VLBI Scale Effects

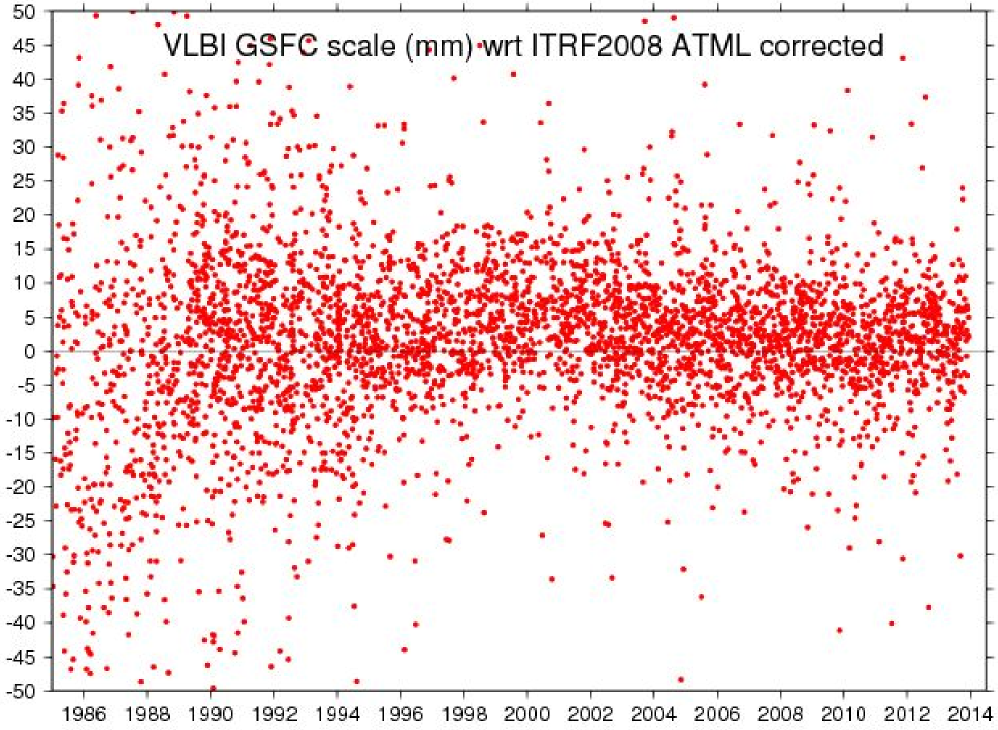
Dan MacMillan
NVI Inc.

Overview

Systematic Errors Contributing to VLBI Scale

- Pressure loading and hydrology loading
- Antenna gravitational deformation
- Atmospheric delay modeling
- Radio source structure

VLBI Scale Series



VLBI daily series relative to ITRF2008

GSFC2011b sinex

Mean difference =1.98 mm (0.33 ppb)

(from Z. Altamimi)

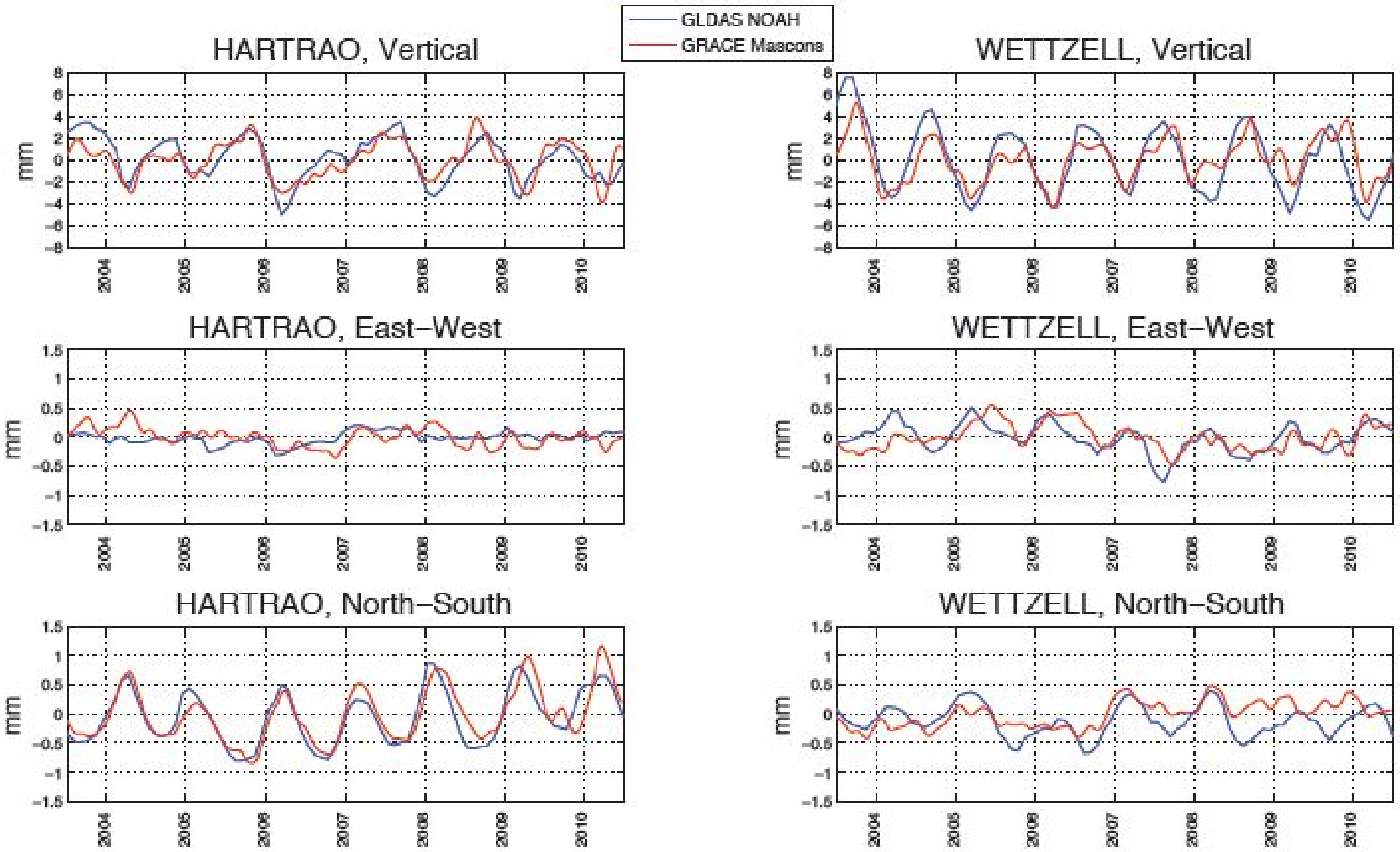
ITRF2008 paper:

(1980-2008 data)

