HG TU WIEN

INTERGEO®
Kongress und Fachmesse für Geodäsie, Geoinformation und Landmanagement
Köln, 5.–7. Oktober 2010

Ray-traced tropospheric slant delays for space geodetic techniques

Vahab Nafisi

Dudy D. Wijaya

Johannes Böhm

Harald Schuh

Geodätische Woche 2010

Köln, 5-7 Oktober 2010

0. Introduction (1)

- Troposphere delay as an error source for all space geodetic techniques

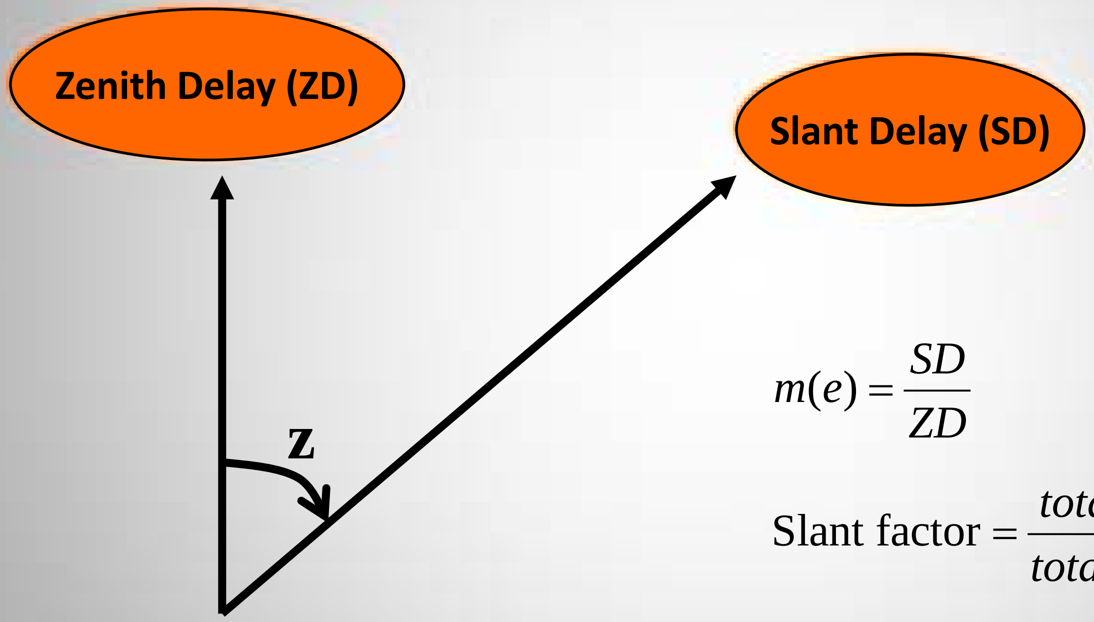
- Model of total delay as a function of surface meteorological parameters only

- Most commonly used model is that of Saastamoinen (1972)

- Parameter estimation techniques (using the least squares method)

