Ray-traced tropospheric slant delays from numerical weather models in VLBI analysis

Vahab Nafisi [1,2]

Matthias Madzak [1]

Andrea Pany [1]

Johannes Böhm [1]

Harald Schuh [1]

Alireza A. Ardalan [2]

(1) Institute of Geodesy and Geophysics, Vienna University of Technology, Austria

(2) Department of Surveying and Geomatics Engineering, College of Engineering, University of Tehran, Iran

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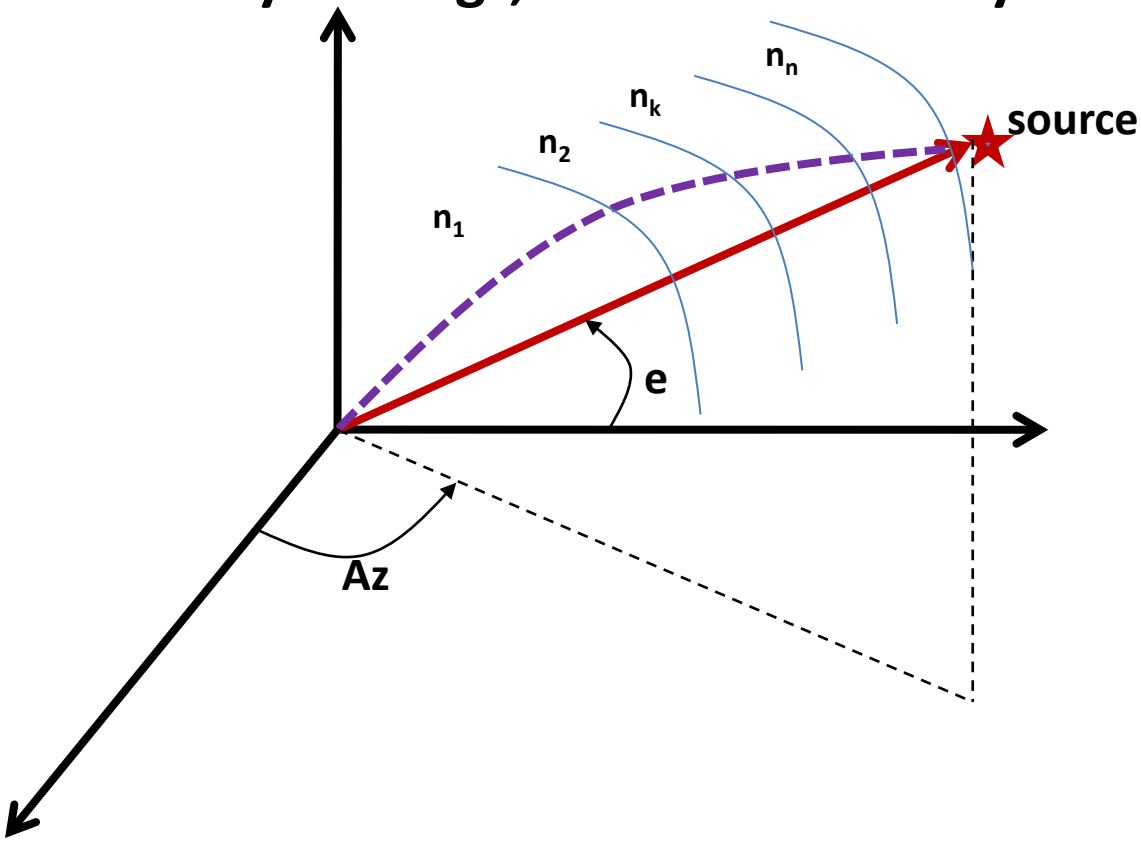
Outlook

- A ray-tracing package and computational aspects

- CONT08 processing results

0. Introduction

- "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 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 Ray-tracing systems (2)

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

$$\frac{\partial n}{\partial \lambda} \qquad \frac{\partial n}{\partial \theta} \qquad \frac{\partial n}{\partial r}$$

