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Quasar Structure Effects on the VLBI Reference Frame: The Case of 1144 − 379

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Abstract

The structure and variability of quasars used in geodetic VLBI has a significant impact on geodetic solutions. We investigate these effects in the case of ICRF2 quasar 1144 − 379. We find that the precision of geodetic solutions is directly related to the multi-frequency temporal variability in the quasar flux density. Worst solutions are found when the quasar is observed at different evolutionary stages at S and X–bands; this introduces significant error into ionospheric corrections. Our results suggests that quasar variability can be more important than quasar structure. Accurate calibration of IVS amplitude data is crucial for mitigation of these effects.

1. Introduction

High-precision studies of Earth processes place stringent requirements on space geodetic techniques. The next generation VLBI2010 system aims to derive station positions to 1 mm accuracy and station velocities to 0.1 mm/year [9]. This is an order of magnitude better than current measurements. Clearly, many systematic and stochastic sources of error will need to be eliminated, or at least substantially mitigated.

Pany et al. [11] performed a simulation study that considered three sources of stochastic noise: wet troposphere delay, station clocks, and measurement error. They concluded that wet troposphere is the most important of these. New, fast-slewing small antennas (e.g., the Patriot 12-meter dishes used in the AuScope array [7]) will allow more robust resolution of the troposphere, mitigating this source of error. This, however, comes at a price. In the VLBI2010 strategy, small antennas spend a very short amount of time on any given source. The decrease in both dish size and source integration time (compared to the current observing strategy) means that many of the currently observed quasars will be too faint for VLBI2010.

Quasar structure is known to affect geodetic measurements. In a seminal work, Charlot [3] developed the formalism for estimating the effects of quasar structure. Astrometric VLBI imaging allows the structure index (SI [5]) of an individual source to be calculated. This quantity is related to the logarithm of the median time delay due to quasar structure observed with all terrestrial baselines. Ma et al. [8] tabulated the median structure index values for all ICRF2 quasars, by combining multi-epoch VLBI maps of these sources. Quasars with a median SI greater than three are considered unsuitable for geodesy.

This analysis ignores the temporal evolution of quasars. While useful as geodetic "beacons", physically these objects are in fact jets of relativistic plasma. The direction and brightness of the jets are related to the physics of jet generation and propagation, and they vary on timescales ranging from days [6] to millions of years [12]. Thus, quasar structure and quasar variability are separate, albeit related, concepts.

In the present contribution, we investigate the effects of quasar variability on geodetic solutions.

2. Methods

The quasar 1144 − 379 is one of the main ICRF2 targets in the southern hemisphere. For example, between 2002 – 2008 it has routinely made up five percent of the scans in IVS observations made by the Hobart26 station. There are 11 other sources observed similarly often, out of a total of approximately 350 sources routinely observed by Hobart26.

2.1. VLBI Imaging

This source has a catalogued structure index of 2.2 at 8.4 GHz [8]. The highest resolution VLBI map of this source (beam size $\sim$ 5 mas), made with the Australian Long Baseline Array (LBA) as part of the TANAMI project [10], shows clear evidence of a milli-arcsecond jet extending to the southeast of the compact core. Some hints of jet structure are also seen in a number of lower resolution VLBA images [4]. Significantly, the VLBI structure of this quasar varies substantially over a seven year period from 2002 to 2008, both in flux density and in the size and direction of extended milliarcsecond components with respect to the compact core.

