Troposphere Delay Raytracing Applied in VLBI Analysis

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Abstract Tropospheric delay modeling error is one of the largest sources of error in VLBI analysis. For standard operational solutions, we use the VMF1 elevation-dependent mapping functions derived from European Centre for Medium Range Forecasting (ECMWF) data. These mapping functions assume that tropospheric delay at a site is azimuthally symmetric. As this assumption does not reflect reality, we have instead determined the raytrace delay along the signal path through the three-dimensional troposphere refractivity field for each VLBI quasar observation. We calculated the troposphere refractivity fields from the pressure, temperature, specific humidity, and geopotential height fields of the NASA GSFC GEOS-5 numerical weather model. We discuss results using raytrace delay in the analysis of the CONT11 R&D sessions. When applied in VLBI analysis, baseline length repeatabilities were better for 70% of baselines with raytraced delays than with VMF1 mapping functions. Vertical repeatabilities were better for 2/3 of all stations. The reference frame scale bias error was 0.02 ppb for raytracing versus 0.08 ppb and 0.06 ppb for VMF1 and NMF, respectively.

Keywords Troposphere, raytracing

1 Introduction

Tropospheric delay modeling is still a significant source of random and systematic error in the analysis of VLBI data. In current tropospheric delay modeling, the elevation dependence of tropospheric delays is described by hydrostatic and wet mapping functions. It is assumed that the atmosphere has no horizontal refractivity variation. Both the NMF mapping functions [4], which used the radiosonde tropospheric profile data, and the VMF1 mapping functions [1], which used the ECMWF weather model data, were derived by computing raytrace delays through uniform atmospheric layers of constant refractivity. In the work described here, we have computed the total (hydrostatic & wet) delays and the wet mapping functions from a numerical weather model for each VLBI observation by raytracing through the three-dimensional refractivity field at the observation epoch.

2 Data and Raytracing Algorithm

Troposphere data is taken from the NASA GSFC GEOS 5.9.1 data assimilation model, which has a temporal resolution of three hours, a horizontal resolution of $0.5^\circ \times 0.625^\circ$, and troposphere profiles with 72 vertical levels. From the model pressure, temperature, relative humidity and geopotential heights, we have calculated the corresponding three-dimensional refractivity fields. For each VLBI observation, the refractivity along the signal raypath was then calculated by spatial interpolation of the refractivity field interpolated to the VLBI epoch. A piecewise linear approach similar to one proposed by Hobiger [3] was used to determine the path of the ray and then to compute the hydrostatic and wet delay components along the path. To minimize computation time, the

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propagation of the ray is constrained to a plane of constant azimuth.

3 Analysis

In a first test, we investigated how much of the observed wet zenith delay is modelled by the raytraced wet zenith delay. The observed VLBI residual zenith delay was estimated in a solution where the a priori tropospheric delay was the NMF hydrostatic delay so that the residual delay is predominantly the wet zenith delay. Figure 1 shows how closely the raytraced wet zenith delay agrees with this estimate of the observed delay for Westford (Massachusetts) over the CONT11 time period. The average correlation for CONT11 sites between the observed estimate of wet zenith delay and the raytraced wet zenith delay was 0.93. The raytraced wet zenith delay accounts for about 90% of the RMS of the estimated wet zenith delay estimates.

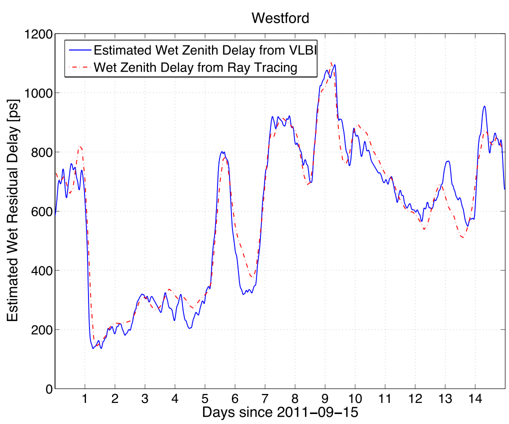

Fig. 1 Comparison of the raytraced wet zenith delay at Westford and the wet residual delay estimated from observed VLBI data.

