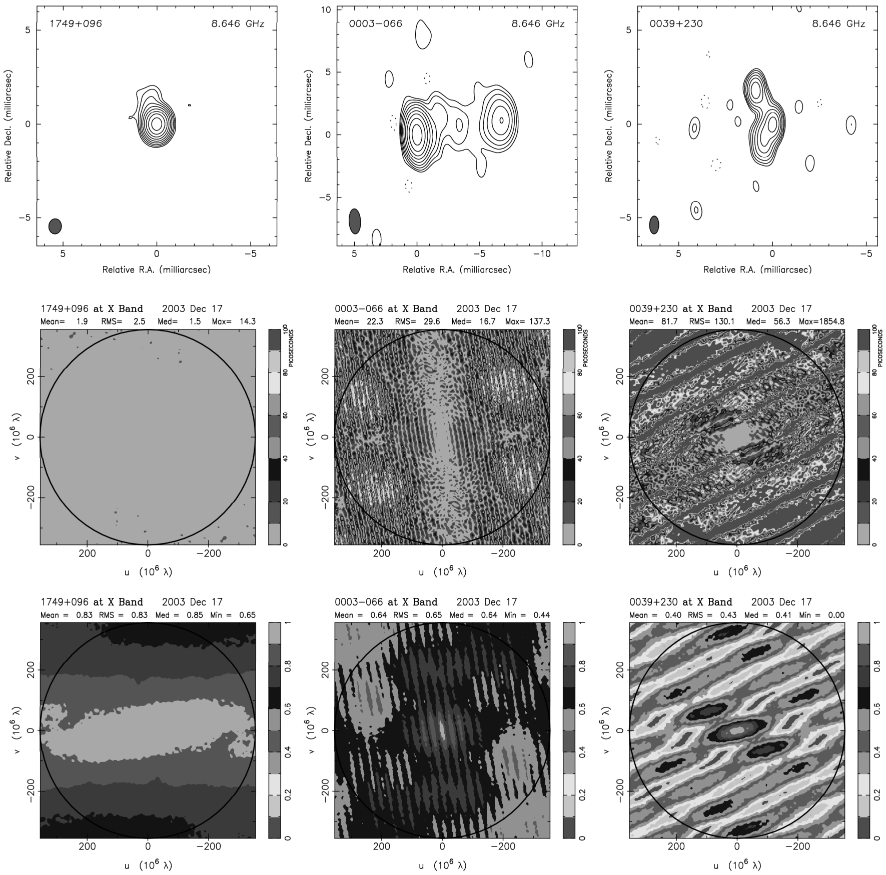

Figure 1. VLBI images at X band (8 GHz) for three ICRF sources (1749+096, 0003−066, 0039+230) as derived from the data of a RDV session conducted on 2003 December 17 (upper sub-panels). The middle sub-panels show the corresponding structure correction maps (used to calculate the structure index), while the lower sub-panels show the corresponding visibility maps (used to calculate the source compactness). The circle drawn in these panels corresponds to baselines that have a length equal to one Earth diameter. The color scale for the structure correction maps goes from 0 to 100 ps, while that for the visibility maps is between 0 and 1 (since visibility amplitudes are normalized by the total source flux density

Altogether, this represents a total of 2697 maps at X band (8 GHz) from 577 ICRF sources, 2388 maps at S band (2 GHz) from 492 ICRF sources, 1072 maps at K band (24 GHz) from 202 sources, and 267 maps at Q band (43 GHz) from 112 sources. There are up to 28 VLBI epochs available at X band for the most intensively-observed source, whereas only one epoch is available for 216 less-observed sources; 81 sources have X-band images available for 10 epochs or more. Less sources have been imaged at S band (compared

Table 1. Structure index series at X band (8 GHz) for a sample of 20 ICRF sources

