Direction of Parsec-scale Jets for 9220 Active Galactic Nuclei

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Abstract

The direction of parsec-scale jets in active galactic nuclei (AGNs) is essential information for many astrophysical and astrometric studies, including linear polarization and magnetic field structure, frequency-dependent synchrotron opacity, proper motion, and reference-frame alignment. We developed a rigorous, simple, and completely automated method to measure the directions from calibrated interferometric visibility data at frequencies ranging from 1.4 to 86 GHz. We publish the results for 9220 AGNs with the typical accuracy below $10^\circ$. An internal check of the method comparing the directions between different observing frequencies as well as with previous publications verifies the robustness of the measured values.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Radio jets (1347); Very long baseline interferometry (1769); Radio cores (1341)

Supporting material: machine-readable tables

1. Introduction

Relativistic jets in active galaxies are prominent in a wide range of the electromagnetic spectrum. Radio emission is predominantly produced by the synchrotron mechanism and may span from subparsec to kiloparsec scales (Blandford & Königl 1979). The jet direction defines a distinguished axis of the AGN as a whole. This axis serves as a useful reference for other directional measurements: the polarization angle (e.g., Rusk & Seaquist 1985; Kovalev et al. 2020b), apparent positional offsets between radio frequencies (e.g., Sokolovsky et al. 2011; Pushkarev et al. 2012; Voitsik et al. 2018; Plavin et al. 2019b; Paschenko et al. 2020), and between distant bands of the electromagnetic spectrum (e.g., Kovalev et al. 2017; Plavin et al. 2019a; Lambert et al. 2021). Studying jet orientations also paves a way to astrophysical insights that include testing binary black hole models (e.g., Valtonen & Wiik 2012), evaluating properties of relativistic jet ejection (e.g., Agudo et al. 2007, 2012; Lister et al. 2013), and looking for the large-scale structure of the universe (Blinov et al. 2020). Improving the current accuracy of absolute astrometry based on AGNs also requires taking the jet emission into account. This is particularly important when comparing reference systems obtained at different frequency bands (e.g., Petrov & Kovalev 2017; Petrov et al. 2019b; Xu et al. 2019; Charlot et al. 2020; Rioja & Dodson 2020) or studying AGN proper motion (e.g., Moór et al. 2011; Titov et al. 2011; Petrov et al. 2019b).

AGN jets on parsec scales are highly collimated (e.g., Pushkarev et al. 2017; Kovalev et al. 2020a), but they still may bend due to interactions with external matter or other processes (Gabuzda et al. 2001; Kosogorov et al. 2022). The brightest visible parsec-scale jets are hosted by blazars and have small viewing angles (Pushkarev et al. 2017). Thus, we see them almost heads-on; such alignment makes these jets brighter due to relativistic beaming (Cohen et al. 2007; Kellermann et al. 2007; Lister et al. 2019). These geometrical conditions lead to a strong amplification in the plane of the sky of any intrinsic changes in jet orientation. Thus, it is crucial to measure jet directions on the scales corresponding to the processes and regions of interest of each particular study. Many astrophysical studies, such as those listed above, focus on parsec or subparsec scales.

Very long baseline radio interferometry (VLBI) observations are well suited for estimating parsec-scale jet directions. This is the only technique that directly resolves central parsecs for thousands of AGNs. Active galaxies have been observed with VLBI for several decades, leading to many discoveries that are supplemented by images and raw observational data. These images have been used to estimate jet directions in multiple works already; see the references above. However, we are not aware of any available catalog with parsec-scale jet orientations systematically measured for thousands of objects. Creating such a catalog is the main goal of this work.

This paper presents a novel, completely automatic approach to measuring jet directions at (sub)parsec scales based on VLBI observations. Section 2 describes the source sample and observations used in this work. In Section 3, we present our method, then in Section 4, we apply it to VLBI observations and compare it with previous results: Lister et al. 2019; Plavin et al. 2019a; Blinov et al. 2020. Jet directions for 9220 objects are provided as machine-readable tables to support their usage by the community.