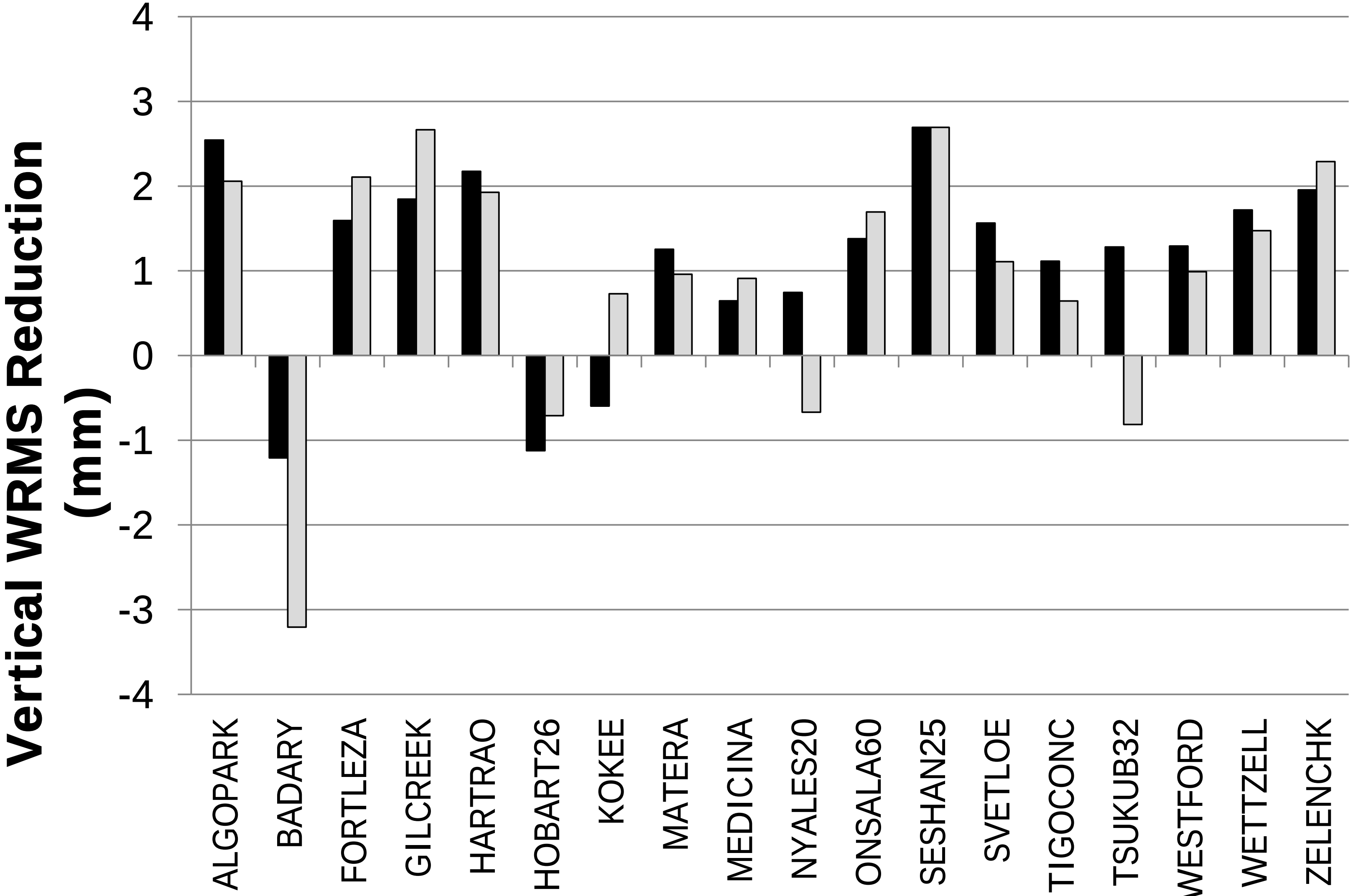
(Altamimi et al.)

=> 0.53±0.10 ppb

Hydrology Loading



Hydrology Loading

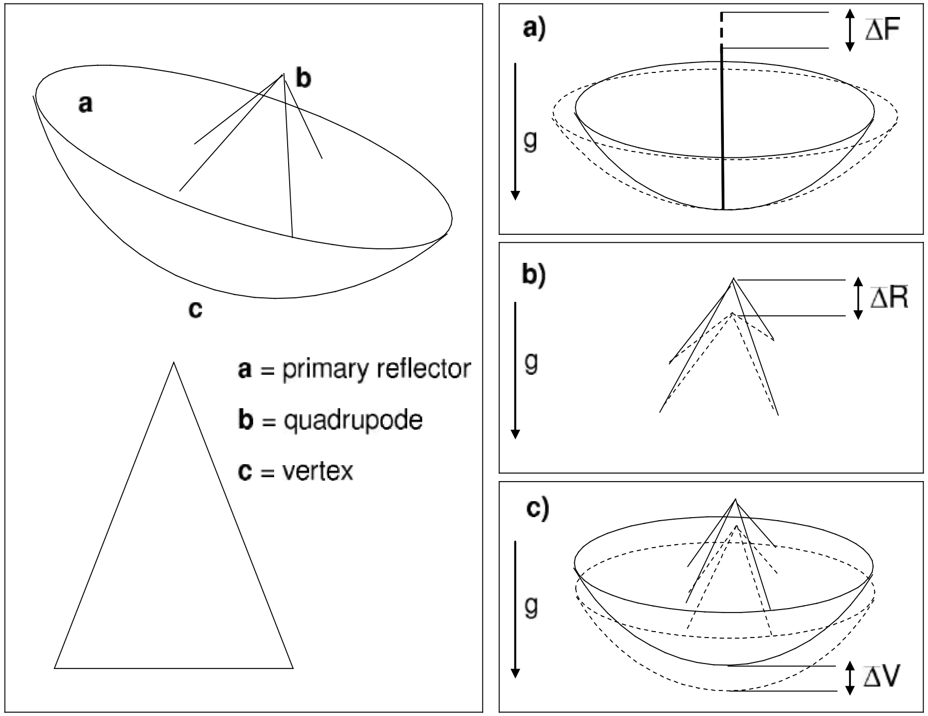


Loading

			Annual	
	Offset ppb	Rate ppb/yr	Cosine ppb	Sine ppb
No Loading	0.44 ±0.03	0.005 ±0.03	-0.15 ±0.02	-0.29 ±0.02
Atmos Loading	0.44	0.001	-0.19	-0.32
Atmos+Hydro Loading	0.30	-0.007	-0.03	-0.01

Estimates are relative to ITRF2008. Data period 1980-2008.

Gravitational Deformation



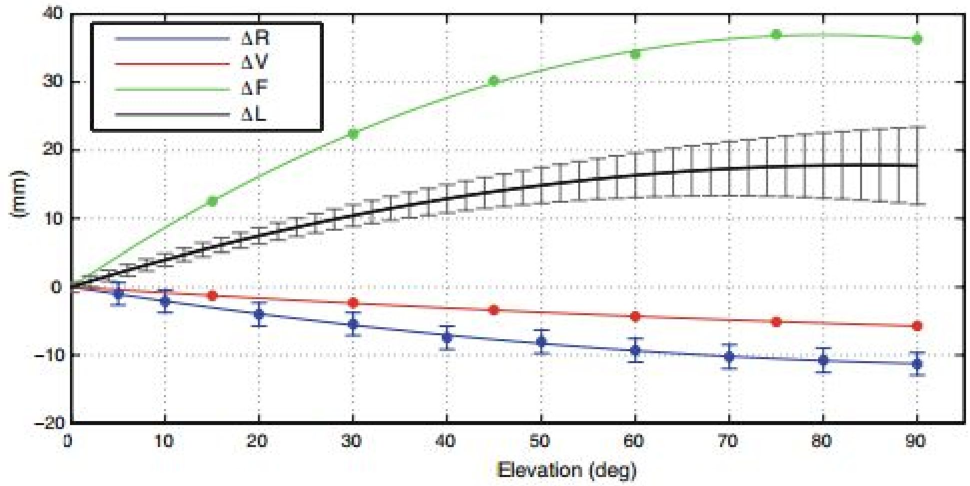
Clark and Thomsen (1988) model for signal path delay depends on variations of

