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Astrometric Suitability of ICRF Sources Based on Intrinsic VLBI Structure

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Abstract

The intrinsic radio structure of the extragalactic sources is one of the limiting errors in the analysis of astrometric and geodetic VLBI observations. Based on VLBI images obtained with the VLBA and other VLBI telescopes around the world, we evaluate this effect for 557 sources (78% of the ICRF) and calculate a so-called "structure index" to define the astrometric source quality. The structure index ranges from 1 for the most compact sources to 4 for the most extended sources. The most recent addition to our data base is for a hundred southern hemisphere sources. We discuss the overall distribution of structure index in the ICRF and the structure index variability with time for those sources that have VLBI images available at multiple epochs. Based on these data, we identify a set of 239 sources that have good or excellent astrometric suitability. We also suggest that the structure index indicator be used as a primary criterion to select defining sources for the next ICRF realization.

1. Introduction

Extensive VLBI imaging surveys reveal that many of the extragalactic radio-emitting sources used to define the International Celestial Reference Frame (ICRF) show extended emission structures on milliarcsecond scales and hence are only imperfect fiducial points in the sky [1, 2, 3, 4, 5]. This extended emission and its frequency and time dependence can introduce significant structural contributions in the measured VLBI group delays, which deteriorate the source position accuracy and the overall quality of the VLBI analysis if not accounted for [6]. It is especially important to quantify these structural effects when realizing the celestial frame so that the most suitable sources, i.e. those that produce the smallest such effects, may be used for defining the frame.

The expected effects of intrinsic source structure on bandwidth synthesis delay observations depend on the exact form of the spatial brightness distribution of the extended radio source relative to the coordinates of the VLBI baseline vector projected onto the plane of the sky [6]. The "structure index", introduced in [2], defines the astrometric source quality according to the median value of the structure delay corrections, τ_{median}, calculated for all projected VLBI baselines that could be possibly observed with Earth–bound VLBI, separating the sources into four classes as follows:

$$\text{Structure Index} = \begin{cases} 1, & \text{if } 0 \text{ ps} \leq \tau_{\mathrm{median}} < 3 \text{ ps}, \\ 2, & \text{if } 3 \text{ ps} \leq \tau_{\mathrm{median}} < 10 \text{ ps}, \\ 3, & \text{if } 10 \text{ ps} \leq \tau_{\mathrm{median}} < 30 \text{ ps}, \\ 4, & \text{if } 30 \text{ ps} \leq \tau_{\mathrm{median}} < \infty. \end{cases}$$

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 8 GHz (X band) and 2 GHz (S band) depending on the source structure at each frequency band.

Initial studies focused on estimating structure indices for as many ICRF sources as possible, based on dedicated imaging observations with the Very Long Baseline Array (VLBA). From these data, structure indices were derived for a total of 389 sources, representing approximately 90% of the ICRF sources north of -20° declination [2, 3]. In addition, structure indices have recently been obtained for 111 southern ICRF sources, most of which at declinations below -20°, which were mapped using a southern hemisphere VLBI network [5]. In this paper, we extend further our calculation by using additional VLBI imaging data, which include those from a dozen Research & Development VLBA (RDV) experiments. This brings the total number of ICRF sources with available structure indices to 557. We also devise a scheme to account for the temporal variability of the structure index for the sources that have been imaged at multiple epochs.

2. Observational Data and Multi-Epoch Structure Index

The VLBI maps used to derive the structure index data base discussed below are part of the Radio Reference Frame Image Data Base (available at http://rorf.usno.navy.mil/rrfid.shtml) and were produced from a total of 28 VLBI sessions conducted between 1994 and 2005. These comprise:

- 8 dedicated dual-frequency (S/X) VLBA imaging sessions conducted between July 1994 and January 1997 [1, 2, 3];
- 13 dual-frequency (S/X) RDV sessions conducted between January 1997 and July 2004; these sessions include the 10 VLBA stations and up to 10 additional geodetic telescopes;
- 5 dedicated southern hemisphere X-band 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 [4, 5];
- 2 VLBA sessions at S/X/K and X/K frequency bands, respectively, in February 2004 and August 2005, as part of a project to extend the ICRF to higher frequencies[1] [7].

Altogether, this represents a total of 1735 maps at X band from 557 sources and 1543 maps at S band from 459 sources. Less sources have been imaged at S band because the southern hemisphere sessions did not observe at this frequency. There are up to 19 VLBI epochs available for some intensively observed sources, whereas only one epoch is available for other less observed sources.

Figure 1 shows a series of maps and structure indices for two ICRF sources, one of which (0048-097) is very compact with a structure index value of 1 at all epochs, whereas the other one (the BL Lac object 1156+295) shows significant structure changes and variability of the structure index over the two-year span of the data. For 1156+295, there is first an increase in the structure index (from 2 to 3), at a time when the source weakened (peak of emission dropping from 0.8 to 0.3 Jy/beam). By superresolving the maps, it appears that the dominant component of the structure became also more resolved at these epochs, possibly because a secondary sub-component was ejected from the core. Following this event, the source quickly brightened (peak brightness rising from 0.3 to 2.0 Jy/beam within a year), with the sub-structure being dominated again by a single sub-component, while the structure index decreased from a value of 3 to a value of 1 at the same time (Fig. 1). This rapid flux and structure variability is typical of BL Lac objects.