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2. Observational Data

For our analysis, we use VLBI observations at frequencies ranging from 1.4 to 86 GHz compiled in the Astrogeo database,\(^6\) a collection from 2021 July. It contains both the restored images and the visibility function measurements that are the original interferometric observables. We only rely on the latter in our analysis, and images are used solely for visualization. The database consists of geodetic VLBI observations (Petrov et al. 2009; Pushkarev & Kovalev 2012; Piner et al. 2012), the VLBA\(^7\) calibrator surveys (VCS; Beasley et al. 2002; Fomalont et al. 2003; Petrov et al. 2005, 2006; Kovalev et al. 2007; Petrov et al. 2008), and other VLBI observations, including the results of Helinboldt et al. (2007), Lee et al. (2008), Petrov et al. (2011a), Petrov et al. (2011b), Petrov (2011), Petrov (2012), Petrov (2013), Schinzel et al. (2015), Shu et al. (2017), Jorstad et al. (2017), Lister et al. (2018), Petrov et al. (2019a), Nair et al. (2019), Petrov (2021), and Popkov et al. (2021).

The full data set used for our analysis contains 17,478 sources observed from 1994 to 2021, 123,456 single frequency images in total. Out of those AGNs, 4671 were observed at least five times, and 14,735 at two or more frequency bands. We note that an all-sky complete flux-density-limited sample was constructed within the VCS program, and consists of 3415 targets stronger than 150 mJy at 8 GHz. The majority of observations, 95% of all source epochs, are at 2, 5, 8, or 15 GHz. The observed objects are radio-bright active galaxies with VLBI flux densities ranging from a few millijanskys to tens of janskys. According to the NASA/IPAC Extragalactic Database, these AGNs have a median redshift of 1.1 and belong to various subclasses. Flat-spectrum radio quasars constitute about a third of the sample, BL Lacertae objects and radio galaxies make up 10% each, and 3% are Seyfert galaxies. The remaining 40% of the sample do not have their optical class reliably determined; these sources are also somewhat weaker on average in terms of their VLBI flux. The sample is dominated by blazars, i.e., AGNs with a small viewing angle of a few degrees. See Lister et al. (2019) for a detailed study of a complete flux-density-limited sample with the MOJAVE program at 15 GHz.

3. Determining the Jet Direction

Studies that make use of parsec-scale jet orientations often estimate them from VLBI images. This was realized both in a fully automated way (e.g., Kovalev et al. 2017; Plavin et al. 2019a) and semiautomatically with manual intervention (e.g., Blinov et al. 2020). Independently of the specific approach, these measurements are fundamentally limited by the information available in the images. Typical VLBI images cannot reach the maximum resolution in the brightest areas (e.g., Hög- bom 1974). Estimation of the jet direction close to the origin is critically dependent on these central regions. Their blending may even make the measurement impossible when the jet brightness quickly falls further downstream.

An alternative is to determine the jet orientation without relying on images by directly analyzing the calibrated visibilities instead. Visibilities, the principal VLBI observables, correspond to the Fourier transform of the brightness distribution in the sky. They are commonly used to infer the brightness distribution itself via a process called “model fitting”: the observed structure is assumed to consist of a number of Gaussian components, whose parameters are fitted to match the visibilities. This approach achieves a higher effective resolution in high-signal-to-noise-ratio regions compared to that of images and allows for the separation of multiple bright features located close to each other. Model fitting has been performed for VLBI observations in numerous works. Common limitations of model fitting include the semimanual nature of the method requiring human-dependent decisions on the model being fitted. A notable massive application of this technique is regularly performed within the MOJAVE program (Lister et al. 2019), which takes the MOJAVE team hundreds of human hours to not only produce models but also analyze and discuss their robustness. The detailed results of their model fitting are publicly available and can be used to determine jet directions (e.g., Lister et al. 2013) among other properties. However, these results cover only 15 GHz observations of 382 brightest jets in the northern sky, a relatively small subsample of all AGNs observed with VLBI. Automated visibility model fitting was also performed by, e.g., Kovalev et al. (2005) and Pushkarev & Kovalev (2015) in difmap (Shepherd et al. 1994). Application of its results was typically limited to parameters of the dominant component.

