Application of ray-tracing through the high resolution numerical weather model HIRLAM for the analysis of European VLBI data

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30th March 2011

20th EVGA Meeting - Bonn (Germany)

Introduction

- An important limitation for the precision in the results obtained by space geodetic techniques like VLBI and GPS are caused by the tropospheric effects due to **neutral atmosphere**
- In recent years **numerical weather models (NWM)** have been applied to improve mapping functions which are used for tropospheric delay modeling in VLBI and GPS data analyses
- A troposphere correction model based on direct calculation of the slant delay applying raytracing to the **Conformal Theory of Refraction** through the Limited Area numerical weather prediction (NWP) HIRLAM 3D-VAR is developed

  1. The advantages of the Conformal Theory of Refraction is that the atmospheric propagation effects are evaluated along the *line of sight* and the known *vacuum elevation angle* is used so no iterative calculations are needed
  2. The advantages of HIRLAM model are the high *spatial resolution* (0.2°x0.2°) and the high *temporal resolution* in prediction mode (every 3 hours)

1. Introduction
   - Delay of a signal propagating through the atmosphere
2. HIRLAM
   - HIRLAM (High Resolution Limited Area Model)
   - ECMWF vs HIRLAM
   - HIRLAM Topography
3. Raytrace approach
   - Raytrace program
4. Moritz approach
   - Application of the Conformal Theory of Refraction
   - Moritz approach
5. Conclusions

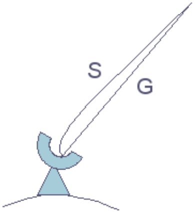
Delay of a signal propagating through the atmosphere

Tropospheric model and computing delays through ray-tracing

Refractivity: curvature and delay

Electrical path length

$$L(\epsilon, \phi) = \int_S n ds$$



S: path of the signal
G: geometrically shorter path

Atmospheric delays can be evaluated along the path of the ray originating from the direction of the ray emission source and passing through the atmosphere to a receiving antenna

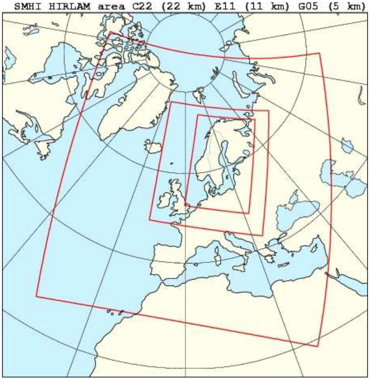
Path delay

$$\Delta L = 10^{-6} \int_S N(s) ds$$

HIRLAM
High Resolution Local Area Model

HIRLAM: High Resolution Numerical Weather Model (NWM)

- Limited Area Model (Europe)
- Synoptic scale (displaying conditions simultaneaously over a broad area)
- Hydrostatic grid point model
- Spatial resolution $0.2° \times 0.2°$
  - Horizontally: 22 to 5 km
  - Vertically: 16 to 60 levels
- Temporal resolution
  - Analysis: 6 hours assimilation cycle (00h, 06h, 12h, 18h)
  - Forecast: every 3 hours
- Initial and boundary conditions: **ECMWF** (European Centre for Medium-Range Weather Forecast)

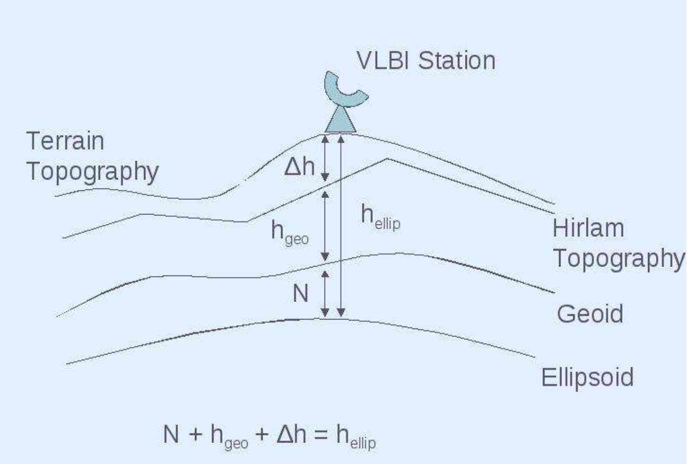


ECMWF & HIRLAM

European Centre for Medium-Range Weather Forecast & High Resolution Local Area Model