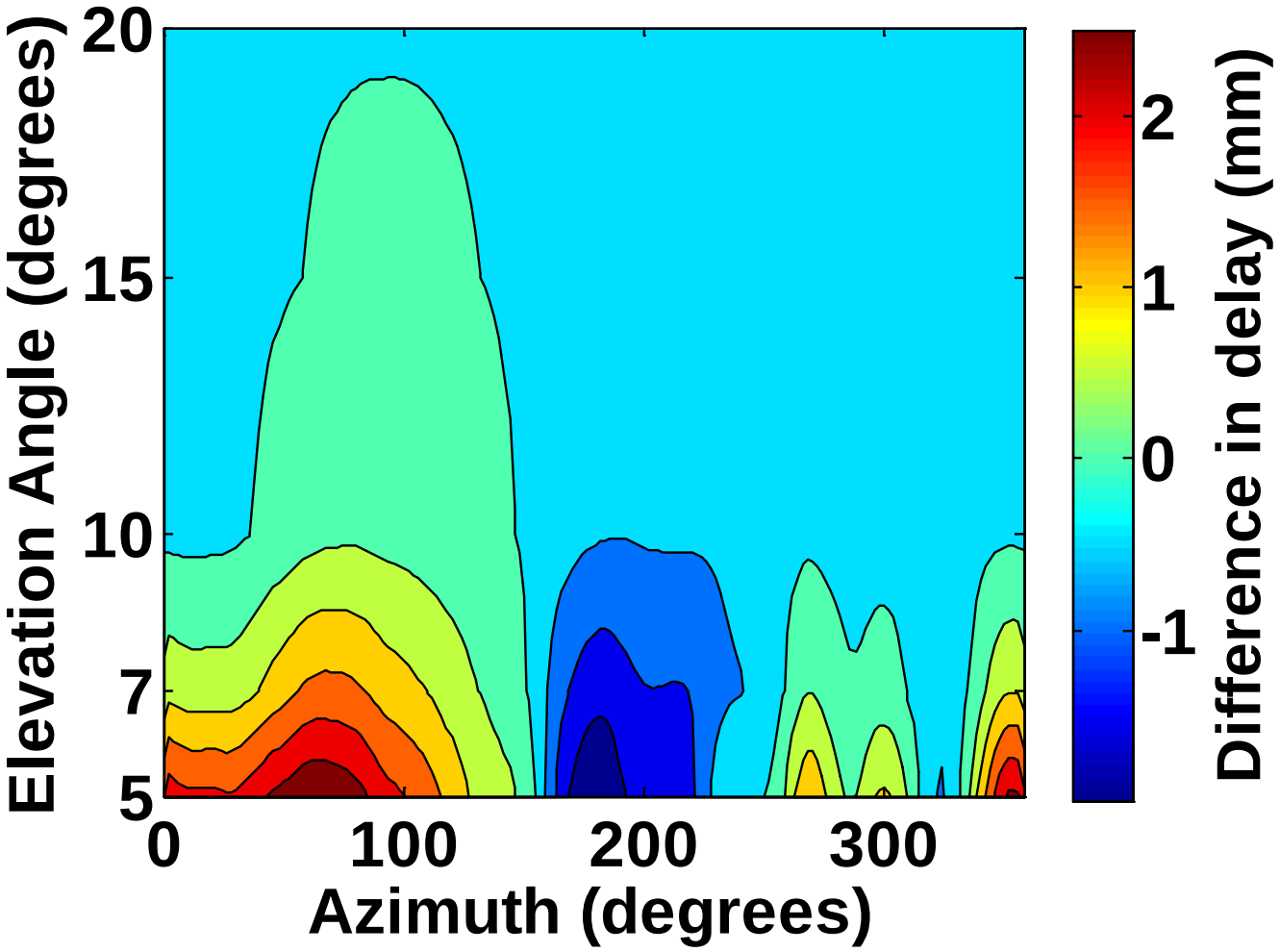
- **Special case : 2D Ray-tracing**

2. Practical considerations for developing a ray-tracing method

- Vertical interpolation (and extrapolation) for meteorological parameters
- Coefficients of refractivity
- Standard atmosphere models for data above upper limit of NWMs
- Horizontal interpolation methods
- Numerical weather models (type and resolution)
- Radius of the Earth
- Gravity model for height conversion
- Time interpolation
- 2D vs 3D ray-tracing methods

