A Classification of ICRF Sources Based on Observed Structure for Ultra-precise VLBI Astrometry and Geodesy

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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. By using VLBI images obtained with the Very Long Baseline Array, we evaluate this effect for 392 sources from the International Celestial Reference Frame (ICRF). Based on this evaluation, we define a "structure index", ranging from 1 for the very compact sources to 4 for the most extended sources, which can be used as an estimate of the astrometric suitability of the sources. The structure index distribution in each ICRF source category (defining, candidate, other) is presented. We also discuss the correlation between structure index and source position accuracy. This classification is useful to select the most compact sources to observe in future VLBI experiments and to down weight past observations on sources with excessive structure.

1 Introduction

The International Celestial Reference Frame (ICRF), the most recent realization of the VLBI celestial frame, is defined by the radio positions of 212 extragalactic sources distributed over the entire sky (Ma *et al.* 1998). These "defining" sources set the initial direction of the ICRF axes and were chosen based on their observing histories with the geodetic networks and the stability and accuracy of their position estimates. The highest quality positions in the ICRF are accurate at the 0.25 milliarcsecond (mas) level. In addition, positions for 294 less observed "candidate" sources and 102 "other" sources with excessive position variation, were also given to densify the frame (Ma *et al.* 1998). Improvements to the ICRF over previous realizations of the celestial frame (e.g. Johnston *et al.* 1995) included modeling of a tropospheric gradient effect which corrected a systematic position offset of nearly 0.3 mas for sources near the celestial equator. The ICRF has been adopted by the International Astronomical Union as the fundamental celestial frame, replacing the FK5 optical frame as of 1998 January 1.

Despite its unprecedented accuracy, the ICRF suffers from errors primarily due to intrinsic source structure. At the milliarcsecond scale, most of the extragalactic sources that form the VLBI celestial frame exhibit spatially-extended structures that are variable in both time and frequency. Such radio structures set limits on the accuracy of source positions estimated with VLBI astrometry unless their effects can be accounted for. Modeling these effects and evaluating their magnitude in the VLBI measurements require knowledge of the brightness distribution of the sources at the epoch of the observations. To this end, an observing program whose goal is to image all the ICRF sources on a regular basis, has been initiated (Fey *et al.* 1996, Fey & Charlot 1997). Based on observations with the Very Long Baseline Array (VLBA), this program has recently reached an important milestone with the completion of first-epoch imaging of approximately 90% of the ICRF sources north $-20°$ declination.

This paper evaluates the overall impact of source structure effects in the ICRF from the available VLBA images of 392 ICRF sources. The "structure index" defined by Fey & Charlot (1997) is calculated and used to quantify the magnitude of these effects in the band width synthesis (BWS) delay VLBI measurements. We discuss the structure index distribution in each ICRF source category (defining, candidate, other) and the correlation between structure index and source position accuracy. Both of these tests show that the structure index is an appropriate indicator of the compactness of the sources and their astrometric quality. The classification proposed here can therefore be used to identify the most suitable sources for highly-precise VLBI astrometry and geodesy.

2 Evaluation of the magnitude of source structure delay effects

The contribution of intrinsic source structure to a BWS delay measurement is derived from the complex visibility measured by a VLBI interferometer. As shown by Charlot (1990), this contribution depends on the brightness distribution of the extended radio source and the coordinates u and v, which are the coordinates of the baseline vector projected on the plane of the sky, expressed in units of the observed wavelength. Because of this sole dependence on the (u,v) coordinates, the overall source structure effect magnitude for a given source is most easily estimated by calculating these effects successively for a range of (u,v) coordinates. Following such a scheme, Fey & Charlot (1997) defined a "structure index" according to the median of the calculated structure corrections for all projected VLBI baselines that could be possibly observed with Earth-based VLBI (i.e with a (u,v) length smaller than the diameter of the Earth), separating the sources into four classes as follows:

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

Based on this definition, two structure indices are obtained for each source, one at X band (3.6 cm wavelength) and one at S band (13 cm wavelength), each of which indicating the compactness of the structure at the corresponding frequency band. Dual-frequency observations allow for an accurate calibration of the frequency-dependent propagation delay introduced by the Earth's ionosphere. For consistency with this calibration, the structure corrections are scaled by 1.08 at X band and 0.08 at S band, prior to the structure index assignment. These scale factors represent the relative contribution of the X- and S-band delay measurements to the dual-frequency–calibrated delay, which is the quantity actually modeled for the determination of astrometric positions. The interested reader is referred to Fey & Charlot (1997) for more details on the structure index definition and Charlot (1990) for a more thorough discussion of the algorithm to calculate source structure effects in the VLBI delay observable.