	ECMWF	HIRLAM
Spatial resolution	$2.5^o \times 2.5^o$	$0.2^o \times 0.2^o$
Number of pressure levels	15	31
Temporal resolution in post processing mode	6 hours	6 hours
Temporal resolution in prediction mode	6 hours	3 hours

HIRLAM Topography



Raytrace program

Davis, J.L., T.A.H. Herring and A.E. Niell,
The Davis/Herring/Niell Raytrace program, 1987-1989

HIRLAM input:

- Profiles 6 hours time resolution (00h, 06h, 12h, 18h)
- 22 km horizontal resolution
- 40 vertical levels refine to approx. 1000 layers
- Atmosphere height extrapolated to 136 km
- Grid model: interpolation between the 4 nearest points around the station

Raytrace program:

- Pressure, Temperature and Relative Humidity profiles at a starting height above sea level for each site and time epoch
- Elevation angle of each observation
- No Azimuth angle dependence
- Calculate 'Path Delay' through the **homogeneous atmosphere**

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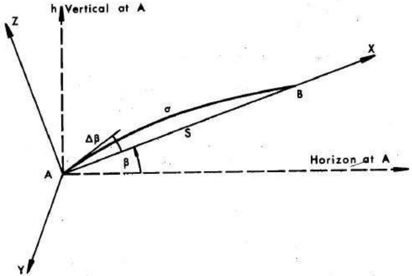
Application of the Conformal Theory of Refraction (I)

Derived by Moritz (1967) and developed by Brunner and Angus-Leppan (1976)

- Solution of Eikonal equation has been included in the equations
- Atmospheric propagation effects are evaluated along the **known chord line** and not along the unknown wave path
- **Vacuum elevation angle** is used so no iterative calculations are needed



Application of the Conformal Theory of Refraction (II)

$$\Delta S = 10^{-6} \int_0^S NdX - \frac{1}{2} 10^{-12} \int_0^S [(\int_0^S \frac{dN}{dY} \varepsilon d\varepsilon)^2 + (\int_0^S \frac{dN}{dZ} \varepsilon d\varepsilon)^2] \frac{dX}{X^2}$$

where ε is a integration variable only

If we neglect the small effect of curvature due to lateral refraction caused by $\frac{dN}{dY} \approx 0$, and $\frac{dN}{dZ} = cos\beta(\frac{dN}{dh})$ where β is the vacuum elevation angle.

Then practical approximation:

$$\Delta S = 10^{-6} \int_0^S NdX - \frac{cos^2\beta}{2} 10^{-12} \int_0^S (\int_0^S (\frac{dN}{dh}) \varepsilon d\varepsilon)^2 \frac{dX}{X^2}$$

Moritz approach (I)

HIRLAM input

Interpolation in time

- Profiles 6 hours time resolution (00h, 06h, 12h, 18h): interpolation in time for each scan

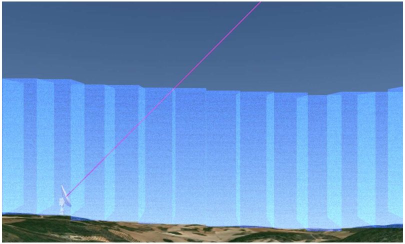
Interpolation in the horizontal

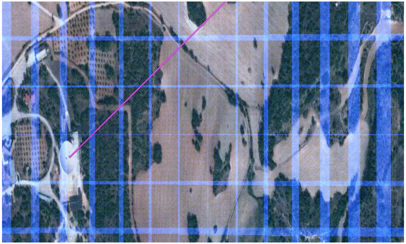
- Grid model: 22 km horizontal resolution
- Interpolation between the 4 nearest points around the station and each ray point in the atmosphere (check if it is in the same vertical profile)