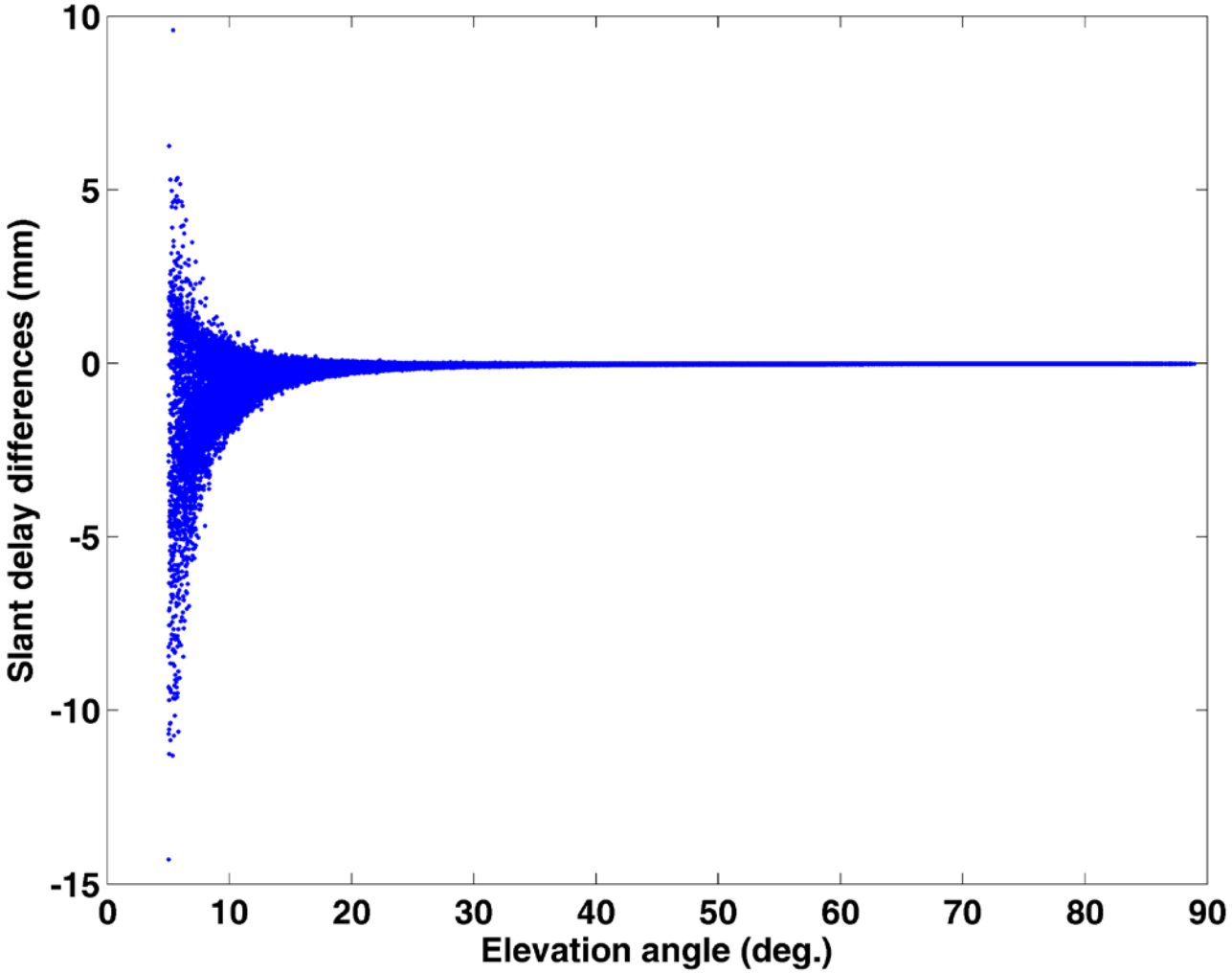
3. VIE ray-tracing system - computational aspects (1)