Source name	Structure index values														
0003−066	3	2	2	2	2	2	2	2	2	2	2	2	3	3	3	...
0014+813	1	2	2	2	2	2	2	2	2	2	3	2	3	2	2	...
0048−097	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	...
0059+581	2	1	1	1	1	1	1	1	1	1	1	1	2	1	1	...
0111+021	3	3	3	3	3	3	3	3	3	3						
0119+041	2	2	2	2	2	2	2	2	2	2	2	1	2	3	3	...
0119+115	2	1	1	1	2	2	3	3	2	2	2	2	2	2	3	...
0133+476	2	2	1	1	1	2	1	1	1	1	1	1	2	1	1	...
0201+113	2	2	2	3	3	2	3	3	3	3	3	3	3	2	2	...
0202+149	2	2	2	2	2	2	2	3	3	3	2	2	3	3	2	...
0229+131	2	3	2	2	2	2	2	2	1	2	1	2	2	2	2	...
0234+285	3	2	2	2	2	2	2	2	2	2	2	2	2	2	1	...
0235+164	1	1	2	2	1	1	2	1	2	1	2					
0238−084	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	
0336−019	2	2	3	2	2	2	2	2	2	2	1	2	3	2	2	...
0402−362	1	2	2	1	2	2	2	3	2	2	2	3	2	3	2	...
0430+052	4	4	3	4	4	4	4	4	4	4	4	4	4	4	4	...
0454−234	2	1	1	2	1	1	1	1	1	1	1	1	2	2	1	...
0458−020	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	...
0528+134	1	1	2	2	2	2	2	2	3	2	2	2	2	2	2	...

to X band) because the southern-hemisphere sessions were carried out only at the single 8 GHz band. 18 sources were observed in all ten K band sessions.

A sample of X-band VLBI images for three ICRF sources, as derived from the data of a RDV session conducted in December 2003, is shown in Fig. 1 (upper sub-panels), along with the corresponding structure corrections maps (middle sub-panels) and visibility maps (lower sub-panels). These maps are the basis for calculation of the source structure index and compactness (see Sec. 3 and 4). Based on this calculation, it is found that only one of the three sources in Fig. 1 (1749+096) has a good astrometric suitability (structure index value of 1); the two other sources (0003−066 and 0039+230), with structure index values of 3 and 4, have a poorer astrometric quality, as also reflected by the extended morphology that their VLBI images reveal. This fraction of suitable sources is consistent with that found in the entire ICRF, as discussed below.

3. Astrometric suitability

Based on the VLBI image database described above, we derived the expected effects of intrinsic source structure on the VLBI delay astrometric quan-

Table 2. Structure index series at K band (24 GHz) for a sample of 18 ICRF sources

Source name	Structure index values									
0149+218	1	1	1	1	1	1	1	1	2	2
0300+470	1	1	1	2	2	1	1	2	2	1
0454−234	1	1	2	2	2	2	2	2	1	1
0458−020	1	1	1	1	1	1	1	1	1	1
0648−165	2	1	2	1	1	1	2	1	2	2
0749+540	1	1	2	2	2	1	1	1	1	1
0754+100	2	2	2	2	2	2	2	1	3	2
0804+499	1	1	1	1	1	1	1	1	1	2
0808+019	1	1	1	1	1	1	1	1	1	1
0953+254	2	2	1	2	2	2	2	2	1	2
1045−188	2	1	2	2	2	2	2	1	1	2
1124−186	1	1	1	1	1	1	1	1	1	1
1308+326	1	1	1	1	1	2	2	2	2	2
1502+106	1	2	1	2	2	2	2	2	2	1
1726+455	1	1	1	1	1	1	1	1	1	1
2008−159	2	1	1	2	1	2	1	2	2	2
2136+141	2	2	2	2	2	2	2	3	2	2
2255−282	1	1	1	1	1	1	1	1	2	1

tities over the entire u-v plane (see Fig. 1, middle sub-panels), following the algorithm of [10]. We then used the "structure index" indicator to define the astrometric source quality, as devised by [6]. Structure index values of 1 and 2 point to excellent and good astrometric suitability, respectively, while values of 3 and 4 point to poor suitability. A given source may have differing structure indices at different frequency bands, depending on properties of the brightness distribution. The structure index may also vary with time because of possible temporal evolution of the brightness distribution.