2.2. Multi-frequency Flux Density Variability

The quasar 1144 − 379 has an acceptable median structure index of 2.2, putting it below the recommended threshold of SI = 3 [8], corresponding to a time delay due to source structure of 10 picoseconds (or 3 mm). Structure index is a useful way of quantifying the additional time delay due to quasar structure at the epoch of observations. However, quasars are rarely stable point sources, instead undergoing significant temporal evolution. Figure 1 shows the 6.7 GHz flux density variability of 1144 − 379 over a period of seven years, as monitored by the University of Tasmania Ceduna 30-meter telescope [2]. Ceduna single dish observations trace out the *total* flux density (i.e., core plus any extended components), rather than just the compact core used for VLBI. However, VLBI flux densities at X–band (8.4 GHz [4]) clearly follow the Ceduna single dish flux. Importantly, S–band (2.3 GHz) flux densities do not appear to follow the X-band flux, with the spectral index (i.e., the ratio of X-to-S–band flux) varying significantly between observing epochs.

S and X–band VLBI snapshots alone are difficult to interpret. However, the Ceduna data clearly shows that the S–band flux density follows the same pattern as X–band and the 6.7 GHz Ceduna C–band data, but with a delay of $\sim$ 150 days. Such frequency-dependent delays are frequently observed in gamma–ray bright quasars [1], and come about due to well–known physical processes in quasars. Observed radio flux comes from relativistic electrons emitting synchrotron radiation. Acceleration of these electrons (e.g., due to shocks) is first manifested at high frequencies, and cascades to lower frequencies as the electrons lose energy. Thus, any new outburst should first appear at high frequencies (i.e., X–band) and appear at lower frequencies (S–band) sometime later. An increase in total flux density, as seen for example at MJD between 53200 and 54000, is indicative of such an outburst.

2.3. OCCAM Positional Analysis

The OCCAM software [13] can estimate (in a least-squares sense) the positions of network stations and radio sources. Repeatability of these positions is a useful measure of solution accuracy.

Source structure and evolution can affect the accuracy of geodetic solutions in two ways. First, the structure of the source will introduce a baseline–dependent time delay (e.g., [3]). Unlike the case of a point source with incorrect coordinates (Section 3.1), standard geodetic VLBI software cannot correct for structure effects. This is because different baselines will each "see" the source at a different source position, corresponding to a brightness-weighted centroid of the emission as seen by that particular baseline.

The second complication is introduced by the time delay between the S and X–band light curves (Figure 1). Observations in two radio bands are required in order to subtract the frequency-dependent ionosphere from geodetic solutions. However, Figures 1 and 2 clearly show that there are epochs when the two bands trace out different source structure. For example, at MJD of 53400, a new outburst has already taken place at X–band (as indicated by the rising X–band flux in the blue curve), while this has not yet happened at S–band (the red curve flux density is at a minimum).

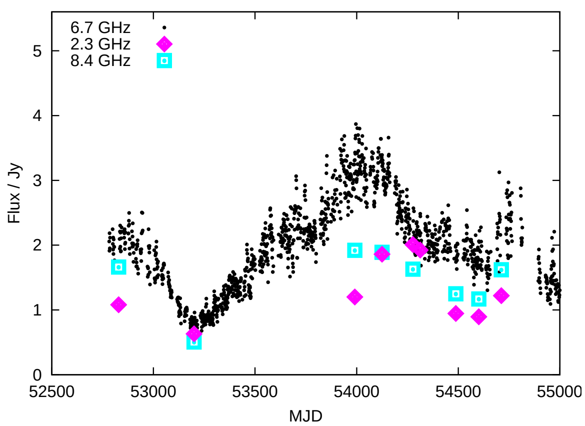

Figure 1. Variability of quasar 1144 − 379. Single dish Ceduna 6.7 GHz data is shown by small black points. Large points are VLBI data [4] at S–band (purple) and X–band (cyan). The X–band light curve lags S–band by ∼ 150 days.