- Mapping function to calculate delays for each observation

- Concept of mapping function



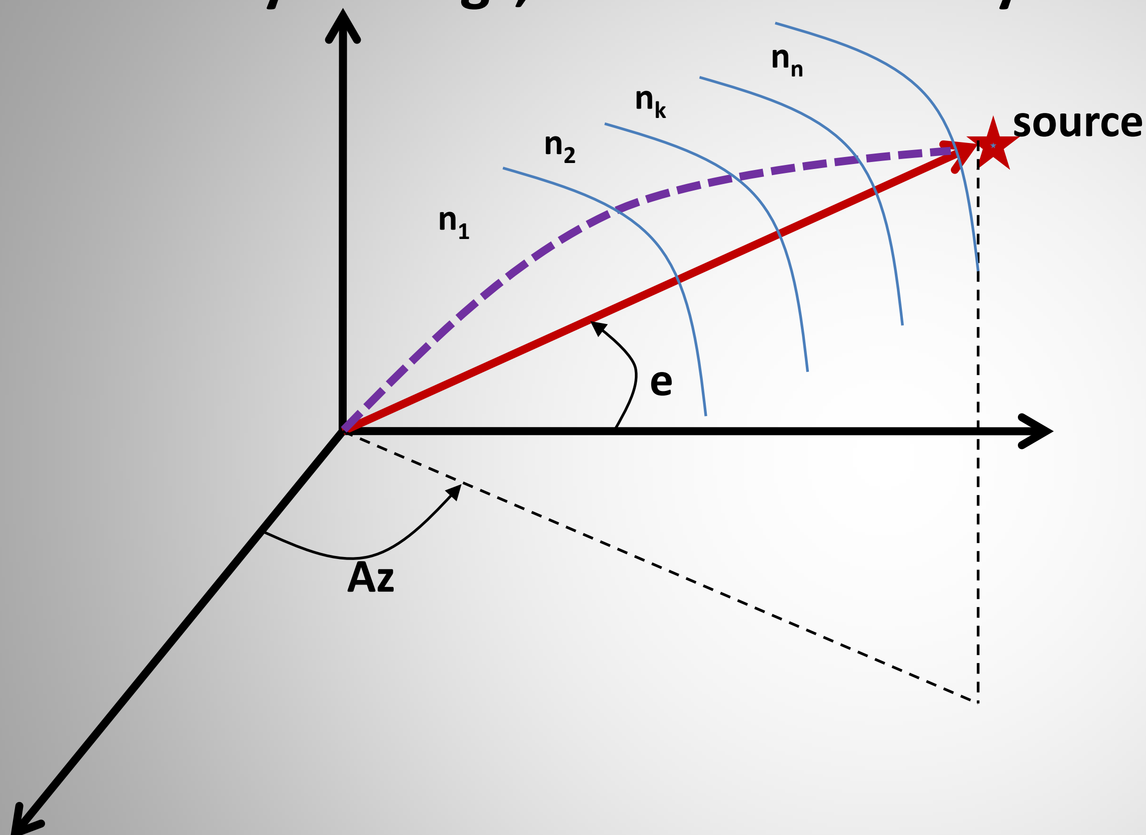
$$m(e) = \frac{SD}{ZD}$$

$$\text{Slant factor} = \frac{total\ slant\ dealy}{total\ zenith\ delay}$$

Zenith delay can be determined as a function of:

- **Meteorological data at the site**
- **Coordinates (height and latitude of the site)**

• "Direct ray-tracing", to find slant delay directly, along the true path



• Solution: Suitable mathematical model + Atmospheric data set

↓ 2D or 3D

↓ Numerical Weather models (NWM)

1. Mathematical model for 3D and 2D Ray-tracing systems (1)

- **Eikonal equation**

$$\left[\nabla L(\vec{r})\right]^2 = n(\vec{r})^2$$

L: **optical path length,**

$\vec{r}$: **vector of positions,**

n : **refractive index,**

∇ : **gradient operator w.r.t positions**

.Refractivity, as a function of meteorological parameters

$$N = k_1 \frac{p_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2} \longrightarrow n = 1 + N \times 10^{-6}$$

1. Mathematical model for 3D and 2D Ray-tracing systems (2)

- **Partial derivatives of the refractivity in spherical coordinate system**

-16 points around a specific point (point of ray-path), for computing partial derivatives $\frac{\partial n}{\partial \lambda}$ **,** $\frac{\partial n}{\partial \theta}$ **and** $\frac{\partial n}{\partial r}$

- Spline interpolation for value of refractivity (or refractive index) in each point

- **Special case : 2D Ray-tracer (ignoring out-of-plane components)**

$$\frac{\partial n}{\partial \theta} = 0 \qquad \frac{\partial n}{\partial \lambda} = 0$$

2. Practical considerations for developing a ray-tracing method at TU Wien

- **Linear interpolation for temperature and exponential for pressure and water vapor pressure**

- **A pre-calculation process for compiling and converting ECMWF file to refractivity (N) profiles for each grid point**

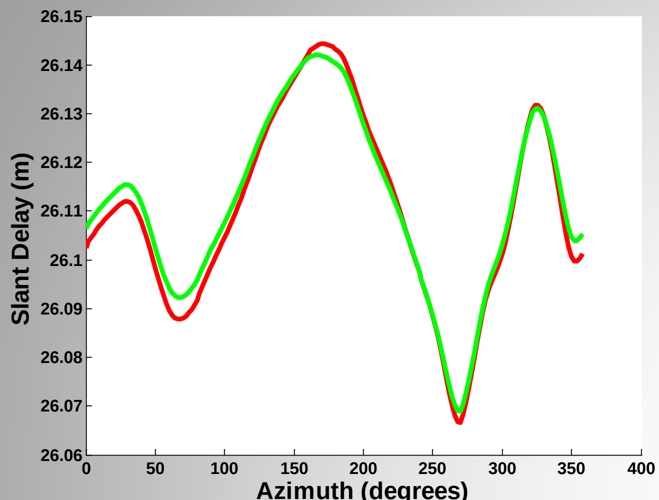
- **Rüeger "best average" constants for refractivity (Rüeger,2002)**

- **US standard atmosphere of 1976 for meteorological data above upper limit of ECMWF up to 76 Km.**

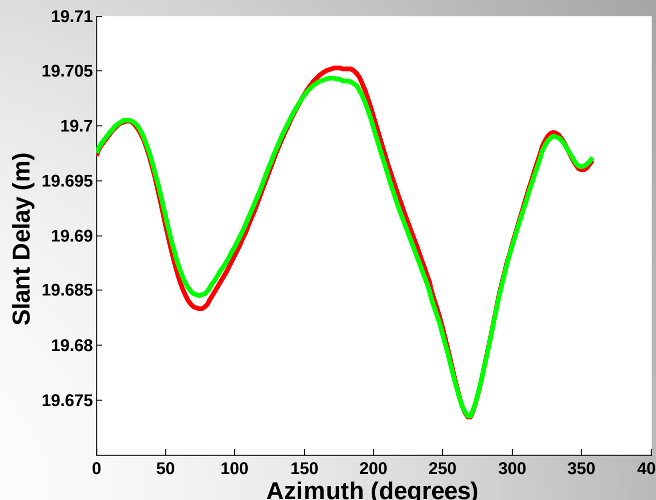
- **Horizontal interpolation (spline, bilinear, weighted mean,…)**