We base our procedure of estimating jet directions on the model-fitting approach. Specifically, we fit two simple models to the calibrated visibilities of each source epoch: one is a single circular Gaussian component, and the other is two Gaussian components. Fitting is performed via a Bayesian nested-sampling algorithm as implemented in the PolyChord library (Handley et al. 2015). Compared to the maximum likelihood fitting implemented in the difmap package, this algorithm does not require an initial guess of parameter values and delivers more principled uncertainty estimates. Note that these uncertainties are still fundamentally underestimated as they do not account for model assumptions and the calibration performed beforehand. Despite this limitation, we find formal uncertainties a useful proxy for actual errors, as discussed further in Section 4. For the purpose of jet direction measurement, we drop source epochs with formal uncertainties exceeding 45°. Additionally, nested-sampling algorithms provide the so-called evidence that aids comparison between different models. We only keep source epochs better described by the two-component model, judging by the evidence value: other observations effectively do not contain any detectable extended jet structure.

Based on the two-Gaussian model fitted to visibilities, we calculate the jet position angle as the direction from one component to the other. Formal uncertainties, which result from the fitting, are propagated through these calculations. It remains to be determined which of the two components is closer to the apex and which is a downstream feature in the jet. Further, we call the bright compact component at the apparent jet origin the VLBI “core” (Konigl 1981). There is no objective and fundamentally correct way to choose the core component in general, so we develop a heuristic approach. Regions closer to the jet origin are most commonly brighter in terms of their intensity or effective temperature (e.g., Kovalev et al. 2005; Homan et al. 2006). This effect has solid theoretical grounds (e.g., Blandford & Königl 1979). We thus propose selecting the brightest component of the two as the apparent jet origin. This

\(^6\) http://astrogeo.org/vlbi_images/

\(^7\) Very Long Baseline Array of the National Radio Astronomy Observatory, Socorro, NM, USA.
Table 1
Measurements of the AGN Jet Directions Separately for Each Frequency Band

| J2000 Name | Frequency (GHz) | $N_{\text{epochs}}$ | PA (deg) | PA Error (deg) | PA Error Type | 180° Correction | Core to Jet Distance |
|------------|----------------|---------------------|----------|---------------|---------------|-----------------|---------------------|
| (1)        | (2)            | (3)                 | (4)      | (5)           |               | (7)             | (8)     | (9)        |
| J1256−0547 | 1.4            | 1                   | −137     | 4             | ASTD          | ...             | 5.3     | ...        |
| J1256−0547 | 2              | 3                   | −123     | 4             | ASTD          | F15             | 2.4     | 0.2        |
| J1256−0547 | 5              | 1                   | −132     | 5             | ASTD          | ...             | 6.8     | ...        |
| J1256−0547 | 8              | 9                   | −116     | 13            | STD           | ...             | 3.0     | 0.5        |
| J1256−0547 | 15             | 146                 | −130     | 13            | STD           | ...             | 0.9     | 0.3        |
| J1256−0547 | 24             | 2                   | −143     | 7             | ASTD          | ...             | 0.9     | 0.2        |
| J1256−0547 | 43             | 116                 | −147     | 10            | STD           | ...             | 0.7     | ...        |
| J1256−0547 | 86             | 1                   | −142     | ...           | ...           | ...             | 0.4     | ...        |
| J2344+2952 | 2              | 5                   | −93      | 1             | STD           | F8              | 12.5    | 0.2        |
| J2344+2952 | 8              | 4                   | −74      | 5             | ASTD          | ...             | 1.9     | 1.0        |