Interpolation in the vertical and refinement

- 40 vertical levels refine to approx. 1000 layers (step size depend on atmosphere height)
- Atmosphere height extrapolated to 136 km
- Station height in the HIRLAM vertical profile (interpolation/extrapolation)
- Heights calculated over WG84 ellipsoid and undulations from potential coefficient model egm96

One example from the side and the top





Not in scale!
Courtesy: Carolina ZG - 3dmax 2010

Moritz approach (II)

Conformal Theory of Refraction, Moritz (1967)

- **Elevation** angle of each observation
- **Azimuth** angle dependence
- Neglect the small effect of curvature due to lateral refraction caused by $\frac{dN}{dY} \approx 0$
- Starting integration at station height
- Size and number of integration steps along the chord line depend on vacuum elevation angle β and the current height of the ray point in the atmosphere (vertical refinement steps). Need to find a compromise with execution time (approx. 250 integration steps)
- Recalculate β at each ray point
- Calculate 'Path Delay' through the **3D inhomogeneous atmosphere** through the chord line

ZWD for CONT08 time series

for Wettzell station using HIRLAM and other techniques (Teke et al. 2010)

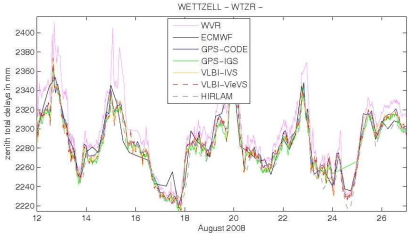


Figure: ZTD multi-technique comparison, Teke et al. (2010)

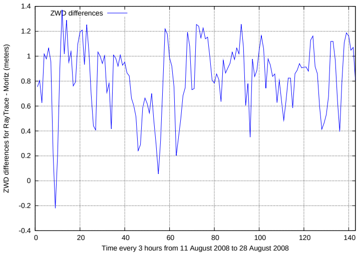


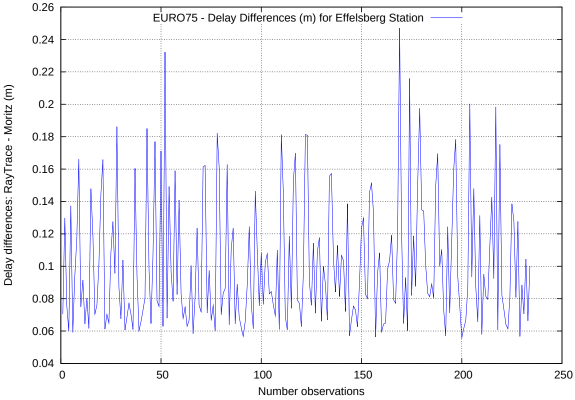
Figure: ZWD differences using HIRLAM profiles: ZWD calculation - scans at el=90°

Forecast and analysis HIRLAM profiles are combinated
Differences between HIRLAM comparison are due to improvements in interpolation (distance calculation)
Mean = 0.83 mm
Standard deviation of the mean = 0.02 mm

Difference in calculated slant delays

Comparison between Raytrace & Moritz Slant delays (I)

Homogeneous vs Inhomogeneous atmosphere



Maximum difference = 24.70 cm

Minimum difference = 5.58 cm

Difference in calculated slant delays

Comparison between Raytrace & Moritz Slant delays (II)

