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## VLBI2010: The Astro-Geo Connection

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### Abstract

VLBI2010 holds out promise for greatly increased precision in measuring geodetic and Earth rotation parameters. As a by-product there will be a wealth of interesting new astronomical data. At the same time, astronomical knowledge may be needed to disentangle the astronomical and geodetic contributions to the measured delays—and phases. This presentation explores this astro-geo “link”.

### 1. New Astrophysics with VLBI2010

Under the watchword VLBI2010 the geodetic VLBI community is planning a major upgrade, including new telescopes, instrumentation and procedures, in order to make a dramatic improvement in the precision of IVS products. The goals are 1 mm (3 ps) station position accuracy, 0.1 mm/year velocity accuracy, with continuous observing and initial results available within 24 h.

Such precision implies (and requires) global source positions with  $\sim 30 \mu\text{as}$  accuracy and stabilities of  $\sim 3 \mu\text{as}/\text{year}$ . The radio sources observed in IVS programs are all Active Galactic Nuclei (AGN) at high redshifts, constituting some of the most distant objects known in the Universe, and are used to define a fundamental inertial frame. Precise astrometric measurements will thus allow a number of basic properties of the Universe as a whole to be investigated with hitherto unprecedented precision. These could include:

- Micro-arcsecond instability of the celestial reference frame (micro-lensing by visible Galactic stars—Sazhin et al. 1998)
- Mass-energy of cosmological gravitational wave background (limits from quasar proper-motion upper-limits—Gwinn et al. 1997)
- Anisotropic Hubble expansion of the Universe? (redshift-dependence of proper-motions—Titov 2009)

The ESA space mission GAIA (Lindgren et al. 2007) will measure the optical positions of many AGN with precisions as good as  $24 \mu\text{as}$  for bright (16 m) objects. IVS and GAIA astrometry, taken together, will determine a very precise alignment of the radio and optical reference frames, and hence permit a detailed investigation of displacements between the optical and radio emission regions.

### 2. AGN Astrophysics

Astronomers have used VLBI to study AGN astrophysics for 40 years. The radio emission from quasars and BL Lac objects (“blazars”) is believed to be due to the synchrotron process, and arises from the collimated, relativistic ( $\Gamma = 5\text{--}20$ ) outflow of plasma jets from a central region whose

physics is dominated by the presence of a central, massive black hole. The 1-sided appearance is due to relativistic Doppler boosting. The bright, compact feature (the “core”) at the inner end of the visible jet provides an apparently obvious positional reference point. Optical emission may arise from either an accretion disk surrounding the black hole, or from the jet, or both (Fig. 1).

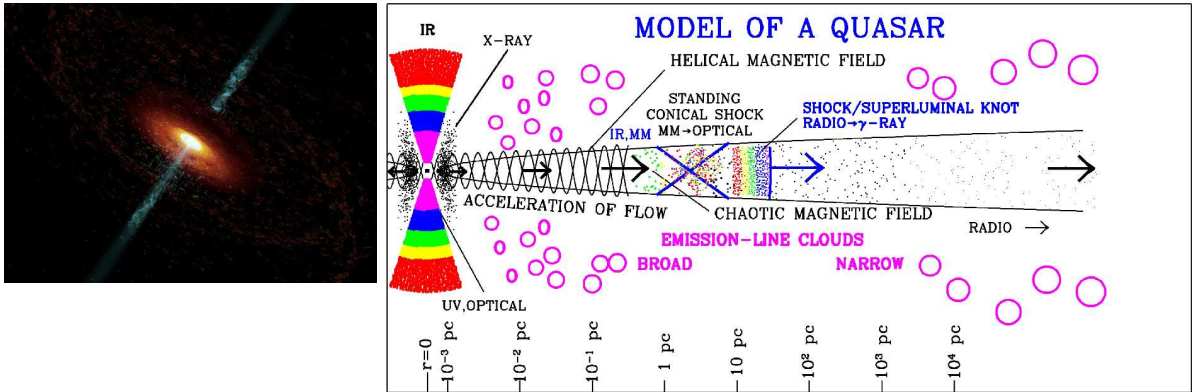


Figure 1. Left: An AGN (courtesy W. Steffen, Cosmovation). Right: An AGN (courtesy Alan Marscher).