Note. Columns are as follows: (1) J2000 name in the RFC catalog (http://astroseo.org/rfc/); (2) frequency band; (3) number of VLBI epochs contributing to the measurement; (4) jet position angle; (5) uncertainty of the position angle; (6) nature of the uncertainty estimate: intraband standard deviation ("STD") if $N_{\text{epochs}} \geq 5$, otherwise average standard deviation at this band ("ASTD") for frequencies below 86 GHz, and none for 86 GHz; (7) 180° correction flag: based on the orientation that we measure at a higher frequency of $\nu$ GHz ("Fv") or based on dedicated studies of specific objects, J0900−2808 in Kosogorov et al. (2022) ("E1") and J0927+3902 in Alberdi et al. (1993) ("E2"); (8) the median distance between the core and the jet components, indicating angular scales probed by this measurement; (9) the median absolute deviation of the core–jet component distance when at least two epochs are available.

This table is available in its entirety in machine-readable form.

Table 2
Frequency-averaged Directions of Parsec-scale Jets with a Single Value for Each AGN

| J2000 Name | Frequencies (GHz) | PA (deg) | PA Error (deg) | 180° Correction | Core to Jet Distance |
|------------|-------------------|----------|---------------|-----------------|---------------------|
| (1)        | (2)               | (3)      | (4)           | (5)             | (6)     | (7)        |
| J0509+0541 | 2, 5, 8, 15, 24   | −177     | 3             | ...             | 2.0     | 0.9        |
| J0823+2223 | 5, 8, 15          | −164     | 3             | ...             | 4.7     | 0.6        |
| J0927+3902 | 1.4, 2, 5, 8, 15, 24 | 100     | 3             | E2              | 1.6     | 0.6        |
| J1256−0547 | 1.4, 2, 5, 8, 15, 24, 43, 86 | −133     | 4             | ...             | 0.9     | 0.7        |
| J2344+2952 | 2, 8              | −83      | 3             | ...             | 7.2     | 5.3        |

Note. Contains the same objects as Table 1, and provides our final estimates of the jet orientation. This table should generally be used unless individual frequencies and corresponding spatial scales are specifically of interest. Columns are as follows: (1) J2000 name in the RFC catalog (http://astroseo.org/rfc/); (2) frequency bands contributing to this measurement; (3) jet position angle; (4) uncertainty of the position angle; (5) 180° correction flag based on dedicated studies of specific objects: J0900−2808 in Kosogorov et al. (2022) (E1) and J0927+3902 in Alberdi et al. (1993) (E2); (6) the median distance between the core and the jet components, indicating angular scales probed by this measurement; (7) the median absolute deviation of the core–jet component distance when at least two frequencies are available.

This table is available in its entirety in machine-readable form.

Selection criterion crucially relies on adequate intensity measurements. They would be hard, if possible, to obtain in image-based methods, but are directly available from our visibility model fitting. We compute the intensity as $I = S/\theta^2$, where $S$ is the flux density, and $\theta$ is the Gaussian effective angular size. The brightest component is then selected unless $\theta$ is poorly determined and has a relative uncertainty above 50%. In these cases, we chose the strongest component in terms of its flux density $S$ as the jet origin.

It is common to have multiple VLBI observations for an AGN at the same frequency performed on different epochs (Section 2). In these cases, we take a median of individual jet directions as the resulting measurement at this frequency, making the estimate more accurate. A by-product of this aggregation is an alternative uncertainty estimate of the jet orientation: namely, the standard deviation of individual directions. This is a conservative upper bound of the uncertainty and includes real changes with time. It is thus directly useful as a measure of how well each object is characterized with a single jet orientation estimate at a specific frequency. This is our focus in this work, while a detailed evaluation of the real jet orientation variability (e.g., Lister et al. 2013) is currently out of scope.