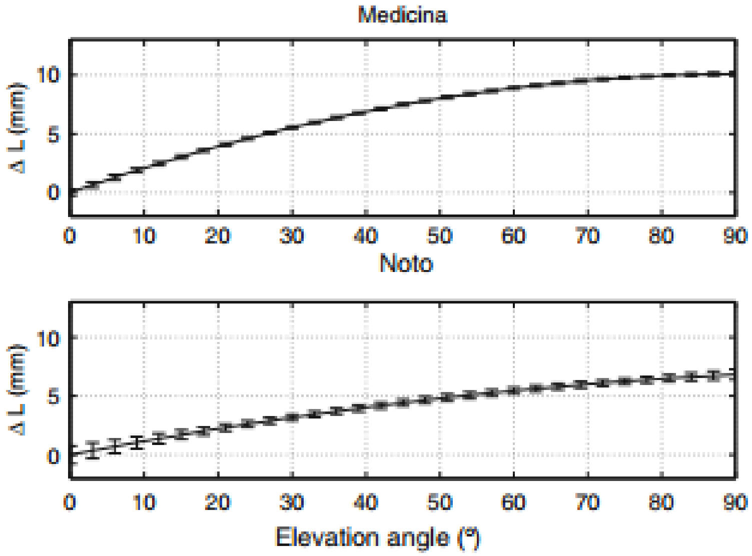
1) focal length
2) vertex position
3) receiver position

$$\Delta L(e) = \alpha_F \Delta F(e) + \alpha_V \Delta V(e) + 2\alpha_R \Delta R(e)$$

- Coefficients depend on dimensions and structure of antenna
- The functions F, V and R have to be measured for each antenna

Gravitational Deformation





- Measurements of Noto and Medicina (Sarti and Abondanza, 2009,2010) laser scanner (F)+ terrestrial (R)+ finite element model (V)

- Model of deformation from Clark and Thomsen (1988) XY mount antenna at Fairbanks (26 meter diameter)

$$\Delta L(e) = -2.4\,(1 - \sin(e))\ \text{mm}$$

Gravitational Deformation

	Offset ppb	Rate ppb/yr
No Model	0.44 ± 0.03	0.005 ± 0.003
Medicina Model	1.24	0.014
Noto Model	0.89	0.011
Fairbanks Model	0.75	0.01

- Scaled each model delay (~ $Diam^2$) to the antenna diameter of each antenna in the solution.

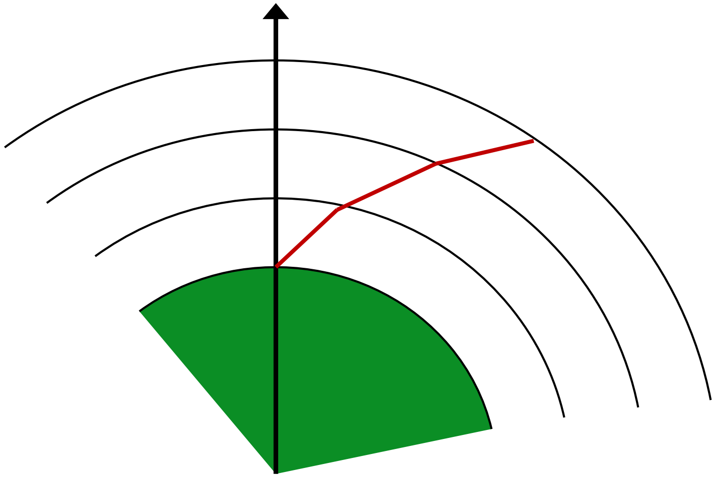
- Estimates are relative to ITRF2008. Data period 1980-2008.

Troposphere Raytracing

- 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

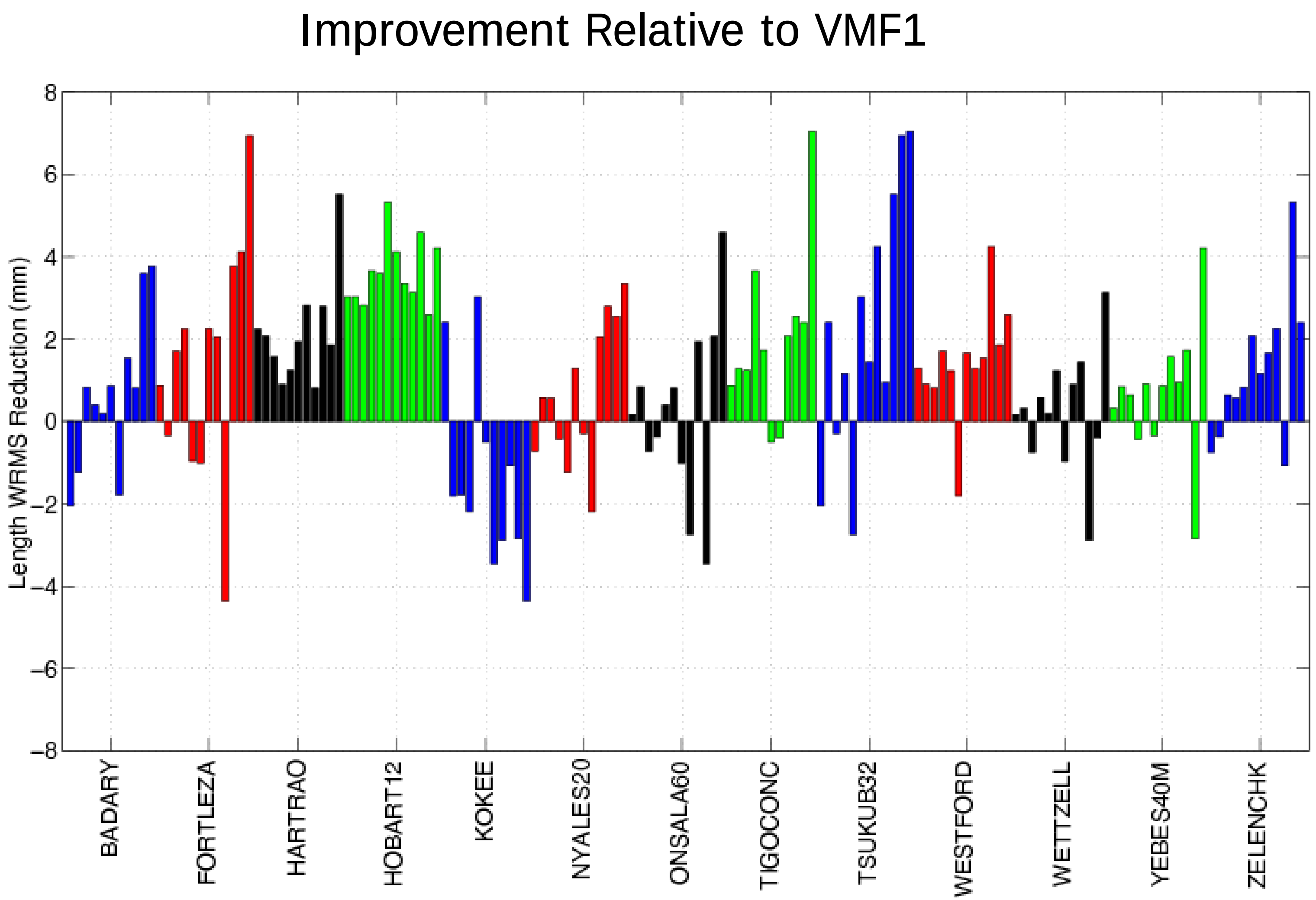
- Refractivity along raypath is determined by interpolation of the 4D refractivity field