For each source, we obtained a series of structure index at each band according to the number of VLBI images available. Table 1 shows a sample of the structure index series available at X band for 20 intensively-observed ICRF sources, while Table 2 shows the results obtained at K band for the 18 sources that have been observed in all ten K band sessions. Overall, it is found that the variability of the structure index is generally not random but follows regular trends, probably reflecting the astrophysical evolution of the sources. Adopting a conservative approach, we chose the maximum value of the structure index as the source quality indicator when multi-epoch structure indices are available. In other words, if a source shows a structure index value of 3 or 4 at one or more epochs, it should be regarded as unsuitable for highly-accurate astrometry even though it has structure index values of 1 or 2 at some other epochs.

By using this multi-epoch indicator, we compared the structure index dis-

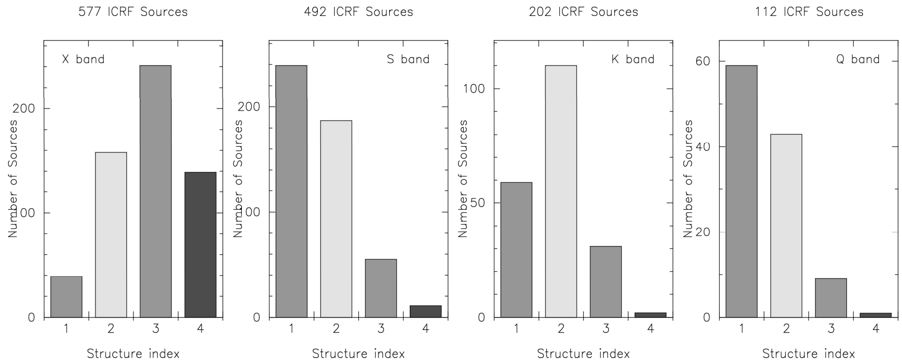

Figure 2. Structure index distribution at X band (8 GHz), S band (2 GHz), K band (24 GHz), and Q band (43 GHz), for all ICRF sources that have been imaged at these frequencies. The fraction of ICRF sources for which the structure index has been derived is 80% at X band, 69% at S band, 28% at K band, and 16% at Q band

tribution for each frequency band (8 GHz, 2 GHz, 24 GHz, and 43 GHz), as shown in Fig. 2. At X band, it is found that roughly one-third of the sources (197 sources out of a total of 577 sources) are astrometrically-suitable according to our criterion (maximum structure index value of either 1 or 2) while at S band, 86% of the sources (424 sources out of a total of 492 sources) fulfil this condition. As noted in [6], the contribution of the S-band structure to the dual-frequency (S/X) calibrated delay is usually smaller compared to the X-band contribution because S band structure delays are downweighted by a factor of 13 in this combination. Although less sources have been imaged at the higher frequencies (K band and Q band), it is striking that the astrometric suitability of the sources appears to be much better compared to that at X band, with about 90% of the sources that have a structure index value of either 1 or 2.

In addition, we have also studied the temporal variability of the structure index by determining the upper and lower values of the structure index for each source and by calculating the scatter about the mean structure index value. This study is most easily carried out at X band because of the many VLBI sessions that have been imaged at this frequency band. For the 81 sources that have X band structure indices available for at least 10 epochs, it is found that the largest shift (difference between the upper and lower structure index values) is 1 or 2 for 90% of these sources, while the scatter about the mean peaks at about 0.5 (Fig 3, left panels). This indicates that a variability of the X-band structure index of one unit is likely for most of the sources. When carrying out a similar calculation for the 18 sources that have been observed in all ten K band sessions, one finds that the largest structure index shift is 0 or 1 for all sources except one (Fig 3, right panels). Therefore, the variability appears to be smaller at K band compared to X band, which is not surprising considering the higher astrometric quality of the sources at K band. However, one has to be cautious in this interpretation because of the poorer statistics.

