Investigating Quasar Structure in VGOS with Simulations

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Abstract Quasar structure is a well-known issue that can be important in determining accurate celestial and terrestrial reference frames. So far, no good strategy to address this issue has been found. A complication is that the structure of quasars can, and often does, evolve with time. Furthermore, the variability and structure of flat-spectrum radio-loud quasars used in geodetic VLBI is highly frequency-dependent. This poses a challenge for next-generation (VGOS) systems currently being built around the world, which aim to observe over a wide range of 2–14 GHz. The structure effects for the same quasar can be very different at different frequencies in this range. On the other hand, we understand the astrophysics of quasars relatively well. In this research, we model the frequency-dependent quasar structure by using the extracted information from real images. To quantify the effects of the changing quasar structure in VGOS observations, the source structure module of the Vienna VLBI Software (VieVS) is extended. In this work we are focusing on a single source (J0136+4751) to explore strategies and calculate the effects of source structure as a function of frequency and time for varying geometries. Ultimately, we hope to address issues related to source structure as seen in Australian and global VGOS observations.

1 Introduction

By measuring the position of radio sources with Very Long Baseline Interferometry (VLBI), the International Celestial Reference Frame (ICRF) is defined. Usually assumed to be point-like, extragalactic sources are often known to have extended structures on the scale of milliarcseconds [2, 5]. In addition, structure varies with time and frequency, possibly restricting the determination of source positions [11, 14, 16]. Further, source structure can cause systematic errors in station positions at the millimeter level [15], although other errors are currently more significant in legacy VLBI. Despite many efforts, so far there is no standard procedure to determine and correct for source structure effects. While this may be acceptable for legacy VLBI, it is an important risk for the broadband method. The greatest concern is associated with phase connection when source structure considerably varies over the broadband frequencies.

The suggested VGOS broadband system uses four bands in the range of 2–14 GHz, each of them 1 GHz wide. Hereby, placement of frequency bands may affect the ability of phase connection [12]. Some initial work on how to handle source structure in VGOS has been done by Niell [8, 9].

In this project, we develop the idea introduced by Niell and enhance it with the information taken from real images. We also expand the current source structure module of VieVS [1, 15], allowing for VGOS simulations and possibly even corrections of source structure effects. The other perspective is developing tools and routines to predict source structure as seen in VGOS (test) observations with the AuScope/AOV array and working on mitigation strategies.

2 Enhancing the Approach of Niell

As previously mentioned, the possibility of connecting phase across the broadband can be affected by rapid

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phase variation of the source itself as a function of frequency. In 2006, Niell did first investigations by using previously published source characteristics [6] as well as some common assumptions.

Starting from a source image using a Gaussian fitting algorithm, one can get the position, size, and brightness of individual components of this source (so-called clean components). The Fourier Transform of the so-called brightness distribution leads to the visibility function. From this, one can calculate the source structure phase as a function of observing frequency. While extracting clean components from source images traditionally has been done manually, we have tried to automate this process. Using various downloading and processing scripts allows us to conduct large-scale investigations.

Coming back to the idea of Niell, we can now replace some of his assumptions with the parameters derived from real images, such as maximum flux density (S_0), position parameters of each components like distance and position angle from the origin (r, θ), major axis (a), axial ratio (b/a), and position angle of major axis (ϕ).

One of the sources that we investigate for this purpose is 0133+476 (J0136+4751) which is an ICRF2-defining source and is well observed (1,450 sessions from the year 2000). We study the mentioned ICRF2 source since based on its images in S (2.3 GHz), X (8.6 GHz), and U (15.4 GHz) bands; it shows source structure evolution during the time that allows us to consider it as a nonpoint-like source. In this research, we have used the Astrogeo VLBI image database (http://astrogeo.org/) to collect 162 available images of 0133+476, which are taken in S, X and, U frequency bands.

Although we are aware that our automated routines for image processing may still have some limitations, they seem to work well for first applications. The following Table 1 is an example for our selected source.

