Tropospheric Delay Raytracing Applied in VLBI Analysis

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Overview

1. Background
2. Raytrace Delay Computation
3. VLBI CONT11 Solutions Using Raytrace Delays
4. Raytrace Delay Results for Intensives
5. Conclusions

Current Troposphere Delay Model

Elevation-dependent Tropospheric Delay

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

Azimuthal-dependence approximated with Linear gradient model ("tilted atmosphere")

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

$$m_{grad}(el) = 1/(\sin(el)\tan(el) + C)$$

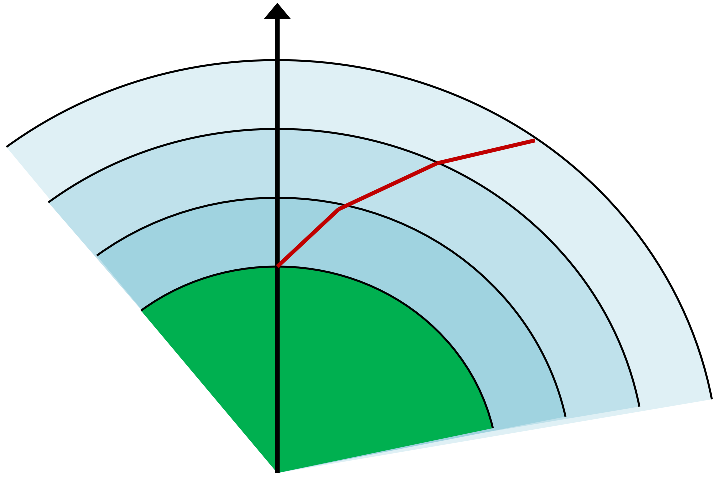
Current Troposphere Delay Model

NMF: (Niell, 1996)

- 1-dim raytrace of N Hemisphere radiosonde troposphere profile data
- Parametrized by day of year (annual period), latitude, and site height

VMF1: (Boehm et al., 2006)

- 1-dim raytrace of ECMWF tropospheric profile data
- Given at 6-hour intervals
- Spatially interpolated to each geodetic site
- Assumed that there is no horizontal refractivity variation



- Mapping functions m(el) were derived by raytracing through uniform atmospheric layers of constant refractivity

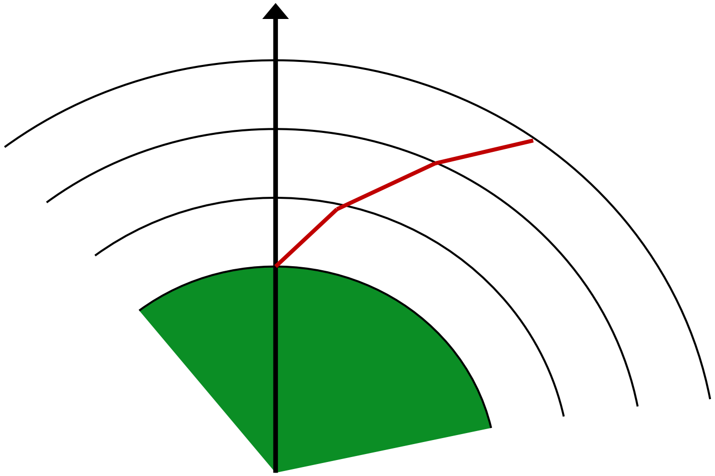
- Refractivity profile computed using the (Pressure, Temperature, Relative humidity) profile above the geodetic site location

Raytracing Approach

- Compute total (dry+wet) delays and wet mapping function from numerical weather model for each VLBI observation

- Weather model is the NASA/GSFC GEOS 5.9.1
  - parameters: pressure, temperature, specific humidity, geopotential height
  - time resolution: 3 hours
  - horizontal resolution: 0.5º x 0.625º (~ 50 km)
  - vertical resolution: 72 levels

- Refractivity along raypath is determined by interpolation of the 4D refractivity field

