Tropospheric Delay Raytracing Applied in VLBI Analysis

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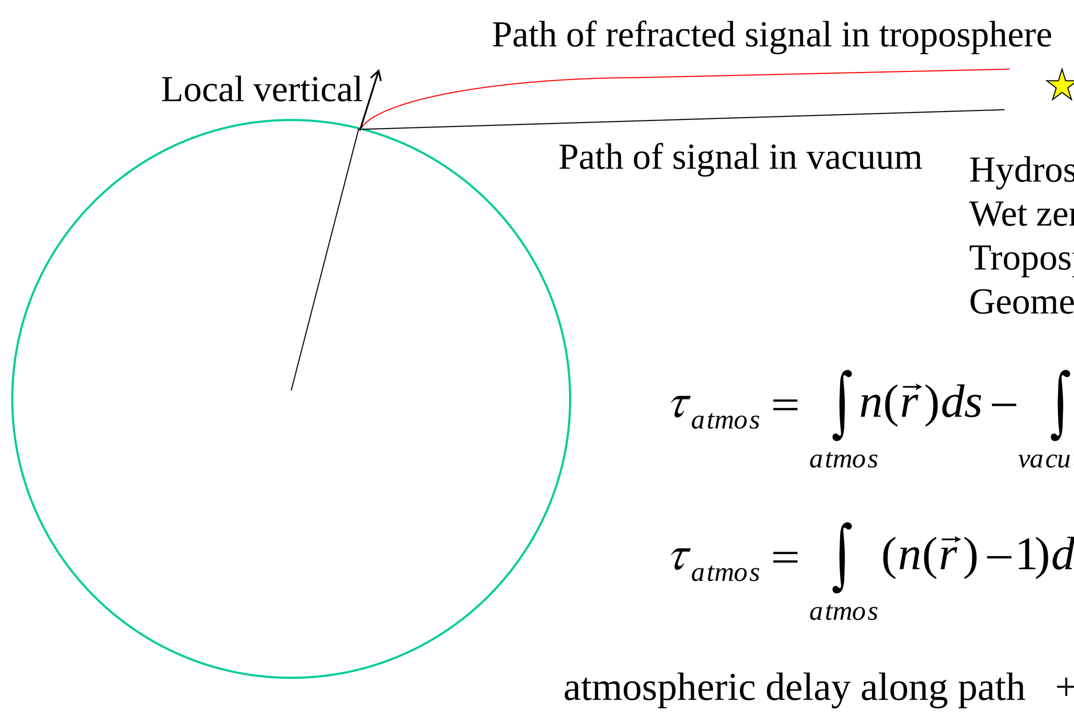
Introduction

Tropospheric delay modeling error continues to be one of the largest sources of error in VLBI analysis. For standard operational solutions, we use the VMF1 elevation-dependent mapping functions derived from ECMWF data. These mapping functions assume that tropospheric delay at a site is azimuthally symmetric. As this assumption does not reflect reality, we have determined the raytrace delay along the signal path through the troposphere for each VLBI quasar observation. We determined 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 from analysis of the CONT11 R&D and the weekly operational R1+R4 experiment sessions. When applied in VLBI analysis, baseline length repeatabilities were better for 66-72% of baselines with raytraced delays than with VMF1 mapping functions. Vertical repeatabilities were better for more than 70% of sites.

1 Raytracing versus Mapping Functions



Hydrostatic zenith delay: 2.3 m
Wet zenith delay: 5-50 cm
Tropospheric Delay at 5 deg: 25 m
Geometric excess at 5 deg contribution: 20 mm

$$\tau_{atmos} = \int_{atmos} n(\vec{r})ds - \int_{vacuum} ds$$

$$\tau_{atmos} = \int_{atmos} (n(\vec{r})-1)ds + \left(\int_{atmos} ds - \int_{vacuum} ds \right)$$

atmospheric delay along path + excess geometric path length

$$N = (n-1)10^6$$

The refractivity N(r) is a function of total pressure P, water vapor pressure P_v and temperature T , which are extracted from radiosonde profile data or 4-D numerical weather model data.