- Use piecewise linear approach to compute raytraced delays

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

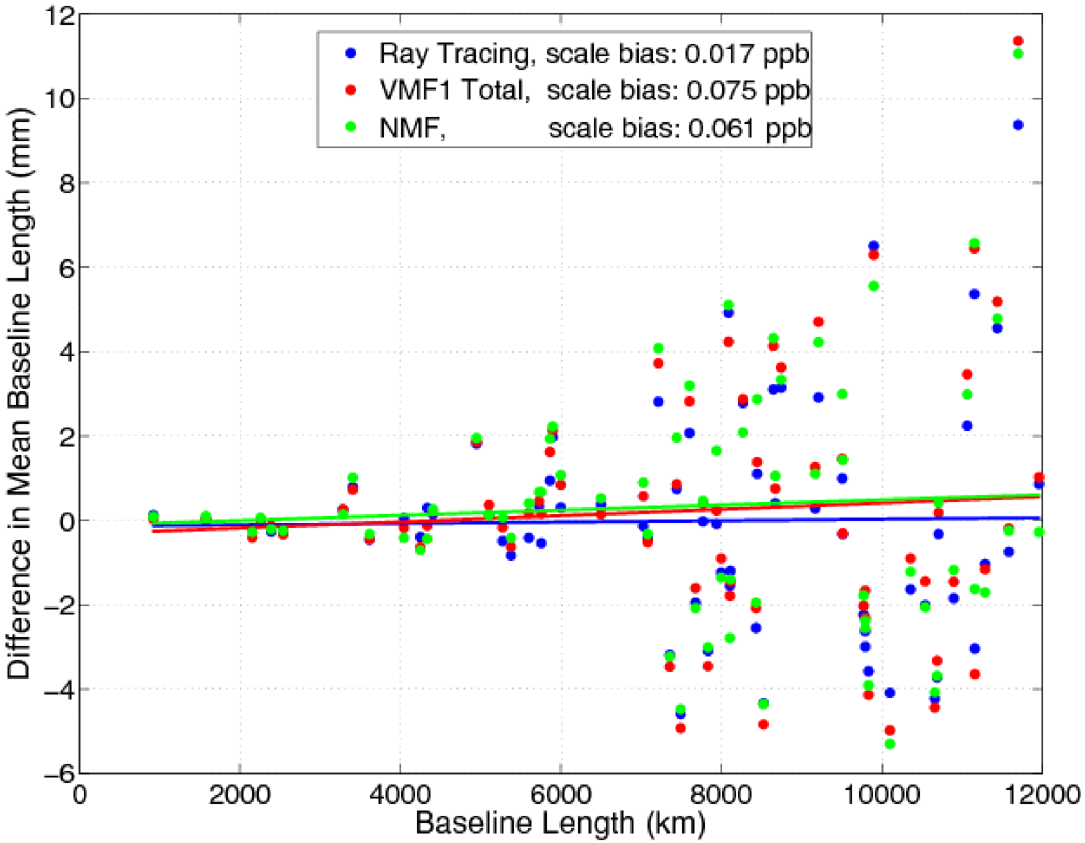
CONT11 Baseline Lengths



- Ordered by baseline length for each site

Troposphere Scale Bias Error

Elevation cutoff test: Difference 5º and 12º solutions CONT11 (2011)
=> measure of atmosphere model error

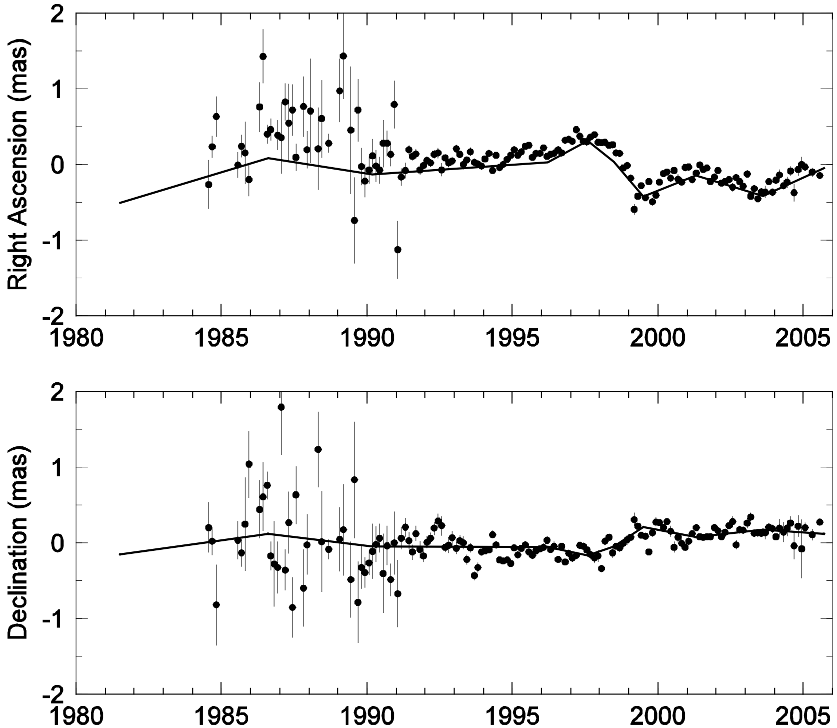


Raytrace: 0.017 ppb   VMF1: 0.075 ppb NMF: 0.061 ppb

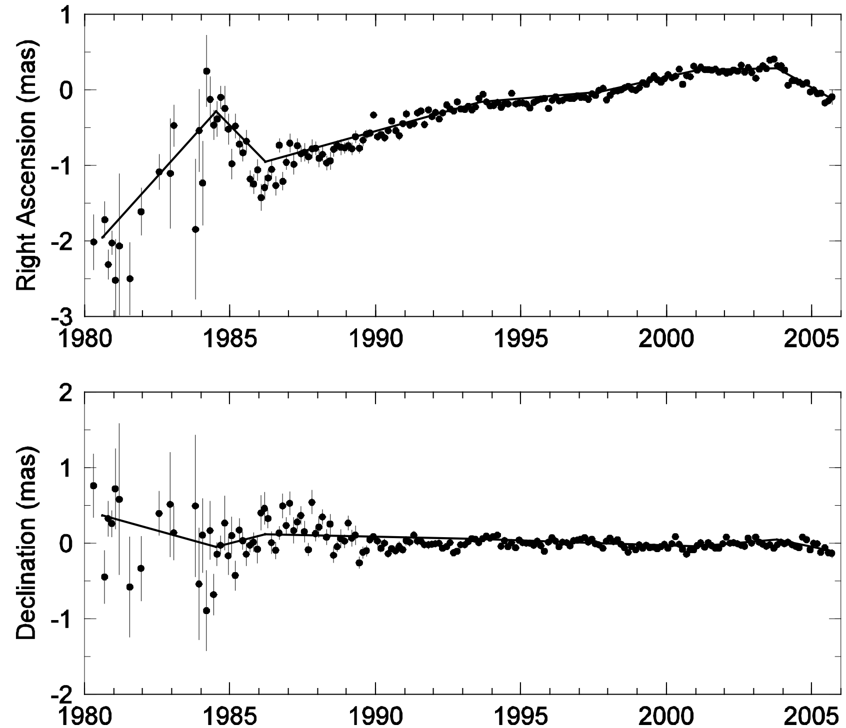
Radio Source Instability

NVI, INC.

- Radio source position estimates can have large rates or even nonlinear variation
  - Identified sources with unstable position time series from among the most frequently observed (geodetic) sources



