Simulating the Effects of Quasar Structure on VLBI Observations

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Abstract The structure of quasars making up the celestial reference frame has long been recognized as a potential issue in the quest to achieve a millimeter-level VLBI terrestrial reference frame. We present Monte Carlo simulations of quasar structure in geodetic VLBI observations using the Vienna VLBI Software (VieVS) package. We outline our simulation strategy, including generation of mock quasar catalogs and calculation of structure group delays, and we present results. The effects of source structure on VLBI observables such as station coordinates and Earth orientation parameters are important at the level of a few millimeters and tens of microarcseconds, respectively, for existing networks. We suggest various strategies for minimizing and correcting for the source structure effect.

Keywords Source structure, celestial reference frame

1 Introduction

Quasars used to define the celestial reference frame are not perfect, stable point sources. Instead, they evolve on timescales as short as months, with bright jet components appearing and disappearing in addition to the stable point-like cores [1]. Source structure is usually quantified using the *structure index* (SI; [2]), a quantity related to the logarithm of the median time delay due to quasar structure observed with all terrestrial baselines. Quasars with median SI greater than 3 are considered unsuitable for geodesy [3] and can pose a challenge to the VGOS targets of 1 mm accuracy in position and 0.1 mm/year in velocity [4].

The effect of quasar structure on geodetic observables is not easy to quantify and depends on a number of factors including the relative brightness of the various quasar components and their projected separation as viewed from a baseline subtended by two antennas. In the present contribution, we simulate the effects of quasar structure on geodetic solutions.

2 Source Structure Simulator

The Vienna VLBI Software (VieVS; Böhm et al., these proceedings) contains a simulation capability. Until now, this simulation module has allowed the user to generate synthetic observations containing contributions from various stochastic sources of error including the wet troposphere, clock variance, and instrumental errors. We have extended this simulator to include the systematic effects of source structure. This capability will be included in the next public release of VieVS.

We model radio sources as two-component structures. The brighter component corresponds to the so-called core, while the secondary component (which may be as far as a few milli-arcseconds away) represents the jet. The amount of structure a source has depends on the relative brightness ratio and separation of the two components. For sources with no structure, only the core is seen.

The measured quantity in geodetic VLBI is the X-band ionosphere-corrected group delay, defined as the slope of phase against frequency across the 750 MHz bandwidth centered at 8.6 GHz. In sources that are not point-like, multiple components beat in and out

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of phase in a complicated way that depends on observing frequency. As a result, the extra phase due to source structure is slightly different in the eight X-band channels (due to the different central frequency of each channel). This additional *structure phase* can be plotted against frequency (Figure 1), and the slope of this plot yields the group delay contribution due to source structure.

In the VieVS source structure simulator, this additional *structure group delay* is added to the simulated group delay for each observation (i.e., each baseline–scan pair).

3 Quantifying the Effects of Source Structure

3.1 Mock Catalogs

To investigate the effects of source structure on geodetic observables, we constructed six mock catalogs: (1) one catalog of perfect point sources (i.e., no structure); (2–5) four catalogs where every source has the same structure index of either 1, 2, 3, or 4; and (6) one catalog where structure indices are assigned to individual sources at random but with the constraint that the distribution of structure indices in this catalog matches the observed distribution for ICRF2 sources [3]. For all catalogs, we used the celestial positions of actual ICRF2 sources but assigned fictitious structures to each source.

For each source, we generated mock images (as shown, for example, in Figure 1) from structure indices as follows. The jet direction (i.e. the direction of the vector joining the two components) was assigned at random. The ratio of the relative brightness of the two components was also chosen at random from the range 0.04–0.44. Together with the structure index, this brightness ratio then determined the component separation; this was typically ≤ 5 mas, consistent with astronomical imaging of many ICRF2 sources.

This procedure was repeated for each source in each of the six catalogs described above.

3.2 Simulations

To quantify the effects of different levels of source structure on geodetic observables, we ran simulations using schedules from the CONT11 campaign. CONT11 has a number of advantages over the usual R1 and R4 experiments, including a larger number of observations and a fixed, large network that minimizes the effects of network geometry.

We ran 30 simulations for each day of CONT11 using our six mock catalogs. Two types of simulations were performed: (a) those including only source structure and (b) those including tropospheric turbulence and clock instabilities in addition to source structure. We added 1 picosecond of white noise to each simulation. For each day in each simulation, we calculated station positions and Earth Rotation Parameters. The quality of solutions was gauged using three metrics: (1) difference between median estimated parameter value and the original input value; (2) standard deviation in the estimated value, and (3) formal uncertainty.

The left panel of Figure 2 shows the effects of different levels of source structure on station coordinates in structure-only simulations. A clear decrease in both accuracy (green line) and precision (red and blue lines) is seen as the amount of source structure is increased. For full simulations (right panel of Figure 2) this signal is less obvious due to the dominant contribution from the troposphere, but still present. Overall, source structure contributes to position uncertainties at the millimeter level and must therefore be corrected or mitigated if the VGOS targets of 1 mm accuracy in position and 0.1 mm/year in velocity are to be achieved.