3D minus 2D ray-traced delays, Station Tsukuba, 12.08.2008



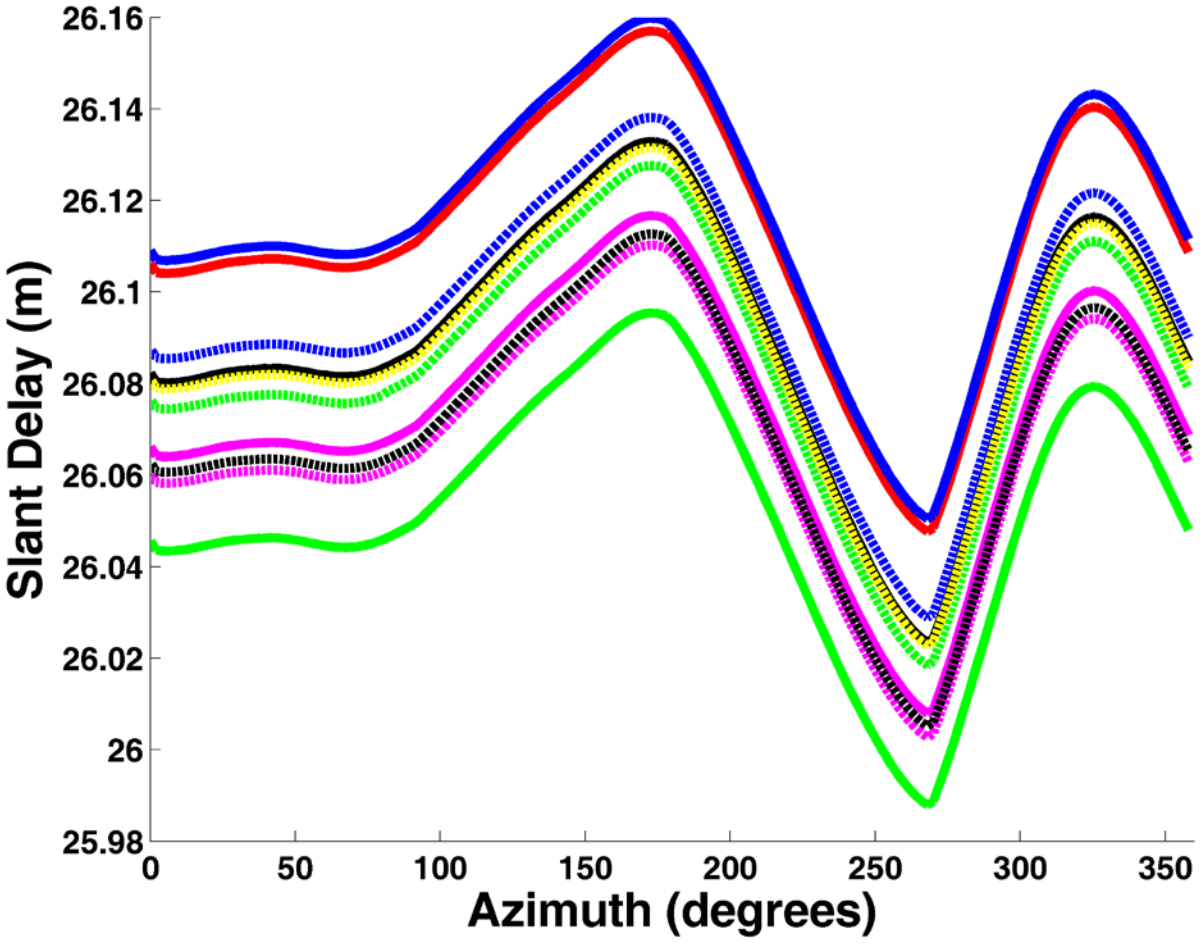
3. VIE ray-tracing system - computational aspects (2)

