Source Structure

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Abstract. The International Celestial Reference Frame (ICRF) as realized by Very Long Baseline Interferometry (VLBI) (Ma, 1998), depends on the assumed point-like nature of the extragalactic radio sources whose positions define the frame. It has long been known (Charlot, 1990; Fey et al., 1996) that these sources exhibit spatially extended structure on the milliarcsecond scales achievable with VLBI. This intrinsic structure can be variable in both time and frequency, and it will set limits on the ultimate accuracy of the source positions determined from the astrometric/geodetic VLBI. We describe efforts underway to determine the structure of individual ICRF sources, quantify the effect of measured source structure with regard to the resultant accuracy of source positions, and mitigate the negative effects of source structure on the accuracy of the ICRF source positions. We also describe an active effort to extend the ICRF to higher radio frequencies, where the effect of source structure is less pronounced.

1 Introduction

Currently, the accuracy of VLBI astrometry/geodesy is limited by instrumental phase stability and the effects of the Earth's troposphere on the observations. Contributions of the VLBI delay observables due to intrinsic source structure can be as high as tens to even hundreds of picoseconds. The current level of accuracy for ICRF source positions is approximately 250 microarcseconds ($\sim$ 20 ps delay on a typical baseline) (Ma, 1998). With improvements in tropospheric modeling and VLBI instrumentation, source structure may become a primary contributor to the overall "error budget" in future ICRF realizations based on VLBI observations.

There are two ways in which source structure can be dealt with in astrometric/geodetic VLBI. One can either attempt to filter-out sources with the worst structure, at a cost of perhaps losing a significant fraction of the sources in the reference frame, or one can use models of the effects based on the source maps to attempt to correct the VLBI data. The former approach is addressed in a recent article (Feissel-Vernier, 2003) by Feissel-Vernier in which a suitable set of astrometrically stable sources was identified based on the analysis of source position time-series. Source filtering is also the basis for the development of the source "structure index" by Fey and Charlot (1997, 2000). The second approach, in which corrections for structure effects are determined and applied to the VLBI data, has been tested on a massive scale by Sovers et al. (2002). In the following sections, developments in source imaging, modeling source structure effects and application to VLBI observables, and the possible reduction of source structure effects by moving the ICRF to higher radio frequencies are all discussed.

2 Imaging Extragalactic Source Structure

Prior to any modeling of source structure or application of structure corrections to VLBI data, a complete database of VLBI images is required from which to compute the corrections. Ideally, one would like to make images from the astrometric/geodetic VLBI observations themselves, however, these data are not optimized for source imaging. Often there is a limited amount of data from a less than desirable network of

stations making the production of reliable images of the ICRF sources difficult. Fortunately, there are a number of ongoing programs designed specifically for the purpose of imaging extragalactic sources.

The largest effort to image ICRF sources is a series of experiments using the Very Long Baseline Array (VLBA) in conjunction with up to 10 additional geodetic antennas. These observations, with the designation RDV, are part of a collaborative effort between the U.S. Naval Observatory (USNO), the NASA Goddard Space Flight Center (GSFC) and the National Radio Astronomy Observatory (NRAO). During each 24-hour RDV session, approximately 80 ICRF sources are observed using dual S/X-band (2.3/8.4 GHz) frequencies. S- and X-band images are produced from these observations and made available on-line from the Radio Reference Frame Images Database (RRFID) at ([1]). The RRFID currently contains 3125 images of 452 ICRF sources. Images of selected sources have also been made available through a series of articles (Fey et al., 1996; Fey and Charlot, 1997, 2000). In addition to being a valuable resource for source imaging, the RDV experiments now provide roughly 20% of the entire database of geodetic/astrometric VLBI observations.