We combine jet direction measurements across all available frequencies. Multifrequency observations allow us to resolve the $180°$ jet direction ambiguity more reliably. The radio spectrum of the extended optically thin jet is typically steeper than that of the partially opaque core (e.g., Hovatta et al. 2014; Plavin et al. 2019b). Thus the observed structure is increasingly core dominated at higher frequencies. A direct spectrum calculation is challenging because of different resolutions and is further complicated by the time variability. We follow a simplistic approach: whenever the estimated jet orientations at two frequencies differ by more than 90°, the one at the lower frequency is inverted, i.e., rotated by $180°$. The resulting jet position angles are listed in Table 1, together with the flags indicating whether this inversion was applied.

Finally, we obtain a single direction estimate for each AGN by averaging the measurements at all individual frequencies. These averages are presented in Table 2. They are useful as the...
most aggregated direction estimates despite being potentially affected by jet bending. We do not perform any weighting so that all frequencies contribute equally to the average. This may increase the statistical error when there are many more epochs in one band than in another. However, we always follow this approach to achieve treatment of all objects as uniformly as possible.

4. Method Evaluation and Comparison

In this section, we evaluate and characterize the achieved performance and the robustness of our jet direction measurement method, including comparison with previous studies. First, many VLBI observations just do not reveal any reliably detected jet structure outside the core, and the resulting images look like Figure 1. We find them to generally be better described by a single-component model or yield large formal uncertainties of the jet direction (see Section 3). Thus, we drop such observations from further analysis. For comparison, an example of a typical image with a long extended jet is shown in Figure 2. After the filtering, 60,594 source epochs remain, which is 6,000,594/123,456% of the total sample; Figure 3 shows a breakdown by the frequency band. All corresponding single-band jet orientation measurements are presented in Table 1.

Observations at different frequencies are sensitive to and probe different angular scales in the jet due to resolution effects and intrinsic properties of synchrotron emission. Scales probed by our direction measurements correspond to distances between the core and the jet components. They vary from hundreds of microarcseconds to tens of milliarcseconds and are listed in tables alongside orientation estimates. Distributions of these distances are shown in Figure 4.

Typical VLBI observations provide significantly nonuniform coverage of the visibility plane, especially in the north–south versus east–west directions. This irregularity results in two orthogonal directions of the best and worst angular resolution, commonly referred to as the beam minor and major axes. We attempt to quantify the systematic effects of this nonuniformity on our orientation measurements. The measured core to jet components distance, as defined above, is 20% to 30% larger on average along the beam major axis compared to the minor axis direction. At the same time, we do not detect any strong preference of jet directions to align with the beam: differences from the uniform distribution are below 10% at frequencies from 2–15 GHz and at 20% or below for all other bands.

We consider statistical model-fitting uncertainties in the jet position angle as lower bounds of the true errors (Section 3). It is thus instructive to compare these formal uncertainties to the scatter of the measured jet directions of a single object. Figure 5 illustrates this comparison with the intraband scatter quantified by the standard deviation. The distribution qualitatively looks as expected: the standard deviation is larger than the formal uncertainty in almost all cases, and a clear correlation is present. The uncertainties we provide in Table 1 are based on this intraband scatter. Specifically, we use the standard deviation for objects with at least five epochs at a single frequency available. The uncertainties given for AGNs with fewer epochs are averages of these deviations within each frequency band; they only reflect average properties at a given frequency. There are no sources with at least five direction measurements at 86 GHz, and uncertainties are not provided at this frequency. We do not directly utilize model-fitting errors to estimate the resulting uncertainties because formal errors are systematically lower than the intraband scatter and thus would impede uniform comparisons between AGNs. The intraband scatter forms a conservative uncertainty estimate because true orientation variations are possible (e.g., Lister et al. 2013). Nevertheless, such estimates are useful when describing the geometry of an object with a single jet direction assessment.