Shown in Fig. 1 are contour plots of the radio emission at X band of four ICRF sources (0138−097, 0108+388, 0544+273 and 2201+315) representative of each structure index class. The corresponding structure-effect maps showing the magnitude of the corrections to the VLBI delay observable as a function of the interferometer resolution are also represented along with indication of the mean, rms, median and maximum values of these structure corrections. Figure 1 reflects the increase of the magnitude of the structure effects as the brightness distribution becomes more extended. For $0108 + 388$, these effects are very large because the source structure is composed of two components of approximately equal strength, causing very low visibility regions in the u-v plane and consequently large structure corrections (see Charlot [1990] for a detailed study of the case of a two-component model). Fey & Charlot (1997) recommend that only sources with a structure index of either 1 or 2 be used for the most precise astrometric or geodetic work. Sources a structure index of 3 should only be used with caution while those with a structure index of 4 should not be used at all.

The initial classification of Fey & Charlot (1997) included 169 sources. By using the additional VLBA maps now available, we have extended this classification, completing the calculation of the

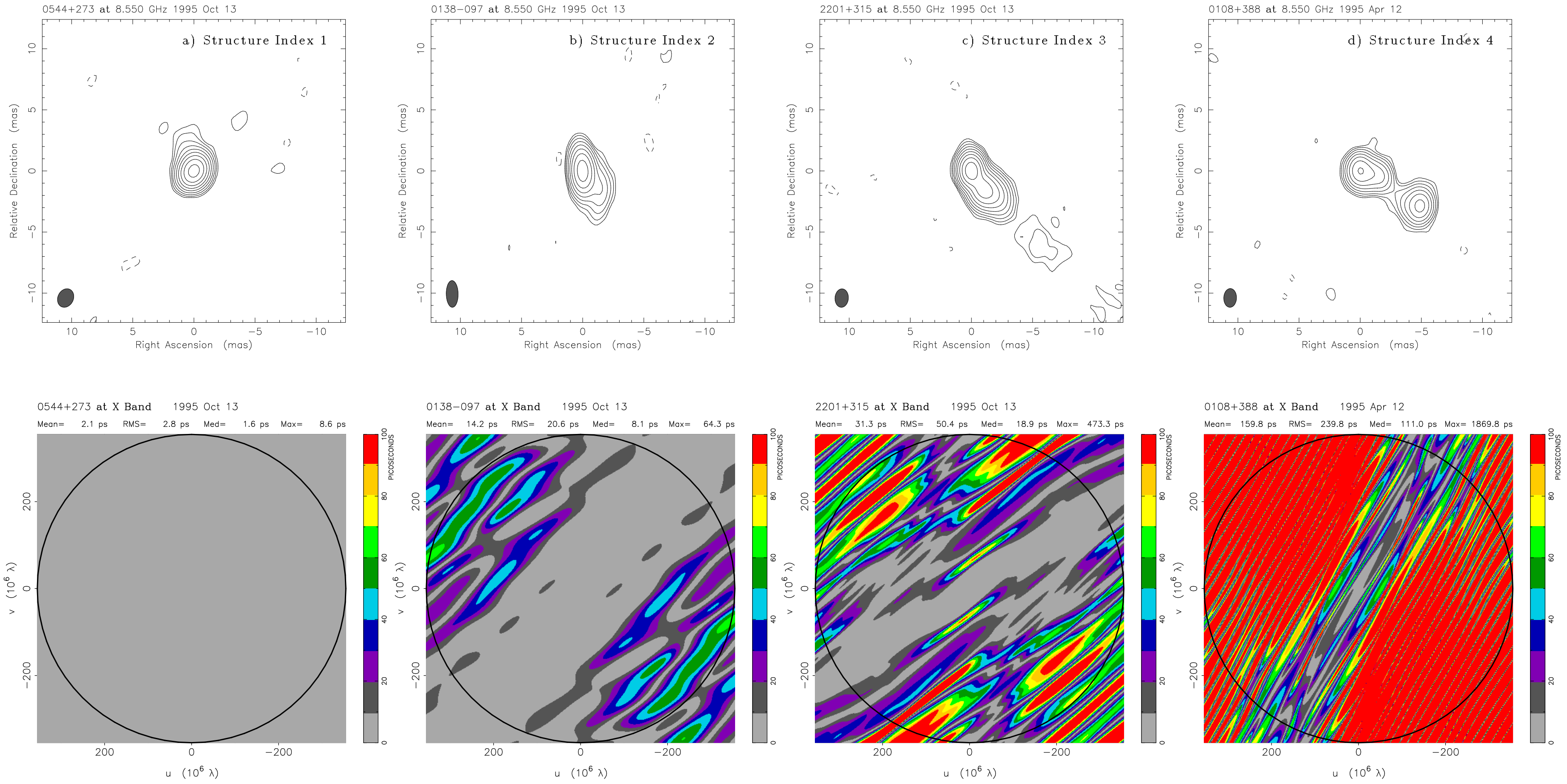