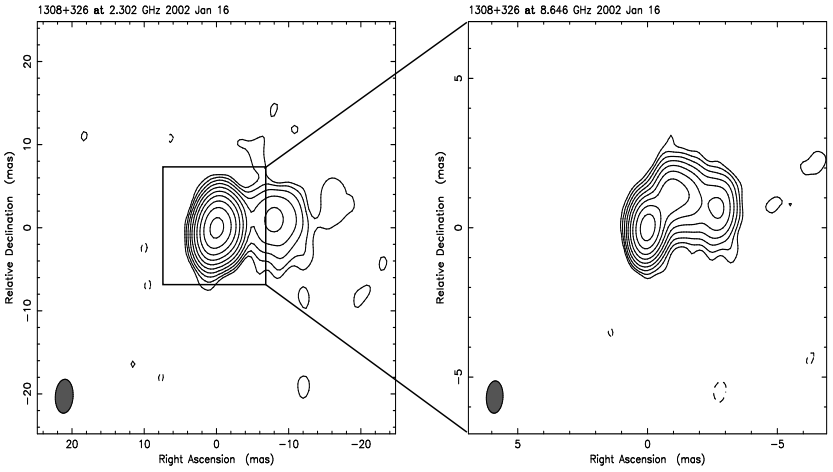

Fig. 1. VLBI radio frequency images at 2.3 GHz (left panel) and 8.4 GHz (right panel) of the ICRF source 1308+326 at epoch 2002 January 16 (RDV-31) taken from the USNO Radio Reference Frame Image Database (RRFID).

The VLBA Calibrator Survey (VCS1) (Beasley et al., 2002) is the largest high-resolution radio survey ever undertaken and triples the number of sources available to the radio astronomy community for VLBI applications. The VCS1 resulted in a catalog containing milliarcsecond-accurate positions of 1332 extragalactic radio sources distributed over the northern sky and in a majority of cases, images of the sources are also available. The images and u-v radius plots for the VCS1 can be accessed on-line via a graphical search engine at ([2]). Additional observations for the Second VLBA Calibrator Survey (VCS2) (Fomalont et al., 2003) were undertaken to fill holes in the sky which were not completely covered by VCS1 and to image ICRF sources with somewhat limited structural information. VCS2 data covers an additional 276 sources including sources near the Galactic plane at declinations $-45° < \delta < -30°$.

[1] http://www.usno.navy.mil/RRFID/
[2] http://magnolia.nrao.edu/vlba_calib/

In an effort to investigate the structure of ICRF sources in the southern hemisphere, the USNO has undertaken a joint program of observations with the Australia Telescope National Facility (ATNF) using the southern hemisphere geodetic stations and ATNF's Long Baseline Array (LBA) (Fey et al., 2000). The goals of this USNO/ATNF program are to image the source structure of all southern hemisphere ICRF sources at least twice and to search for new astrometric sources in order to densify the ICRF in the southern hemisphere. Initial astrometric and imaging results from this joint effort have recently been published in a series of journal articles (Ojha et al., 2004; Fey et al., 2004a, 2004b).

3 Modeling Source Structure

Having a database of reliable VLBI images in hand, one can begin the task of source structure modeling. In VLBI observations for astrometry/geodesy, the primary observable is the delay, τ, which is equal to the derivative of the total phase, ϕ_t, with respect to the observing frequency, ω. For a theoretical point source, the total phase is simply equal to the geometric phase, ϕ_g, which is a function of the interferometer baseline vector, $\mathbf{b}$, and the reference direction vector to the source, $\mathbf{s}_0$. For a source with an extended brightness distribution an additional structure phase, ϕ_s, is introduced, and the delay observable can be written (Charlot, 2002) as

$$\tau = \frac{\partial \phi_g}{\partial \omega} + \frac{\partial \phi_s}{\partial \omega} = -\frac{1}{c}\mathbf{b} \cdot \mathbf{s_0} + \tau_s. \quad (5)$$

The first term is the derivative of the geometric phase with respect to frequency or the geometric delay. The second term, τ_s, is the delay induced by the extended source brightness distribution, a quantity which we would like to remove from the data. In addition to the effect on the delay, source structure has an effect on the total phase as a function of time or the phase-delay rate (Charlot, 2002). The effects of source structure on this phase-delay rate should also be accounted for in a complete analysis of VLBI observations for astrometry and geodesy, but will not be discussed further here. For a comprehensive discussion of the theoretical modeling of the effects of source structure on astrometric/geodetic VLBI observations see (Charlot, 1990).

