The Misalignment Angle Distribution of Relativistic Jets from the Radio Reference Frame Image Database

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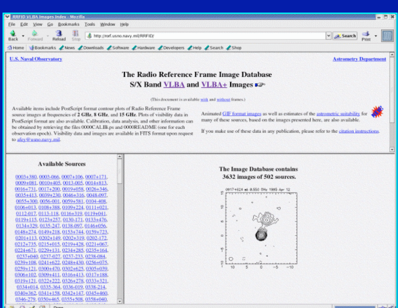
1) The Radio Reference Frame Image Database

1.1) General Description: The U.S. Naval Observatory (USNO) maintains a multi-epoch database of VLBI images of objects that comprise the Radio Reference Frame. This Radio Reference Frame Image Database (RRFID) consists of Very Long Baseline Array (VLBA) snapshot observations at 8 and 2 GHz (with the addition of up to 10 geodetic antennas that provide global coverage), and is intended to allow monitoring of these sources for variability or structural changes so they can be evaluated for continued suitability as radio reference frame objects. The Image Database currently contains 3632 images of 502 sources from 1994 to 2004 (although the imaged data is sparse after 1998). The web-based interface to the RRFID is shown below, it is available at rorf.usno.navy.mil. The RRFID has recently begun adding high-frequency images at 24 and 43 GHz as well. Some of these RRFID observations are reported by Fey, Clegg, & Fomalont (1996), Fey and Charlot (1997), and Fey and Charlot (2000).

1.2) Our Analysis of the RRFID: For the past several years, we have been engaged in an analysis of the images that make up the first five years of the RRFID, covering the years 1994 through 1998. This portion of the database comprises 2786 images of 450 sources. Our analysis is divided into two parts:

1) A multi-epoch kinematic survey of the 8 GHz images of all sources that have been observed at 3 or more epochs (approximately 90 sources), to measure apparent jet speeds. These speed measurements have been completed, and the results have been presented at other conferences (e.g., Piner, Fey, & Mahmud 2004). A paper on the speed measurements is in preparation.

2) An analysis of single-epoch images at 8 and 2 GHz for all 450 sources for the purposes of obtaining those measurements that can be made from single-epoch images, such as: position angle and bending of the parsec scale jet, misalignment with the kiloparsec-scale structure, jet opening angles, core and component spectral indices, and transverse structure in the jets. *In this poster, we present our analysis of the misalignment between the pc and kpc-scale jets in these sources.*



2) Background on Misalignment Angle

Misalignment angle (or ΔPA) refers to the difference in the measured position angle of the parsec-scale jet (measured by VLBI) and the kiloparsec-scale jet (measured by the VLA). Small intrinsic bends can be amplified by projection effects into large apparent bends, and the goal is to learn something about the intrinsic properties of the radio jets from this apparent misalignment angle distribution.

The misalignment angle distribution has been studied since the earliest VLBI imaging surveys. Pearson & Readhead (1988) and Wehrle et al. (1992) plotted misalignment angle distributions for 18 and 21 sources, respectively, and both found that the *distribution was bimodal, with peaks at 0° and 90°*, but their number of sources was small. A misalignment angle distribution for a larger sample of 86 sources from the Caltech-Jodrell Bank VLBI survey was presented by Xu et al. (1994). They did not find the bimodal distribution for their overall sample of 86 sources, but when they split the sources into 2 groups according to optical polarization, they recovered the bimodal distribution for the highly-polarized sources, and found that the distributions for the 2 groups differed with 98% significance. Appl, Sol, & Vicente (1996) assembled 155 misalignment angles from the literature, and found similar results to Xu et al.

The existence of a bimodal distribution of misalignment angle implies 2 intrinsically different groups of radio sources, possibly those with single or binary black holes at their centers (suggested by Conway & Murphy 1993 and Appl et al. 1996). The difference in the ΔPA distributions for high and low polarization sources also implies intrinsic differences in these sources that go beyond their optical polarization properties. Thus, confirming whether or not these misalignment properties are present in a larger sample of radio sources is quite important.

3) Measurement of Misalignment Angle in the RRFID

3.1 Sample Selection: We considered all sources that had been observed at least once in the RRFID during the first five years of observation (1994-1998), or 450 sources. From these 450 sources, we selected those that had both resolvable parsec-scale structure in the RRFID images, and had a VLA image with resolved structure or a VLA position angle published in the literature. This yielded a final sample of 223 sources for which we made misalignment angle measurements. For sources observed at multiple epochs, we used the epoch with the lowest rms noise for the position angle measurement.

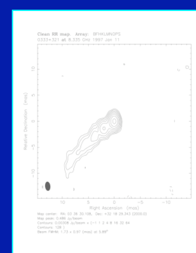
This sample is about a factor of 3 larger than the sample of 86 misalignment angles published from the Caltech-Jodrell Bank survey by Xu et al. (1994). It is about 50% larger than the sample of 155 misalignment angles assembled by Appl et al. (1996) from the literature, and this sample has the advantage of being drawn from a single VLBI survey.

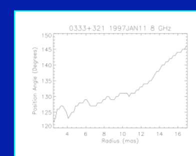
3.2 Method of Measurement: Measurement of position angle has historically presented problems, because authors are trying to characterize by a single number a quantity that is a function of radius in the case of bent jets. On the parsec-scale, authors have used such varying criteria as the position angle of the closest component or the brightest component (which will vary with observing frequency or epoch), and varying criteria have been employed on the kpc scale as well. This has resulted in the confusing situation of multiple misalignment angles spanning the range from near 0° to near 180° being published for some extreme sources (e.g. 1633+382, Piner 1998).