Radio source 2145+067



Radio source 4C39.25

Radio Source Instability

- Modeled the position variation of unstable sources either by

(1) estimating global spline parameters to fit the variation

or (2) estimating positions for each 24-hour observing session

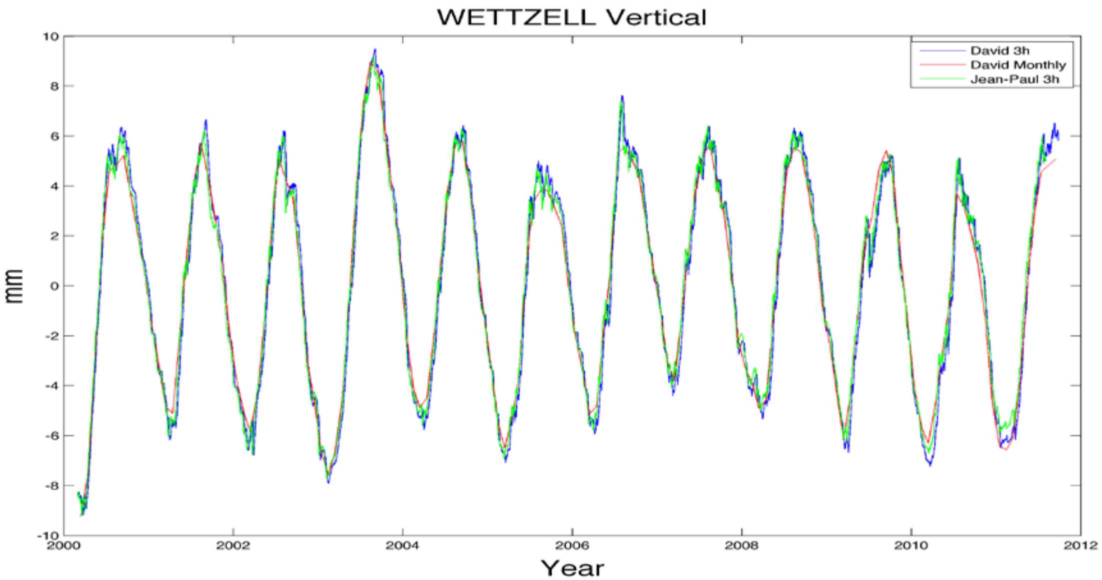
Effect of radio source instability =>

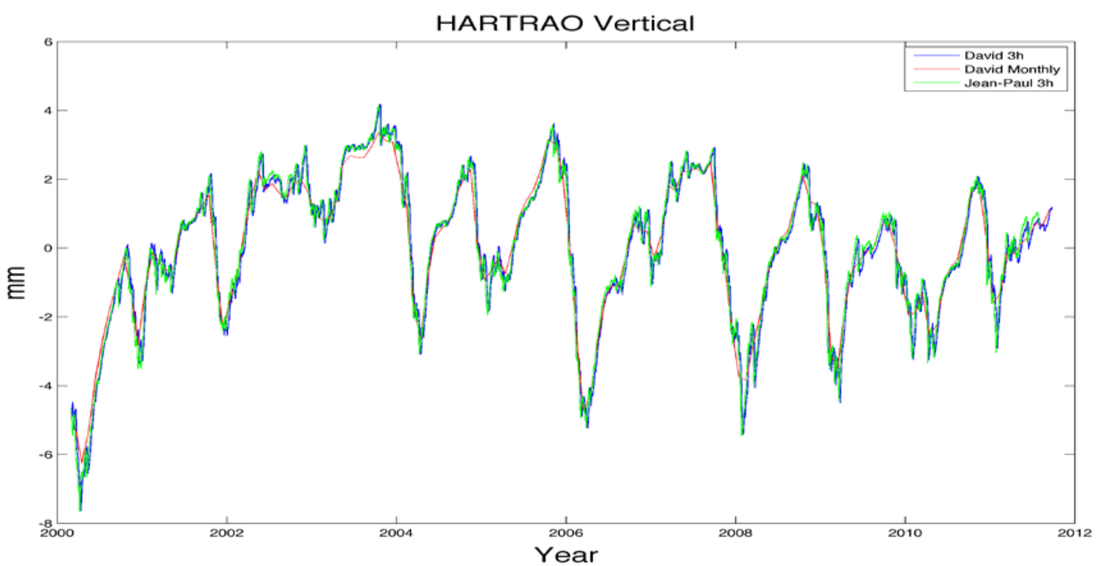
1) Spline	-0.02 ± 0.01 ppb	0.004 ± 0.002 ppb/yr
2) Local	-0.02 ± 0.02 ppb	0.008 ± 0.002 ppb/yr

Scale Error Budget

Error Source	Annual Cos	Annual Sin	Rate ppb/yr	Bias ppb
Gravitational Deformation	--	--	−0.005 to −0.009	−0.78 to −0.31
Hyd Load	−0.16	−0.31	0.008	0.14
Atm Load	0.04	0.03	0.004	0
Atmosphere	--	--	0.010	0.08
Radio source	---	--	−0.006	0.02
ITRF2008	−0.16 ± 0.02	−0.30 ± 0.02	0.025 ± 0.010	0.53 ± 0.10

Current Troposphere Delay Model





Comparison between:

1) GSFC 3hr GLDAS
2) GSFC GLDAS monthly
3) J.-P. Boy 3hr GLDAS

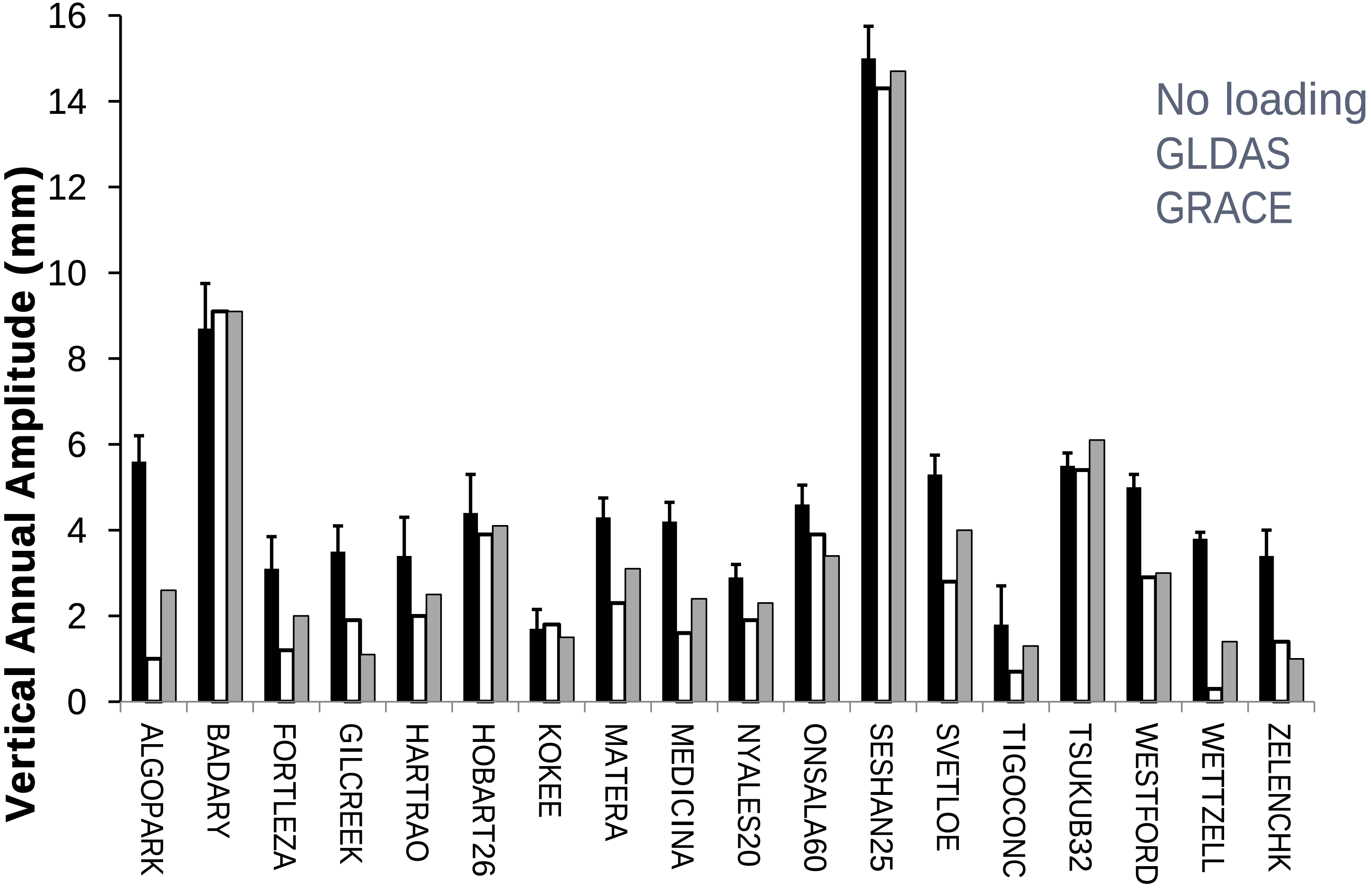
- 3-hour series are very similar
- Differences < 0.5 mm

Hydrology Loading

NVI, INC.