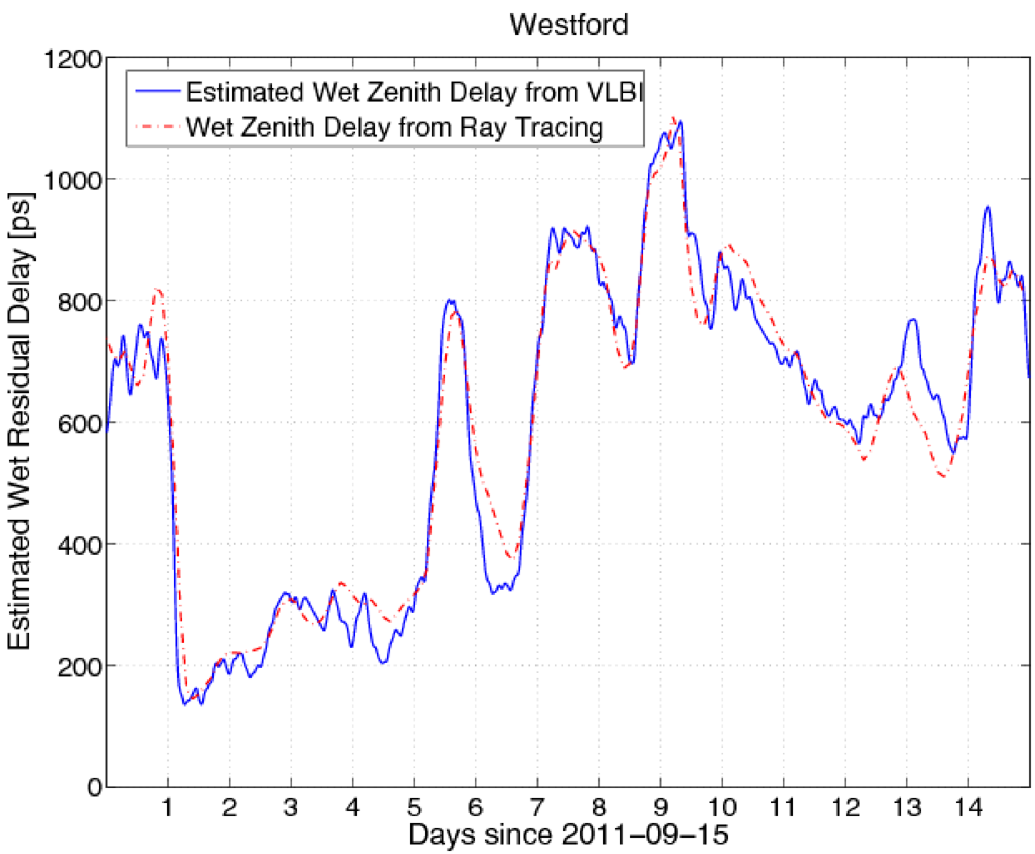


- Use piecewise linear approach to compute raytraced delays

- Constrain propagation of the ray to a plane of constant azimuth (to minimize computation time)

Observed/Raytraced Wet Zenith Delay

- NMF hydrostatic delay = a priori tropospheric delay
- Estimate wet zenith delay from VLBI data



WESTFORD
CONT11 wet zenith delay

- Average correlation all over all CONT11 sites = 0.93
- Raytraced delay accounts for ~90% of the observed delay

Validation Using VLBI Data

- VLBI data sets
  - CONT11
  - UT1 Intensives

- Compare troposphere delay models:

  - NMF hydrostatic delay + NMF wet mapping function
  - VMF1 total (dry+wet) delays + VMF1 wet mapping function
  - Raytrace total (dry+wet) delays + wet raytrace mapping function

- Estimated parameters: site positions, clocks, wet zenith, gradients

- Observation weighting options
  - Baseline weighting
  - Elevation dependent weighting
  - Correlated noise