VLBI imaging of AGN is vigorously carried out by the astronomical community. For example, the MOJAVE program (Lister et al. 2009) uses the VLBA (10 antennas) at 15 GHz to monitor structural variability in 135 sources, observing 25 sources each month. Observations comprise typically ten 5-minute observations per source with 45 baselines, yielding  $\sim 450$  visibility measurements, with spacings between observing epochs tailored to known source activity. Imaging, using closure-phase relations, provides maps down to  $\sim 0.5$  mas resolution and *internal* component separations and proper motions already with accuracies of  $\sim 30 \mu\text{as}$  and  $\sim 3 \mu\text{as}/\text{year}$ , respectively—comparable to the *global* precision which will be reached by VLBI2010 (see Figs. 2 and 3).

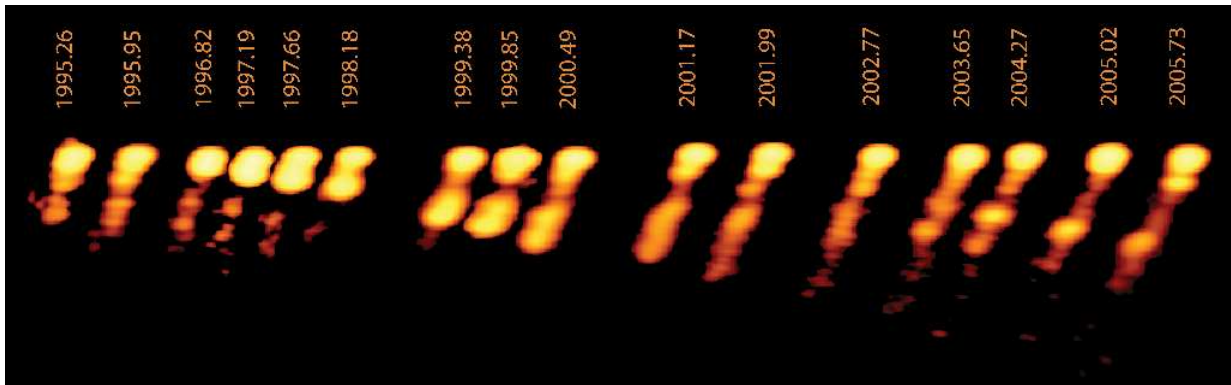


Figure 2. Seyfert Galaxy 3C 111 (redshift 0.0485) from VLBA 2 cm MOJAVE observations 1995–2005. Beam  $0.5 \times 1.0$  mas. Extent (2005.73)  $\sim 11$  mas. From Kadler et al. 2008 (courtesy Christian Fromm).

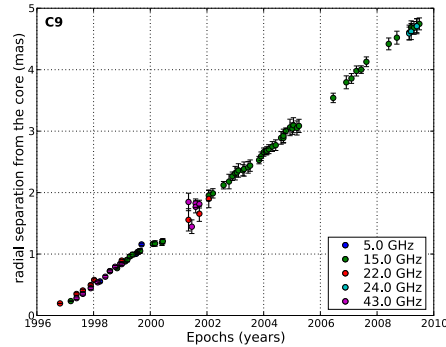


Figure 3. Outward motion of jet component C9 in 3C 345 (courtesy Frank Schinzel).

There is a long tradition of astronomers using the IVS data base to supplement their own observations of structural variations (see Fig. 4 for an ancient example). However, the use of sub-netting for geodetic runs greatly decreases the astronomical yield. Currently  $\sim 230$  sources are used for IVS S- and X-band observations. As an example, the R1409 run observed 60 sources in a total of 1092 observations. Only 48 of these sources had any closure phases ( $\geq 3$  antennas), only 36 had four or more antennas, and there were only nine sources with 100 or more visibility measurements.

