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


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# 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 model of the troposphere based on direct calculation of the delay via raytracing through the Limited Area numerical weather prediction (NWP) HIRLAM 3D-VAR model is developed and applied to Europe VLBI data.

- The advantages of this model are the high spatial resolution  (0.2 deg x 0.2 deg) and the high temporal resolution in prediction mode (every 3 hours).

# SUMMARY

- Delay of a signal propagating through the atmosphere
- Mapping functions
- Compute Delays through Ray-Tracing
- HIRLAM (High Resolution Limited Area Model)
- Application for the analysis of European VLBI
- Conclusions
- Future work

# Delay of a Signal Propagating through the Atmosphere

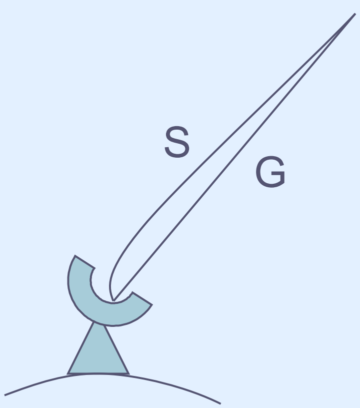
Electrical path length

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

Index of refraction

$$n - 1 = 10^{-6} N$$

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




S: path of the signal
G: geometrically shorter path

Excess propagation path or path delay

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

$$\Delta L(\epsilon,\phi) = \int_S (n-1)\, ds + S - G$$

Refractivity = Dry + Wet

$$N = k_1 \frac{p_d}{T} Z_d^{-1} + k_2 \frac{p_w}{T} Z_w^{-1} + k_3 \frac{p_w}{T^2} Z_w^{-1}$$

$p_d$ partial pressure of dry constituents
$p_w$ partial water vapor pressure
T absolute temperature
$Z_d$,$Z_w$ compressibility factor for dry air and water vapor
$k_1$, $k_2$, $k_3$ constants

$$\Delta L = \Delta L_w + \Delta L_h$$

# MAPPING FUNCTIONS (I)

$$\Delta L(\epsilon) = \Delta L_w^z \cdot m_w(\epsilon) + \Delta L_h^z \cdot m_h(\epsilon)$$

$$m(\epsilon) = \frac{1 + \frac{a}{1+\frac{b}{1+c}}}{\sin\epsilon + \frac{a}{\sin\epsilon + \frac{b}{\sin\epsilon + c}}}$$

- Niell Mapping Function (NMF)
  - Radiosonde data
  - Station height, latitude and day of the year
- Isobaric Mapping Function (IMF)
  - Raytracing through radiosonde data
  - Height of the 200 mbar pressure level and the ratio of the wet path delay along a straight line at 3.3º elevation and zenith delay

# MAPPING FUNCTIONS (II)

- Vienna Mapping Function (VMF)
  - Raytracing through the numerical weather model ECMWF (European Centre for Medium-Range Weather Forecast) (2.5º x 2.5º)
- HIRLAM Based Mapping Function (HBMF)
  - Raytracing through the numerical weather model HIRLAM (High Resolution Limited Area Model) (0.2º x 0.2º)

| | 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 |

# COMPUTE DELAYS THROUGH RAY-TRACING

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

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

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

  - Pressure, Temperature and Relative Humidity profile at  a starting height above sea level
  - Elevation angle of each observation
  - No Azimuth angle dependance
  - Profile time resolution (00h, 06h, 12h, 18h)
  - Calculate 'Path Delay' through the atmosphere

