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Structure Corrections in Modeling VLBI Delays for RDV Data

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Abstract

Since 1997, bimonthly S- and X-band observing sessions have been carried out employing the VLBA and as many as 10 additional antennas. Maps of the extended structures have been generated for the 160 sources observed in ten of these experiments (≈200,000 observations) taking place during 1997 and 1998. This paper reports the results of the first massive application of such structure maps to correct the modeled VLBI delay in astrometric data analysis. For high-accuracy celestial reference frame work, proper choice of a reference point within each extended source is crucial. Here the reference point is taken at the point of maximum emitted flux. Overall, the weighted delay residuals (≈30 ps) are reduced by 8 ps in quadrature upon introducing source maps to model the structure delays of the sources. Residuals of some sources with extended or fast-varying structures improve by as much as 40 ps. Scatter of "arc positions" about a time-linear model decreases substantially for most sources. Based on our results, it is also concluded that source structure is presently not the dominant error source in astrometric/geodetic VLBI.

1. Introduction

With the exception of some exploratory studies (*e.g.* [3]), analyses of VLBI data during the past 25 years have assumed that the compact extragalactic radio-emitting objects observed in geodetic and astrometric experiments are point sources. It has been known for some time [5] that most, and probably all, such sources have internal structures at the milliarcsecond level. Extended structures, when viewed from various baselines at varying times, can give rise to VLBI delay contributions of tens or even hundreds of picoseconds [6]. Since the current accuracy of the celestial reference frame (ICRF) is ≈250 μas (≈20 ps on a typical baseline) [7], correcting for these source structure contributions should be of some importance.

At this point in the development of the VLBI technique, when formal precisions have reached the 10 μas level, it is important to assess the level at which source structure contributes to systematic mismodeling of the observables. Potential benefits of doing so include possible improvement of the ICRF accuracy, as well as a better characterization of the VLBI "error budget". If source maps could be routinely introduced into analyses of astrometric experiments, it would be a start on the road to determining truly fiducial points in the sky.

2. Experimental Data and Analyses

Since 1997 GSFC, USNO, and NRAO have carried out bimonthly dual-frequency (S- and X-band) VLBI experiments employing the Very Long Baseline Array (VLBA). The observing sites in these "RDV" experiments include all 10 VLBA antennas plus other stations in North America, Europe, Asia, and the Pacific. The first ten of these experiments (1997 Jan. to 1998 Aug.) were chosen for this study. They comprise 206,744 observation pairs (delay + delay rate) of 160 extragalactic radio sources. Mapping the source structures was done with the methods of [6]. The resulting data base of 800 pairs of maps serves as the basis for modeling structure corrections from the CLEAN components of the maps.

All subsequent analysis was done with the JPL software Modest [9]. The *a priori* terrestrial and celestial frames were ITRF 2000 and ICRF Ext.1, respectively [1] [7]. Source structure contributions to the observables were modeled following the work of Charlot [2]. OJ 287 served as the right ascension reference. Station clock parameters were estimated every 6 hours, zenith wet tropospheric delays every hour, and (E, N) tropospheric gradients daily. Earth orientation (UTPM and two nutation angles) were also estimated for every experiment, as well as station antenna axis offsets for each station. Observable weighting included additional elevation-dependent noise, whose scaling factor was adjusted for each baseline in each experiment in order to make χ^2 per degree of freedom ≈ 1. Depending on the fit (see below), 6 to 7000 parameters were estimated from the observables.

Source structure effects were evaluated employing two sets of alternate approaches: on one hand, treating source coordinates as either universal or session-specific parameters, and on the other hand, omitting or applying delay and delay rate structure corrections to the modeled observables. In the session-specific case a new source position was estimated for each source in each experiment (with the exception of the adopted RA reference source). Only 47 of the 160 sources are observed in all 10 experiments, but these data comprise approximately 70% of the total observations in the data base. Comparison of the scatter of source positions of these 47 sources permits evaluation of the impact of source structure correction during the 1.5-year data span.