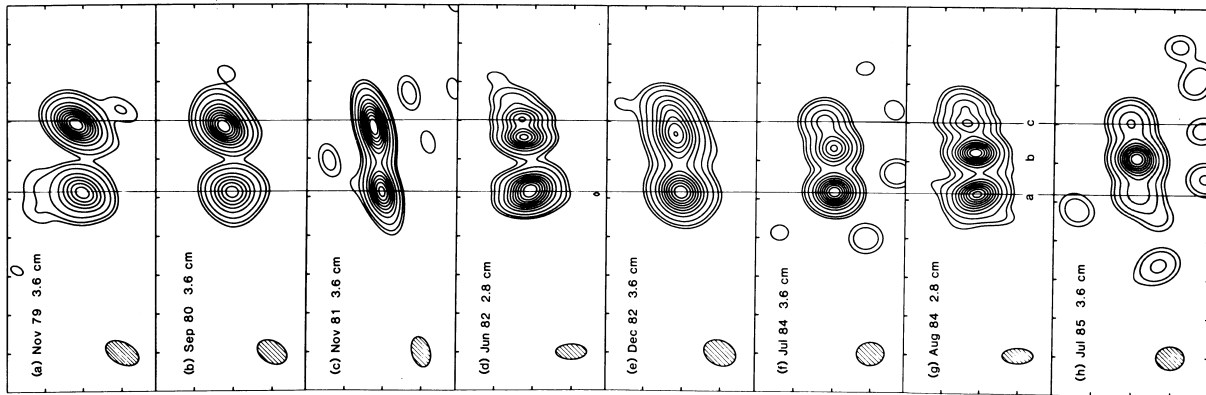


Figure 4. X-band images of quasar 4C 39.25 (redshift 0.699), mostly from the NASA Crustal Dynamics Program, 1979–1985 (Shaffer et al. 1987).

### 3. VLBI2010 and AGN Properties

Implementation of the VLBI2010 goals will require a considerable change in IVS observing methodology. No doubt the process will proceed via a gradual transition but it is worth considering the final situation and the method elements required to get there, as I understand (or do not understand) them:

- A network of  $\sim 30$  fast-slewing, 12 m-class antennas
- Broadband group delays derived from four wide frequency bands from 2–14 GHz (or broadband “phase delays”  $(\phi_{\text{tot}}(\nu)/(2\pi\nu))$  derived from the (ambiguity-resolved) total phase,  $\phi_{\text{tot}}$ )
- Dual polarization observing (and full polarization correlating?)
- Rapid source changes every 15–30 s (between how many sources?)
- Continuous 24 h observing (and correlating? real-time VLBI?)
- Accounting for thermal and gravitational deflections of antennas
- Accounting for electronic drifts and avoiding RF interference
- **Accounting for radio source structure**

An astronomer hoping to raid the VLBI2010 data base might then expect some fantastic material—from daily monitoring of (230?) sources in four frequency bands in dual polarization with 30 antennas. Some exciting uses could be:

- Monitoring jet component outflows
- Spectral and polarization evolution of jet components
- Component flux-density variations on daily and intra-day timescales. (Note the variability on an *hourly* timescale of the geodetic favourite B 1156+295; see Savolainen & Kovalev 2008.)
- Short timescale positional variations of the “core”

It is here, however, that the contrasting interests of the geodetic and astronomical VLBI communities become apparent. Sources for IVS observations would ideally be non-variable, achromatic points; such sources would in general, however, be of only marginal interest for astrophysical VLBI studies. To the extent that no sources are likely to fulfill such idealized IVS requirements, **astronomers and geodesists will need to work closely together** to meet the VLBI2010 goals. In the remaining sections of this contribution the effects of some of the properties of real astronomical sources on VLBI2010 methodology are considered.

#### 4. Source Strength and Spectrum

Synchrotron sources are sometimes referred to as either “steep” or “flat” spectrum objects. However, VLBI2010 will use a wide frequency range (2–14 GHz) which spans a factor of 7 and account will need to be taken of the flux-density in all four bands. Suitable sources will need to be above the detection threshold of an IVS observation in each of the four bands; and the whole spectrum will need to be monitored continuously since variability can occur in all the bands. Fig. 5 shows an example of a typical synchrotron source spectrum.