Validation Using VLBI Data

- **Baseline weighting**

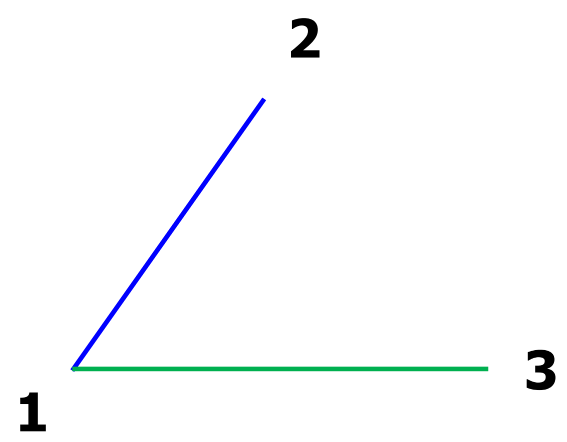
Add a baseline-dependent noise to the formal observation uncertainty => chisquare/dof = 1

$$\sigma'^2_{12} = \sigma^2_{12} + \epsilon^2_{12}$$

- **Elevation dependent weighting**

Add an elevation-dependent noise

$$\sigma'^2_{12} = \sigma^2_{12} + [\,\underline{\epsilon_1 m(el_1)} + \epsilon_2 m(el_2)]^2$$



- **Correlated Noise**

Second baseline from station 1

$$\sigma'^2_{13} = \sigma^2_{13} + \underline{[\epsilon_1 m(el_1)} + \epsilon_3 m(el_2)]^2$$

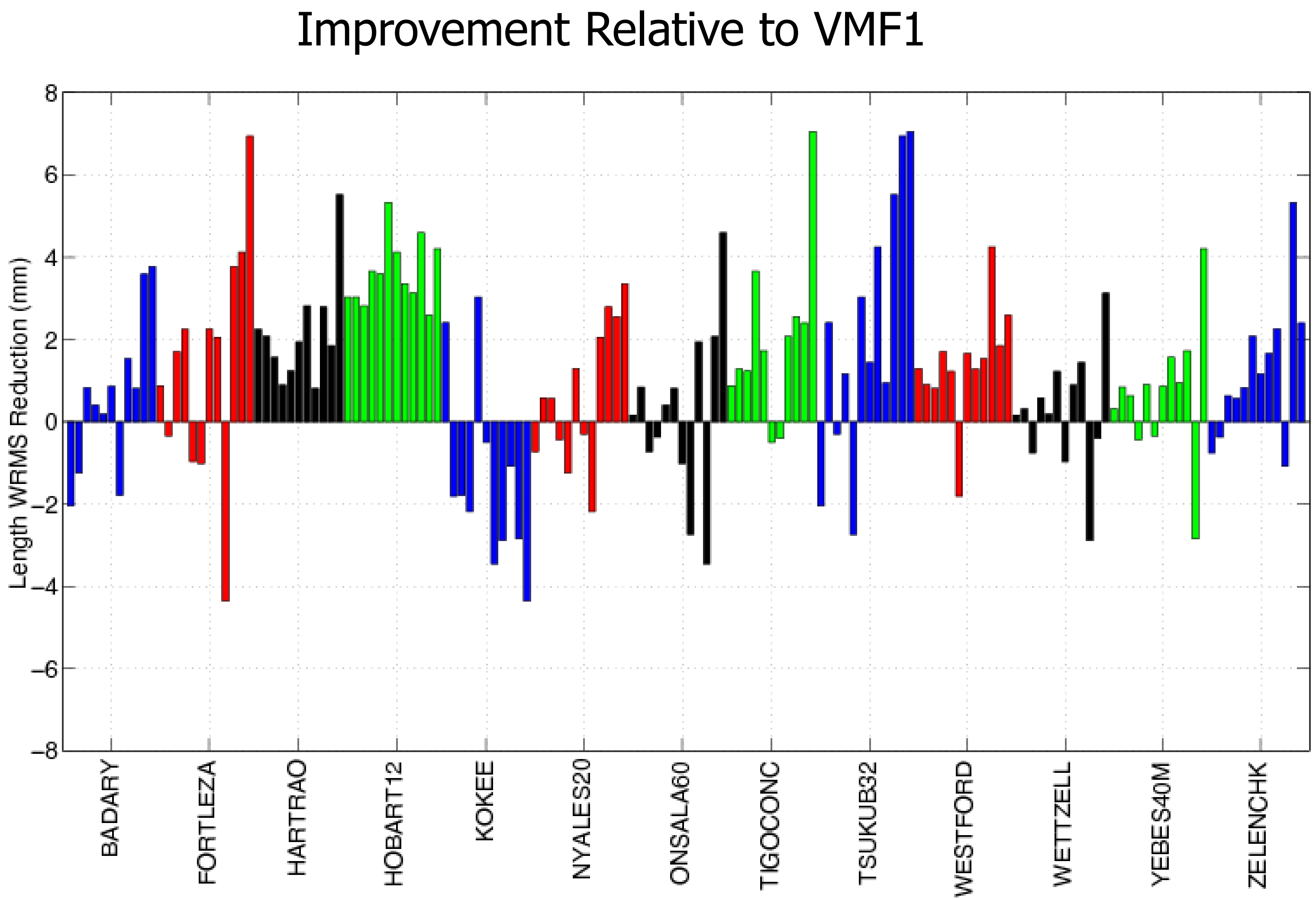
Observations are correlated => correlated noise term in the off-diagonal element of the covariance matrix between observations