- Loading service
  http:/lacerta.gsfc.nasa.gov/hydlo/
- Compressed directory: loading series for 170 VLBI sites
- Separate text files each site: new sites added on request
- Loading series also on global grid with resolution 1x1 deg
- Latency of GLDAS model is currently 1-2 months

Hydrology Loading



Troposphere Delay Model Error

Atmospheric Delay Modeling

- Errors in atmospheric modeling at low elevations

- Scale dependence on elevation cutoff

10º - 5º elevation cutoff solutions
=> -0.01 ± 0.005 ppb/yr
=> -0.13 ± 0.05 ppb

- Mapping function error

VMF – NMF => bias ~ -0.1 ppb
seasonal amplitude ~ 0.1 ppb

Current Troposphere Delay Model

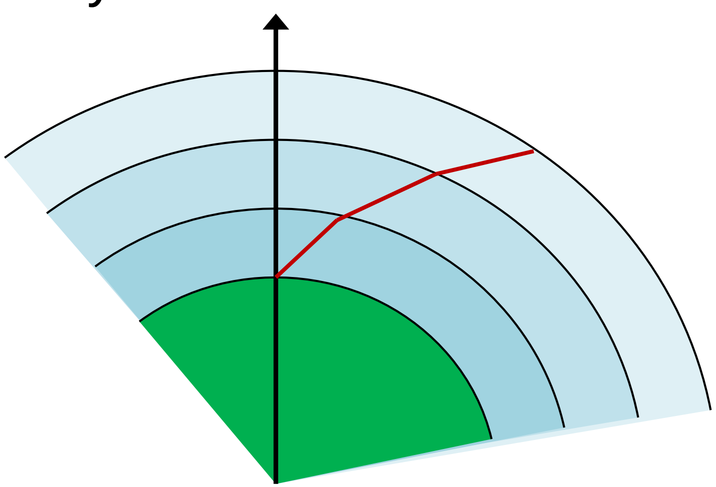
NVI, INC.

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



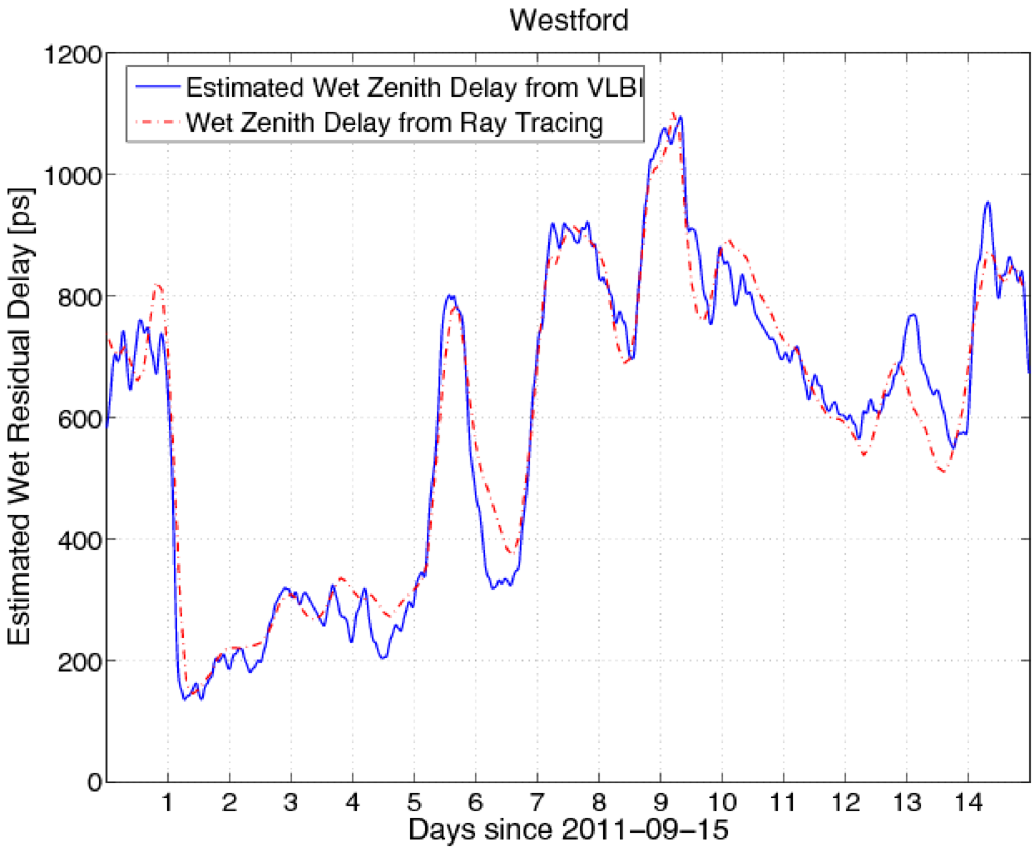
- Mapping functions m(el) were derived by raytracing through uniform atmospheric layers of constant refractivity

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

Observed/Raytraced Wet Zenith Delay

NVI, INC.

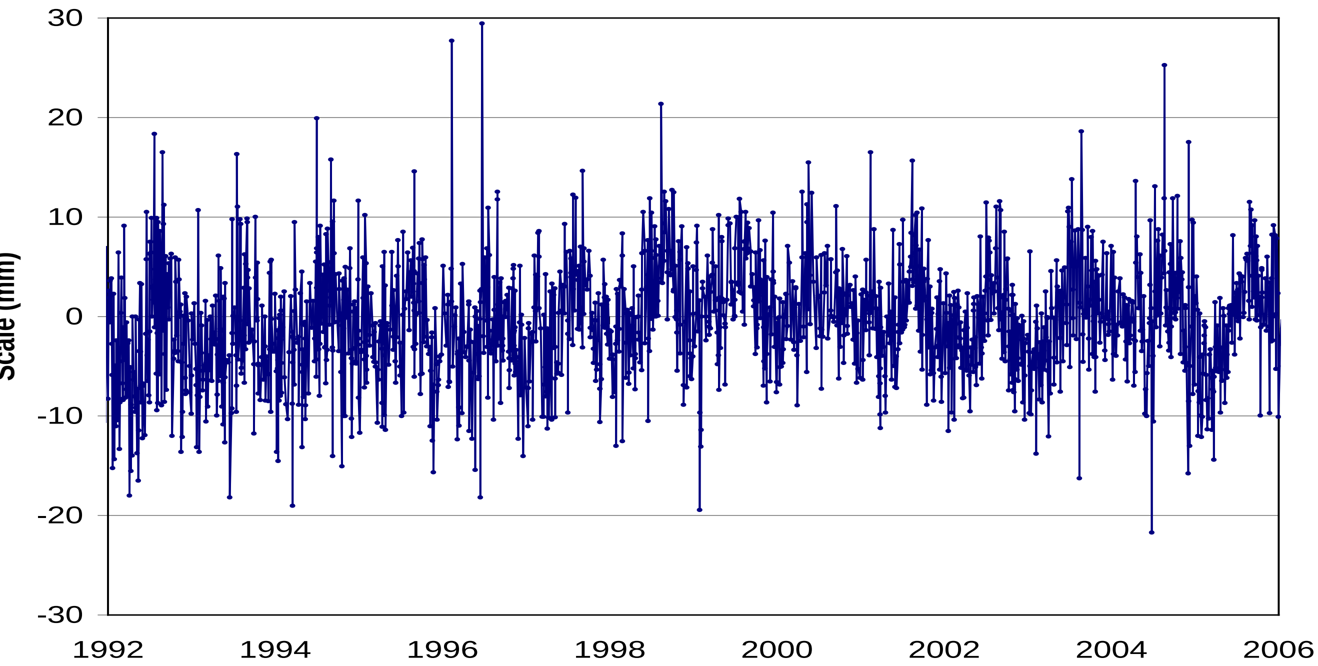
- NMF hydrostatic delay = a priori tropospheric delay
- Estimate wet zenith delay from VLBI data