3. Results for VIE ray-tracers (1)

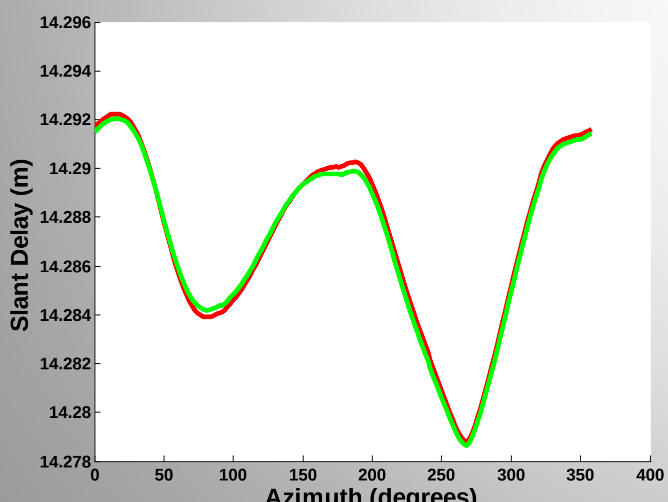
Computed delays for TSUKUBA site, using 2D and 3D ray-tracers



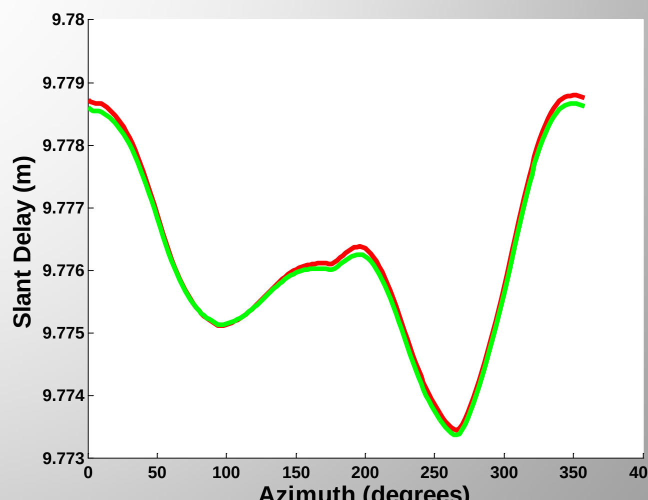
5-deg. Elevation angle



7-deg. Elevation angle



10-deg. Elevation angle

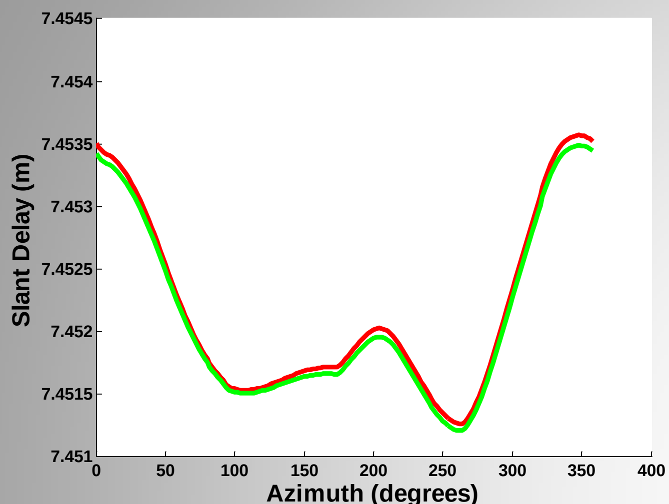


15-deg. Elevation angle

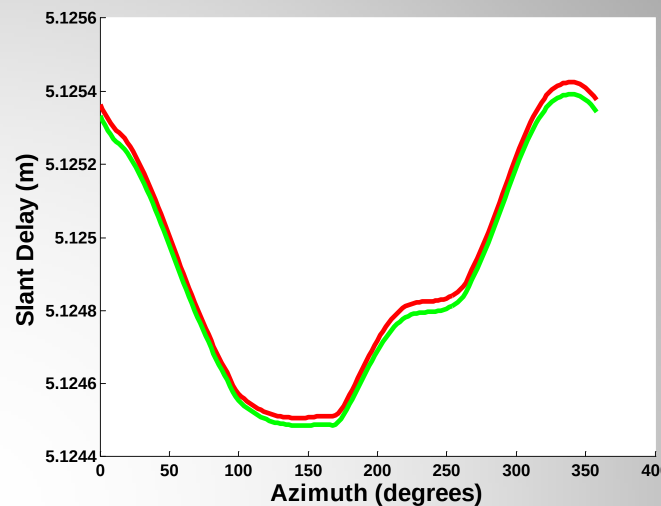
red: 2D, green: 3D

3. Results for VIE ray-tracers (2)

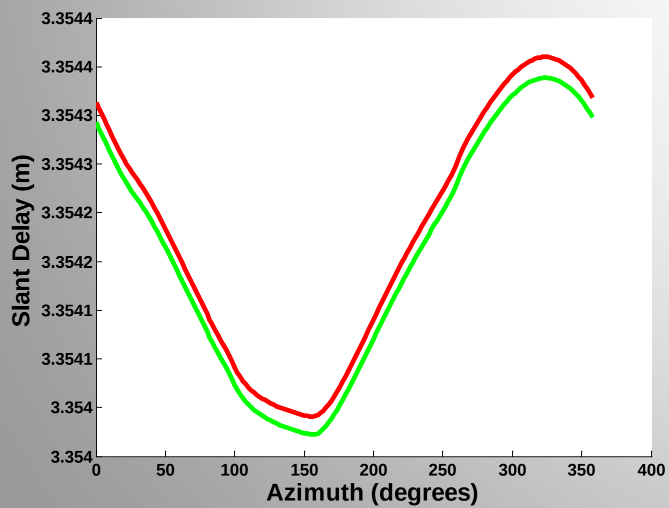
Computed delays for TSUKUBA site, using 2D and 3D ray-tracers