3D minus 2D ray-traced delays, CONT08 observations



3. VIE ray-tracing system - computational aspects (3)

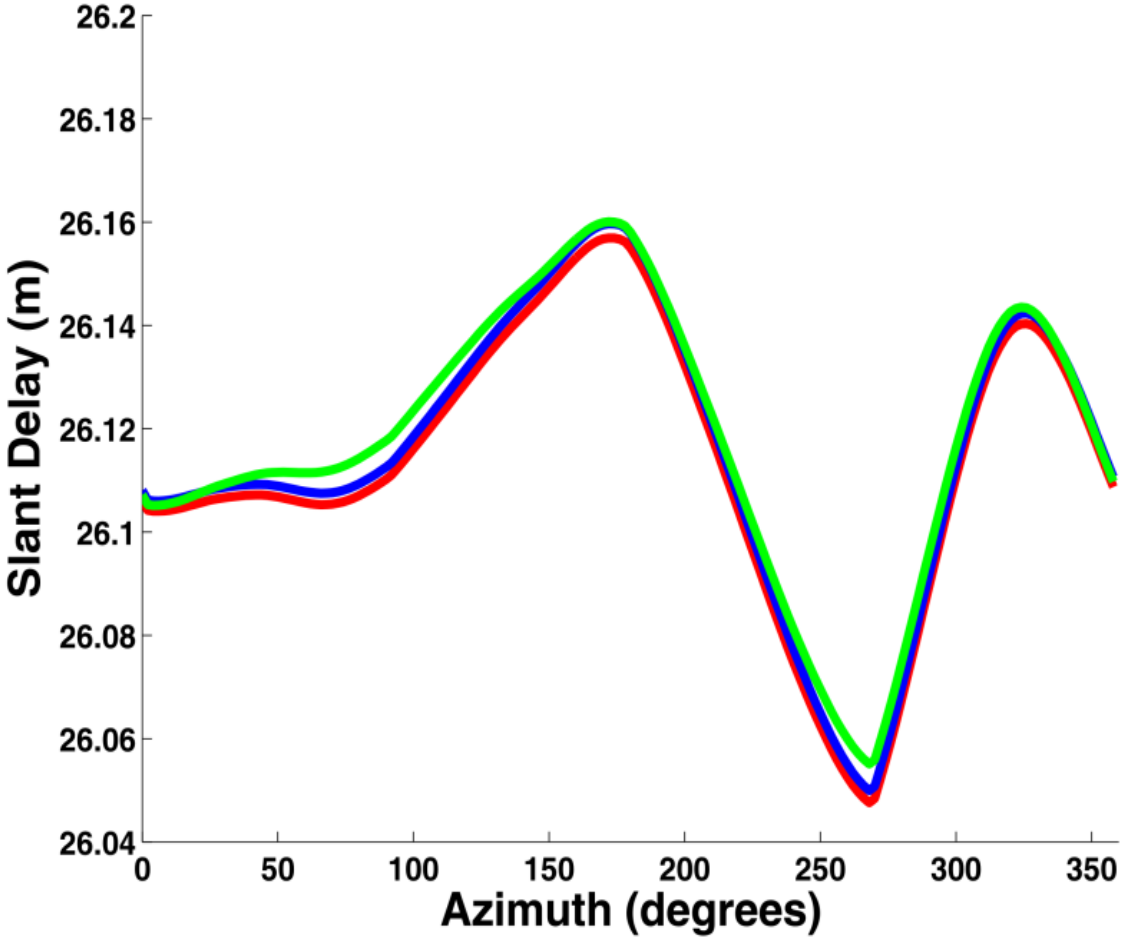
different refractivity constants



- Station Tsukuba
- 5° outgoing elevation angle
- 12.08.2008

3. VIE ray-tracing system - computational aspects (4)