Validation Using VLBI Data

CONT11 Baseline Length WRMS

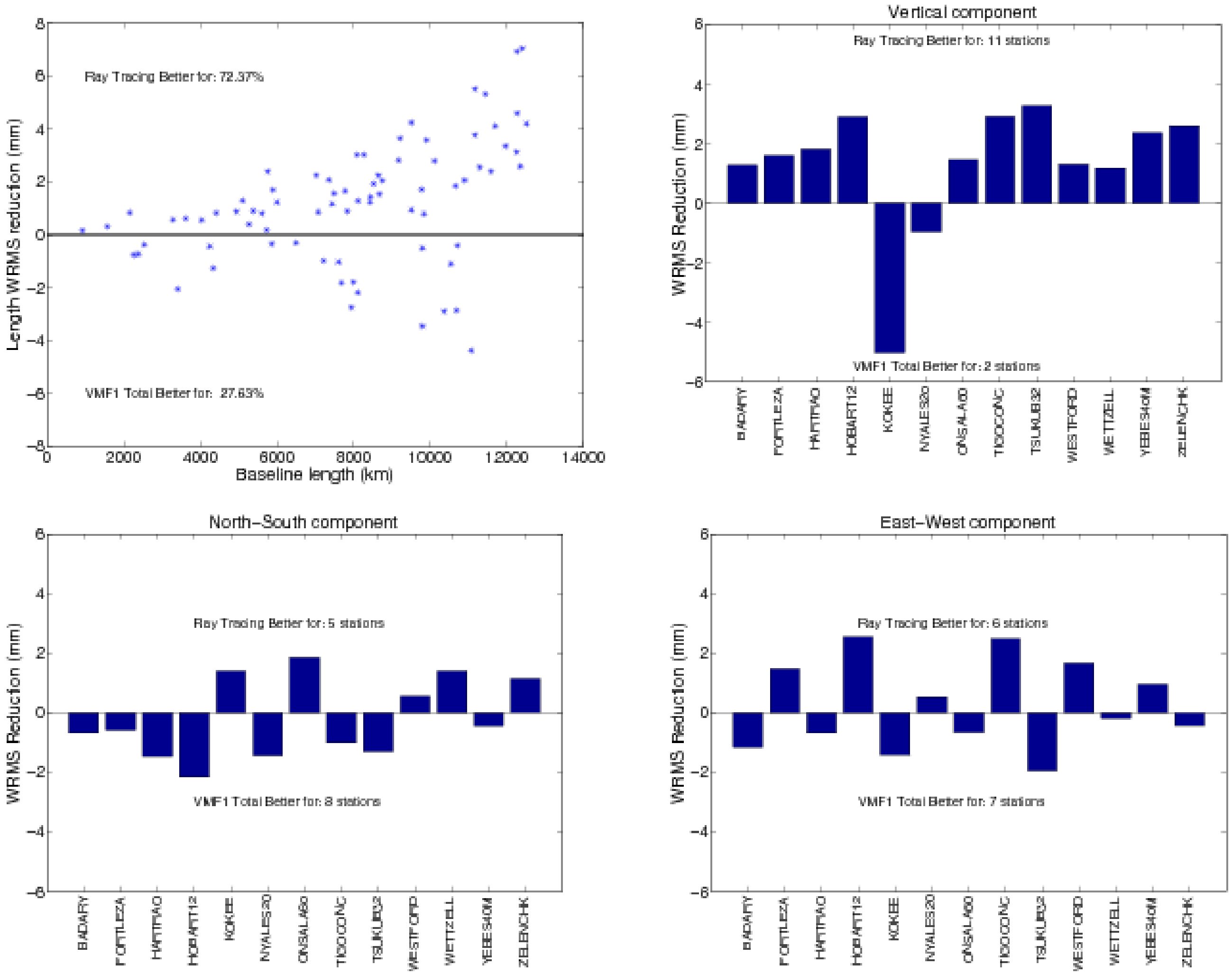
	NMF	VMF1 Total	Raytrace
Weighting	Average (mm)	Average (mm)	Average (mm)
Baseline	6.89	6.75	6.41
Elevation-dep	6.50	6.31	6.04
Correlated noise	6.35	5.96	5.73