Following the algorithm described by Niell [8] and using the parameters shown in Table 1 we can reproduce his investigations. By further combining this with the VieVS source structure module, we can do this for arbitrary frequencies and different geometries (Figures 1 and 2). As is well known, the observed source structure depends on the projected baseline, which itself is the product of baseline length and its orientation in space. The two figures show that baseline criteria, such as length and angle, can dramatically influ-

Table 1 Extracted parameters from source image. Source Name: J0136+4751, Observation Date: 2015 March 17, Image Frequency: 8.7 GHz, RA: 24.2441 degrees, DEC: 47.8581 degrees, FITS file generator: Alexandr Pushkarev, Instrument used: VLBA, Database: Astrogeo Center.

S_0 (Jy)	r (mas)	θ (degree)	a (mas)	b/a	ϕ (degree)
1.84	0.0	0.0	3.01	0.31	45.19
0.09	2.63	-35.19	2.91	0.37	44.53
0.08	0.79	-55.39	2.79	0.23	44.42

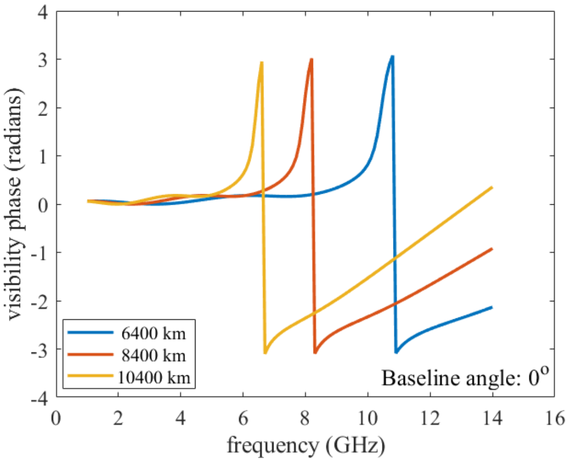

Fig. 1 Visibility phase as a function of frequency for baseline lengths of 6,400 km (blue), 8,400 km (red), and 10,400 km (yellow). Varying the baseline length with a fixed angle (0°) causes a shift in frequency. Adopted source model is as in Table 1.

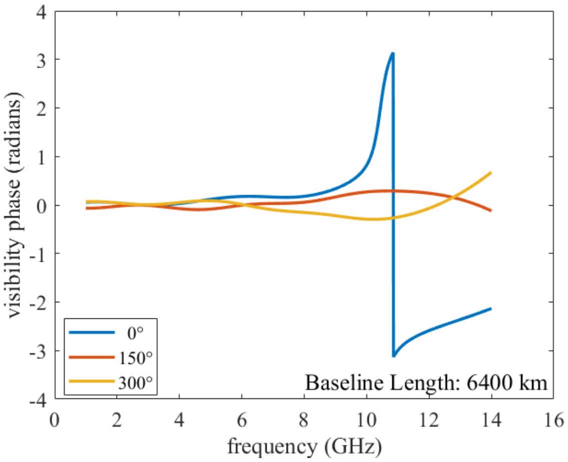

Fig. 2 Visibility phase as a function of frequency for baseline angles of 0° (blue), 150° (red), and 300° (yellow). Varying baseline angle with a fixed baseline length (6,400 km) makes big changes in phases.

ence the source phase. For example, it is clear from Figure 1 that the overall trend is similar and baseline length variation only changes the frequency at which the phase starts varying rapidly. Figure 2 is an example of dramatic source phase change over the VGOS frequency band when the baseline angle is varied. Such a rapid phase change can cause serious problems for the VGOS broadband delay.

3 What Images Can Tell Us About Source Structure in VGOS Bands

A well-known problem with source structure is their evolution with time and frequency. Unfortunately, we do not have enough images in all frequency bands and at all times to correct observed delays using contemporaneous images in each case.

3.1 Time Variability

Our automated routines help us to create time series of flux densities, structure indices, and delay for each source based on the available image in different reference frequencies. As an example, Figures 3 and 4 show the time series of flux density and structure index of our candidate source using X-band images.

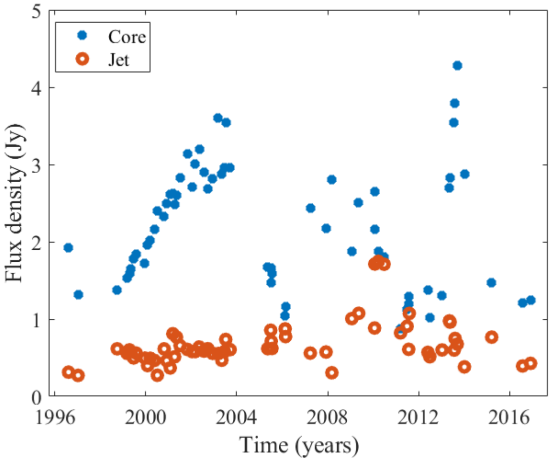

Fig. 3 Changes in flux density of core and jet as a function of time show that we cannot consider this source as a point-like source.