We then ran a VLBI solution for the CONT11 series of sessions applying as the a priori delay the total raytraced delay for each observation. It is still necessary to estimate the usual troposphere parameters; residual wet zenith and gradient delays were estimated as piecewise linear functions with 20-minute and six-hour intervals, respectively. The wet mapping function was computed from calculated wet raytraced delays for each observation. For comparison, two additional solutions were performed that used: 1) NMF mapping functions and 2) the VMF1 total delay as the a priori troposphere delay and the residual wet delay estimated using the VMF1 wet mapping function. We also evaluated three different data weighting strategies: 1) baseline reweighting, 2) elevation-dependent weighting, and 3) correlated noise. Baseline reweighting adds a constant noise contribution in quadrature to the observation uncertainties such that the χ^2 per degree of freedom is unity. Elevation-dependent weighting instead adds noise of the form $\alpha/\sin(elev)$ to the observation uncertainties. Correlated noise [2] includes an elevation-dependent off-diagonal correlation between simultaneous observations on baselines that share a common station. Table 1 summarizes the results of these test solutions in terms of the average baseline length WRMS repeatability. The best weighting strategy for all three troposphere options was correlated noise, and the best troposphere modeling choice was to use raytraced delays and mapping functions.

Table 1 CONT11 baseline length WRMS.

	NMF	VMF1 Total	Raytrace
Weighting	Average	Average	Average
Baseline	6.89	6.75	6.41
Elevation-dep	6.50	6.31	6.04
Correlated noise	6.35	5.96	5.73

Figure 2 shows the improvement in baseline length repeatability using raytraced delays versus using VMF1. For each site, the baseline length improvement is shown for all baselines to the site. The measure of improvement is the reduction (in quadrature) of the WRMS (weighted root mean square) repeatability. Because the baselines are ordered by length, it can be seen that the improvement generally increases with length. Most baselines improve except for Kokee (Hawaii). Length repeatabilities are improved for 72% of the baselines. Kokee is located on the Hawaiian island of Kauai at an elevation about 800 m higher than the ocean surface. The GMAO grid cells that contribute to the raytrace delay calculation may not reflect the true local troposphere behavior at Kokee. Improvement of site position repeatabilities (raytrace versus VMF1) are shown in Figure 3, where site vertical coordinate repeatabilities are improved for 11 of 13 sites.

Whenever mapping function improvements have been made in the past, reference frame scale errors

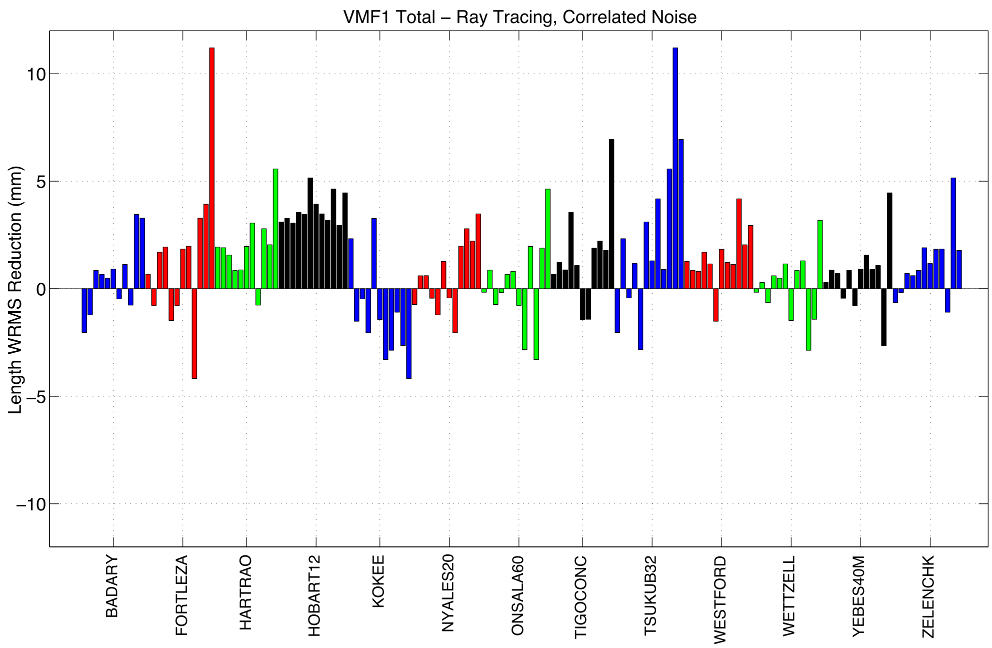

Fig. 2 Improvement in baseline length for different baselines of the CONT11 sessions. Baselines for each site are ordered by length.