Fig. 1: Top: Contour plots of the radio emission at 3.6 cm wavelength for the four ICRF sources a) $0544+273$, b) $0138-097$, c) $2201+315$ and d) $0108+388$, representative of each structure index class. The X-band structure index of these sources is indicated in each panel. Bottom: Color plots showing the magnitude of the structure correction (absolute value) induced in the BWS delay by the extended radio emission at X band for the same four sources. The structure correction is plotted as a function of the length and orientation of the VLBI baseline projected onto the sky, expressed in millions of wavelengths (u, v coordinates). The color scale is identical in each panel and ranges from 0 to 100 picoseconds (ps). All structure corrections larger than 100 ps are plotted as red. The circle drawn in these plots has a radius equal to one Earth diameter, corresponding to the longest baselines that can be theoretically observed with Earth-based VLBI. The mean, rms, median, and maximum values of the structure corrections for all baselines contained within this circle are indicated in each panel.

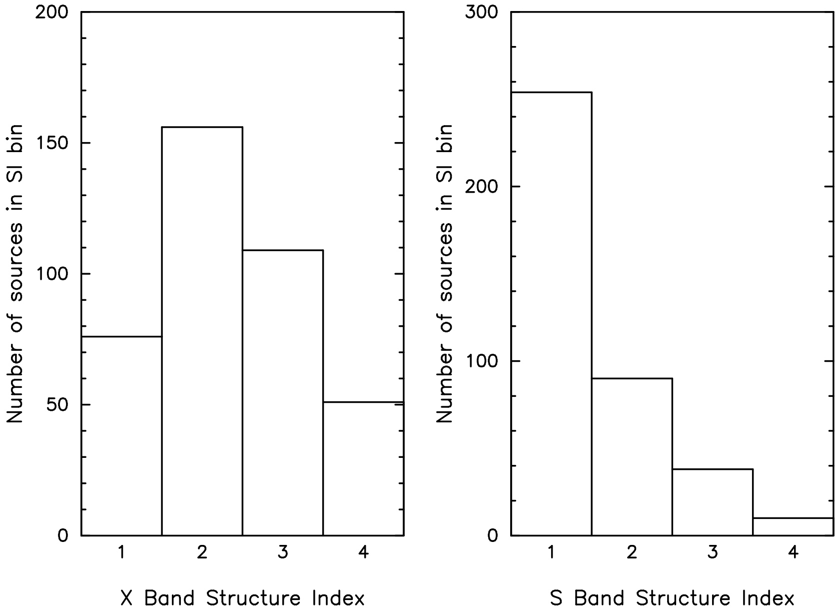

Fig. 2: Distribution of the X- and S-band structure indices for 392 ICRF sources.

X- and S-band structure indices for 392 ICRF sources[1] Such a sample, about two-third of the ICRF catalog, provides a strong basis for evaluating the overall astrometric suitability of the ICRF sources, as discussed in the next section.