CONT11 Baseline Lengths



- Ordered by baseline length for each site

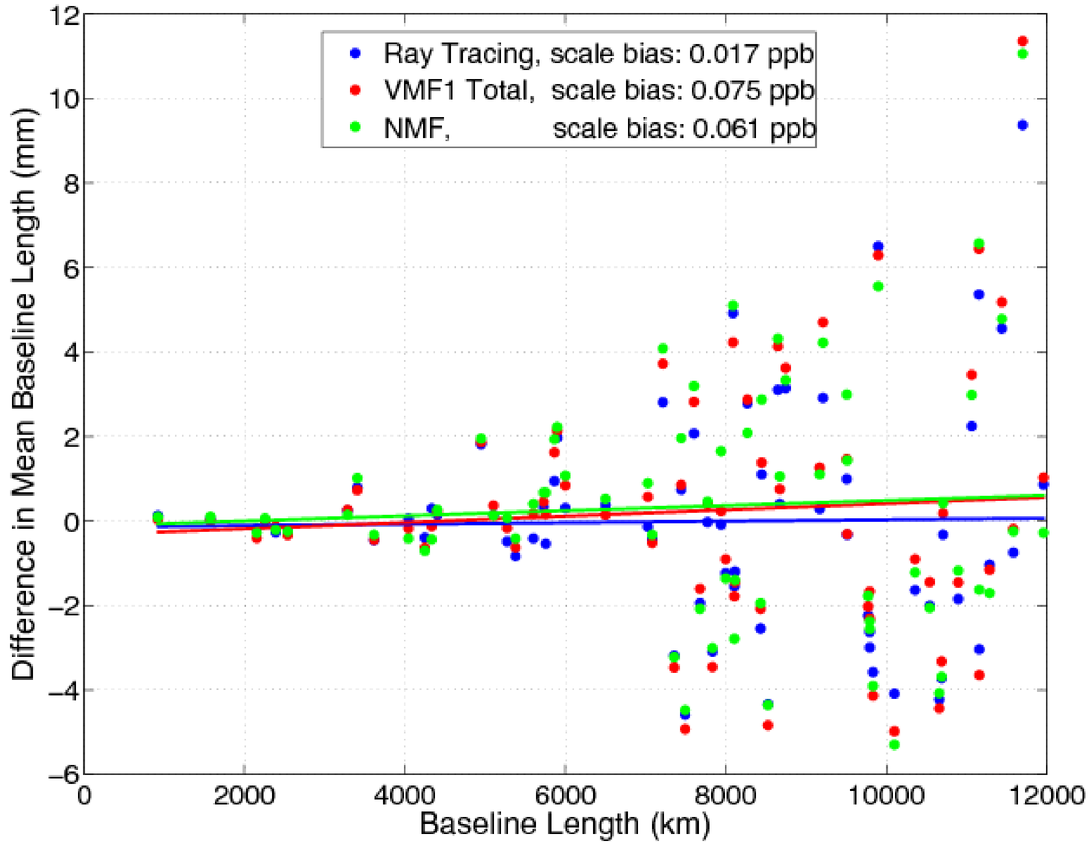
CONT11



Ray Tracing Better for: 72.37%
VMF1 Total Better for: 27.63%
Length WRMS reduction (mm)
Baseline length (km)
Vertical component
Ray Tracing Better for: 11 stations
VMF1 Total Better for: 2 stations
WRMS Reduction (mm)
BADARY
FORTLEZA
HARTRAO
HOBART12
KOKEE
NYALES20
ONSALA60
TIGOCONC
TSUKUB32
WESTFORD
WETTZELL
YEBES40M
ZELENCHK
North–South component
Ray Tracing Better for: 5 stations