Figure 3 similarly shows that inclusion of source structure degrades the quality of solutions for Earth Rotation Parameters. Further details on these simulations and results can be found in [5].

4 Mitigation Strategies

There are two main strategies for mitigating the effects of source structure: selecting quasars to have little structure or applying appropriate corrections.

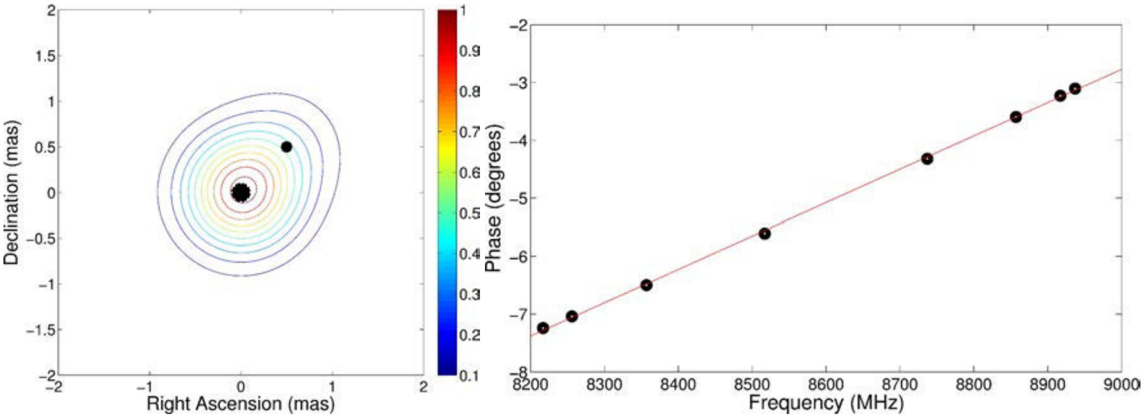

Fig. 1 *Left panel*: Simulated two-component source with structure index 2.7. The flux density ratio of the two components (filled circles) is 5:1. Each component is modeled as a δ-function, and the structure is convolved with a 1 mas beam. Colors represent scaled flux density. *Right panel*: Structure phase as a function of frequency for this source observed with a 9,280 km baseline parallel to the source jet axis. The structure contribution to the group delay is given by the slope of phase against frequency. Black points represent the eight X-band channels.

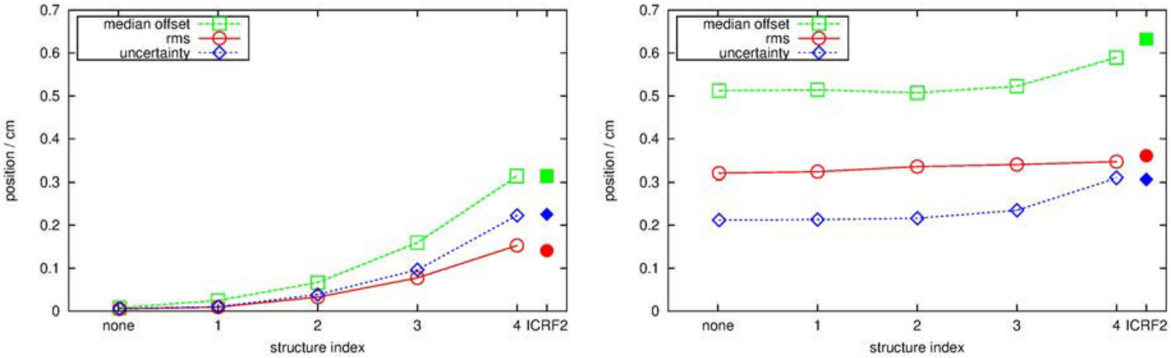

Fig. 2 Effects of source structure on station coordinate offsets (measured−true value, shown in green), debiased rms (red), and median formal uncertainty (blue) over 15 days of CONT11. Left panel: structure-only simulations; right panel: full simulations. Median values over all stations are shown. Filled symbols are for the ICRF2 distribution of structure indices.

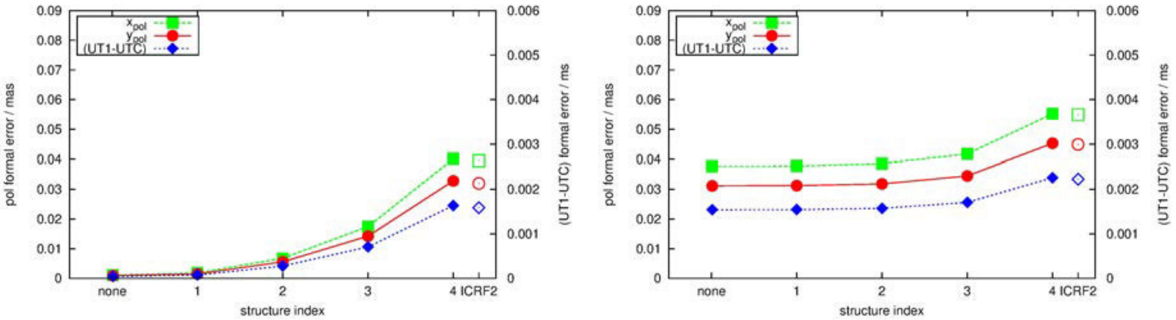

Fig. 3 Effects of source structure on the median formal uncertainty for x_{pol}, y_{pol}, and (UT1-UTC). Left panel: structure-only simulations; right panel: full simulations. Open symbols are for the ICRF2 distribution of structure indices.