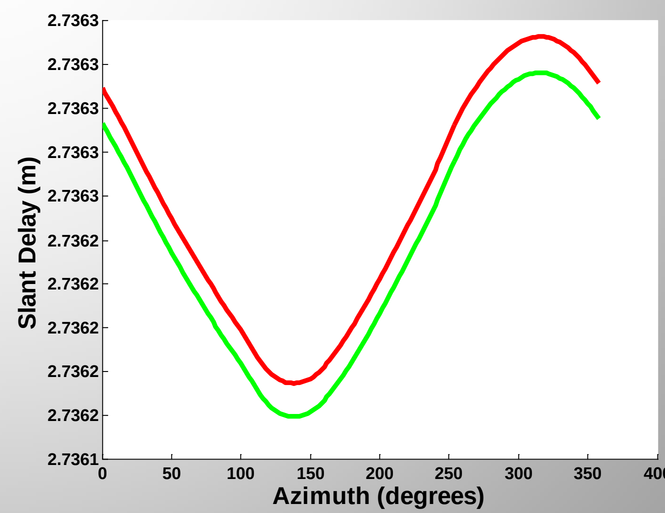
20-deg. Elevation angle



30-deg. Elevation angle



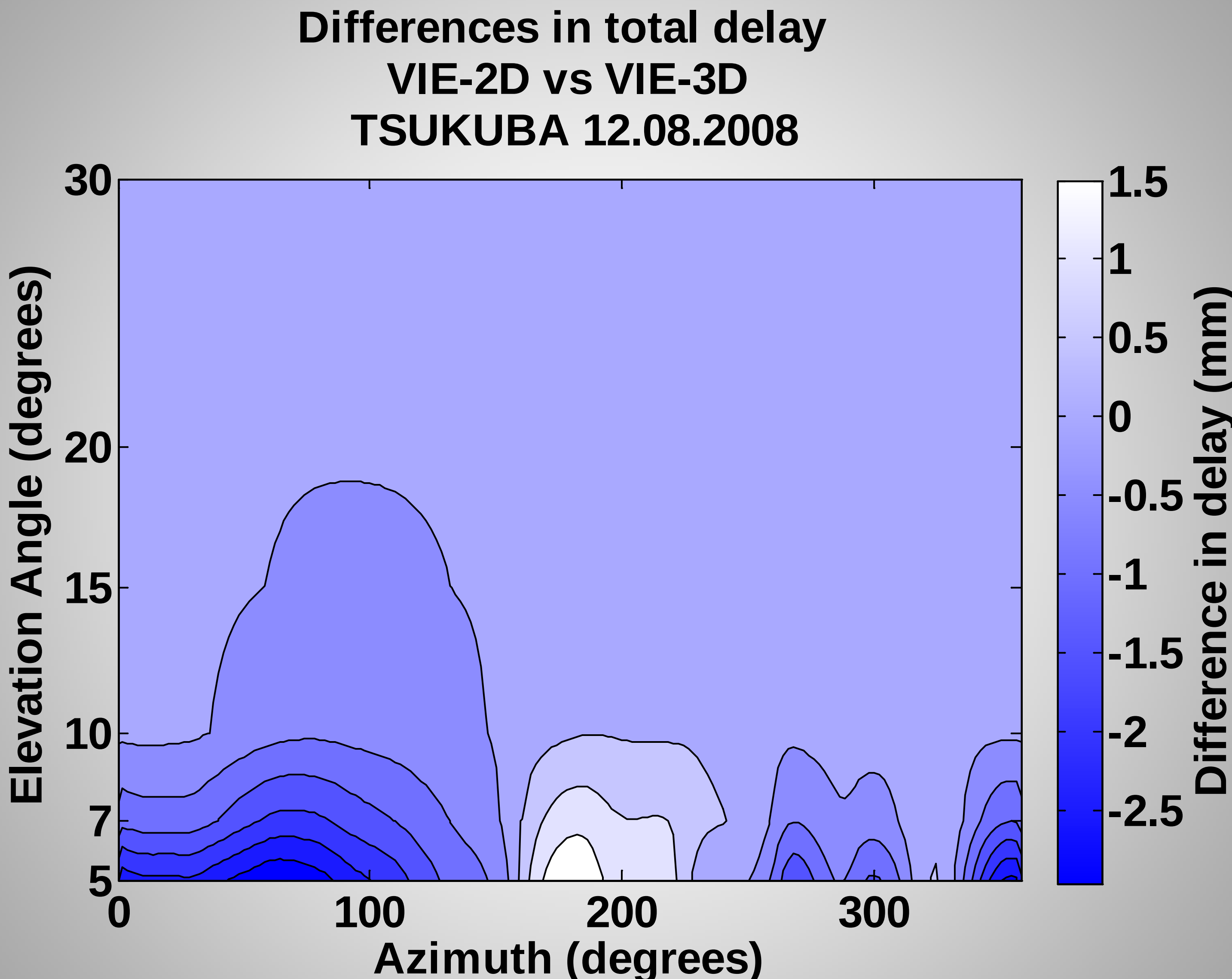
50-deg. Elevation angle



70-deg. Elevation angle

red: 2D, green: 3D

3. Results for VIE ray-tracers (3)



4. Results of ray-tracing campaign (1)

❖ **Aim: investigations about effect of different elements of ray-tracers on the final results and preparing benchmarking results for other ray-tracers**

❖ **Task: Computing total ray-traced delays at every degree (outgoing) elevation (>5°) and azimuth, plus the bending effect at the first epoch (0 UT)**

❖ **Under the umbrella of IAG WG 4.3.3 chaired by Thomas Hobiger**

❖ **First half of 2010**

4. Results of ray-tracing campaign (2)

Participants in this benchmarking campaign

1) UNB Raytracer : Felipe Nievinski, Landon Urquhart and Marcelo Santos (University of New Brunswick,Canada)

2) KARAT Raytracer (2D and 3D): Thomas Hobiger et al. (NICT, Japan)

3) Horizon-Eikonal : Pascal Gegout (GRGS, Toulouse, France)

4) GFZ: Florian Zus et al. (GFZ, Potsdam, Germany)

5) Vienna Raytracer (2D and 3D) : Vahab Nafisi , Dudy Wijaya, Johannes Böhm (Vienna University of Technology, Austria)

4. Results of ray-tracing campaign (3)

Different considerations, in different ray-traces