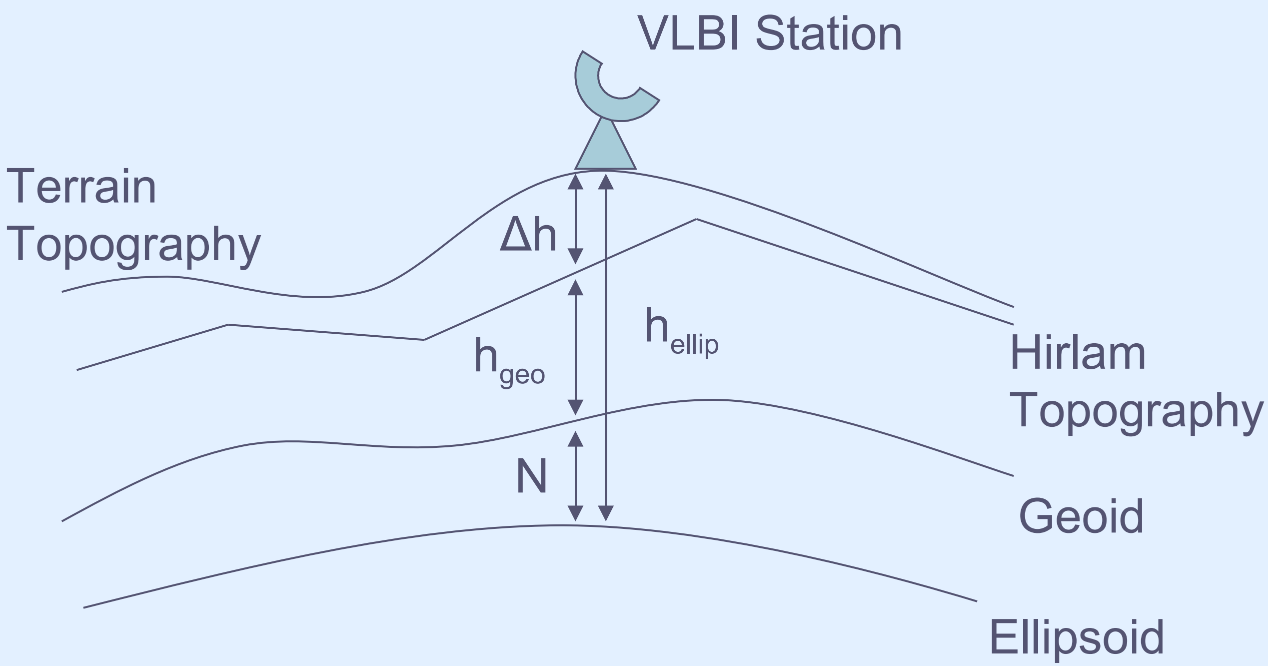
# HIRLAM (High Resolution Local Area Model) (I)

- High Resolution Numerical Weather Model (NWM)
- Limited Area Model (Europe)
- Synoptic scale (displaying conditions simultaneaously over a broad area)
- Numerical short-range (<48h) weather forecasting system
- Hydrostatic grid point model

# HIRLAM (High Resolution Local Area Model) (II)


- Spatial resolution 0.2º x 0.2º
  - 22 to 5 km horizontally
  - 16 to 60 levels vertically
- Temporal resolution
  - Analysis: 6 hours assimilation cycle (00h, 06h, 12h, 18h)
  - 3 hours cycle also available
- Initial and boundary conditions
  - ECMWF model (European Centre for Medium-Range Weather Forecast)