#### 5. Source Structure

All synchrotron sources have a finite angular size (otherwise they would have infinite brightness temperature), that is, **all sources have structure**. A further complication is that AGN source structures are highly asymmetric, vary with time and are, in general, different at different

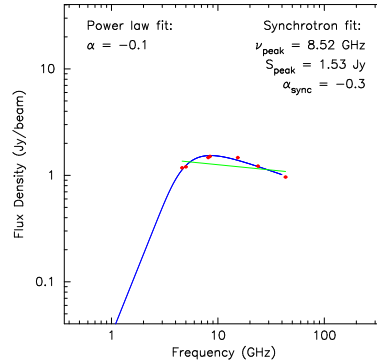


Figure 5. Radio spectrum of the synchrotron source 0827+243. The straight (green) line is a single power-law fit to the points; the (blue) curve is the fit of a synchrotron spectrum (courtesy Kirill Sokolovsky).

frequencies. And, of course, the resolution of VLBI observations will vary by a factor of 7 over the range of VLBI2010 observing frequencies. It is useful here to distinguish two distinct regimes in which the effects of source structure can be considered:

**Visible Structure:** Here the extent of the detected emission is greater than the observing beamwidth<sup>1</sup>. Such structure can be recognized by imaging high-resolution VLBI observations.

**Invisible Structure:** Here the extent of the detected emission is less than the observing beamwidth. You do not see it—but it is there.

### 5.1. Effects of Visible Structure

The effects of visible source structure on VLBI delay measurements have been discussed by Charlot (1990). In general the delays (and phases) do not correspond to a unique point within the structure for all baselines; the delays do not “close”. Thus a geodetic solution where sources are treated as points will have a large “structural delay noise” contribution to the residuals.

The current IVS approach is to classify sources based on the expected magnitude of the structure delay,  $\tau_{\text{str}}$ , using the “structure index” (Fey & Charlot 1997 & 2000) and to observe only those sources where the effect should be small at both X- and S-band. Adopting this methodology for VLBI2010 will require selecting sources with suitably low structure index at all four frequency bands. To remove systematic errors down to 1 mm (3 ps), only a structure index of 1 ( $\tau_{\text{str}} < 3$  ps) will be permissible. Both these requirements will thus limit the number of sources which can be used. (See also further restrictions mentioned in Section 5.2.) Note that because source structures can vary, so too can their structure index; their structures must thus be monitored. The VLBI2010 observations themselves can be used to monitor visible source structure, in order to determine a current structure index. The observing schedule must be constructed to permit reasonable imaging—and maybe geodesists will be convinced that global fringe-fitting (Schwab & Cotton 1983) is useful in this context. In any case, geodesists must learn to love their sources as much as their antennas, and keep updating a source data base for planning observations. Perhaps observations of a source should be rejected if subsequent imaging reveals too great a structure index.

<sup>1</sup>A measure of the angular resolution in VLBI images,  $\sim 0.4$  of the fringe spacing on the longest baseline

The other approach, which is rarely used in practice (but see Petrov 2007), is to calculate structural delay corrections for each baseline, based on an image of the source structure and a reference point within it. Currently there appears to be little return from this laborious effort, presumably because tropospheric delay noise is comparable to, or greater than, structural delay terms. However, it is hoped that VLBI2010 observations, with their rapid source changes, will reduce this tropospheric component considerably, making source structure corrections worthwhile. Will VLBI2010 data be sufficient to determine structural corrections? Imaging will require scans with large enough sub-arrays (e.g.,  $\geq 5$  telescopes) to provide sufficient closure phase relations.

As a diversion I would like to suggest a (possibly crazy) idea. Structural delay terms arise when there is a rapid change of structure phase,  $\phi_{\text{str}}$ , with frequency,  $\nu$ , and can be sensitive, for example, to the relative flux density and separation of beating sub-components (see Charlott 1991). This corresponds to a rapid change of  $\phi_{\text{str}}$  with resolution coordinates  $u, v$ . When imaging, interferometer visibility data is traditionally assigned to a  $(u, v)$  grid before Fourier transformation to the image plane, with a cell size determined by the expected image size and the sampling theorem. This is sufficient only when the visibility plane is fully sampled—which in the case of geodetic VLBI data it certainly is not. Can we construct a more faithful image by using a much finer-scale  $(u, v)$  sampling, with no averaging of the data in either time or frequency, which preserves rapid  $\phi_{\text{str}}$  gradients? Perhaps such a procedure could result in more precise relative flux densities, for example, and this in turn could lead to more robust structure delay estimates. Again, global fringe-fitting would be the key algorithm in this process by forcing a separation of geometric and structural terms.