Ray-tracer	NWM	Upper limit of Trop. (km)	Supplementary atmosphere	Radius of curvature of the Earth	Interpolation methods
GFZ	ECMWF-model level	150	-	local radius of curvature of the reference ellipsoid	Refractivity: log-linear interpolation
Horizon-eikonal	ECMWF-model level	80	-	WGS84 reference ellipsoid	Refractivity: exponential
KARAT- Thayer	ECMWF-pressure level	86	US 76	Euler's formula	Temperature and relative humidity :linear Pressure.: logarithmically
KARAT-Eikonal	ECMWF-pressure level	86	US 76	Euler's formula	Temperature and relative humidity :linear Pressure.: logarithmically
UNB- bent3D	ECMWF-pressure level	100	CIRA86	ellipsoidal coordinates	Temperature and specific humidity: linear, Pressure: logarithmically
VIE-3D	ECMWF-pressure level	76	US 76	Gaussian mean curvature	Temperature: linear Pressure and water vapor pressure: exponential
VIE-2D	ECMWF-pressure level	76	US 76	Gaussian mean curvature	Temperature: linear Pressure and water vapor pressure: exponential

4. Results of ray-tracing campaign (4)

Data set # 1

TSUKUBA site (Japan)

$\phi = 36^{\circ}.1031$

$\lambda = 140^{\circ}.0887$

$h = 85.09m$

$N = 38.92m$

Epoch : 12.08.2008 , 0^{h}

$\text{ECMWF Model}, 0.1 \times 0.1$

Data set # 2

WETTZELL site (Germany)