4.1. Multifrequency Effects

As discussed in Section 3, the extended jet regions typically have steeper spectra compared to the VLBI core. This can make jets stronger, easier to detect, and more extended at lower frequencies. At the same time, it becomes more probable to incorrectly resolve the 180° ambiguity in their direction: the jet component may become stronger than the core, an effect that was noted before in both astrophysical (Kovalev et al. 2008) and astrometrical (Xu et al. 2021) contexts. An example in Figure 6 shows a case when the jet direction differs between the frequencies. Note that in this example, the core component is brighter than the features in the jet at 8 GHz. However, due to the spectral properties it becomes fainter at 2 GHz. Following Section 3, we flip the direction estimated at the lower frequency in such cases; the arrow in Figure 6 illustrates the corrected direction. There are around 200 objects with their 2 or 5 GHz jet orientation flipped following this criterion and less than 0.5% at each of the higher frequencies.

It is unlikely for a jet component to be stronger and brighter than the core even at the highest available frequency, though it can be possible. In fact, we are aware of two AGNs where this effect was found in dedicated studies: J0900−2808 (Kosogorov et al. 2022) and J0927+3902 (4C +39.25, e.g., Alberdi et al. 1993). Taking the results of those works into account, we manually flip our estimated jet directions for these two objects. Their images at the highest frequencies are shown in Figure 7 overlaid with the corrected jet directions. The 180° flips are indicated in Table 1.
A key advantage of visibility-based approaches in describing the observed structure is a higher effective resolution, as discussed in Section 3. This is illustrated in Figure 8 by examples when the jet direction is successfully measured on the shortest scales present in the data. Here, J0541+5312 has its orientation determined closer to the jet origin than possible using the restored image. This orientation stays essentially the same for the more extended jet. The jet of J0509+0541 is hardly visible in Figure 8 (middle) at 1.4 GHz: its emission is basically unresolved in the image. Nevertheless, our model-fitting approach detects the second bright component and determines the correct jet orientation, as evidenced by the comparison with a higher-resolution 15 GHz image.

Effects such as temporal variations (e.g., Lister et al. 2013) or apparent bending of the jet influence any method of measuring its direction. Such effects likely have a stronger impact on the results of our method compared to approaches based on restored VLBI images or observation at other frequencies.
Figure 6. VLBI images of the same AGN at 8 and 2 GHz. The lower-frequency jet direction was flipped following the criteria outlined in Section 3. The residual difference between these directions is attributed to apparent jet bending.

Figure 7. VLBI images of the two AGNs where we had to explicitly flip the jet direction due to the available information from specific detailed studies. See the discussion in Section 4.

Figure 8. VLBI images illustrating the jet direction determination at the shortest angular scales possible. Note the arrow length that corresponds to the separation between the two model components. Left: an example of a straight jet. Middle: the jet is not visible at the restored image, but our visibility-based approach successfully detects it. See the right panel showing the same AGN observed at a higher frequency: the jet orientation is in agreement.
Determining jet directions at lower and higher frequencies has different advantages. We perform the final per-source aggregation to make our results useful for a wider range of studies. That is, we combine and average all measurements for each AGN together across all observing frequencies. These averages are provided in Table 2 with uncertainties estimated on the basis of individual errors at each frequency. These are based on a uniform and detailed manual model fitting of the jet structure seen by VLBA, and the corresponding models are extensively tested for robustness. The results of both comparisons are presented in Figure 9. Note that the figure only includes AGNs where the jet orientation was determined; see Figure 3. We show the distribution of jet direction differences between different frequency pairs: 2 and 8 GHz, 5 and 8 GHz, 8–15 GHz. These are pairs with the largest number of overlapping AGNs. The pairs that do not include the lowest frequency of 2 GHz show an excellent agreement with the differences less than 10° for 68% of objects and less than 30° for 95%. Measurements at 2 GHz are consistent with higher frequencies but have a somewhat higher spread: up to 45° at a 95% level compared to 8 GHz. Qualitatively, this is the expected behavior due to the resolution being both inversely proportional to frequency, and the difference in core and jet spectra (Section 3).