In theory, structure corrections due to the added delay can be determined from the VLBI maps and applied to the delay observables. In practice, τ_s is computed from a linear fit to the source structure phases determined for each frequency channel in the bandwidth synthesis observations (Charlot, 2002). Because astrometric VLBI data typically consist of dual-frequency S/X-band observations, the structure corrections must be determined for each band individually and applied with weights consistent with the weighting of the S/X-band observables which go into the calculation of the dual-frequency delay. These weighting factors are 1.08 at X band and 0.08 at S band (Fey and Charlot, 1997), thus the S-band data and the structure corrections are down-weighted by a factor of $\sim$1/13 relative to the X-band values.

There are two practical difficulties in the determination and application of the delay structure corrections. The first is the choice of the fiducial reference point $\mathbf{s}_0$ for the source brightness distribution in the maps. The computation of the source structure corrections relies on the choice of this point which also defines the absolute position of the source in the

reference frame. For a typical core-jet VLBI source, one would ideally prefer a dominant compact core with little or no morphological changes in the brightness distribution over time. Since VLBI sources are often not ideal, both the choice of the image reference point and source registration from one epoch to the next are made more difficult. Different methods for determining this reference point over multiple epochs were tested in Charlot (2002) for the ICRF source 2200+420. The results show that the application of source structure corrections based on an incorrect choice of reference point can actually increase the scatter in the source position over time relative to the scatter in the position with no corrections for structure. The best results were obtained in Charlot (2002) by manually choosing the reference position on a per epoch basis, a task which can be tedious for a large number of sources with a long time series of observations.

A second difficulty in the determination of the dual-frequency source structure corrections is the registration of the S- and X-band maps relative to one another. The S- and X- band data recorded simultaneously often produce significantly different structures which are complicated by the factor of ∼4 difference in resolution between the two frequencies. The errors introduced by improper registration are somewhat mitigated by the fact that the computed S-band corrections are down-weighted by the factor of ∼1/13 in the combined dual-frequency source structure corrections.

Despite these difficulties in properly registering the VLBI maps, source structure modeling has been tested for a large multi-epoch S/X-band data set in Sovers et al. (2002). Ten epochs of VLBI data spanning ∼1.5 years comprised of over 200,000 S/X-band observations (delay + delay-rate) of 160 extragalactic radio sources were used in the study. A database of 800 pairs (S- and X-band) of maps from the Radio Reference Frame Image Database (Fey et al., 2002) were used to derived structure corrections from the image CLEAN components. The study found that modeling the delay induced by source structure improved the overall VLBI model by ∼8 ps in quadrature, a significant portion of the ∼30 ps overall weighted root-mean-square delay residuals. For individual sources, improvement in the scatter of the delay residuals over time ranged from 6.5 to 16.8 ps for sources with structure indices ranging from 1 to 4 (see below) (Sovers et al., 2002).

4 Source Structure Selection and Filtering

The modeling and application of source structure corrections is both labor and computationally intensive in practice. However, even if one cannot directly apply structure corrections to VLBI data, source structure can still be a useful indicator of source quality for application to the ICRF. There are two methods by which the sources with the most compatible structure for astrometry/geodesy may be selected. First, one can categorize source structure based on the images of the sources and the structure corrections computed from these images. Second, one can examine the statistical impact of source structure on the astrometric stability of the source position time series. Both of these techniques have been used to filter undesirable sources from astrometric/geodetic observations as discussed below.

Fey and Charlot (1997, 2000) developed the first indicator of astrometric source quality based on structure corrections derived from source images.

They termed this indicator the source "structure index". The structure index is the median value $\tau_{\rm median}$ of the structure delay corrections computed from the VLBI source maps. These structure delay corrections are determined for pixels in a 512×512, u-v grid for all baselines less than the diameter of the Earth (Fey and Charlot, 1997). Fey and Charlot categorize ICRF sources according to structure index as follows:

$$\text{Structure Index} = \begin{cases} 1, & if\ 0\ ps \leq \tau_{\rm median} < 3ps; \\ 2, & if\ 3\ ps \leq \tau_{\rm median} < 10ps; \\ 3, & if\ 10\ ps \leq \tau_{\rm median} < 30ps; \\ 4, & if\ 30\ ps \leq \tau_{\rm median} < \infty. \end{cases} \quad (6)$$

Thus the best astrometric sources receive a structure index of 1 while the worst sources have a value of 4. Figure 2 shows the distribution of S- and X-band structure indices for the 388 ICRF sources observed in Fey and Charlot (2000). At X-band, roughly 60% of the ICRF sources fall into the compact category (structure index of 1 or 2) while 40% of the sources are either marginal (sturcture index of 3) or unacceptable (structure index of 4) for VLBI astrometry. At S-band, approximately 90% of the sources have structure indices of 1 or 2 indicating both compact structure and the fact that the S-band source structure corrections are down-weighted by a factor of $\sim$1/13.