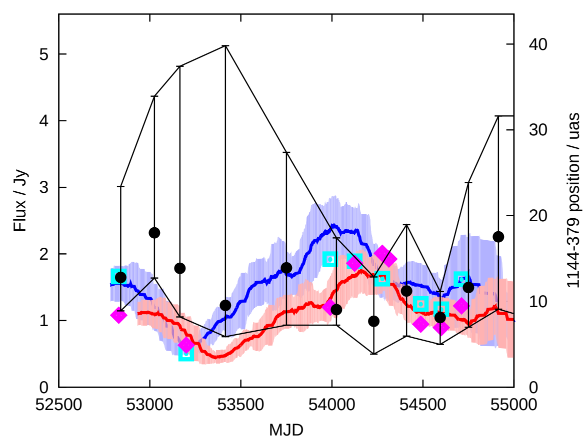

Figure 2. Deviation from the mean position of 1144 − 379 (black points). Colored regions (approximation for S–band in red (lower); X–band in blue (upper)) are scaled (and shifted by 150 days in case of S–band) 6.7 GHz flux densities.

3. Results and Discussion

Hobart26 position and radio source coordinates were determined for the 212 IVS sessions between 2002 and 2008 in which 1144 − 379 was observed.

3.1. Station Positions

An intriguing feature of this source is that, despite being only observed around five percent of the time, it significantly affects geodetic solutions. A linear trend was fitted to the position data in X, Y, and Z coordinates, and for each session the deviation from the expected value was noted. The same analysis was then repeated, but this time with the source $1144-379$ excluded from the solution. We then compared the rms of Hobart26's position with and without this source. Exclusion of $1144-379$ in 75 percent of the cases significantly improved "bad" solutions, in which the measured Hobart26 position was more than 5 cm from the expected value.

Excluding any of the other 11 sources frequently observed with the Hobart26 antenna made no difference to station position repeatability. Moreover, incorrect initial specification of source coordinates for one of these sources ($1057-797$) also seemed to make no difference to the solutions—the OCCAM software managed to correctly solve for both the source and station position when the source's ICRF2 coordinates were deliberately offset by as much as 10 mas. Significantly, the catalogued structure index for $1057-797$ is 3.4, well in excess of the structure index of 2.2 found for $1144-379$ [8].

4. Source Positions

Apart from station positions, OCCAM also calculates positions of radio sources for each IVS session. The effects of source structure and evolution on geodetic solutions can be estimated from these source positions as follows. The average source position for $1144-379$ was calculated from the 212 IVS sessions between 2002 – 2008. The deviation from this mean was then calculated for each individual source position. In Figure 2 we show the median, 25th, and 75th percentiles for these deviations, binned in time. There are typically 15–50 individual 24–hour sessions in each bin.

There is a strong correlation between the positional stability of $1144-379$ (black points) and source evolution at S and X–bands. In the first four time bins, the source shows large deviations from its mean position. At the same time, a very different evolution is seen at S and X–bands. While the MJD of 53050 X–band flux is falling, the corresponding S–band is rising. In the region between 53050 and 53500 the X–band flux turns over much earlier than the S–band flux. Only after MJD of 53500 do both the S and X–band flux have the same first derivative (they are both rising). Physically this corresponds to the emergence of a new jet component [14] – precisely the physical mechanism responsible for source structure.

Remarkably, solutions *improve* as the jet component evolves in the range between the MJDs of 53500 and 54200. This suggests that source structure matters less than the difference between structures at S and X–bands. In other words, it is better to have source structure at *both* S and X–bands, than just one band (as is the case for example at MJD ~ 53500). As expected, the best solutions are obtained in the region 54200 to 54700, where there is minimal structure at both S and X–bands (indicated by a flux density minimum in both bands). For MJDs greater than 54700 the S and X–band fluxes begin to diverge again, resulting in poor solutions.

5. Conclusion

Our results suggest that temporal variability of quasars may be even more important to geodesy than their structure. Multi-frequency flux density monitoring is required to assess the suitability of any given quasar for geodesy at a particular epoch. To this end, amplitude calibration of IVS data would be very valuable. Quasar variability makes the structure index a potentially unreliable indicator of geodetic suitability. More importantly, our result suggests that structure index analysis alone very likely underestimates the effects of quasar structure (by ignoring the frequency dependence) on geodetic accuracy.

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