A crucial choice in correcting for source structure effects is the adoption of a reference point for each source. This is by no means trivial, and in fact may be more difficult than the process of generating the structure maps. Ideally, this fiducial point should be the center of the driving engine. As components are ejected and observed, the centroid or peak of the observed radio flux can vary substantially both with time and with frequency. Detailed studies of sequences of maps are required to try to approximate the true fiducial point within each extended source. For the experiments considered here, such studies are only in their initial stages [4]. In the present analyses the reference point of each source was taken at the maximum of the observed flux at each of the two frequencies (X- and S-bands).

3. Results

A broad-brush characterization of the results of fits to the ten RDV experiments includes overall weighted delay and delay rate residuals on the order of 30 ps and 90 fs/s. Formal uncertainties of source coordinates and other angular parameters (UTPM, nutation angles) are in the range of several tens of microarcseconds. Corresponding uncertainties of station coordinates and the antenna axis offsets are in the 1 mm range.

For the purposes of the present paper, two aspects of the VLBI parameter estimation are singled out. First, examination of the delay residuals should indicate whether modeling structural delays via source maps improves the overall fit between experiment and theory. Second, comparison of the variation of source coordinates from experiment to experiment with/without applied structure corrections should show whether the structure delay corrections are indeed removing systematic errors introduced by variations in the appearance of the sources during 1997–98. These two aspects of the analysis are discussed in turn in the two following sections.

3.1. Delay Residuals

When source structure is not modeled, the weighted root-mean-square (WRMS) delay residuals for the 206,744 observations are 31.17 picoseconds with a single estimated position of each source, and 30.67 ps if a new set of source coordinates is estimated for each of the ten experiments. The RSS difference of these values (5.6 ps) may partly arise from source structural variations with time, and indicates the possible approximate scale of this effect during the 1.5-year data span.

Modeling additional structural delays by employing source maps reduces the above WRMS delay residuals to 30.17 and 29.75 ps, respectively. This indicates that accounting for the extended and time-varying appearance of each source improves the VLBI model by ≈8 ps (3 mm) in quadrature. The origin of this improvement can be probed more deeply by examining the behavior of weighted delay residuals for groups of sources. One relatively simple way of grouping them is by means of the "structure index" SI introduced in [6]. This integer ranges from 1 to 4 and increasing values indicate increasing average structural VLBI delay corrections. (A given source may have differing values of the structure index at S- and X-band, SSI and XSI respectively).

The improvement in delay residuals is defined as ΔD

$$(\Delta D)^2 = \sum_{i=1}^{N_{obs}} w_i \; (D^2_{i,uncor} - D^2_{i,str}) \; / \sum_{i=1}^{N_{obs}} w_i \;, \tag{1}$$

where the summation extends over the N_{obs} observations i weighted by w_i, and $D_{i,(uncor,str)}$ is the delay residual in a fit in which the source structure is respectively (uncorrected, corrected). Table 1 shows the weighted delay residual improvement for the four classes of structure index in both frequency bands. These results are from the "arc position" fits. Residual improvement

Table 1. Delay Residual Improvement (ps) *vs*. X- and S-band Structure Indices

XSI	N_{obs}	ΔD	SSI	N_{obs}	ΔD
1	76862	6.5	1	164151	6.4
2	76903	4.2	2	23483	8.2
3	32746	11.7	3	6912	13.8
4	8035	16.8	4	0	...

increases with increasing complexity of the source structure, with the biggest impact of structure modeling being evident for structure indices of 3 and 4.

3.2. Source Coordinates

In order to examine the impact of structure modeling on aspects of the fit other than the residuals, it is also prudent to examine the behavior of some of the estimated parameters. The logical choices for initial study are the source right ascension (α) and declination (δ). By analogy with the delay residuals discussed in the previous section, measures of improvement can be defined for source coordinate scatter in an arc-position solution. Time-linear least squares fits were done for the ten pairs of source coordinates of each of the 47 sources that were observed in all 10 experiments. "Improvement" then means that the time variation of source coordinates is more stable when source structure is modeled. The definitions of scatter improvement are