An important point to note is that source structures can change dramatically over the factor of 7 range of frequencies of VLBI2010. Often they are larger at lower frequencies (because steep-spectrum extended jet features become more dominant) and this may counteract the moderating influence of larger beamwidths. A more serious issue arises from the VLBI2010 goal of using broadband group delays (or even “phase delays”) by phase interpolation between frequency bands. With the present IVS observing scheme, source structure delay corrections should, in principle, be made at both S- and X-band. However, S-band is only used as an “auxiliary” band for correcting the X-band ionospheric delay, and any contaminating S-band structural delay term,  $\tau_{\text{str}}^{\text{S}}$ , is “diluted” by a factor  $(8.4/2.3)^2$ . VLBI2010 analysis will require accurate interpolation of the phases *between* the four frequency bands, simultaneously solving for the dispersive ionospheric path. Thus source structure *phase* corrections, evaluated with respect to a suitable reference point, will be necessary in all four bands. Even for the case of the VLBI2010 fall-back plan, when group delays are determined from only the upper three frequency bands around  $K_u$ -band, such corrections will be necessary in these bands.

## 5.2. Effects of Invisible Structure

When the extent of a source is less than the interferometer beamwidth, the delay and phase response corresponds closely to that of a point source at the position of the radio brightness centroid. For present IVS observations the typical source position accuracies of  $250 \mu\text{as}$  correspond to  $\sim 1/3$  of the X-band beam. VLBI2010 observations will enter a new regime where the required source position accuracies are  $\sim$  **1/30 of the beam**. Variations of the invisible structure will thus result in a significantly variable source position. Structural variations in the low redshift source 3C 111 were shown in Fig. 2. Fig. 6 shows the structure at a single epoch and, bottom left, the

beam, and the same image reduced in size to correspond to a redshift of 0.6. Clearly, the visible structural variations would lead to an instability of the centroid position if the source were at that redshift.

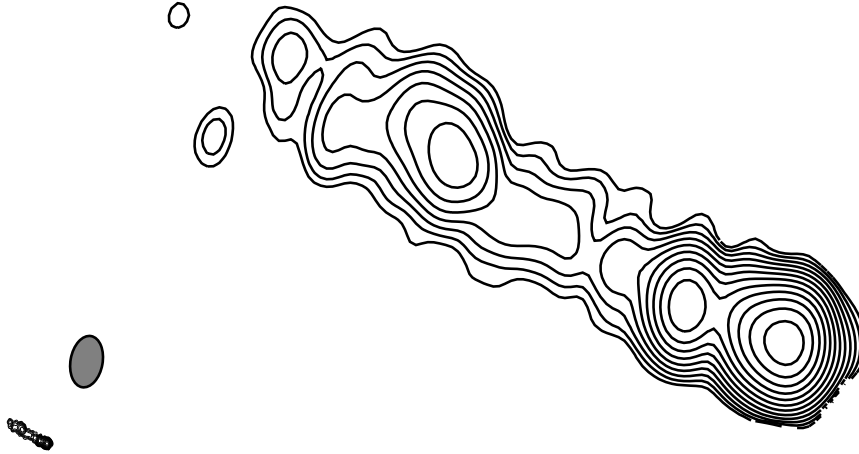


Figure 6. Source 3C 111 (redshift 0.048) at epoch 2005.73. The image at the extreme bottom left is as it would appear at a redshift of 0.6. The beamwidth is  $0.9 \times 0.5$  mas at PA  $-10^\circ$ ; the overall source extent of 11 mas becomes 0.9 mas (courtesy Christian Fromm).

A possible remedy to ameliorate the effect of variable centroid positions is to use the fact that most mas-scale source structures are highly *linear* and that the position instability is likely to be along the jet direction. This direction is roughly stable for most sources, leading to a more stable component of position in the direction transverse to the jet. One could thus consider giving low weights to data from baselines oriented close to the (known) inner jet direction, and high weights from baselines transverse to it. Observations could even be planned to avoid jet directions. Such a scheme is not unprecedented in IVS analysis (see Elevation-Dependent Weighting, Malkin 2008). The idea of assuming component motions to be along inner jet directions has been used by Rioja & Porcas (2000) to decompose the measured relative motions between the quasars 1028+528A,B.

### 5.3. Frequency-dependent Centroids and Core-shifts

Centroid positions will, in general, also be frequency-dependent, arising either from the effect of frequency-dependent beamwidths (see Rioja, *these proceedings*), or from real, frequency-dependent source structures, or from both (see, e.g. Porcas & Rioja 1997). These position changes must be taken into account when determining VLBI2010 broadband group delays and “phase delays” or the correct phase interpolation between the four frequency bands may not be made.