The mapping function approach applied the simplifying assumption that the troposphere was azimuthally symmetric about the zenith direction at a geodetic site.

$$\tau_{total}^{symmetric}(el) = m_{hydrostatic}(el)\tau_{dry}^{zenith} + m_{wet}(el)\tau_{wet}^{zenith}$$

To account for azimuthal asymmetry, additional linear gradient parameters G_N and G_E are estimated. The gradient tropospheric delay through the atmosphere is

$$\tau_{gradient}(el,az) = m_{grad}(el)[G_N\cos(az) + G_E\sin(az)]$$

Mapping functions , m(el), were derived by raytracing through uniform atmospheric layers of constant refractivity, where the refractivity of each layer is computed using the P, T, and P_v from a profile centered at the geodetic site location. This is what is meant by 1-dimensional raytracing.

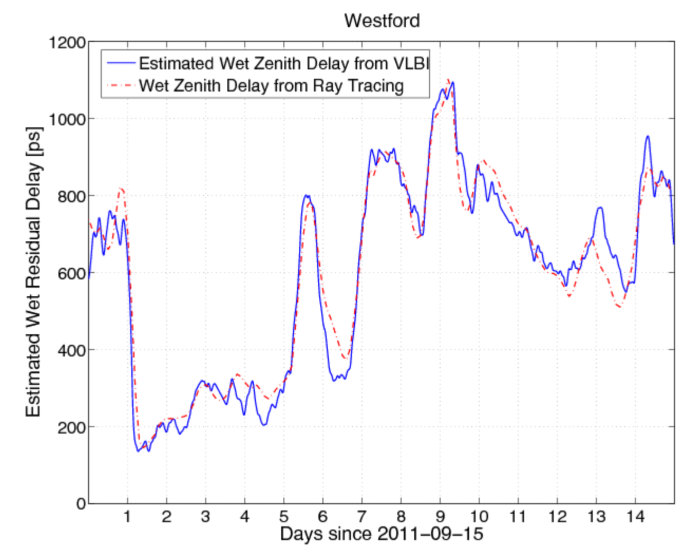
1) NMF (Niell, 1996) mapping functions: 1-dimensional raytrace of radiosonde troposphere profile data for a set of Northern Hemisphere locations => NMF is parametrized by time of year (assuming an annual period variation), latitude, and site height. Assumed that Southern Hemisphere temporal variation is 180 degrees out of phase with the Northern Hemisphere.

2) VMF1: (Boehm et al., 2006) 1-dimensional raytrace of ECMWF (European Center for Medium Range Forecasting) tropospheric profile data given at 6-hour intervals and spatially interpolated to each geodetic site. It is assumed that there is no horizontal refractivity variation.

Raytracing Algorithm

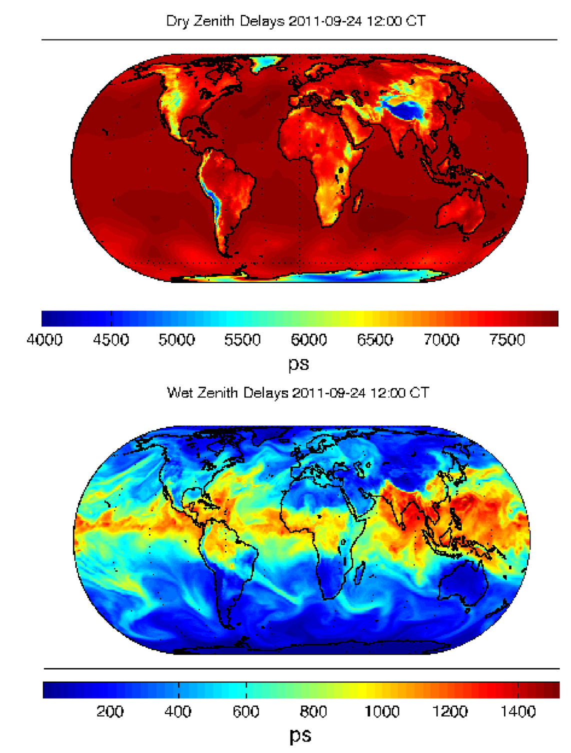
- Build the 3D refractivity field from NASA/GSFC GEOS 5.9.1 numerical weather model profile data
- Interpolate refractivity field data to the VLBI epoch
- Assume that the raypath stays in a plane of constant azimuth
- Raytrace using a piecewise linear approach (see Hobiger et al., 2008) to find the ray path
- Evaluate the hydrostatic and wet delays along the path => a priori total and wet delays for each VLBI observation
- Compute a wet partial derivative for each observation = (raytraced wet delay)/(raytraced wet zenith delay) for each observation
- Current processing time: 1000 VLBI observations at 5 deg elevation -> 1 second