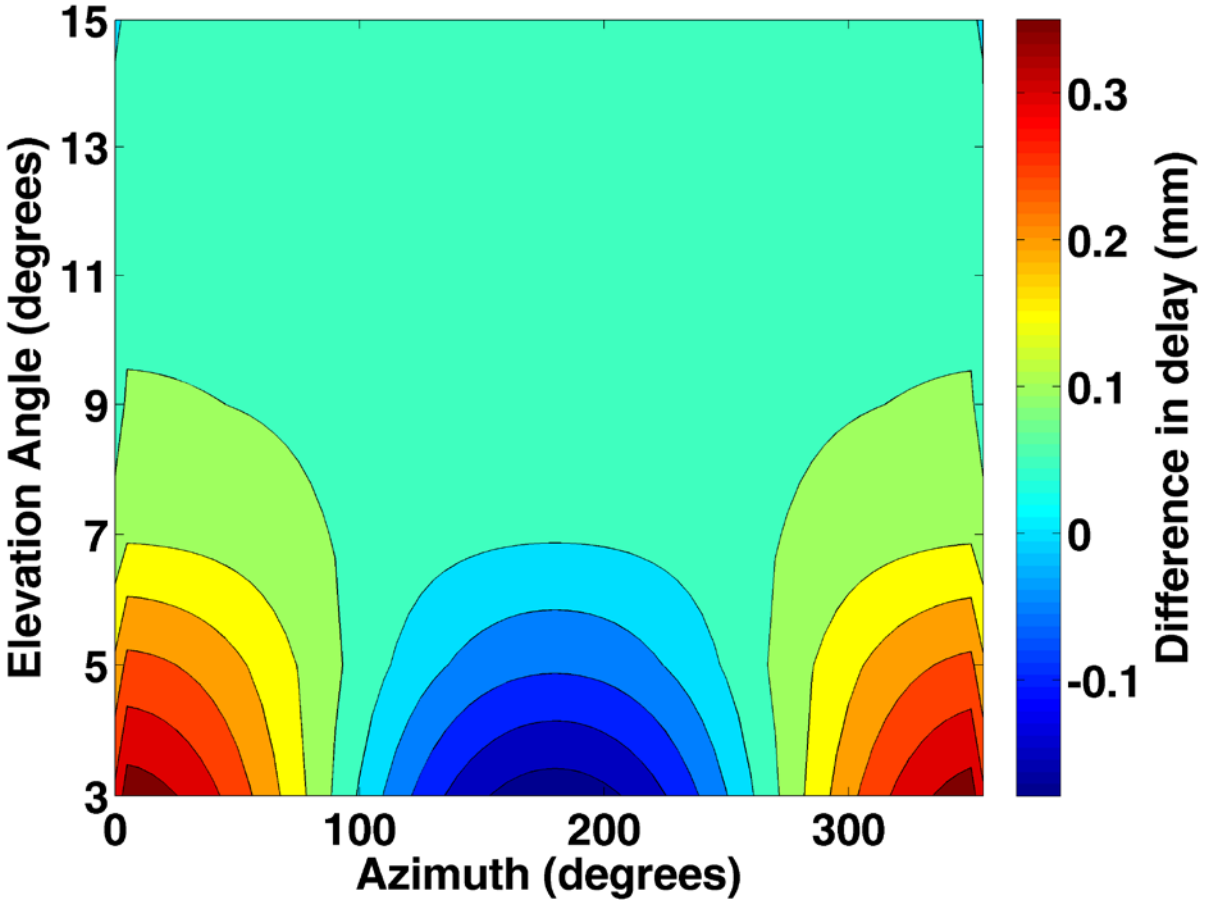
Different radius of the Earth



- Station Tsukuba (Latitude=36.1)
- Gaussian, Eulerian and constant radius
- Maximum 8mm, in slant delay at 5°

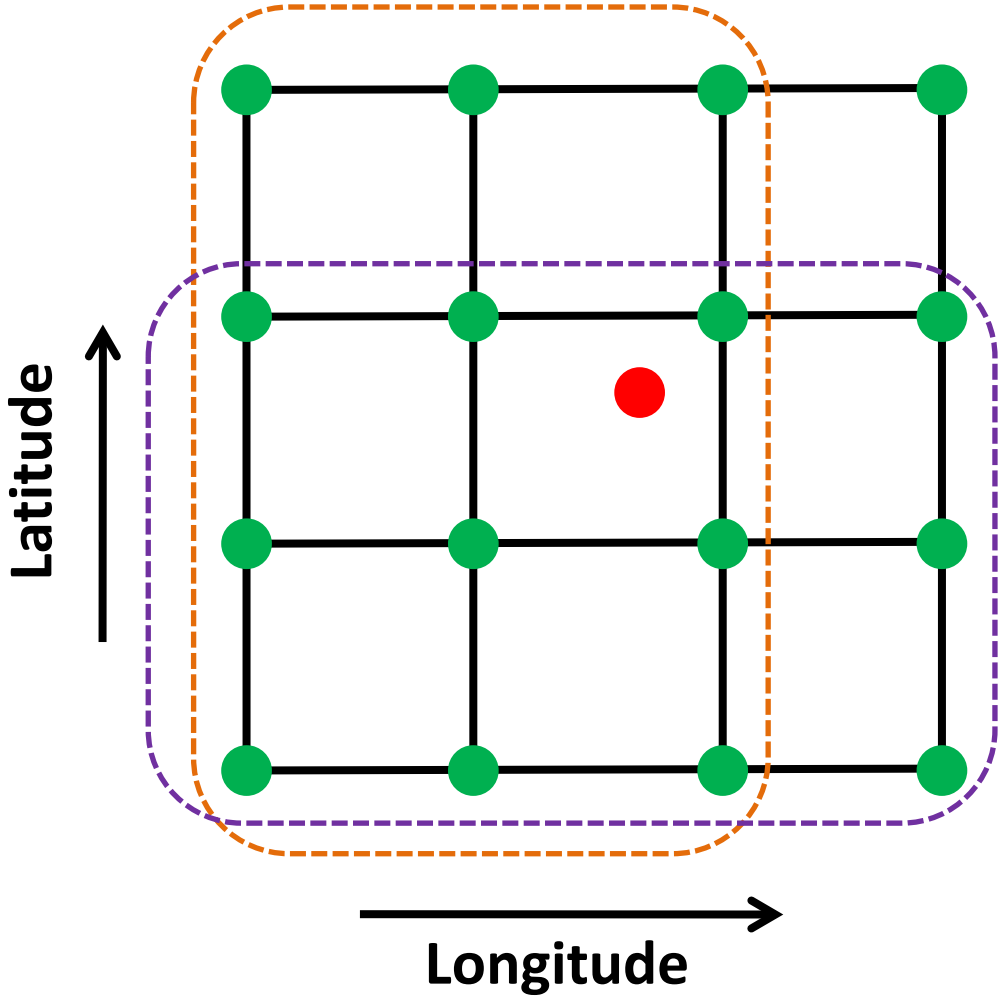
3. VIE ray-tracing system - computational aspects (5)