Based on the source structure index, correlations between the observed radio structure and the astrometric position accuracy and stability of the sources have been found (Fey and Charlot, 2000). These correlations indicate that the more extended sources have larger position uncertainties and are less positionally stable than the more compact sources. The structure index therefore provides a reliable tool by which sources for use in astrometric/geodetic VLBI may be selected or eliminated. This

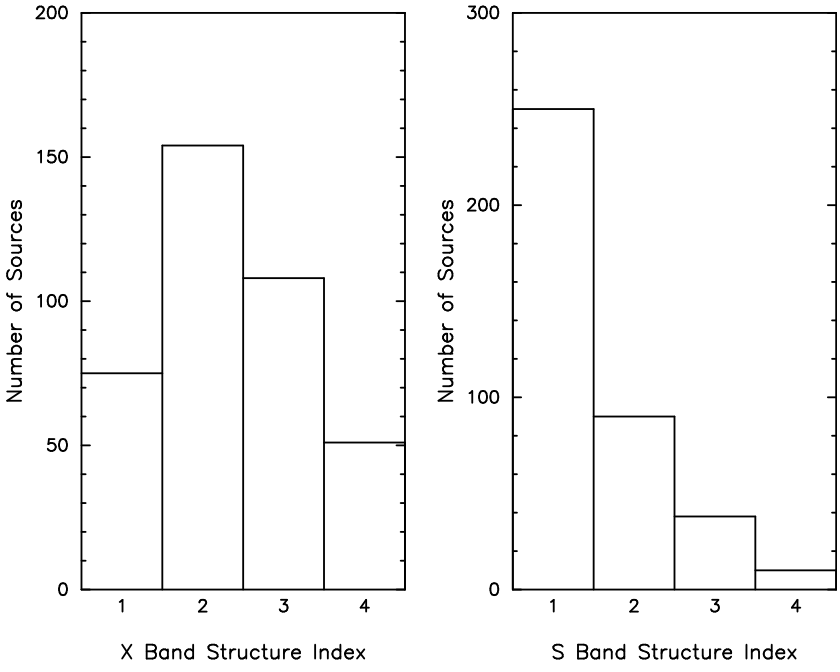

Fig. 2. Distribution of source structure indices for sources at 2.3 GHz (right panel) and 8.4 GHz (left panel) for the 388 sources in Fey and Charlot (2000).

structure index filter requires much less effort (indices can be computed from a single epoch and updated periodically) than would be required to apply actual structure corrections to the VLBI observables in time. The structure index values for many northern hemisphere ICRF sources can be obtained from ([3]).

The second approach to source filtering is discussed in a recent article by Feissel-Vernier (2003), in which various statistical tests applied to the VLBI source position time series were utilized. Specifically, the standard deviation, the Allan standard deviation, the least-squares derived linear drift, and the normalized linear drift were determined for the time series of source positions in right ascension and declination. These quantities were then used alone and in various combinations to select/exclude sources for use in determining reference frames. Testing was performed by computing a set of yearly reference frames based on the sources selected by the various schemes, determining the standard deviation characterizing the scatter of the rotation angles about the axes of the frames, and comparing these standard deviations to that computed for the 212 ICRF defining sources. In all cases, the selection schemes resulted in improved stability of the yearly reference frames over the current ICRF (Feissel-Vernier, 2003). Feissel-Vernier recommends the set of selected sources be considered for use in future realizations of the ICRF and for the scheduling of future VLBI observations.