The above example indicates that 1156+295 was a highly suitable reference source at epoch 1999.0, whereas this was not the case a year earlier. In this respect, it is important to account for

[1] Only the X band and S band structure indices are discussed in this paper. For results at K band, see [7, 8].

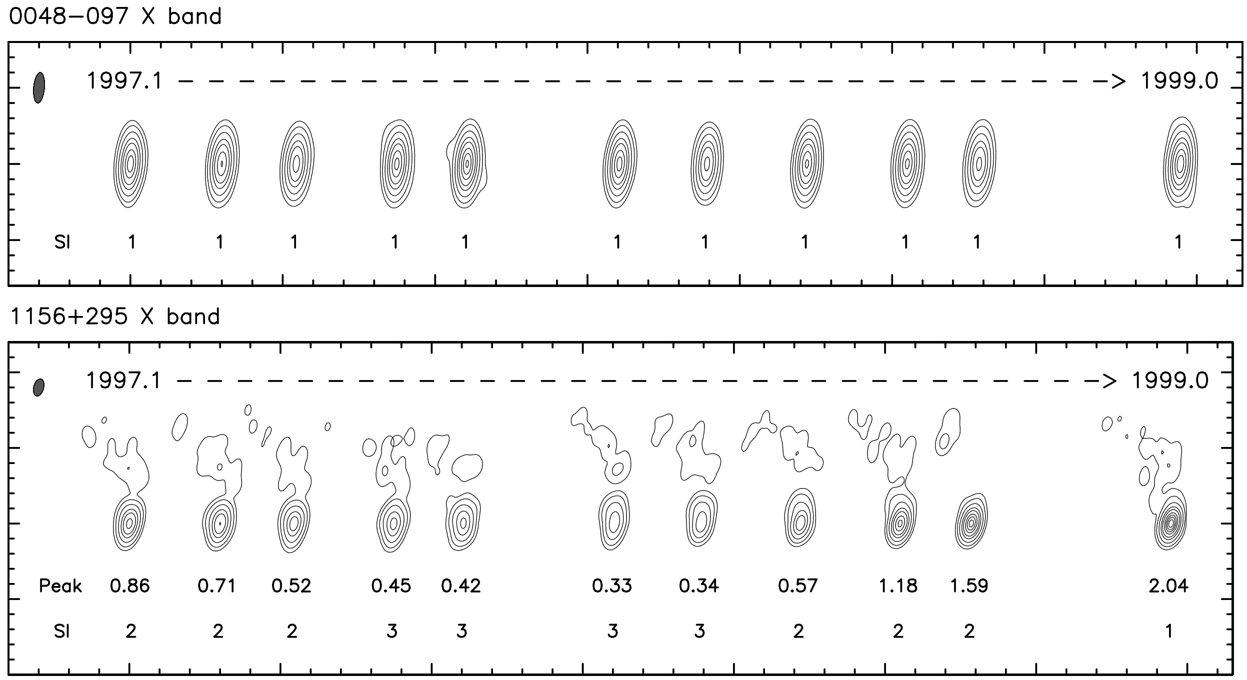

Figure 1. VLBI images of the ICRF sources 0048–097 and 1156+295 at X band for 11 successive epochs spanning the period 1997.1–1999.0. The maps are aligned horizontally according to the dominant structural component and are spaced linearly according to their observing epochs. The interval between minor tick marks (vertical scale) is 1 mas. The structure index (SI) is indicated below each map. For comparison, the peak brightness (Peak), expressed in Jy/beam, is also indicated below each map in the case of 1156+295. Contour levels are drawn at 0.0035, 0.014, 0.056, 0.175, 0.35, 0.70, 1.05, 1.40, and 1.75 Jy/beam.

the structure index variability when defining the astrometric suitability of a given source. 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. As before, we suggest that only those sources that have values of the structure index of either 1 or 2 should be identified as high-quality sources. 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. Examples of sources excluded based on this multi-epoch criterion include 0014+813, 2145+067, and 2234+282. It is interesting that these sources also show significant position instability, as reported by several authors during this meeting [9, 10].