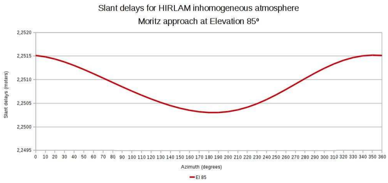
Homogeneous vs Inhomogeneous atmosphere

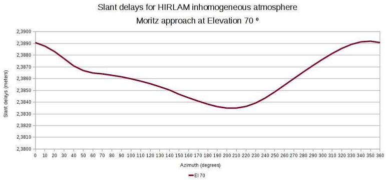
Station	# obs	Max diff (m)	Min diff (m)
EURO75			
EFLSBERG	234	0,25	0,06
MEDICINA	263	0,37	0,05
ONSALA60	214	0,33	0,05
NYALES20	190	0,35	0,05
WETTZELL	225	0,37	0,06
NOTO	164	0,29	-0,18
EURO77			
WETTZELL	221	0,37	0,06
NYALES20	178	0,31	0,05
ONSALA60	208	0,35	0,05
MEDICINA	248	0,39	0,05
EURO79			
MEDICINA	341	0,33	0,05
SVETLOE	348	0,27	-2,84
WETTZELL	318	0,35	0,05
ZELENCHK	102	0,23	0,05
EURO76			
SVETLOE	261	0,27	0,06
WETTZELL	199	0,42	0,06
NYALES20	182	0,35	0,05
ONSALA60	195	0,36	0,06
MEDICINA	270	12,61	-16,09
EURO78			
SVETLOE	250	0,23	0,05
WETTZELL	223	0,34	0,06
NYALES20	193	0,33	0,05
ONSALA60	160	0,31	0,05
MEDICINA	272	0,4	0,05
EFLSBERG	307	0,25	0,06

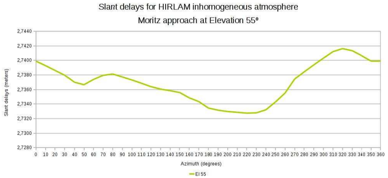
Table showing maximum and minimum differences between Raytrace & Moritz Slant delays

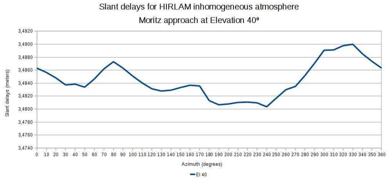
Inhomogeneous atmosphere for Effelsberg

Moritz approach for EURO75 HIRLAM profile





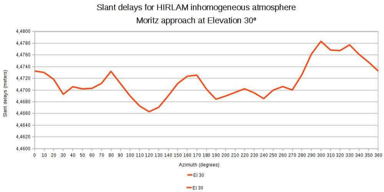


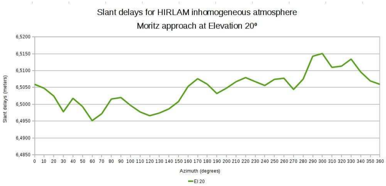


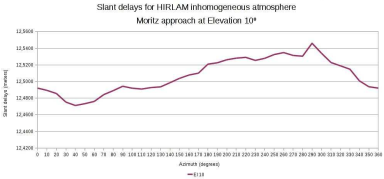
Effelsberg 25th March 2005 12:00

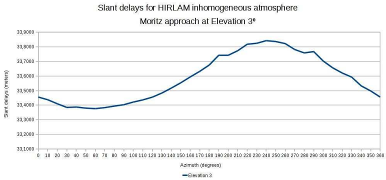
Inhomogeneous atmosphere for Effelsberg

Moritz approach for EURO75 HIRLAM profile









Effelsberg 25th March 2005 12:00

Conclusions and Future work

Conclusions

- We have calculated slant delays using homogeneous and inhomogeneous atmosphere
- Raytrace approach simplifies to an homogeneous atmosphere
- Moritz approach includes the effect of an inhomogeneous atmosphere in the delay
- Differences between Raytrace and Moritz approach are the inhomogeneous atmosphere contributions
- Comparison of ZWDs and slant delays at elevation 90° using Moritz approach is in the order of 1 mm level due to improvements in the interpolation
- We calculate more precise and accurate slant delays with Moritz 3D approach

Future work

- Comparison of Moritz slant delays raytrace through HIRLAM to other NWM e.g. ECMWF and other approaches e.g. KARAT
- We will analyze VLBI European data using the calculated slant delays as apriori

Thank you!
Questions?

HIRLAM Surface Pressure vs Pressure@Stations