5 Extension of the ICRF to Higher Frequencies

Prompted by the desire to move the NASA Deep Space Network (DSN) toward Ka-band (32 GHz) frequencies, a pilot program to investigate the possibility of extending the ICRF to higher frequencies, namely K-band (24 GHz) and Q-band (43 GHz). VLBA observations at K- and Q-band were initiated by a collaboration of institutions including NASA/JPL, GSFC, USNO, NRAO, and Bordeaux Observatory in May 2002. There are a number of motivations for this joint program of astrometric observations see Jacobs et al. (2002) for a full description. One of the goals of the program is to study source structure at higher frequencies. The expectation is that at higher frequencies the sources should appear more compact since the extended emission in AGN is usually steep spectrum, and the centroid of the observed emission should be closer to the AGN central engine. The more point-like source structure should enable more precise astrometry than traditional S/X-band VLBI.

Images and u-v radius plots from the program are now available on the RRFID web site. Thus far, 783 images of 231 extragalactic sources have been produced. Figure 3 shows two example maps for the ICRF source 1308+326 at 24 and 43 GHz. Initial imaging results (Fey et al., 2003) show that sources are more spatially compact at K-band than at the current standard X-band. The distribution of structure indices calculated from the first epoch of 24/43 GHz images (Figure 4) shows a shift toward lower values as the frequency of observation increases. Over 95% of the sources observed have structure indices of 1 or 2 at K- and Q-band. For 28 overlapping sources observed at X-band at a similar epoch, only 86% of the sources have structure indices of 1 or 2. For all ICRF sources measured at X-band, this number drops to 60% as discussed above. These preliminary source structure results are consistent with the standard theory of compact extragalactic radio sources and suggest

[3] http://www.observ.u-bordeaux.fr/public/radio/PCharlot/structure.html

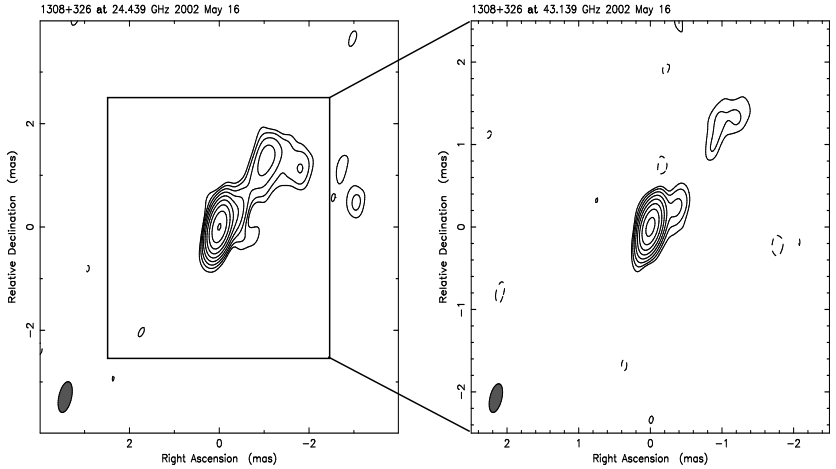

Fig. 3. VLBI radio frequency images at 24 GHz (left panel) and 43 GHz (right panel) of the ICRF source 1308+326 at epoch 2002 May 16 (BR079A) taken from the USNO Radio Reference Frame Image Database(RRFID).

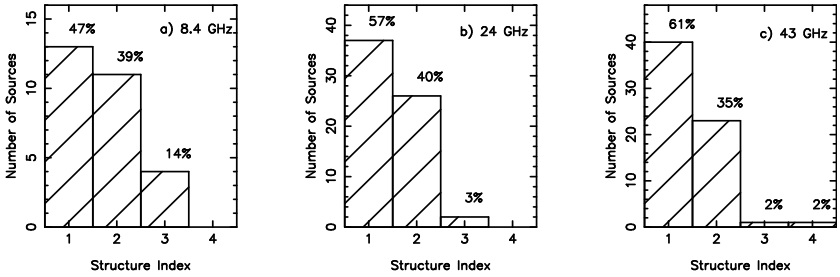

Fig. 4. Distribution of source structure indices for sources at a) 8.4 GHz, b) 24 GHz, and c) 43 GHz. A total of 65 sources were observed at 24 and 43 GHz on 2002 May 15. Also shown are the values for the 28 overlap sources observed at 8.4 GHz on 2002 Jan 16.

that reference frames defined at these higher radio frequencies will be less susceptible to the effects of intrinsic source structure than the current ICRF.

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