4.1 Quasar Selection

In the first approach, ICRF2 sources are imaged at regular intervals [2, 6], and those sources with large structure indices (typically SI ≥ 3 [3]) are scheduled less often than sources that exhibit less structure. This is the standard strategy currently used in scheduling IVS observations. There are two potential difficulties with this approach.

First, the reduction in quasar structure by excluding many sources significantly limits the density (and homogeneity of distribution) of sources in the celestial reference frame. Most quasars brighter than $\sim$100 mJy at X-band have already been identified, and this situation will therefore not be improved with additional observations, unless a move to much higher frequencies (e.g., 32 GHz [7]) is made.

Secondly, quasars evolve significantly on timescales of months to years, and care must be taken when deciding which quasars are "stable" on any given day. Fortunately, a number of astrophysical metrics can be used to evaluate or even predict the amount of structure a source has. These include direct VLBI imaging [8, 2, 3], or variability properties of radio sources [9, 10]. It should therefore be possible to flag sources as being presently unsuitable for observation; this list would be updated continuously.

4.2 Structure Corrections

An alternative approach uses VLBI images of radio sources to correct for structure. Quasar variability is again a problem, as corrections applied using an outdated model for the quasar are likely to cause more harm than good. This, however, should not be a problem for future VGOS-style observations, in which source images will be a standard data product [11, 12]. An important issue is whether the expected astrometric accuracy and amplitude calibration will allow for structure corrections of sufficient quality to be applied to the data. We aim to investigate these issues in the near future with the source structure simulator described in this paper.

5 Scheduling with Respect to Source Orientation

A very different approach to the source structure problem is to use some a priori knowledge of quasar physics to schedule quasars. Although quasar structure varies appreciably on human timescales, it invariably consists of either a core or a core plus jet. The *direction* of the jet does not change appreciably (although some jets do precess). It has been suggested by R. Porcas [13] that jet direction information can be used in scheduling, since even for sources with significant jet components, structure effects are zero if the jet is oriented perpendicular to the observing baseline. Figure 4 shows the impact of jet–baseline orientation on simulated group delays due to source structure.

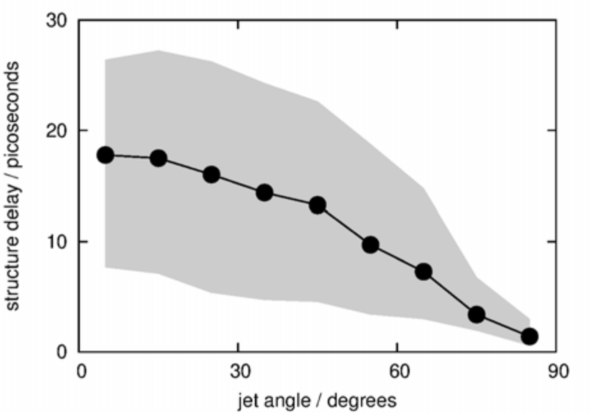

Fig. 4 Structure group delays per observation as a function of relative jet–baseline orientation, for an SI=3 simulated mock catalog. The points are medians, and the shaded region is the interquartile range. Even high structure index sources contribute very little to the structure group delay if the jet direction is almost orthogonal to the observing baseline.

Single-baseline scans are rare in geodetic VLBI. It is therefore likely that, for any scan of an extended source, at least one baseline will have an unfavourable orientation with respect to the jet direction. Given some crude knowledge of source structure, however, it should be possible to optimize the observing strategy for that particular source. For example, our simulations in Figure 4 suggest that for two equal-length orthogonal baselines, smaller total structure delays may be obtained by having one baseline be orthogonal and the other parallel to the quasar jet axis, rather than two baselines at 45°. A more sophisticated approach would also include baseline length information, since shorter baselines suffer less from source structure effects. In this way, a combination of source structure, jet orientation, and baseline information could inform the scheduling process.

6 Broadband Observations

Some additional complications relating to source structure arise in the case of broadband (2–14 GHz or similar) observations. Quasar structure is frequency-dependent in the sense that sources typically exhibit less structure at higher frequencies. Time-variable properties of quasars also depend on observing frequency. Finally, even quasars showing little structure exhibit *core shifts*, a synchrotron self-absorption effect that causes the location of the observed quasar core to change with frequency. Understanding the multi-frequency behavior of quasar structure (and its temporal evolution) is necessary for making any meaningful corrections to broadband VGOS data.

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