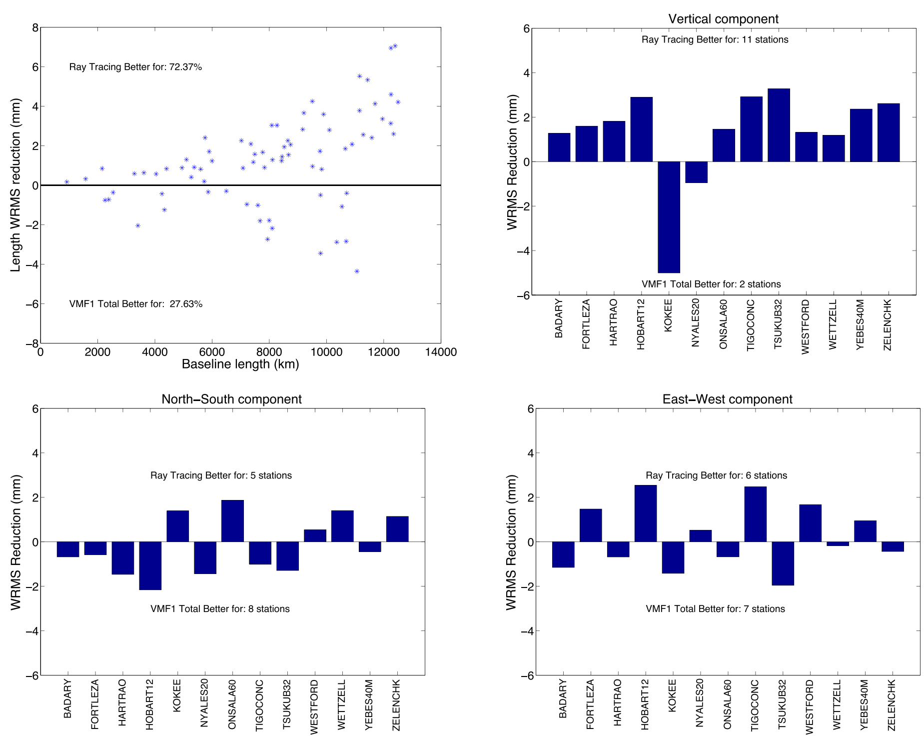

Fig. 3 Improvement in baseline length and in station position (up, east, north) estimates for the CONT11 experiment sessions.

have been reduced. We have estimated the scale bias error by performing an elevation cutoff test using two solutions, one with a minimum elevation cutoff of 5° and the other with a cutoff of 12°. The idea of the cutoff test is that troposphere modeling error increases as elevation decreases and that a measure of this error is given by how much position estimates at the higher cutoff change when low elevation data is included in a solution. For each baseline, the mean baseline length difference between the baseline length series estimated from each of the cutoff solutions was computed. The scale bias is the slope of the best-fitting line in Figure 4 through the differences as a function of baseline length.

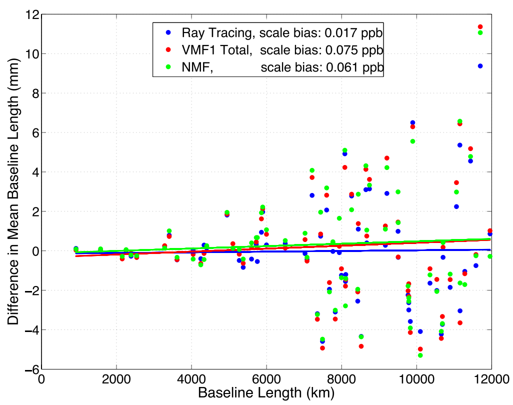

Fig. 4 Scale bias from mean baseline length differences between solutions with minimum elevation cutoff at 5° and 12°.

For the raytrace delay solution, the scale bias was 0.017 ppb. For solutions where VMF1 or NMF were used, the scale biases were 0.061 ppb and 0.075 ppb, respectively.

4 Conclusions

Raytracing has the potential to significantly improve VLBI analysis. Applying raytraced delays in the analysis of the CONT11 experiment sessions improves the baseline length repeatabilities for 72% of baselines and vertical repeatabilities for 11 out of 13 sites compared with using the VMF1 model. We are currently producing raytracing results for the entire GEOS-5 time period (2000 to the present) as part of a raytracing service to provide tropospheric delay corrections for all VLBI sessions at http://lacerta.gsfc.nasa.gov/tropodelays/. The current latency is 24 hours, which allows the raytracing service to provide delays to the VLBI community for application of tropospheric corrections within one day after a session is observed.

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