$$(\Delta\alpha)^2 = \sum_{i=1}^{10} w_{\alpha_i} \left[(\alpha_{i,uncor} - \bar{\alpha}_{i,uncor})^2 - (\alpha_{i,str} - \bar{\alpha}_{i,str})^2 \right] / \sum_{i=1}^{10} w_{\alpha_i} \qquad (2)$$

$$(\Delta\delta)^2 = \sum_{i=1}^{10} w_{\delta_i} \left[(\delta_{i,uncor} - \bar{\delta}_{i,uncor})^2 - (\delta_{i,str} - \bar{\delta}_{i,str})^2 \right] / \sum_{i=1}^{10} w_{\delta_i} \qquad (3)$$

for right ascension and declination, respectively. Here the barred quantities represent the coordinates calculated from linear least-squares fits of the time dependence of the coordinates of each source, $w_{(\alpha,\delta)_i}$ are weights, and as before, the subscripts $(uncor, str)$ stand for coordinates from fits (uncorrected, corrected) for structure delay. Plus and minus signs of $\Delta\alpha$ and $\Delta\delta$ denote improvement and worsening, respectively (in the latter case, *e.g.*, $\Delta\alpha^2$ is negative, and the metric $\Delta\alpha$ is calculated as $\Delta\alpha = -\sqrt{|\Delta\alpha^2|}$).

The average source coordinate scatter improvement values $\langle\Delta\alpha\rangle$, $\langle\Delta\delta\rangle$ are (−3, 24) μas for the 47 sources if the averages are weighted by the number of observations of each source. Table 2 shows details of the scatter improvement resulting from introduction of source structure delay modeling for the 47 frequently observed sources. Here the sources are classified by their structure indices. It is seen that the overall (−3, 24) μas improvements in RA and dec scatter are not

Table 2. Source Coordinate Scatter Improvement (μas) *vs.* X- and S-band Structure Indices

XSI	N_{obs}	$\langle\Delta\alpha\rangle$	$\langle\Delta\delta\rangle$	SSI	N_{obs}	$\langle\Delta\alpha\rangle$	$\langle\Delta\delta\rangle$
1	62394	−8.4	4.3	1	124785	−2.8	22.7
2	54475	3.6	6.8	2	13097	−17.1	18.1
3	21013	6.5	115.4	3	0	...	...

uniformly distributed among sources with different structure indices. In particular, the right ascension results may be influenced by inappropriately fixing the RA orientation of the reference frame. This possibility will be investigated in the near future. Improvement in declination scatter can reach a substantial fraction of the current ICRF accuracy estimate of 250 microarcseconds.

3.3. VLBI Error Budget

The present fit to RDV data has implications for the astrometric/geodetic VLBI error budget. Source structure mismodeling was found to contribute ≈8 ps (3 mm) to the ≈30 ps (10 mm) WRMS residual delay. Assuming that the two other major contributors to unexplained discrepancies between theory and experiment are presently the instrumental and tropospheric delays, and that their mismodeling is of roughly equal magnitude, the conclusion is that each amounts to ≈20 ps or 6 mm. When the troposphere error is routinely reduced below 1 mm (3 ps) [8], the focus in reducing errors will have to be switched to instrumental systematics, and source structure corrections will need to play a larger role in VLBI analyses.

4. Conclusions

Modeling source structure with maps improves VLBI analysis, predominantly for sources with extended X-band structures. The improvement is larger for bad structures, and larger for declination than for right ascension. Impact of unmodeled source structure on the VLBI error budget is not overwhelming. It is estimated to be smaller than either the present unmodeled tropospheric or instrumental effects by at least a factor of 2. For sources that happen to be undergoing substantial activity during the VLBI observation period, modeling structural changes is extremely important.

Further exploratory work should be able to determine how effectively existing source maps can be used to correct observations in other experiments that are a few months removed from the mapping epochs. When troposphere errors can be reduced to 1–2 mm by improved WVRs, structure effects will become more prominent in the VLBI error budget. Detailed studies of time sequences of maps should permit location of the invariant (fiducial) points within sources. Future studies may show whether source structure produces an irreducible inherent uncertainty of the fiducial points on the sky. If so, the achievable accuracy of an inertial reference frame based on extragalactic radio sources would be ultimately limited by such fuzziness.

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