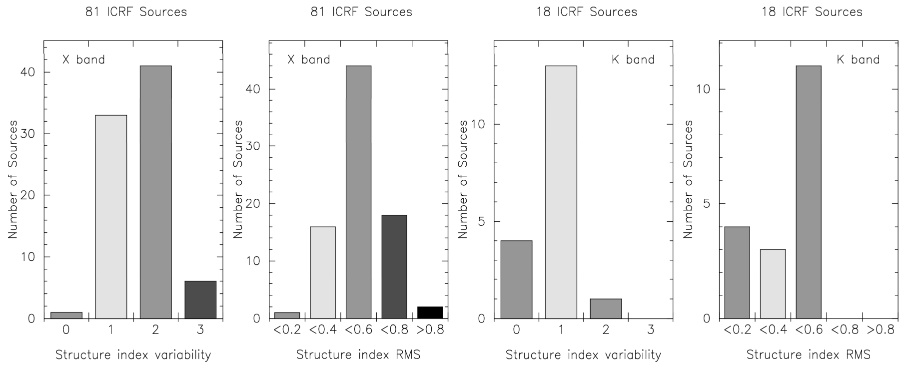

Figure 3. Variability of the structure index at X band (8 GHz) and K band (24 GHz) for all the ICRF sources that have data available in at least ten different epochs (81 sources at X band and 18 sources at K band). The variability is defined as the difference between the higher and lower values of the structure index over these epochs, while the RMS is calculated against the mean structure index value

4. Source compactness

The source compactness may be defined in a similar way as the structure index [6] from statistics of the visibility amplitude (correlated flux density) over all the u-v plane. This calculation is carried out for all projected VLBI baselines that could be possibly observed with Earth-bound VLBI based on the spatial brightness distribution of the source. The compactness is then defined according to the median of such values, after normalization of the visibility amplitudes by the total source flux density. With this normalization, the compactness has a value of 1 for a point-like source while it has a value of 0 for a source that is totally resolved out. It should be stressed that the compactness defined in this way does not provide a measure of the "true" source compactness but rather a measure of the source compactness relative to the interferometer resolution. A sample of the visibility maps that have been used for this evaluatation is shown in Fig. 1 (lower sub-panels) for three ICRF sources with different VLBI morphologies. As previously, we adopted a conservative approach when multi-epoch values are available for the compactness with the minimum of all values used as the compactness indicator for each source.

Based on the above definition, we compared the source compactness at each frequency band (2 GHz, 8 GHz, 24 GHz and 43 GHz) for all ICRF sources that have been imaged so far (Fig. 4). Unlike in the case of the structure index, there is no such a striking difference when going to the higher frequencies. There is a possible trend indicating that the sources become slightly more compact at higher frequencies (about 30%, 31% and 35% of sources with compactness higher than 0.6 at X band, K band and Q band, respectively) but this may not be significant. On the other hand, the sources appear to be more compact at S band (about 45% of sources with compactness higher than 0.6). We have also