It has long been known from both measurements and theory that the bright, compact “core” feature seen at the end of jets has a frequency-dependent position—the “core-shift”. This arises from the frequency-dependent opacity of synchrotron radiation, which results in a gradual shift of the peak of radio emissivity away from the “jet base” at lower frequencies (see Fig. 7). Kovalev et al. (2008a) have investigated the prevalence of core-shifts in a sample of 29 sources for which a secondary (presumed achromatic) feature in the jet could be used as a reference point. They found a typical (sample median) shift of  $440 \mu\text{as}$  between S- and X-band core positions, which clearly

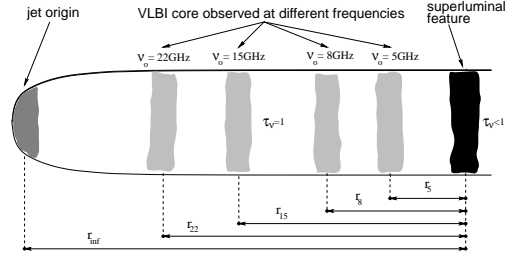


Figure 7. Frequency-dependent synchrotron opacity in jets (Lobanov 1998).

cannot be ignored at VLBI2010 levels of precision. The radio emission from synchrotron jets has been modeled, with predictions of core-shifts from the jet base,  $\Delta \mathbf{x}$ , varying as a power-law with wavelength ( $\Delta \mathbf{x}(\lambda) \propto \lambda^\beta$ ) or, re-writing:

$$\Delta \mathbf{x}(\nu) = \Delta \mathbf{x}_{\text{ref}} (\nu/\nu_{\text{ref}})^{-\beta}$$

where  $\Delta \mathbf{x}_{\text{ref}}$  is the core-shift at a reference frequency  $\nu_{\text{ref}}$ ,  $\beta = 1/k_r$  and  $k_r$  is determined by the physical conditions in the jet (Lobanov 1998). For equipartition of energy in particles and magnetic field,  $k_r = 1$  and  $\beta = 1$ , and  $\Delta \mathbf{x}_{\text{ref}} \propto (\text{luminosity})^{2/3}$  (Blandford & Königl 1979). Examples of measured core-shifts are given in Fig. 8.

The consequences of core-shifts on the use of group delays for global astrometry have been investigated by Porcas (2009). A “chromatic” core position introduces an additional interferometer phase term as a function of frequency, equivalent to a “dispersive” path (see Fig. 9). This is also true if the “core” is used as the reference point for visible structure corrections (see Section 5.1). In general, group delays measure a “reduced” core-shift from the jet base,  $\Delta \mathbf{x}_{\text{group}}(\nu)$  of

$$\Delta \mathbf{x}_{\text{group}}(\nu) = (1 - \beta)\Delta \mathbf{x}(\nu)$$

Curiously, for the astrophysically significant case of  $\beta = 1$ , group delays measure **no** core-shift at all *at any frequency* because the phase term is a *constant over all frequencies*. They do, however, measure the position of the jet base. Note that “X-band positions” listed for the ICRF sources and the VLBA Calibrator Survey (VCS) also refer to this point, and not to the position of the

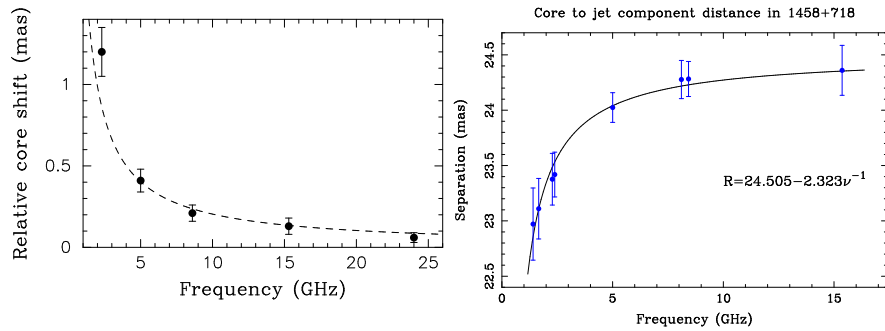


Figure 8. Left: Frequency dependence of the core position of 0850+581 measured relative to its position at 43 GHz. The curve represents the best fit for the function  $r_c \propto \nu^{-1/k_r}$ , where  $k_r = 1.1 \pm 0.1$  (from Kovalev et al. 2008b). Right: Frequency dependence of the distance between the position of the core of 1458+718 (3C 309.1) and the centroid position of a reference feature in the jet. The curve fitted to the data is for the pure synchrotron self-absorption case with  $k_r = 1$  (from Kovalev et al. 2008c).