$\phi = 49^{\circ}.15$

$\lambda = 12^{\circ}.88$

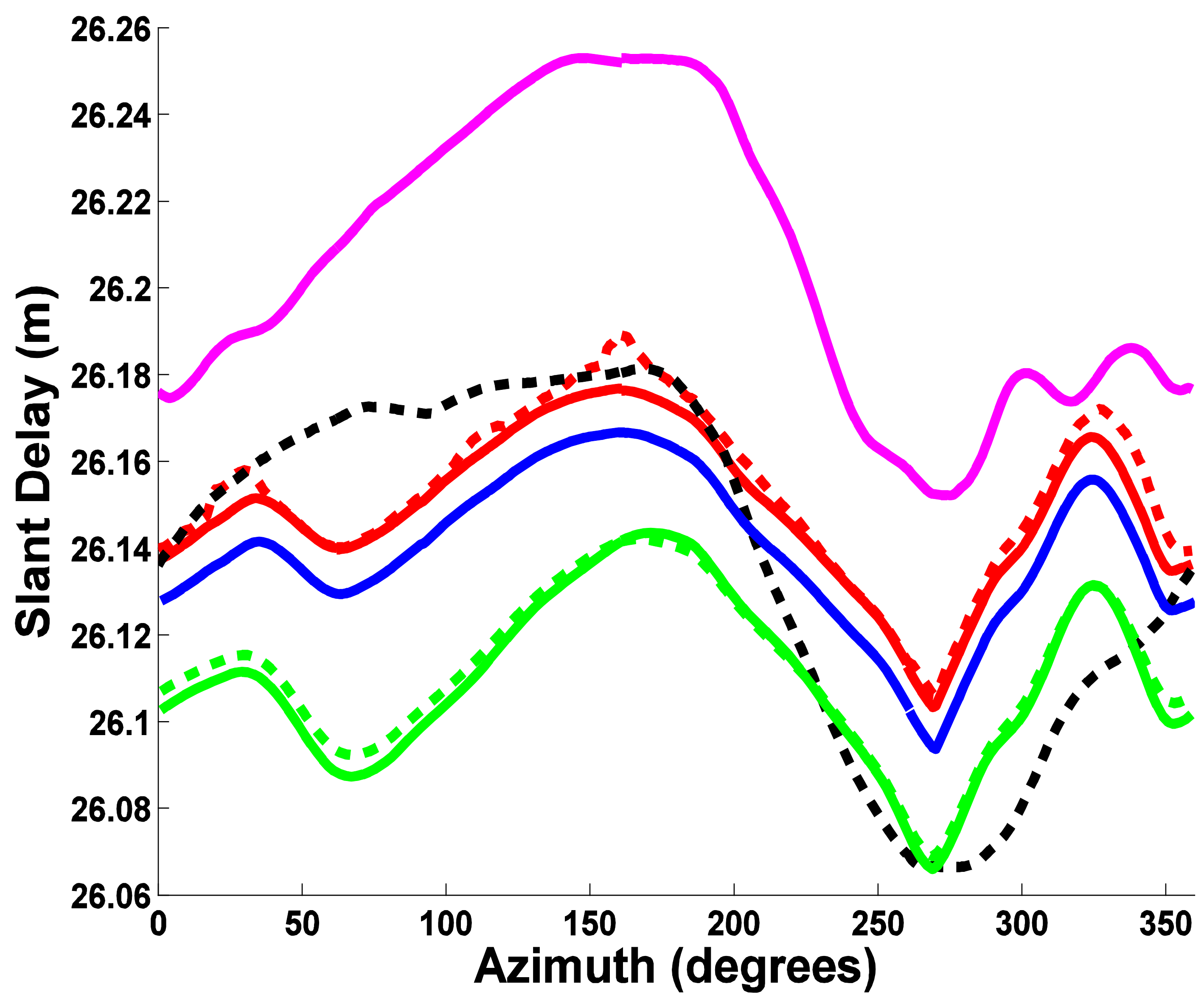
$h = 699.56m$

$N = 50m$

Epoch : 01.01.2008 , 0^{h}

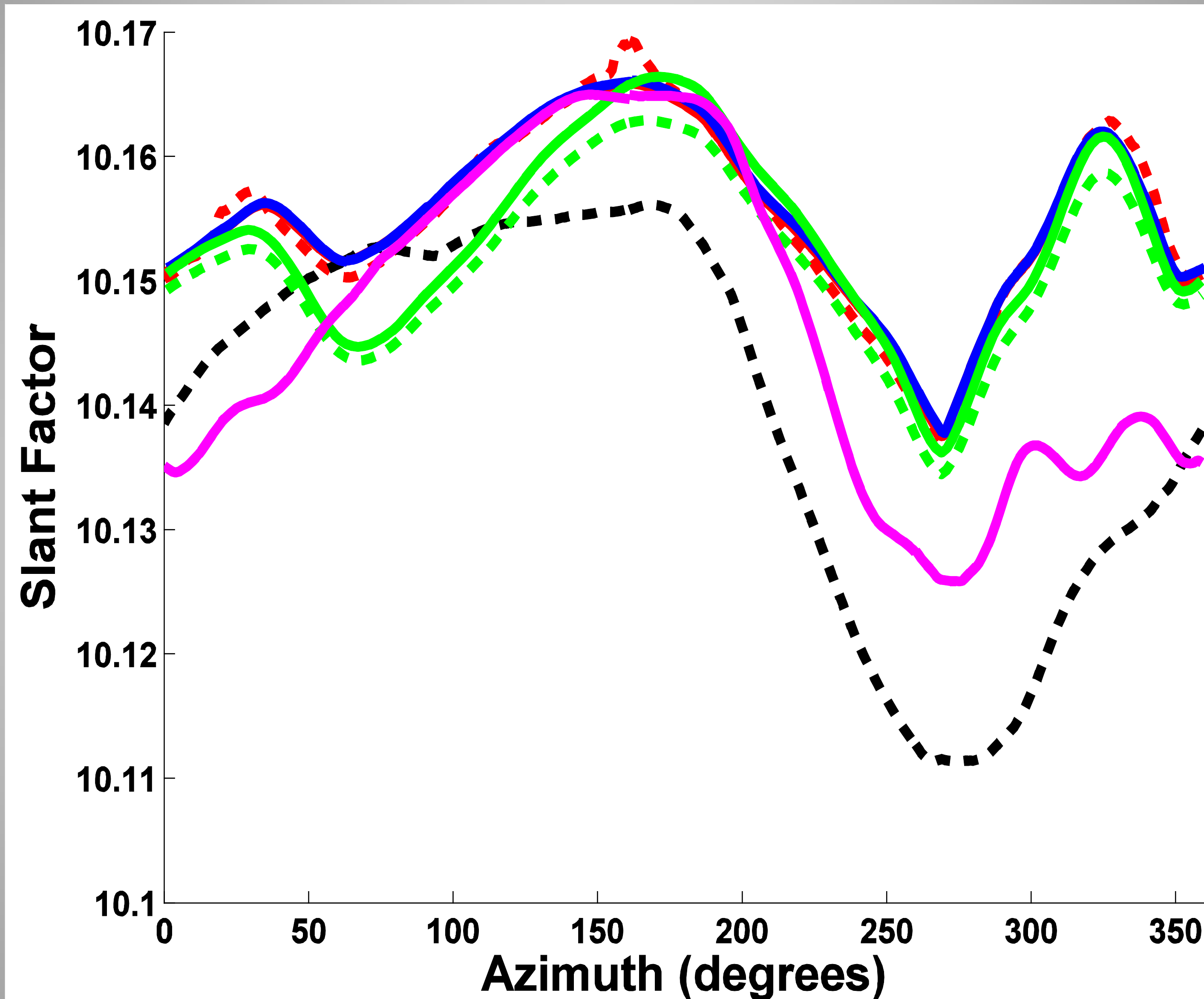
$\text{ECMWF Model}, 0.1 \times 0.1$

4. Results of ray-tracing campaign – Tsukuba, 5 deg. Elevation angle (5)



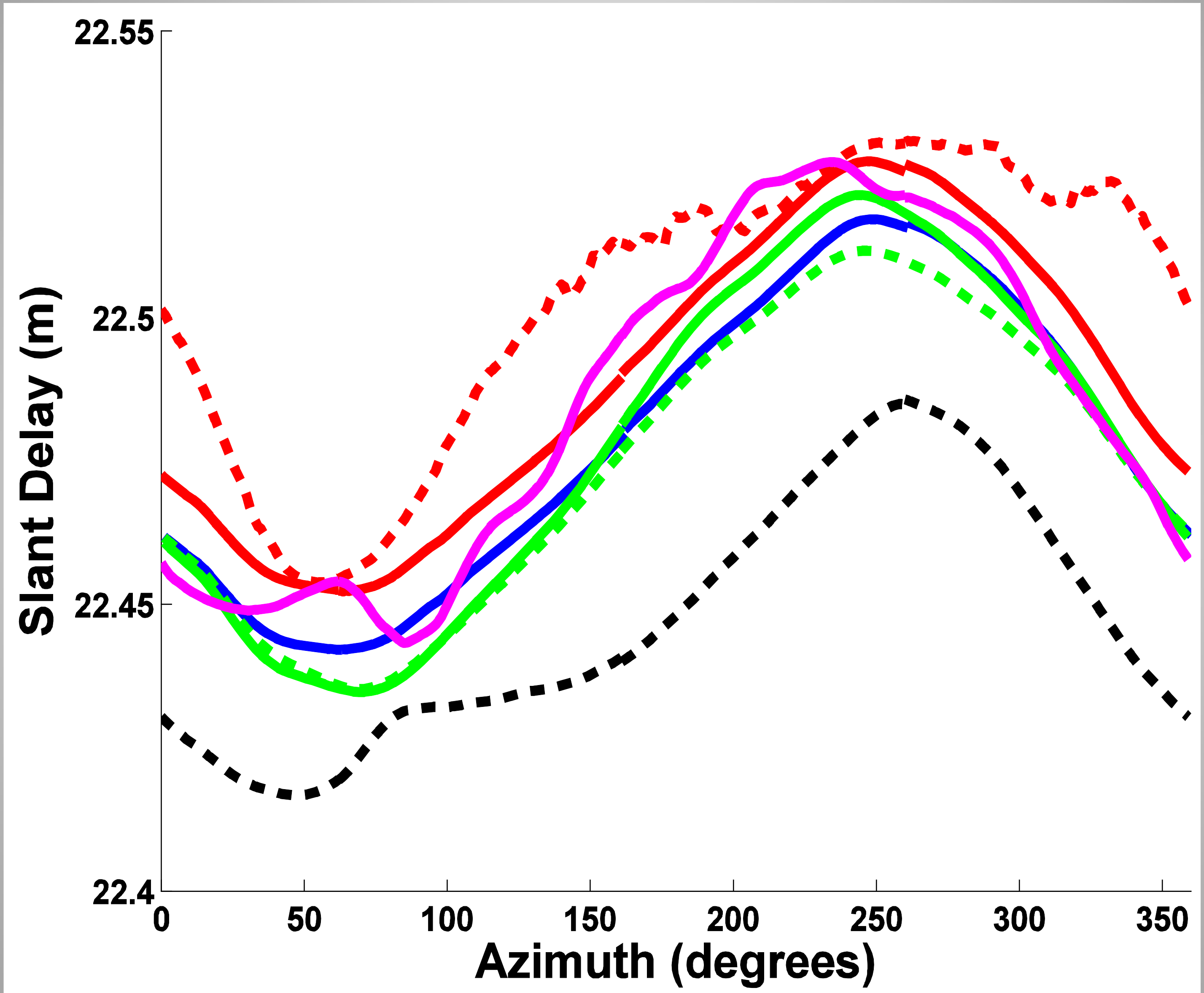
12.08.2010

4. Results of ray-tracing campaign – Tsukuba, 5 deg. Elevation angle (6)



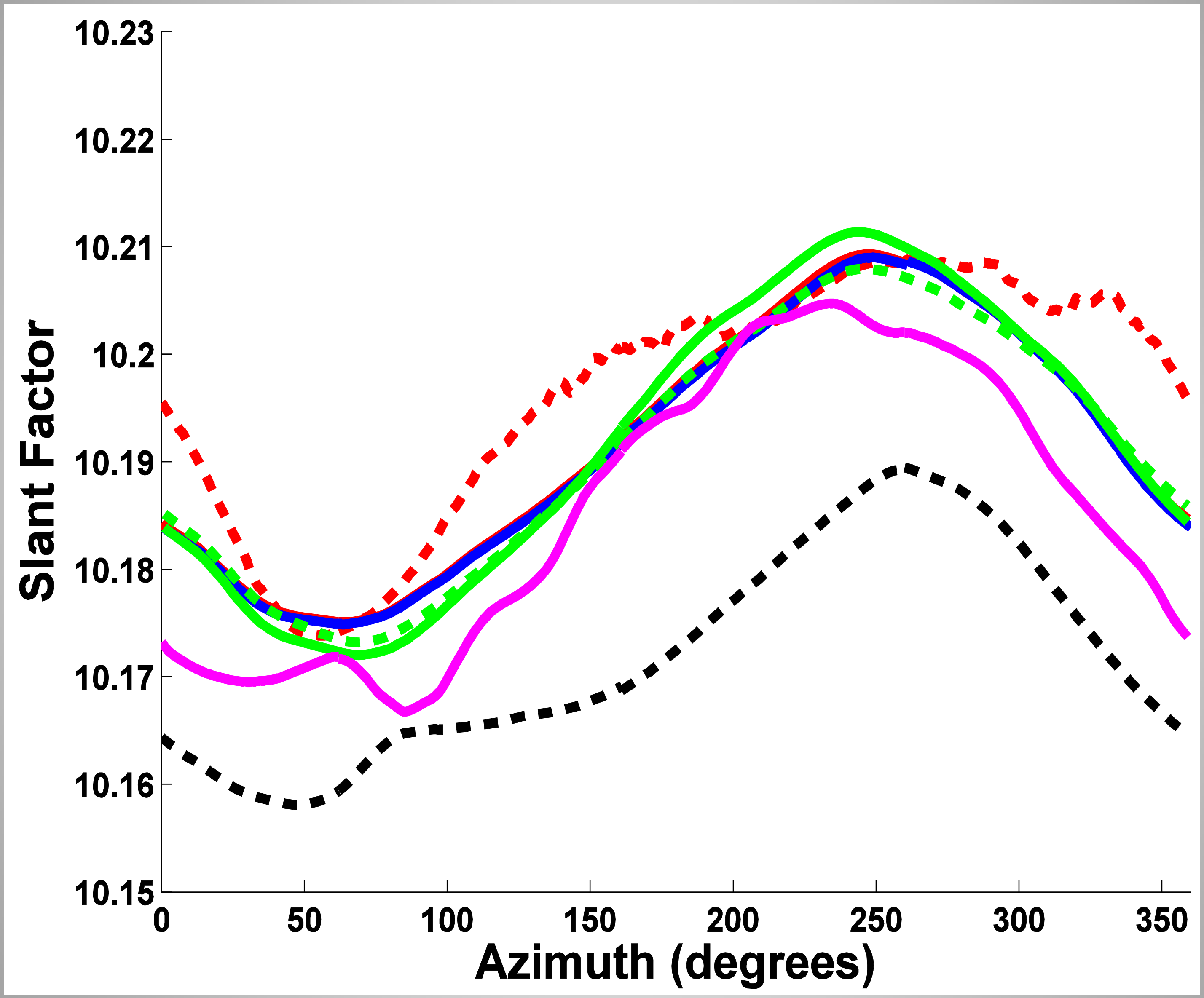
12.08.2010

4. Results of ray-tracing campaign – Wettzell, 5 deg. Elevation angle (7)



01.01.2008

4. Results of ray-tracing campaign – Wettzell, 5 deg. Elevation angle (8)



01.01.2008

4. Results of ray-tracing campaign – remarks (9)

Rule of thumb: The error in the station height is approximately 1/5 of the slant delay error at the 5 degrees elevation angle (Böhm, 2004)

For precision of 2mm for station heights we must care about elments of ray-tracer system

For a precision of 2 mm in station height, the biases between slant factors have to be smaller than 0.005. If the zenith delay is 2 m this corresponds to 1 cm at 5 degrees elevation, and 1/5th of this is 2 mm.

We need to estimate residual zenith delay

5. Concluding remarks and future works (1)

- **Developing a 3D ray-tracer based on Eikonal equation**

- **Some simplifications for a 2D ray-tracer (ignoring out-of-plane components)**

- **Discrepancies between results of different ray-tracers (ray-tracing campaign), because of different interpolation and extrapolation methods, upper limit of troposphere, data sets**

5. Concluding remarks and future works (2)

- **Focus on different Numerical Weather Models in future**

- **Validation of results obtained by VIE ray-tracers, using VLBI observations**

- **Ray-traced delays as a part of Vienna VLBI Software (VieVS) in future**