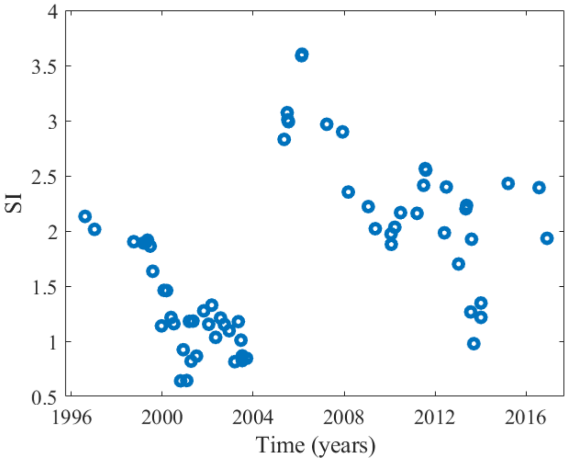

Fig. 4 Source structure index as a function of time for X-band images. X-band structure index varies from 0.5 to 3.5 during the time. This source is a good candidate to study source structure effects.

For core-dominated emission, the core shift effect means that light curves at different frequencies will be shifted in time. Higher frequencies (closer to the true jet base) will arrive before lower frequencies. For non-accelerating jets (which do not exist in reality), we expect the time lag to go as 1/freq (see [14] and [7]). In any case, two high frequencies separated by the same number of GHz will have a smaller time lag than two low frequencies separated by the same amount.

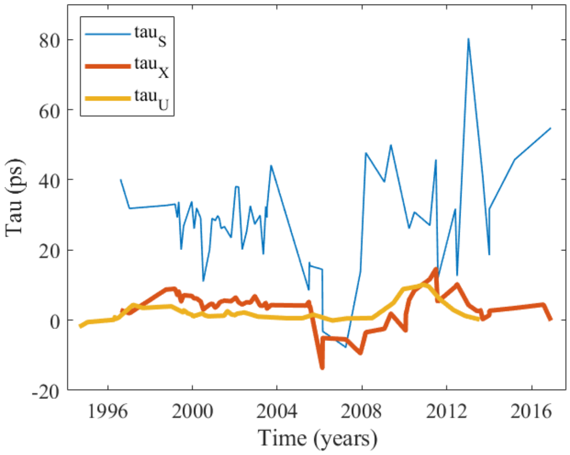

Fig. 5 Delay as a function of time for S, X, and U band in their own reference frequencies (2.3, 8.6, and 15.4 GHz).

This fits our findings: in Figure 5, we have used S-, X-, and U-band images to compare the structure de-