VMF1 Total Better for: 8 stations
East–West component
Ray Tracing Better for: 6 stations
VMF1 Total Better for: 7 stations

Scale Bias Error CONT11

Elevation cutoff test: Difference 5º and 12º solutions
=> measure of atmosphere model error



Raytrace: 0.017 ppb VMF1: 0.075 ppb NMF: 0.061 ppb

Intensive UT1 Sessions

- Compute VLBI LOD at midpoint between each pair of daily UT1 values
- Interpolate IGS LOD to these midpoint epochs

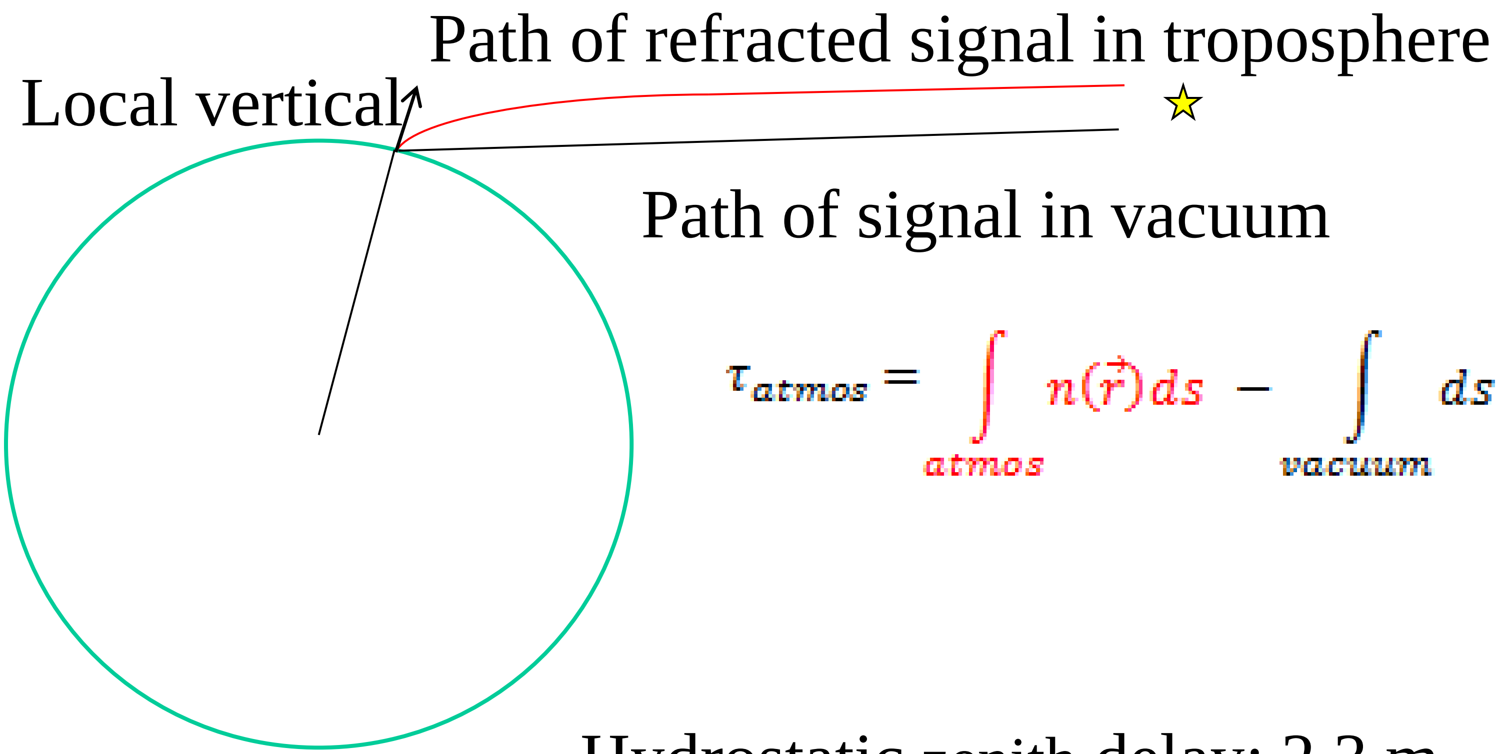
WRMS difference (VLBI – GPS) LOD (μs/day)