Different upper limits of the troposphere (76km vs 100 km)



3. VIE ray-tracing system - computational aspects (6)

Horizontal interpolation (spline, bilinear, weighted mean)

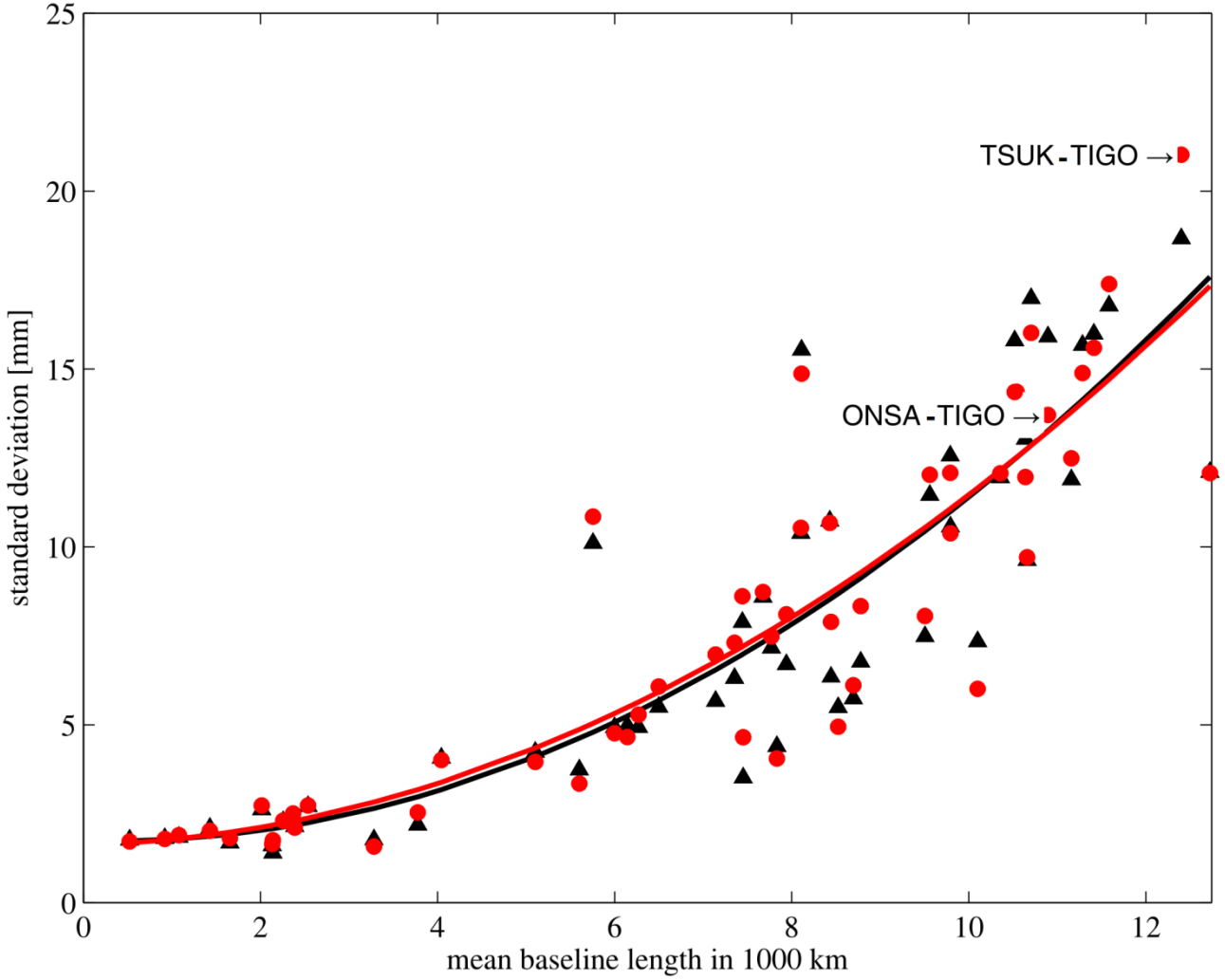


maximum 1 mm, in ZTD

4. VIE ray-tracing system - CONT08 results