# HIRLAM (High Resolution Local Area Model) (III)



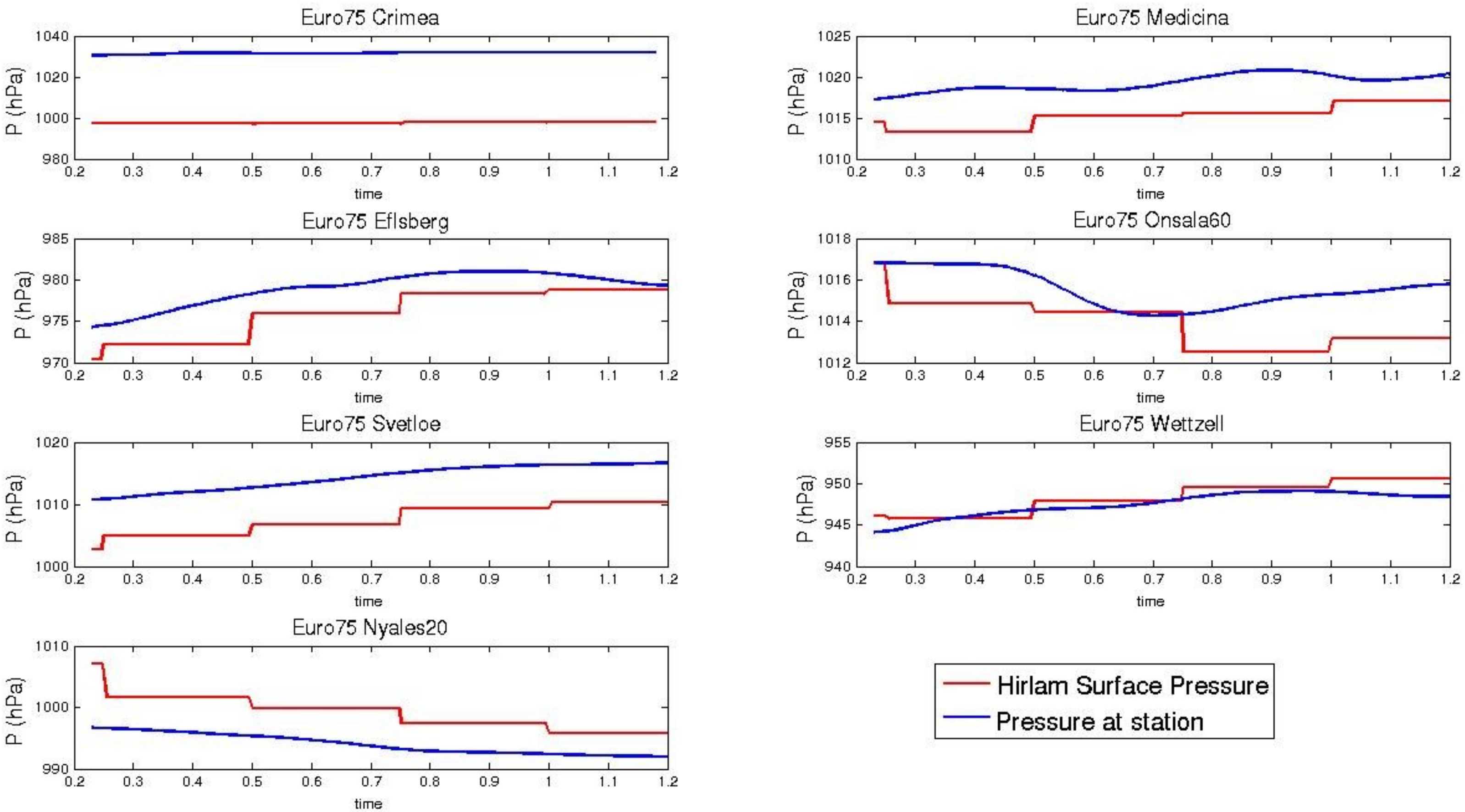

$N + h_{geo} + \Delta h = h_{ellip}$

Temperature
Pressure
Relative Humidity

$$\Delta L = \Delta L_w + \Delta L_h$$

# HIRLAM (High Resolution Local Area Model) (IV)

- Hirlam Surface Pressure vs Pressure@Stations

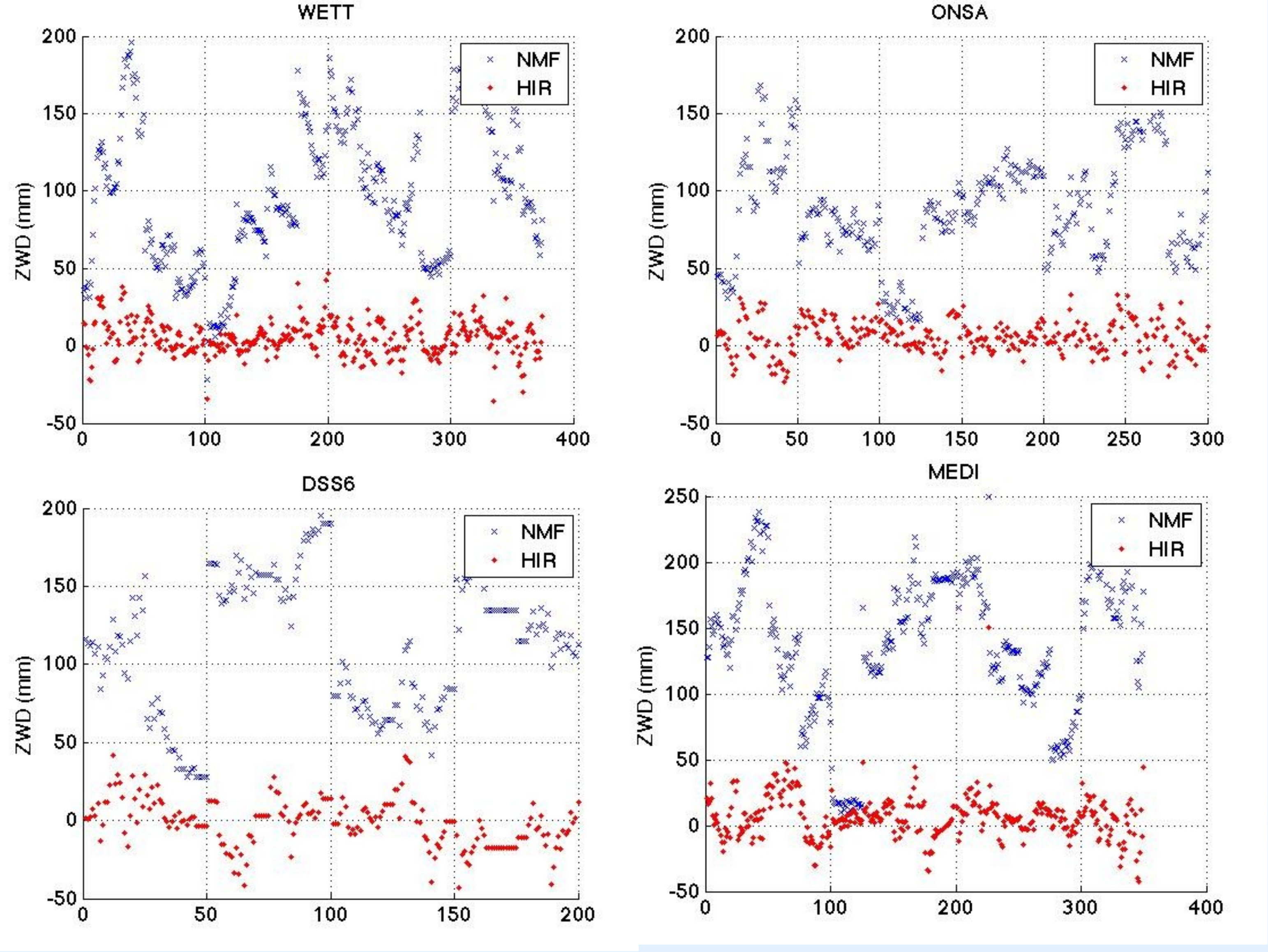


# Application for the analysis of European VLBI (I)

- HIRLAM data used for 15 EURO experiments
  - EURO75 to EURO89 (2005 to 2007)
  - 12 different stations involved
    - CRIMEA, DSS65A, EFLSBERG, MATERA, MEDICINA, METSAHOV, NOTO, NYALES20, ONSALA60, SVETLOE, WETTZELL, ZELENCHK
  - Badary station not included in HIRLAM grid (EURO87)
  - HIRLAM files: 22 km horizontal resolution, 40 vertical levels and 6 hours resolution time (00h, 06h, 12h, 18h)
  - Grid model: interpolation between the 4 nearest points around the station
- For each site and time epoch
  - Pressure, Temperature and Relative Humidity for 40 vertical levels from HIRLAM model