WESTFORD
CONT11 wet zenith delay

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

VLBI Scale Series



VLBI daily series relative to ITRF2008

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")

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

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

Overview

1. Background
2. VLBI scale difference in ITRF2008
3. Systematic effects that contribute to the VLBI scale
4. VLBI scale error budget

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**

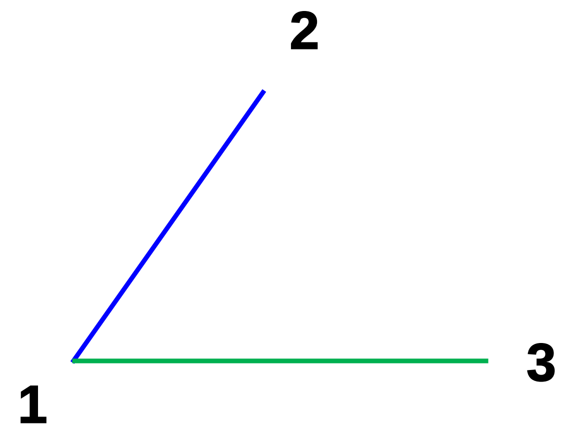
Add a baseline-dependent noise to the formal observation uncertainty => chisquare/dof = 1

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

- **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

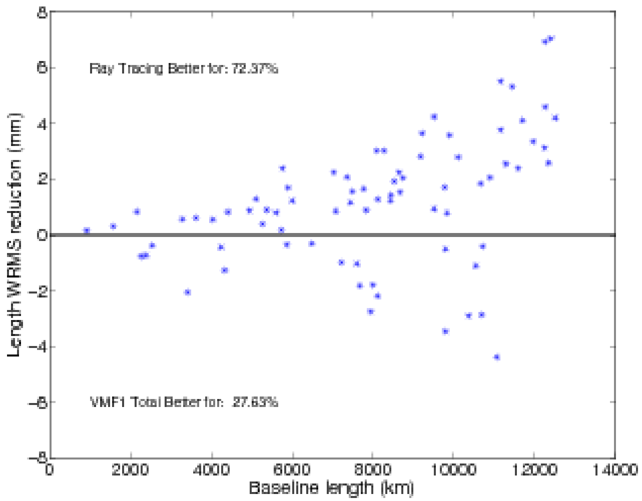
Validation Using VLBI Data

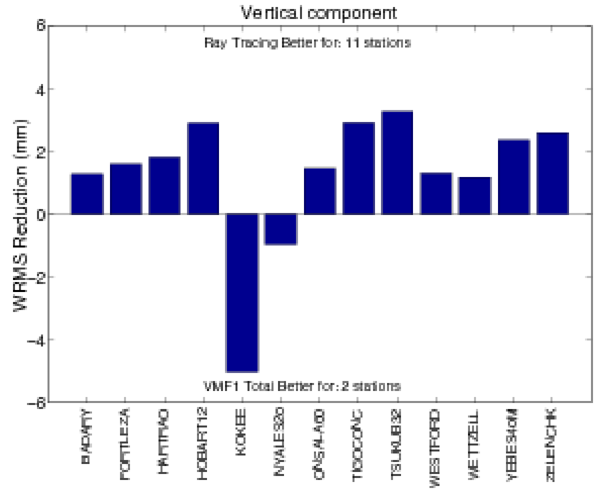
CONT11 Baseline Length WRMS

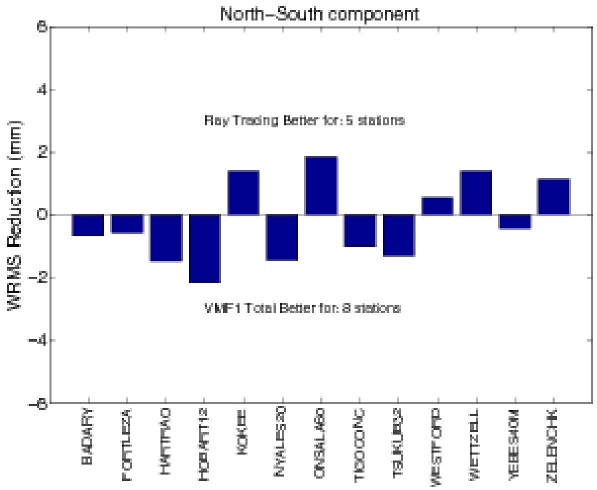
	NMF	VMF1 Total	Raytrace
Weighting	Average (mm)	Average (mm)	Average (mm)
Baseline	6.89	6.75	6.41
Elevation-dep	6.50	6.31	6.04
Correlated noise	6.35	5.96	5.73

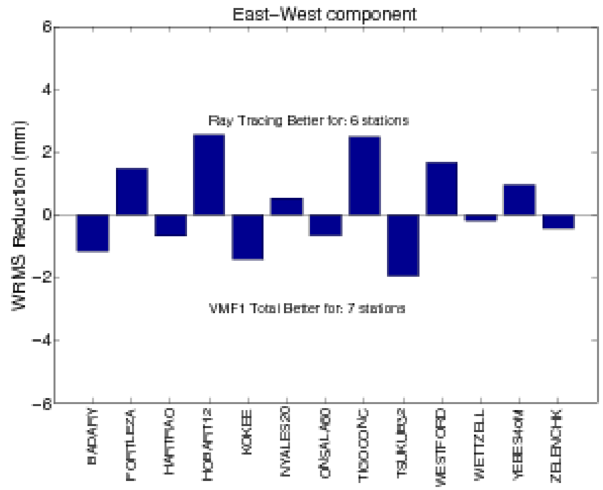
CONT11

NVI, INC.