2 Zenith Delays



How much of the observed wet zenith delay is modeled by the raytraced wet zenith Delay? =>

- Apply a priori hydrostatic delay model: Saastamoinen hydrostatic zenith delay x NMF hydrostatic mapping function.
- Estimate residual wet zenith delay from VLBI data
- Average correlation for CONT11 sites between estimated wet zenith delay and raytraced zenith wet delay = 0.93
- The wet zenith raytrace delay accounts for about 90% of the RMS of the wet residual delay estimated from VLBI data



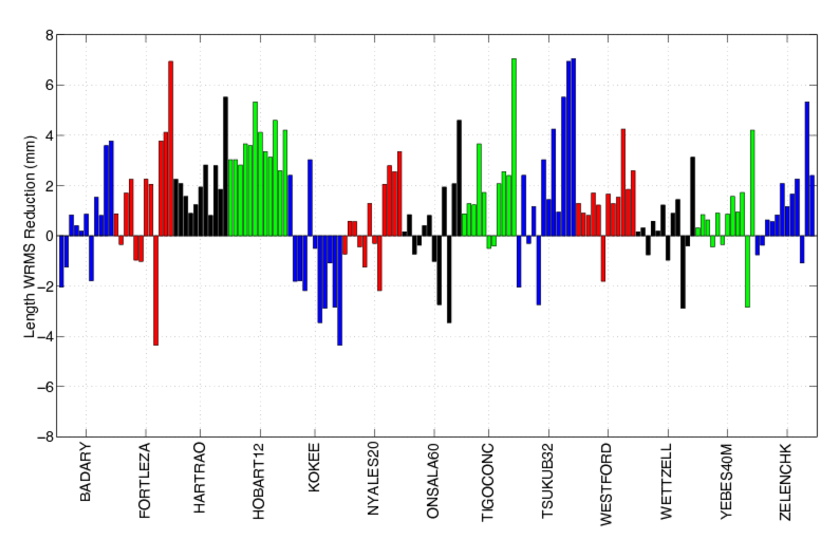
Global distribution of raytraced dry zenith (hydrostatic) and wet zenith delays at one epoch (20ll-Sept-24-12UT

3 CONT11 Experiment Results

CONT11 is a series of continuous 24-hour R&D VLBI experiment sessions over the period September 15-29, 2011 using a network of 14 stations. The purpose of the CONT11 campaign was to acquire state-of-the-art VLBI data over a time period of about two weeks to demonstrate the highest accuracy of which the VLBI system is capable. This supports high resolution Earth rotation studies, investigations of reference frame stability, and investigations of daily to sub-daily site motions.