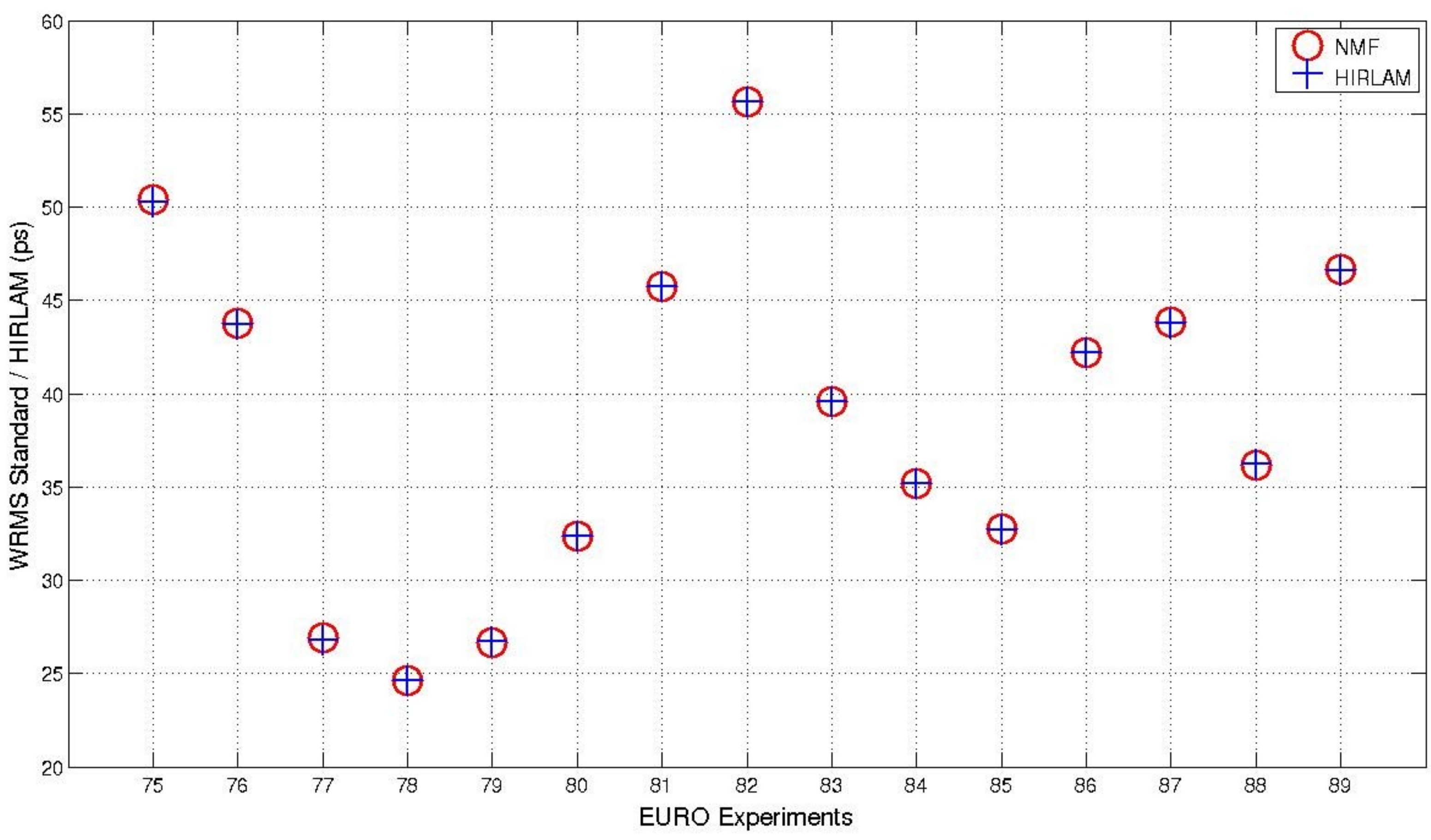
# Application for the analysis of European VLBI (II)