We systematically quantify the performance of our jet direction measurements in two ways. First, we check for internal consistency by comparing orientations for the same AGN estimated at different frequencies. Second, we compare our results to the inner jet directions from the MOJAVE program (Lister et al. 2019), which is highly consistent with higher frequencies but have a somewhat higher spread: up to 45° at a 95% level compared to 8 GHz. Qualitatively, this is the expected behavior due to the resolution being both inversely proportional to frequency, and the difference in core and jet spectra (Section 3). Figure 9 also indicates that our 15 GHz measurements agree very well with the corresponding MOJAVE ones (Lister et al. 2019). They use the same VLBI observations, a similar general approach, but fit more detailed models that get manually examined to ensure robustness, from which the jet direction was derived based on the feature nearest to the core over all epochs.

Finally, we compare the accuracy of the jet direction measurements presented here with existing results based on restored VLBI images. An earlier work of ours (Plavin et al. 2019a) relied on parsec-scale jet orientations to gain astrophysical insights from a radio–optical comparison. The apparent directions of 6337 AGN jets were estimated, even though only 4023 of those corresponded to the VLBI-Gaia matches and were utilized in that study. The interband differences among these measurements are shown in Figure 10 and are generally consistent between the frequencies. Comparison with Figure 9 clearly shows that in the current work, we significantly improve on both quantity and quality. Indeed, there are more AGNs with direction measurements, which is partially explained by additional VLBI observations. The apparent directions of 6337 AGN jets were estimated, even though only 4023 of those corresponded to the VLBI-Gaia matches and were utilized in that study. The interband differences among these measurements are shown in Figure 10 and are generally consistent between the frequencies. Comparison with Figure 9 clearly shows that in the current work, we significantly improve on both quantity and quality.

A more recent study by Blinov et al. (2020) explored the global alignment of parsec-scale AGN jets; they measured jet orientations in a semimanual way. We show the corresponding diagnostic plots in Figure 10. The number of AGNs with orientation estimates remained essentially the same, as in Plavin et al. (2019a), and is significantly lower than we present.
in this work. Figure 10 shows a good average consistency of direction estimates, as evidenced by 68% quantiles. However, the resolution of the 180° ambiguity was not performed, as these ambiguities did not affect the analysis in Blinov et al. (2020). They lead to larger 95%-level differences especially prominent at lower frequencies, 2 and 5 GHz. A notable exception is the agreement between 8 and 15 GHz directions: it is tighter for Blinov et al. (2020) measurements compared to our results for the majority of objects. We believe this exception is caused by image-based approaches probing somewhat larger angular scales: they can be less affected by spatial and temporal variations (see Section 3).

Neither Plavin et al. (2019a) nor Blinov et al. (2020) included tables with jet direction measurements. We obtained the results of the latter in private communication with the authors.

5. Summary

This paper presents a novel, completely automatic approach to estimating parsec-scale jet directions based on VLBI observations ranging from 1.4 to 86 GHz. We use visibilities, the primary Fourier-space interferometric observables, to achieve the highest possible effective resolution. We apply this method to calibrated VLBI observations collected in the Astrogro database and measure positional angles for the largest sample of parsec-scale AGN jets to date, which consists of 9220 objects. The results are presented in Table 1 separately for each available frequency band, and in Table 2, as aggregated averages with a single direction for each AGN. The probed angular scales range from a tenth of a milliarcsecond to tens of milliarcseconds (Figure 4).

We demonstrate the performance of our approach and the robustness of its results by analyzing the consistency of the jet orientation at different dates and different observing frequencies. Further, we find a good agreement with jet directions measured by the MOJAVE team. The automatic method presented in this paper should be used with care when performing detailed studies of individual AGNs: description of the observed emission with two components can be too simplistic for jets with a complex resolved structure; treating the jet orientation as a single number can be suboptimal when variations with time, frequency, or distance are present. Nevertheless, our measurement results are justified on a statistical basis and are useful for studies of large AGN samples. Orientations estimated for each observing frequency separately (Table 1) can further be used as an indicator of variations between spatial scales.

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