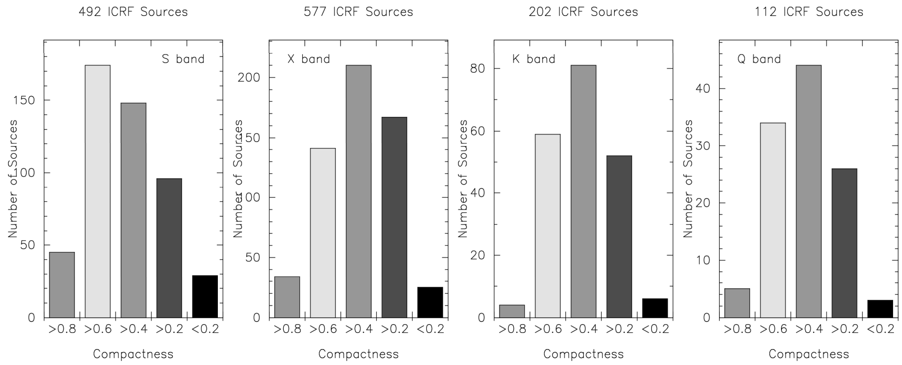

Figure 4. Distribution of compactness at S band (2 GHz), X band (8 GHz), K band (24 GHz), and Q band (43 GHz), for all ICRF sources that have been imaged at these frequencies. The smallest value of the compactness found for each source has been used in this study when multi-epoch values are available

studied the compactness variability in a similar way to that carried out for the structure index, and the corresponding histograms are shown in Fig. 5 for the sources that have been observed in at least 10 different epochs (81 sources at X band and 18 sources at K band). About 62% of the sources show a variability lower than 0.4 at X band, while the corresponding fraction is 82% at K band. This may reflect a lower structure variability at higher frequency but since the statistics at K band are poor, it is again difficult to make a firm statement.

5. Conclusion

We have evaluated the astrometric suitability at the standard 8 GHz geodetic frequency for 80% of the ICRF sources, based on multi-epoch VLBI images of their brightness distributions. It is anticipated that the remaining 20% of ICRF sources for which the astrometric suitability has not been assessed (mostly in the southern sky) will be imaged in the near future through further VLBI observing programs in the southern hemisphere. In addition, the astrometric suitability for roughly one-third of the ICRF sources has been estimated at 24 GHz, taking advantage of a new VLBI observing program that was set up 5 years ago to extend the ICRF towards higher frequencies.

The comparison between statistics on astrometric suitability at 8 GHz and those at 24 and 43 GHz strongly indicates that the sources are much more astrometrically suitable at the higher frequencies. On the other hand, no significant difference in source compactness is found between the 8 GHz, 24 GHz, and 43 GHz bands. Both the astrometric suitability and source compactness are subject to variability, although generally in a smooth way, because of the astrophysical evolution of the sources. The astrometric suitability of the sources already imaged, which has been discussed in this paper, will continue to be refined as new VLBI sessions are processed and new structure maps become

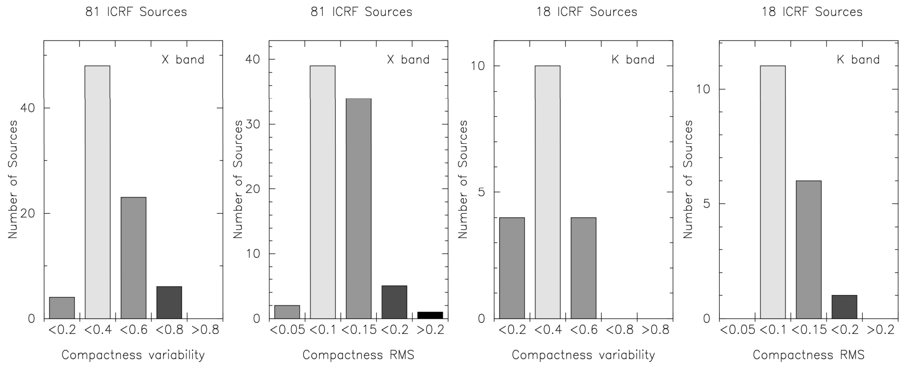

Figure 5. Variability of source compactness at X band (8 GHz) and K band (24 GHz) for all the ICRF sources that have data available in at least ten different epochs (81 sources at X band and 18 sources at K band). The variability is defined as the difference between the higher and lower values of the source compactness over these epochs, while the RMS is calculated against the mean compactness value

available. This information will be essential for selecting the proper defining sources and generating the next ICRF by 2009.

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