- Zenith Wet Delays time series



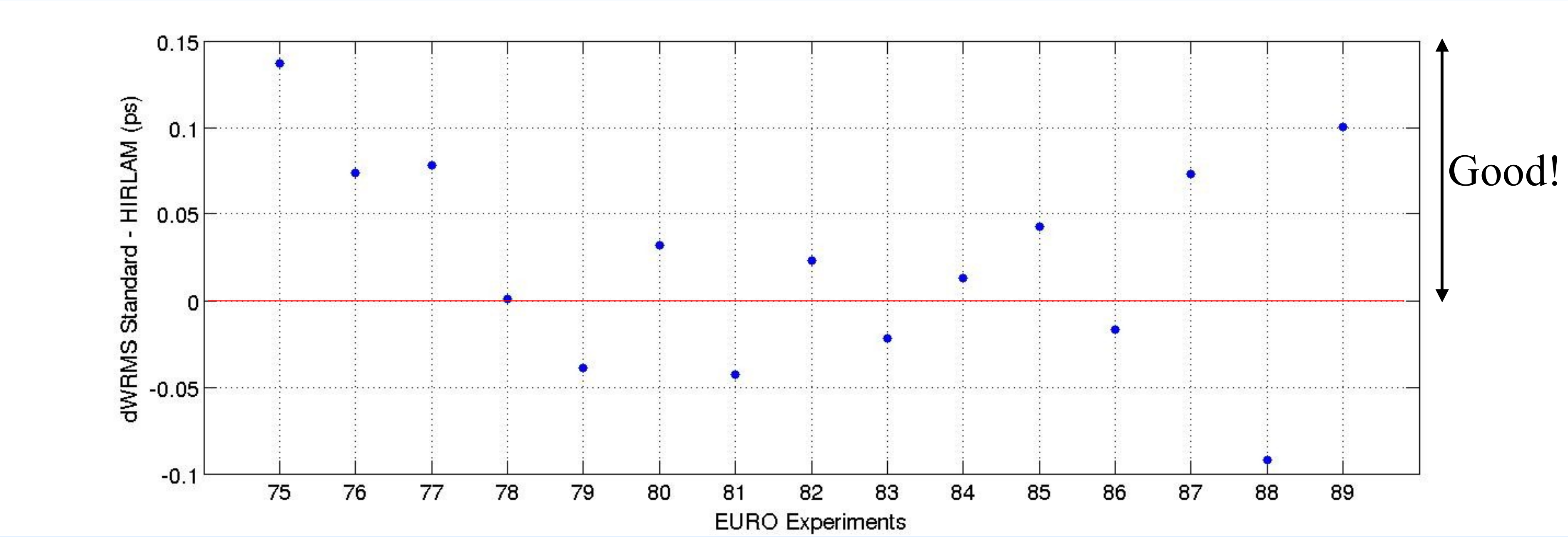
# Application for the analysis of European VLBI (III)

- Comparison WRMS Residual Delay



# Application for the analysis of European VLBI (IV)

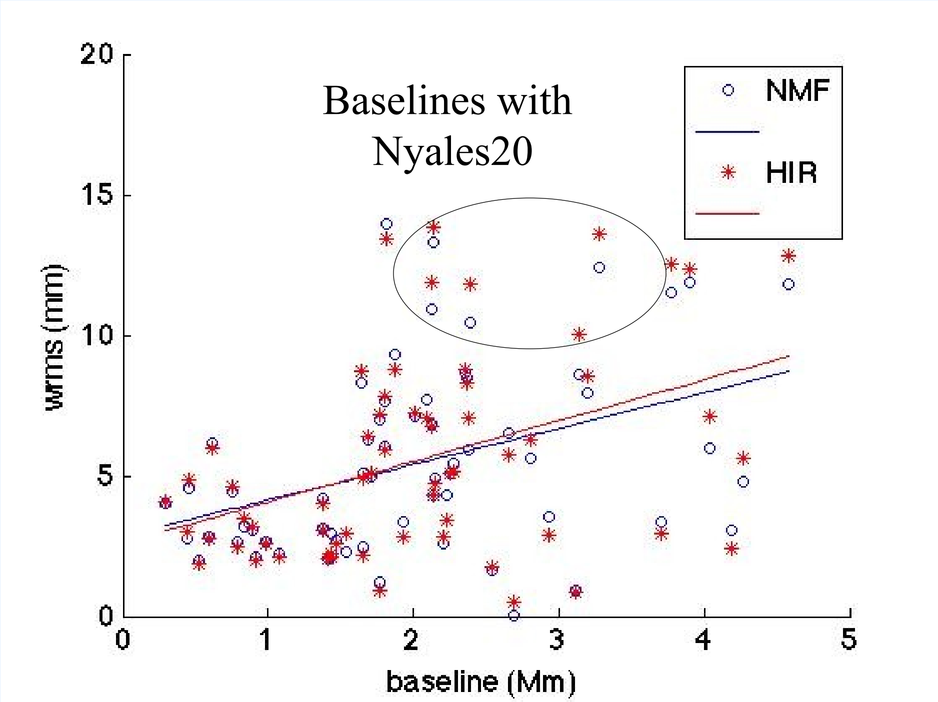
- Differences WRMS Residual Delay between NMF and HIRLAM