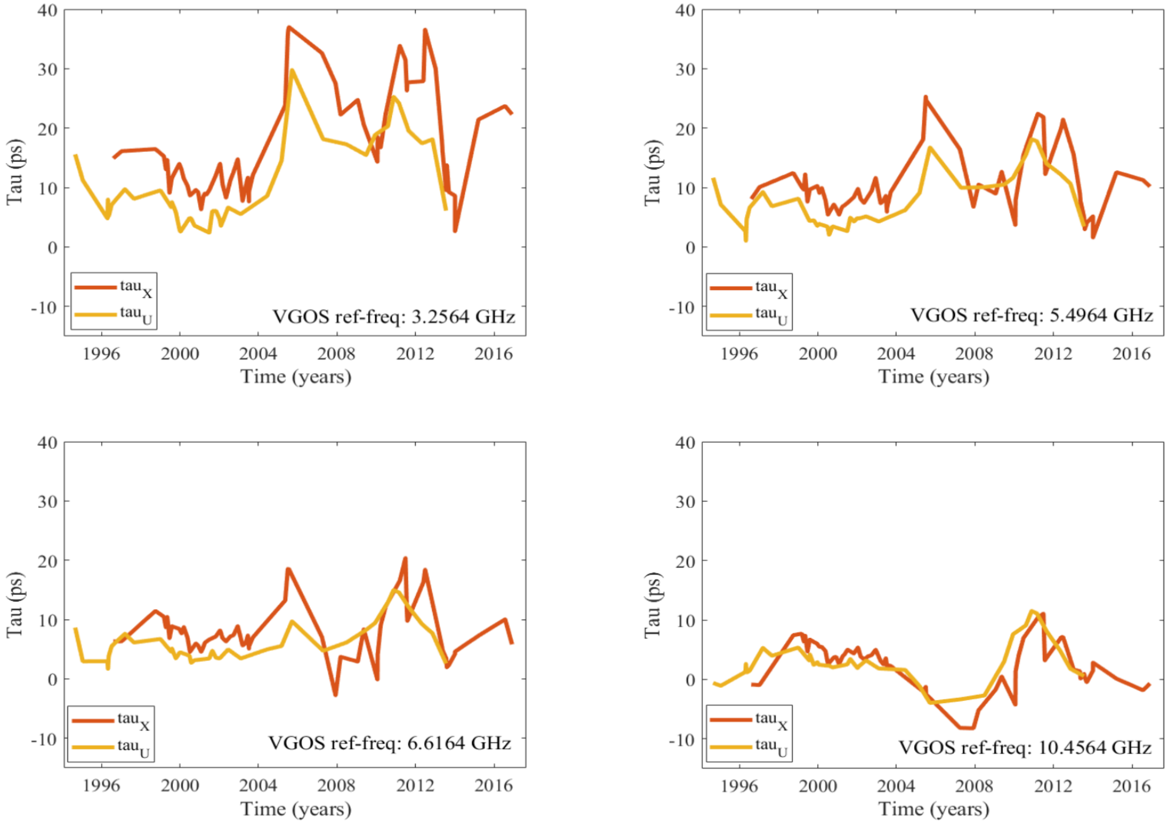

Fig. 6 Delay as a function of time using different X-band and U-band images for source 0133+476 in VGOS reference frequencies. In these figures, the source structure is a fixed parameter with the reference frequency of the image.

lays as function of time in their own reference frequencies. We find that there is a good correlation between X- and U-band images. The S-band delays appear less correlated with either U- or X-band, than U and X with each other. As expected, because U and X frequencies are actually quite close, the structure is similar. On the other hand, the delays resulting from S-band images are very variable, which may be due to the low resolution of S-band images. As a consequence, we decided not to use the S-band images for further investigations.

3.2 Application of Images at Different Frequencies

Most images are available in S, X, and possibly higher frequencies, commonly used for astrometry. So the question is how does the source behave over the whole VGOS frequency range? How far of the image's reference frequency is it safe to use the structure information for other frequencies? While this is not a guarantee, because we actually do not have other frequency bands' images, a preliminary conclusion tells us that we can use X- or U-band images as proxy for the whole VGOS frequency range. We have used X-band (or U-band) images for the Hobart12–Ishioka baseline (8,096 km) using the actual geometry at the image reference time to derive the structure delay at four VGOS bands. When using the VGOS reference frequency that is closer to the image frequency (in either X- and U-band) we get good agreement. In Figure 6, even though similar trends can be seen for both X- and U-band delay for all the VGOS reference frequencies, there still exist minor differences between the two lines. However, as the VGOS reference frequency approaches the image frequencies for each band, these minor differences become less. This can be especially seen in VGOS frequency 10.4564 GHz. We therefore conclude that we can use source information available in either X- or U-band to be suitable for investigating source structure effects in all VGOS bands.

4 Next Steps

The approach developed here can be applied to more well observed sources with multiple images and for various reference frequencies. The established connection with the VieVS structure module further allows investigations using real geometries and actually observed schedules. More work also needs to be done on improving our routines for automatically deriving the source models. At UTAS, we also plan to connect these theoretical investigations with real observations. The ongoing VGOS tests on the Hobart12–Ishioka baseline are a good testbed, as are the VGOS results from CONT17 reported by Elosegui [4].

5 Conclusions

Using new, automated procedures for deriving source models allows us to take the next step in investigating source structure in VGOS.

The overall aim of these investigations is to identify the critical parameters which we need to know about; how they are expected to change with time; and, ultimately, how to observe sources with VGOS, so that they do not adversely influence (or even prohibit) geodetic and astrometric results.

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