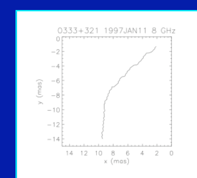
We have attempted to address this problem on the parsec-scale by numerically measuring the jet ridgeline over its entire visible range for each source, so that multiple strategies for specifying a parsec-scale position angle can be tried quickly and easily. We read in the final Difmap FITS image from the RRFID, and use bilinear interpolation (Press et al. 1988) to interpolate the image from a Cartesian grid to a polar grid. The jet ridgeline is then defined as the set of all position angle points that have the maximum flux density at each radial value. The jet ridgeline is followed from slightly larger than the beam size until the jet flux density falls to near the rms noise level.

The figures at right show this method for two sample sources, one at X-Band (8 GHz) and one at S-Band (2 GHz). The first graph in each case shows the jet position angle vs. radius, the second graph in each case shows the jet ridgeline in the (x,y) plane for comparison with the images. Values such as the average parsec-scale position angle or the initial parsec-scale position angle can then be obtained quickly from these numerical results. We are in the process of producing such plots for all resolved sources in the RRFID.

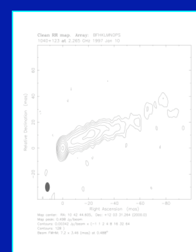
On the kpc scale, our options are more limited because we have assembled results from the literature without direct access to the image data, but for consistency we have chosen to adopt the method of Xu et al. (1994) for measuring the kpc-scale position angle. Thus, at kpc scales we measure the position angle of the brightest feature in the lowest-frequency published image, and in the case of nearly equally bright features, we use the one that minimizes the misalignment angle.

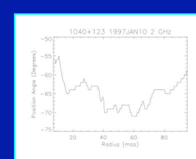


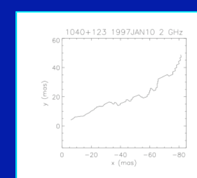




Numerical measurement of the parsec-scale jet ridgelines for two sample sources. See the box at left for an explanation of the numerical method.







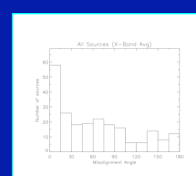
4) Results

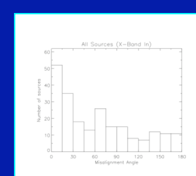
The three single histograms at right show misalignment angle distributions based on three different methods of measuring the parsec-scale position angle using the numerical method described above: the average of the X-Band (8 GHz) position angle over the measured range, the initial X-Band position angle (position angle at the smallest radius at which it could be measured), and the average of the S-Band (2 GHz) position angle over the measured range. We find similar distributions for all three measurement methods, and a Kolmogorov-Smirnov (K-S) test confirms that there is no significant statistical difference between the three ways of measuring the parsec-scale position angle.

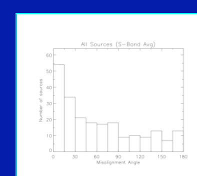
The appearance of these histograms from the RRFID (with 223 sources) is similar to those obtained by Xu et al. (1994) and Appl et al. (1996) with 86 and 155 sources, respectively. A K-S test confirms that there is no significant statistical difference between the results obtained by us and by Xu et al. or Appl et al. (for all sources combined into one histogram). In particular, the existence of any bimodal distribution is not readily apparent, as was also noted by Xu et al. and Appl et al. for their distributions that included all measured sources.

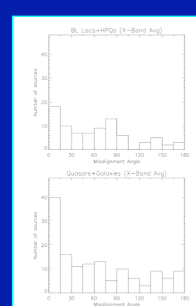
Following Xu et al. (1994), we have also investigated the misalignment angle distributions when the sources are grouped according to their optical polarization, with BL Lacs and HPQs in one class, and LPQs and galaxies in a second class. Those histograms are shown at right, for two methods of measuring the parsec-scale position angle (average X-Band position angle and average S-Band position angle). There are indications of a possible misaligned peak in the high-polarization histograms, but it is not statistically significant in the sense that a K-S test shows no significant difference between the misalignment angle distributions of the two polarization classes. This is in contrast to the results from the Caltech-Jodrell Bank survey reported by Xu et al. (1994), who found that the misalignment angle distributions for the two polarization classes differed with 98% confidence. The fact that the significance of the bimodal misalignment angle distribution has tended to go down as sample size has increased (at first being apparent in whole samples, then only in highly-polarized subsets of larger samples, to here being not statistically apparent at all) casts some doubt on its statistical reality.

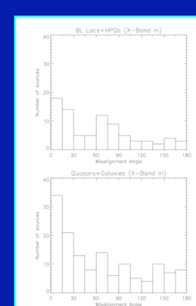
In conclusion, we have measured the misalignment angle distribution for extragalactic radio sources with the RRFID VLBI survey to obtain a sample size about three times larger than has been used in previous studies from single VLBI surveys. Our major result to date is that we do not find any statistically significant difference between the misalignment angle distributions for high-polarization and low-polarization sources, in contrast to earlier studies that had used smaller numbers of sources. Future work will focus on Monte Carlo modeling of the misalignment angle distribution from the RRFID, in order to determine if single-population, beamed, simple-bending models can match the observed distribution, or if two populations of radio sources will still need to be invoked.











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