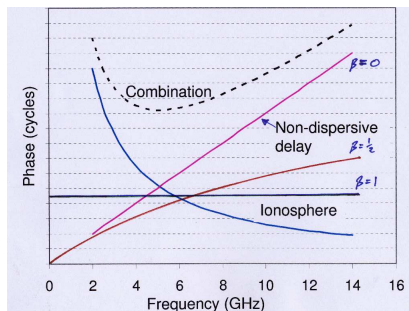


Figure 9. Modified “Petrachenko” plot showing dispersive phase for core-shifts with  $\beta = 0.5$  and  $\beta = 1$  (adapted from Petrachenko 2009).

X–band core, which is offset by (typically)  $\sim 170 \mu\text{as}$  (corresponding to the median S–X shift of  $440 \mu\text{as}$ ). These jet base positions are much closer to the central AGN black holes (which **are**, unfortunately, black!) and may even be more stable than “core” positions.

For VLBI2010 it will be necessary for the dispersive contributions to the broadband group delays and “phase delays” of both the ionospheric paths *and* core-shifts to be estimated and removed. Whereas the ionospheric contribution must be estimated for every scan, it can be hoped that a 3-parameter description of the core-shift ( $\beta$ , and the magnitude and position–angle of  $\Delta\mathbf{x}_{\text{ref}}$ ) for each source may be stable for months or years, and can be stored (and updated) in a source database. This would, of course, be a valuable resource for astrophysical studies. (An inferior scheme would be to avoid observations with baselines along jet directions—see Section 5.2.) Hobiger et al. (2009) have investigated how ionospheric and *discrete* core-shift contributions affect the integer phase ambiguity estimates when interpolating the phase between the four separate frequency bands. However, it seems unlikely that the *continuous* nature of the core-shift phase contribution, both within and between the bands, will make this phase interpolation more difficult.

A special case occurs when  $\beta=1$ , where the effect of the core-shift is a *frequency-independent* phase offset,  $\phi_{\text{cs}}$ . For the typical core-shift value at X–band of  $170 \mu\text{as}$ ,  $\phi_{\text{cs}}$  can reach values up to  $\sim 50^\circ$  on long baselines such as Westford to Wettzell, when oriented parallel to the core-shift direction. When  $\beta=1$  the core-shift has *no* effect on the estimate of VLBI2010 broadband group delays, which are derived from phase differences and phase gradients only (Petrachenko 2009). Source positions derived from this analysis (after removal of the ionospheric delay contribution) refer to the position of the jet base at all frequencies. However,  $\phi_{\text{cs}}$  *does* make a contribution to the total phase,  $\phi_{\text{tot}}$ , and hence must be accounted for when using VLBI2010 broadband “phase-delays”. Petrachenko (2009) has outlined a procedure whereby the unknown integer cycles of phase,  $n(\nu)$ , (where  $\phi_{\text{tot}}(\nu) = \phi(\nu) + 2\pi n(\nu)$ ) can be deduced from group delays by successively refining estimates of the non-dispersive delay,  $\tau$ , and the ionospheric path,  $K$ . This method assumes that any constant phase terms (e.g., instrumental phases) have been accounted for. The core-shift phase,  $\phi_{\text{cs}}$ , is such a term, however, which cannot be estimated from a single scan. Thus determination of the  $n(\nu)$  for each broadband “phase delay” will require either prior knowledge of  $\Delta\mathbf{x}_{\text{ref}}$  or it must be estimated *simultaneously* with the  $n(\nu)$  from a number of scans. Note that source positions derived from “phase delays” will refer to the position of the core at the frequency for which the total phase is estimated if  $\phi_{\text{cs}}$  is included as part of the “phase delay”, but to the jet base if it is removed.

## 6. Acknowledgements

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