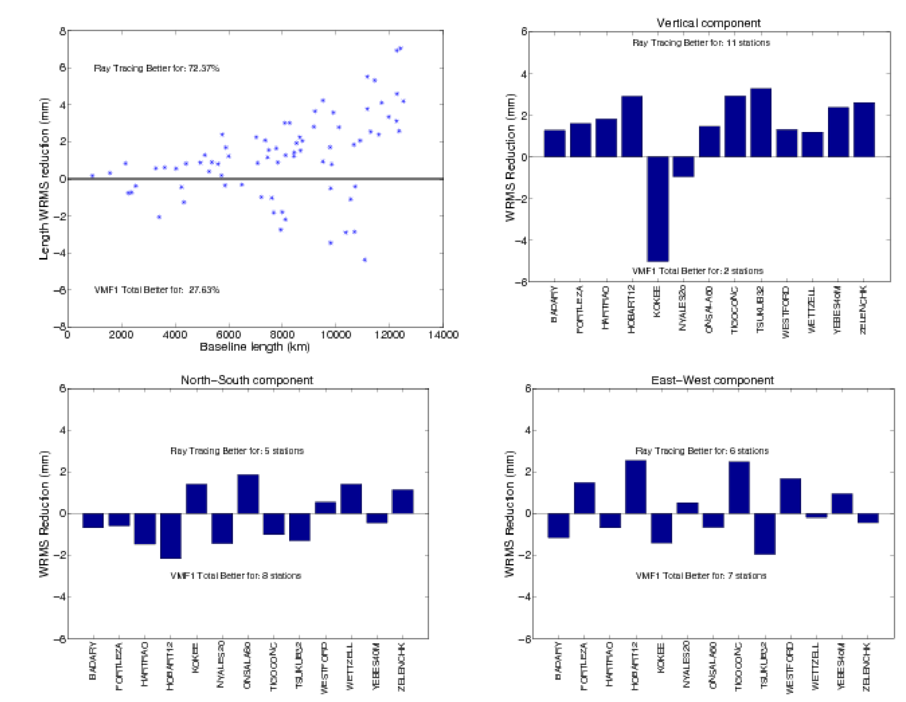
We ran VLBI solutions with raytraced delays:

- Applied a priori tropospheric raytraced delays for each observation
- Still necessary to estimate troposphere parameters
- Residual wet zenith delays (piecewise linear at 20 minute intervals) were estimated with a wet delay partial derivative computed from the raytracing (~mapping function) for each observation.
- Gradient parameters were estimated every 6 hours

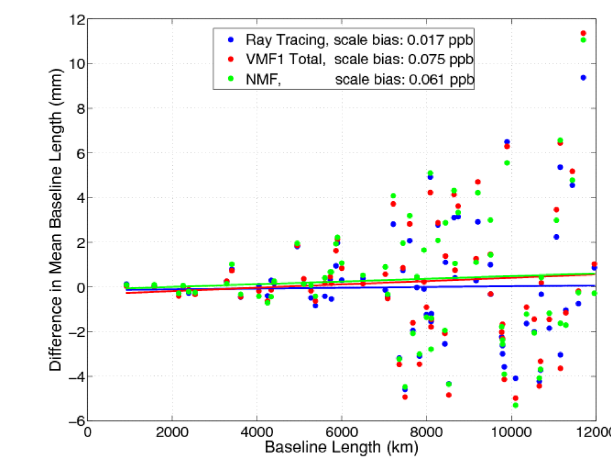


- For each site, baseline WRMS length repeatability improvement is shown for all baselines to the site
- Measure of improvement is the reduction (in quadrature) of the WRMS (weighted root mean square)
- Ordered by baseline length for each site => improvement increases with length
- Most baselines improve except for Kokee (Hawaii)

3 CONT11 Continued

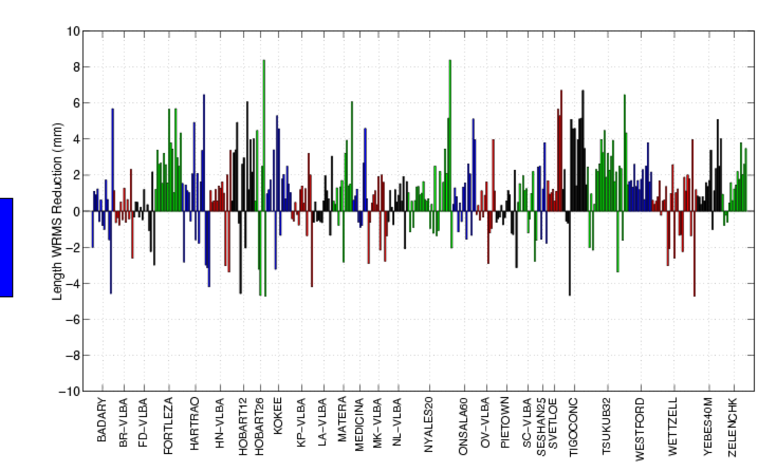


- Baseline length repeatabilities are better with raytrace delays than with VMF1 for 72.3% of baselines
- Site coordinate vertical repeatabilities are better for 11 of 13 stations