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

Scale Error Budget

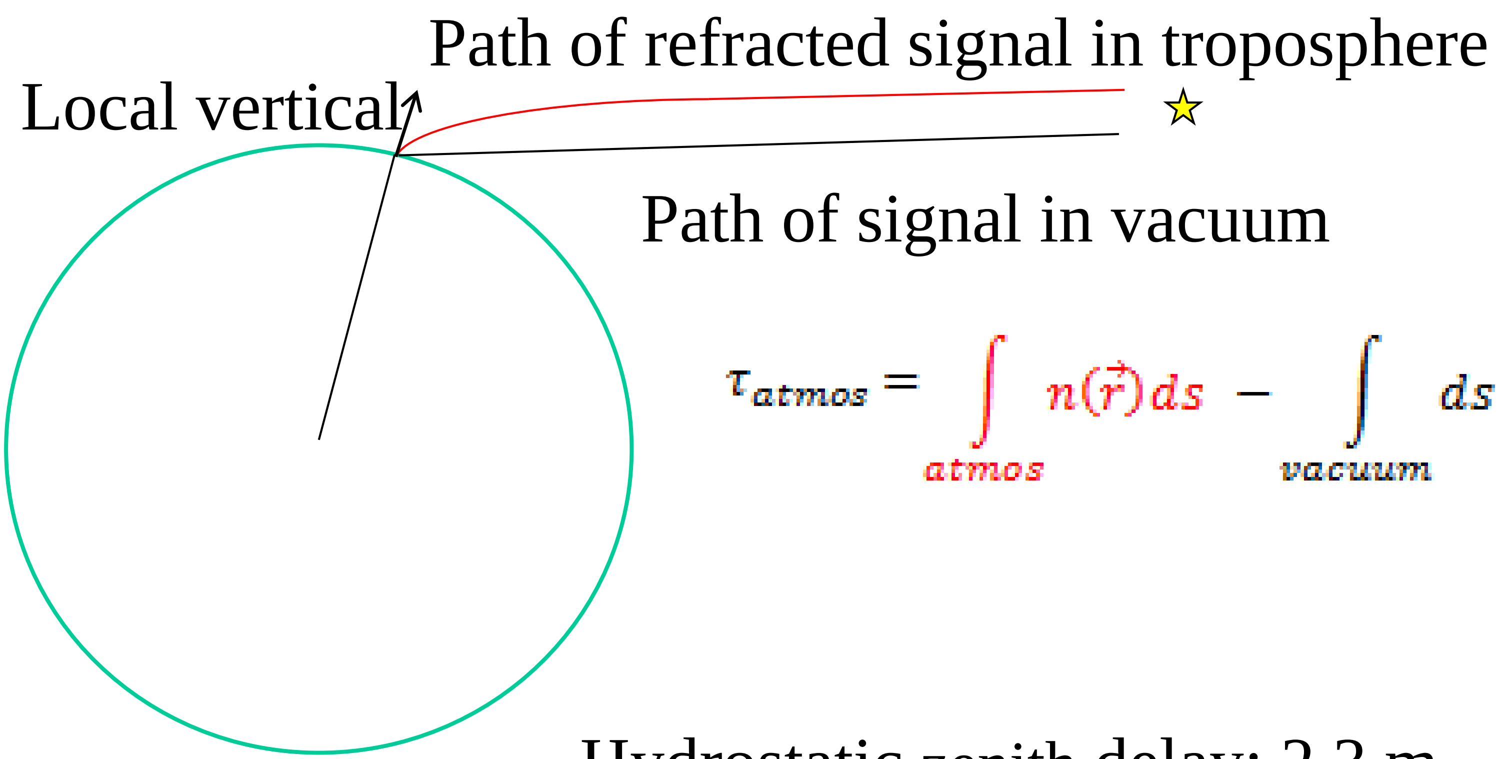
Summary

- Most (0.54 ppb) of the scale bias (VLBI-SLR) of 0.68 ppb in ITRF2005 can be explained by inconsistent application pole tide model convention, atmosphere delay model error, and smaller contributions from loading

- VLBI scale has a real annual variation, which is equivalent to modulating the scale by ~ 0.5 ppb, due to annual site variations of various effects (hydrology loading, antenna thermal deformation, etc.) and the predominance of VLBI sites in the Northern hemisphere

- Hydrology loading, pressure loading, antenna thermal deformation, and mapping function error contribute about 0.3 ppb to the annual variation of scale

Raytrace vs. Mapping Function



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

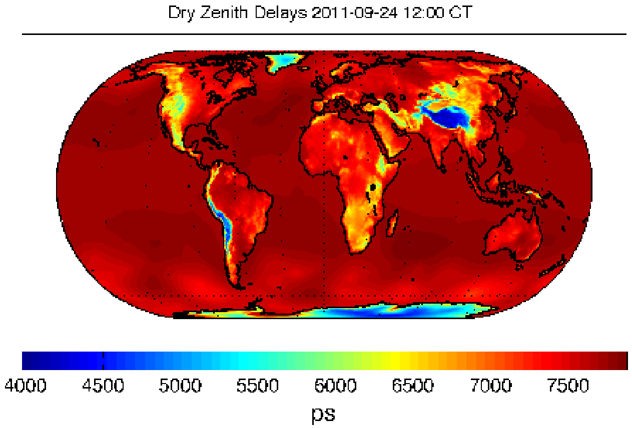
Hydrostatic zenith delay: 2.3 m

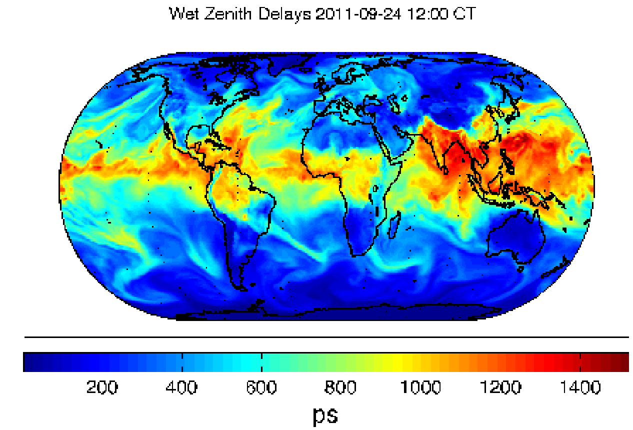
Wet zenith delay: 5-50 cm

Tropospheric Delay at 5 deg: 25 m

Geometric excess at 5 deg contribution: 20 mm

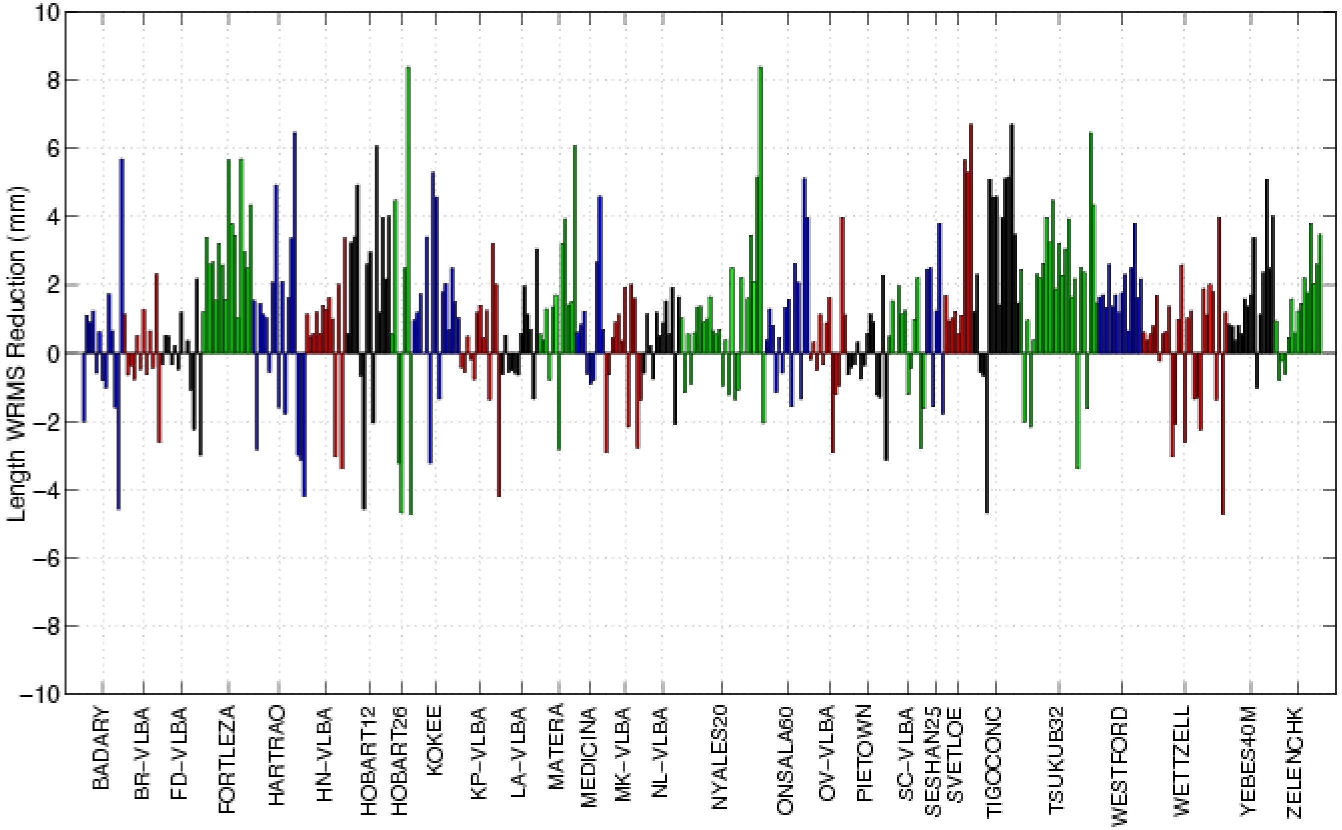
Raytraced Zenith Delay





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

2011-2013 Experiment Sessions



Validation Using VLBI Data

NVI, INC.

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