3 The "structure index" as an indicator for astrometry

In this section, we examine the structure index distribution in the ICRF catalog and discuss the correlation between structure index and ICRF source position accuracy. Figure 2 shows the overall structure index distribution for the 392 ICRF sources which structure corrections have been evaluated. At X band, 232 sources (approximately 60% of the sources in our sample) have a structure index of either 1 or 2, an indication of compact or very compact structures suitable for high-precision VLBI astrometry and geodesy. The remaining 160 sources with a structure index of either 3 or 4 have more extended structures which are likely to affect the observed VLBI delays. Such sources, especially those with a structure index of 4 (approximately 13% of the sources in our sample), should be avoided in VLBI experiments requiring the highest accuracy. At S band, source structure effects appear to be less significant, as reflected by the large number of sources with a S-band structure index of either 1 or 2 (343 sources out of 392). This is a consequence of the S-band structure corrections being scaled by a factor of 0.08 when calculating the dual-frequency calibrated structure delays. Without scaling, the S-band corrections are very large because source structures are generally more extended at S band than at X band. Comparing the X- and S-band structure indices individually for each source indicates that with a few exceptions all sources that have a S-band structure index of either 3 or 4 have also a X-band structure index of either 3 or 4. Therefore, the X-band structure index alone appears to be a good selection criteria for the choice of the most compact sources.

In Fig. 3, the X-band structure index distribution is compared for each ICRF source category. The difference in distribution between the defining-sources and other-sources categories is striking. While two-third of the defining sources (109 sources out of 164) are found to have a structure index of either 1 or 2, only 45% of the "other" sources (37 sources out of 82) have similar structure indices. This confirms that a large fraction of the "other" sources were rejected during the construction of the ICRF because of structure problems. The candidate-sources category appears to have a distribution intermediate

[1]Source images can be obtained from http://www.usno.navy.mil/RRFID. Structure-correction maps and structure indices are available from http://www.observ.u-bordeaux.fr/public/radio/PCharlot/structure.html.

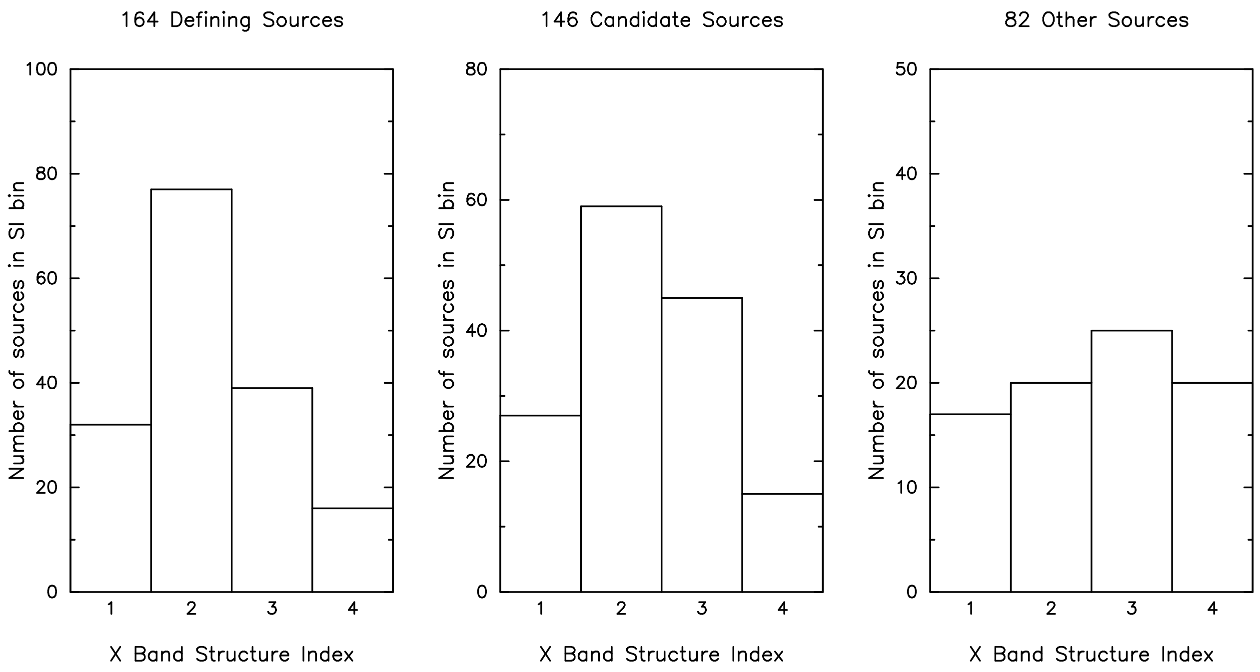

Fig. 3: Distribution of the X-band structure index for the ICRF defining, candidate and "other" sources.