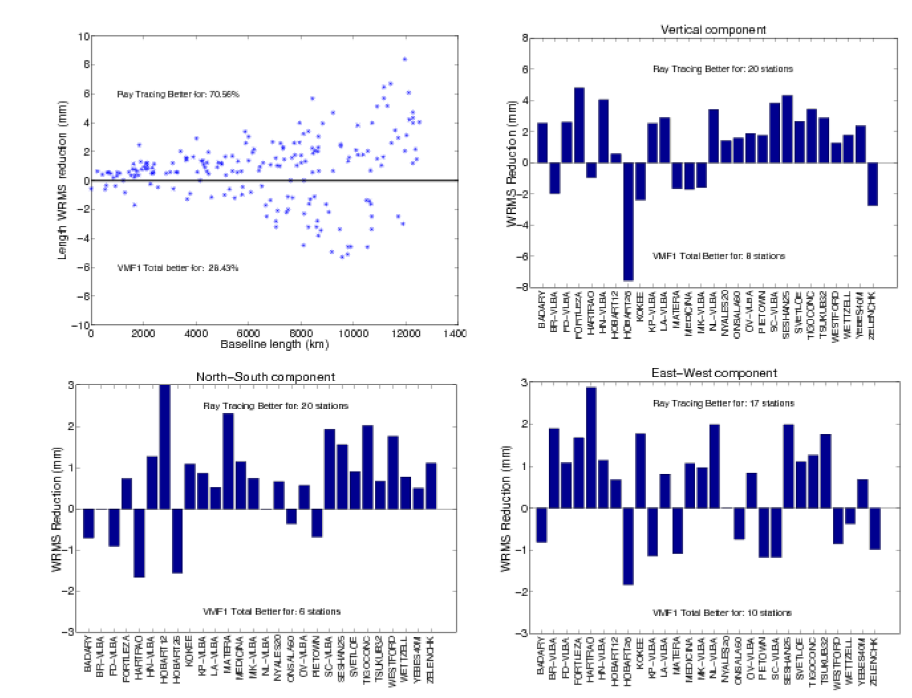


- Determine estimate of scale bias error due to troposphere delay modeling error
- Difference between mean baseline length estimates from solution (1) with all observations down to 5 deg and solution (2) solution applying a minimum elevation cutoff of 12 deg,
- Scale bias = slope of best-fit-line through differences in mean baseline length
- Raytrace scale bias =0.017 ppb < bias for VMF1and NMF (0.075 and 0.061 ppb)

4 2011-2013 Experiments



- For each site, baseline length repeatability improvement is shown for all baselines to the site (ordered by baseline length)
- Improvement increases with length



- Length repeatabilities are improved versus VMF1 for 71% of baselines
- Site UEN repeatabilities are better for 20,17, 20 sites, respectively out of 28 sites

Conclusions and Future Work

- VLBI geodetic analysis results (length and site UEN repeatabilities, scale bias) are improved compared with VMF1when raytrace delays from the GEOS-5 numerical weather model are applied as an apriori model for each VLBI observation
- Raytrace delay calculations (1000 observations per second) are fast enough to allow near realtime use in VLBI analysis
- We are producing raytrace delay files for all VLBI experiment sessions on an operational basis for period 2000-present.
- Raytrace delay service is at http://lacerta.gsfc.nasa.gov.tropodelays

References

Boehm, J., B.Werl, and H. Schuh (2006), Troposphere mapping functions for GPS and very long baseline interferometr y from European Centre for Medium-Range Weather Forecasts operational analysis data, *J. Geophys. Res.*, 222, B02406, doi:20.1029/2005JB00003629.

Hobiger, T., R. Ichikawa, Y. Koyama, and T. Kondo (2008), Fast and accurate raytracing algorithms for real-time space geodetic applications using numerical weather models, *J. Geophys. Res.*, 113, D20302, doi:10.1029/2008JD010503.

Niell, A. E.. (1996), Global mapping functions for the atmosphere delay at radio wavelengths, J. Geophys. Res., 101(B2), 3227-3246.

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