3. Discussion

As noted above, we have now obtained structure indices for 557 sources at X band and 459 sources at S band (representing 78% and 64% of the current 717 sources of the ICRF, respectively). The X-band structure index distribution (Fig. 2) shows that 242 sources (or equivalently a portion of 43% of the sources) are astrometrically suitable at this frequency according to our criterion (structure index value of either 1 or 2). This is less than the percentage of good sources we reported before (57%, as quoted in [8]) because our new multi-epoch approach led us to downgrade some sources with variable structure that were found suitable in our previous single-epoch analyses. At S band, 88% of the sources have a structure index value of either 1 or 2 (Fig. 2). This indicates that the contribution of the S-band structure to the dual-frequency calibrated delay is usually smaller compared to the X-band structure contribution (as already noted in [2]). Comparing the X- and S-band structures indices individually for each source shows that, with three exceptions, all sources that have an S-band structure index of either 3 or 4 have also an X-band structure index of 3 or 4. Based on the S-band structure index, we thus exclude only 3 additional sources, which leaves a total of 239 ICRF sources astrometrically suitable at both frequencies.

In Fig. 3, the X-band structure index distribution is compared for each ICRF source category (defining, candidate, "other", "new") [11, 12]. As expected, the distribution is somewhat better for the defining sources than for the candidate and "other" sources. However, only about half of the ICRF defining sources have a structure index value of either 1 or 2. The portion of suitable sources drops down to 40% for the candidate sources and 37% for the "other" sources, while it is 54% for the "new" sources. Overall, these results confirm that revision of source categories will be mandatory when a new realization of the ICRF is made.

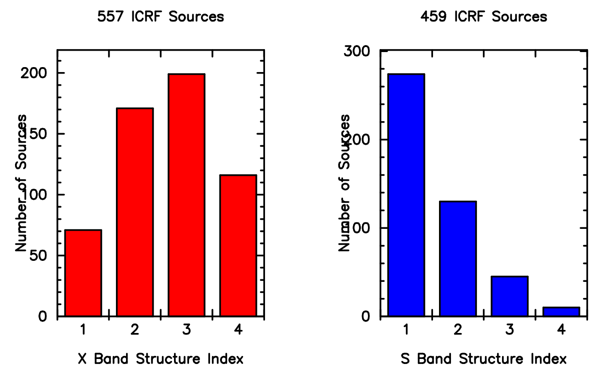

Figure 2. The structure index distribution at X band and S band for all ICRF sources that have a structure index available at these frequencies.

Additionally, we also studied the structure index distribution for the sample of 199 sources identified as stable in [13]. Of the 193 such sources that have a structure index available at X band, 41% were found to have a structure index value of 3, while 11% have a structure index value of 4. We recommend that these sources, which have extended or very extended structures, be excluded from the potential list of defining sources when building the next ICRF. In fact, some of these sources (e.g., 2200+420) have long been known for showing correlated structure and position variations [14]. We also point out that the comparison between the structure index and stability criterion presented in [13] is inappropriate because it is based on the S-band structure which contributes only a small part to the overall structure effect, as originally reported in [3].

4. Conclusion

We have evaluated the astrometric suitability of roughly 80% of the sources in the ICRF based on multi-epoch VLBI maps of their structures. It is anticipated that the remaining 20% of ICRF sources for which this 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. Based on this analysis, we have identified a sample of 239 astrometrically suitable ICRF sources which have compact or very compact structures according to our "structure index" indicator. We suggest that this indicator be used as a primary criterion to select defining sources for the next ICRF realization. It is possible that this sample of suitable sources be reduced in the future in the case that some sources are downgraded as new maps are being made for additional VLBI epochs.

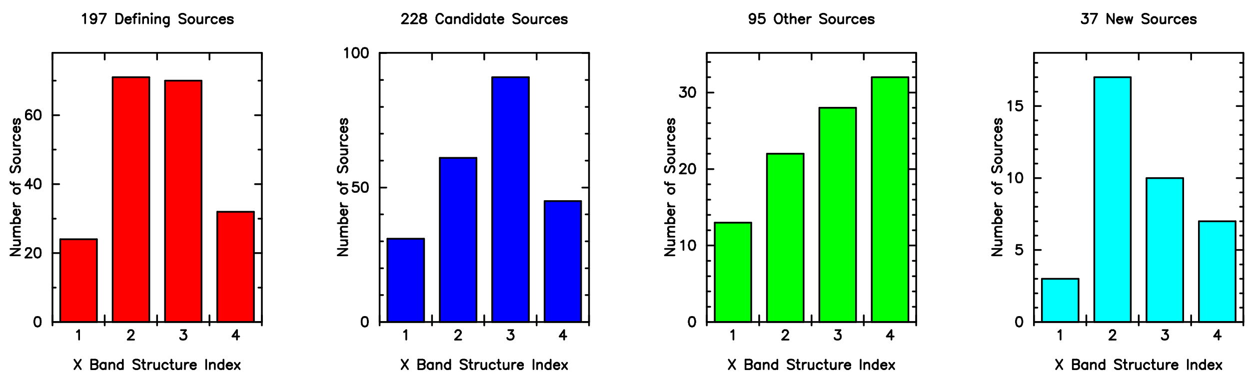

Figure 3. Distribution of the X-band structure indices in each ICRF source category (defining, candidate, "other", "new"). The 557 ICRF sources with currently available structure indices are included in this figure.

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