between that of the defining-sources and other-sources categories, with 59% of the candidate sources having a structure index of either 1 or 2. We note that their distribution is almost identical to the overall structure index distribution at X band (Fig. 2), which is consistent with the fact that some of the candidate sources could be designated defining sources in future realization of the ICRF as more data become available or analysis improves, whereas some others would fall into the other-sources category. The defining-sources category includes a majority of compact or very compact sources, as expected from their empirical selection at the time the ICRF was built (see Ma *et al.* 1998). However, despite the stringency of their selection, about one-third of the defining sources are found to have a structure index of either 3 or 4, indicating that they are somewhat spatially extended and thus are probably not appropriate for defining the celestial frame with the highest accuracy. Such sources, especially those with a structure index of 4, should be given specific attention in the ICRF maintenance process and be rejected in future realizations of the ICRF if they show unexpected behavior as we may anticipate from the value of their structure index.

An additional test consists in comparing structure index and ICRF source position accuracy on a statistical basis. For this comparison, we have plotted the distribution of uncertainties in right ascension and declination for each X band structure index class (Fig. 4). As shown in these plots, the histograms of source position uncertainties progressively deteriorate from an approximately Gaussian distribution for the structure index 1 class to an almost random distribution for the structure index 4 class. While the structure index 1 and 2 histograms look similar, the structure index 3 histogram has apparently an excess of sources near 0.3–0.4 mas position accuracy. This deterioration of the position accuracy is also confirmed when calculating the median and mean uncertainties in right ascension and declination for each X band structure index class. As shown in Table 1, such values are found to increase regularly as the structure index becomes larger. Note that only sources with more than 100 observations in the ICRF have been retained for this calculation. Position uncertainties for sources with a limited number of observations are dominated by the noise of the measurements rather than by systematic effects caused by extended structures. The results of Fig. 4 and Table 1 confirm the previous finding of Fey & Charlot (1997) which indicates that the more extended sources have larger position uncertainties. They also confirm that the structure index is an appropriate indicator for selecting the most suitable sources to observe in highly-precise astrometric and geodetic VLBI experiments.