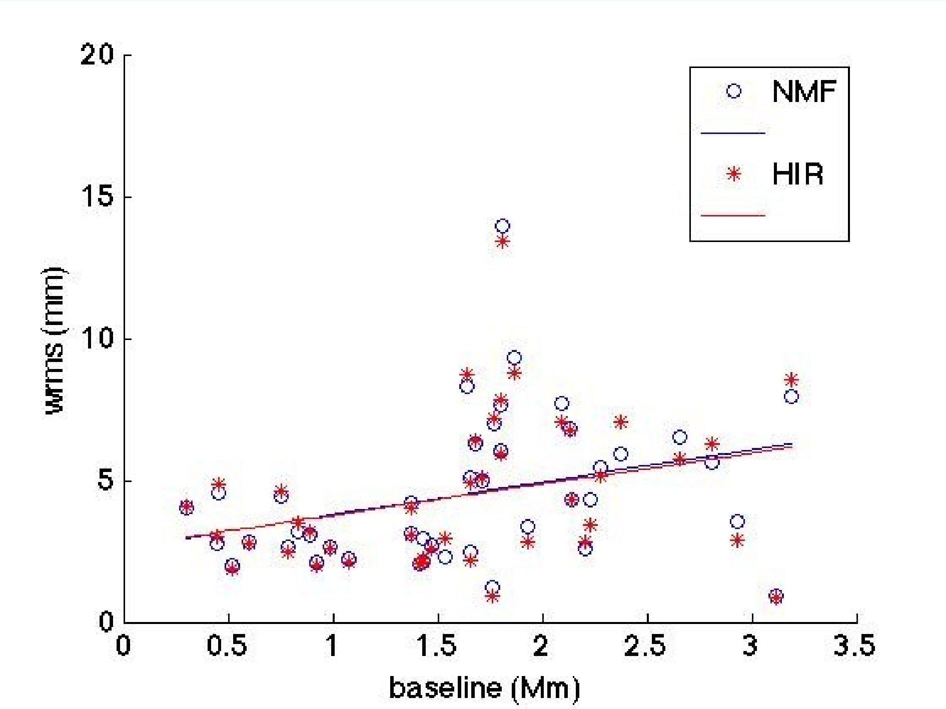



- 9/15 experiments improved WRMS
- 4/15 experiments get worse WRMS

# Application for the analysis of European VLBI (V)

- Baselines repeatibility




| | rate | offset | | rate | offset |
|---|---|---|---|---|---|
| NMF | 1.27 ppb | 2.8 mm | NMF | 1.15 ppb | 2.6 mm |
| HIRLAM | 1.45 ppb | 2.6 mm | HIRLAM | 1.10 ppb | 2.6 mm |

# CONCLUSIONS

- We have used HIRLAM to model slant delay.
- Estimated ZWD are smaller and closer to 0 than using NMF.
- WRMS improves in 9/15 experiments with HIRLAM approach.
- We haven’t found significance changes in baseline repeability.
  - NWM resolution is no good enough for some stations.

# FUTURE WORK

- Create 4D Ray-Tracing program fully elevation and azimut dependent for each observation using HIRLAM profiles.
- Use forecast HIRLAM profiles combinated with analysis to improve time resolution (3 h).
- Calculate HIRLAM based mapping functions to compare with.
- Use HIRLAM to estimate wet delays and NMF to estimate dry delays.

# Thank you for your attention!

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