	NMF	VMF1	Raytrace	Numsess
Kokee-Wettzell	25.4	25.2	24.3	80
Tsukuba-Wettzell	28.2	28.3	26.1	59

Summary

- Compared with VMF1, baseline length repeatabilities are improved with raytracing for 70% of baselines
- Site vertical repeatabilities are improved for 11 of 13 CONT11 sites
- Troposphere scale bias for raytrace solution = 0.017 ppb compared to 0.075 ppb for VMF1 and 0.061 for NMF
- Raytraced wet zenith delay accounts for 90% of the observed wet zenith delay estimated from the VLBI data
- Computation time for the raytraced delay for each observation is 1 msec
- Raytracing service is available that provides raytrace delays for all VLBI sessions since 2000 at   http://lacerta.gsfc.nasa.gov.tropodelays

Raytrace vs. Mapping Function



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

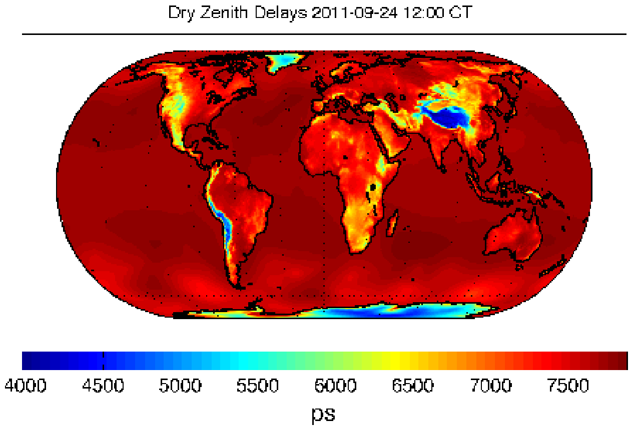
Hydrostatic zenith delay: 2.3 m

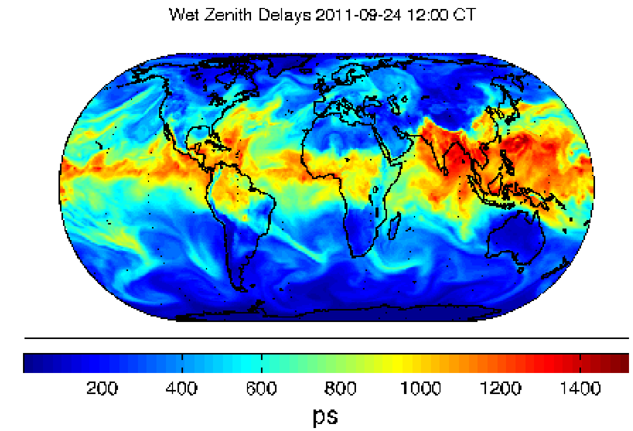
Wet zenith delay: 5-50 cm

Tropospheric Delay at 5 deg: 25 m

Geometric excess at 5 deg contribution: 20 mm

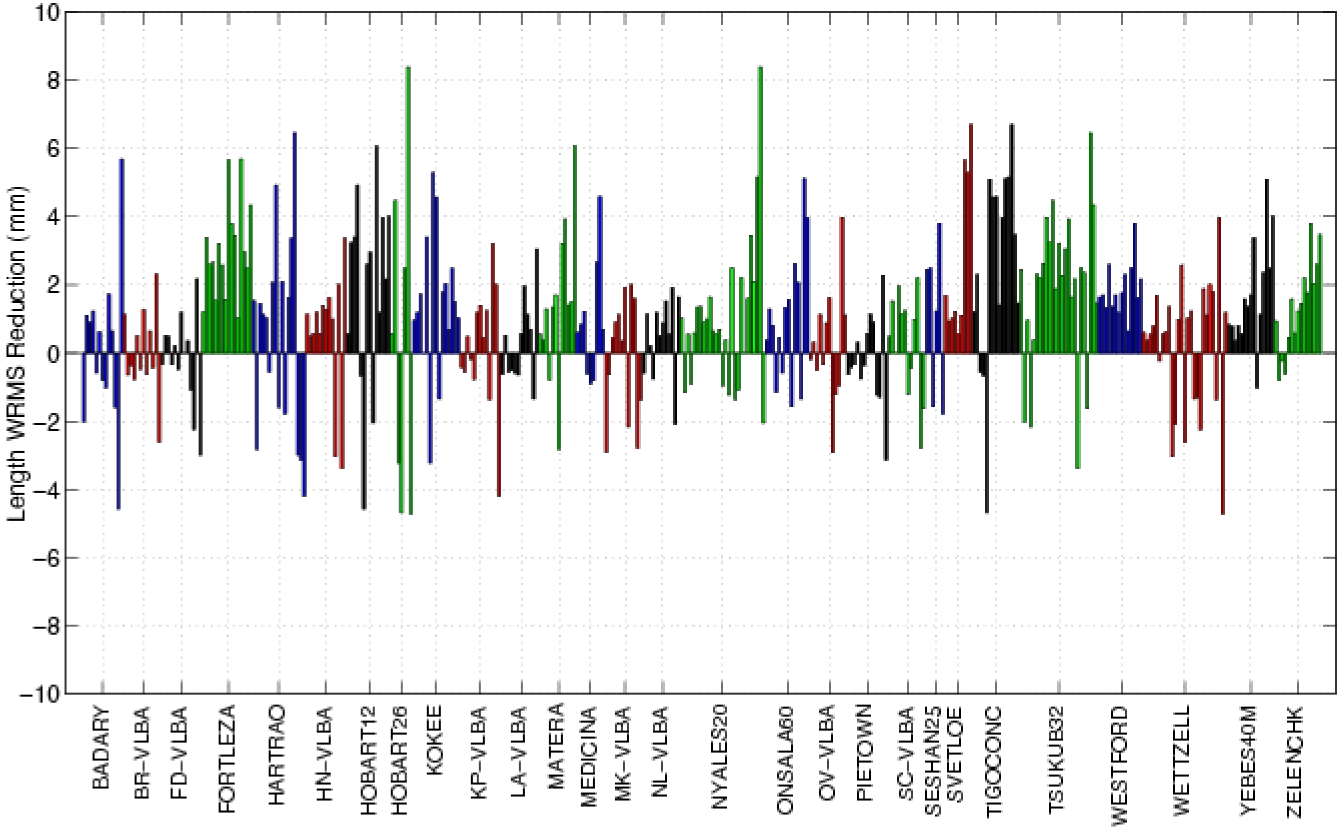
Raytraced Zenith Delay





Raytraced hydrostatic zenith (hydrostatic) and wet zenith delays at one epoch (2011-Sept-24-12UT)

2011-2013 Experiment Sessions



Validation Using VLBI Data

2011-2013 Baseline Length WRMS

	NMF	VMF1 Total	Raytrace
Weighting	Average (mm)	Average (mm)	Average (mm)
Baseline	10.76	10.16	9.93
Elevation-dep	10.78	10.34	10.13
Correlated noise	10.78	10.35	10.12

2011-2013 Experiment Sessions