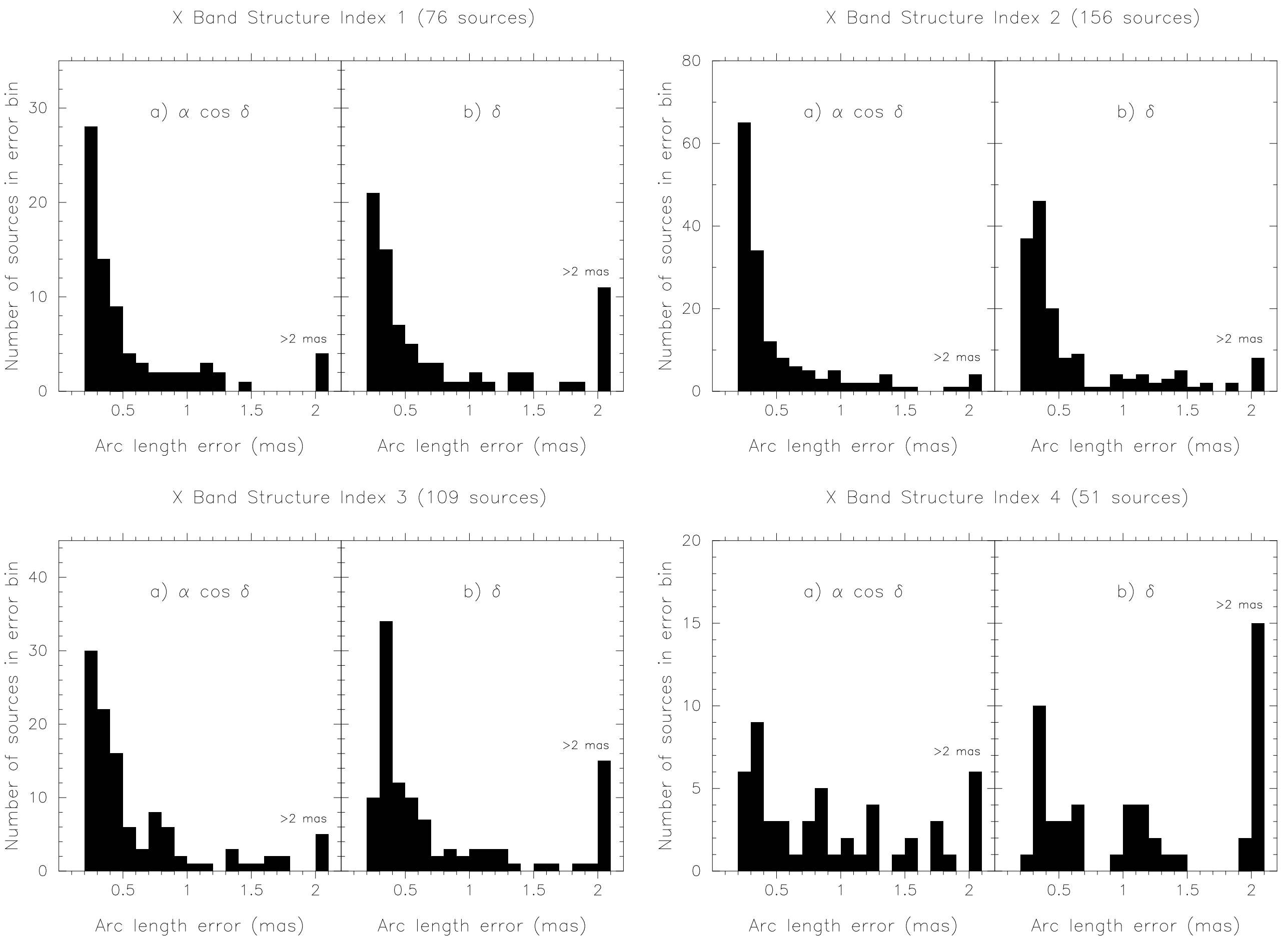

Fig. 4: Distribution of ICRF position uncertainties in a) $\alpha \cos\delta$ and b) δ for each X band structure index class.

Table 1: X band structure index versus ICRF mean and median position uncertainties in $\alpha \cos\delta$ and δ.

Structure index	Nb of sources	Mean uncertainty* $\alpha \cos\delta$ (mas)	Mean uncertainty* δ (mas)	Median uncertainty $\alpha \cos\delta$ (mas)	Median uncertainty δ (mas)
1	50	0.34	0.43	0.28	0.31
2	108	0.39	0.46	0.29	0.32
3	73	0.44	0.54	0.33	0.36
4	36	0.54	0.72	0.76	1.07

*excludes sources with uncertainties in $\alpha \cos\delta$ or δ larger than 2 mas.

4 Conclusion

By using new VLBA images of ICRF sources, we have extended the initial work of Fey & Charlot (1997), completing the classification of 392 ICRF sources based on their observed structures. This sample covers approximately 90% of the ICRF catalog north of $-20°$ declination. Each source is assigned a structure index representing its compactness and astrometric suitability at the corresponding observed frequency band (X or S). This classification shows, as expected, that most of the ICRF defining sources have compact structures, whereas the majority of the ICRF "other" sources are spatially extended. A small percentage of the ICRF defining sources, however, is found to have extended radio emission unsuitable for high-precision VLBI astrometry and geodesy. These should be monitored carefully in the future to further assess their quality.

A correlation between the structure index and the ICRF source position accuracy has been found, indicating that the more extended sources have larger position uncertainties. This confirms that the structure index is an appropriate indicator for selecting the most suitable reference frame sources. The structure index can also be used to estimate the additional noise introduced into the VLBI delay measurements by intrinsic source structure for application of source-dependent weighting scheme. In the future, we will continue to evaluate the astrometric suitability of the ICRF sources as new VLBI maps become available, and in particular report any structure index variation. We will also investigate the direct application of structure corrections to the VLBI delay observable to improve the position accuracy of the ICRF sources with excessive structure.

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