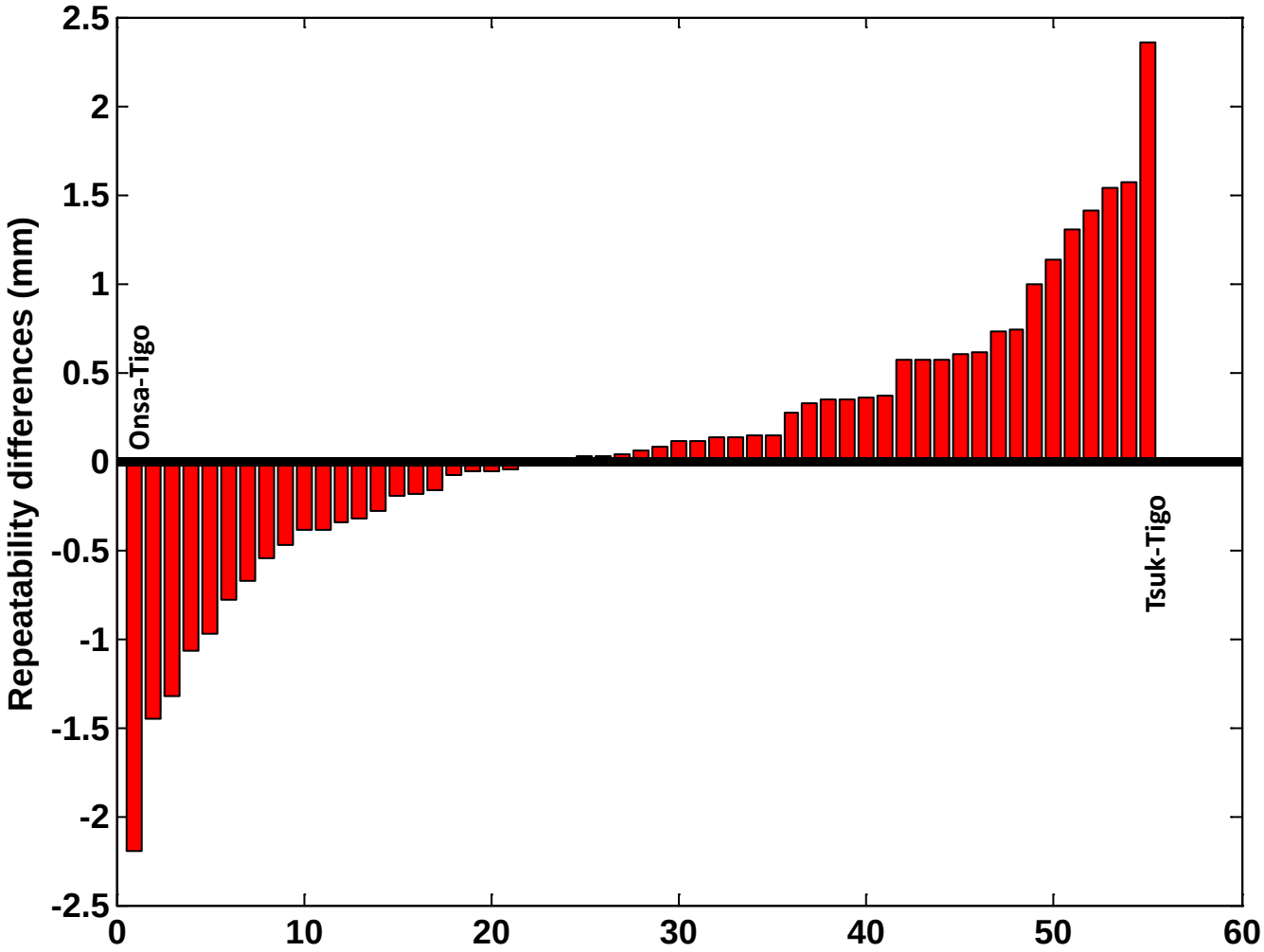
4. VIE ray-tracing system - CONT08 results (1)

Baseline length repeatabilities for CONT08 using ray-traced delays (red signs) and delays from the ECMWF/VMF1 (black signs) versus baseline lengths. Residual zenith delays and gradients are estimated.



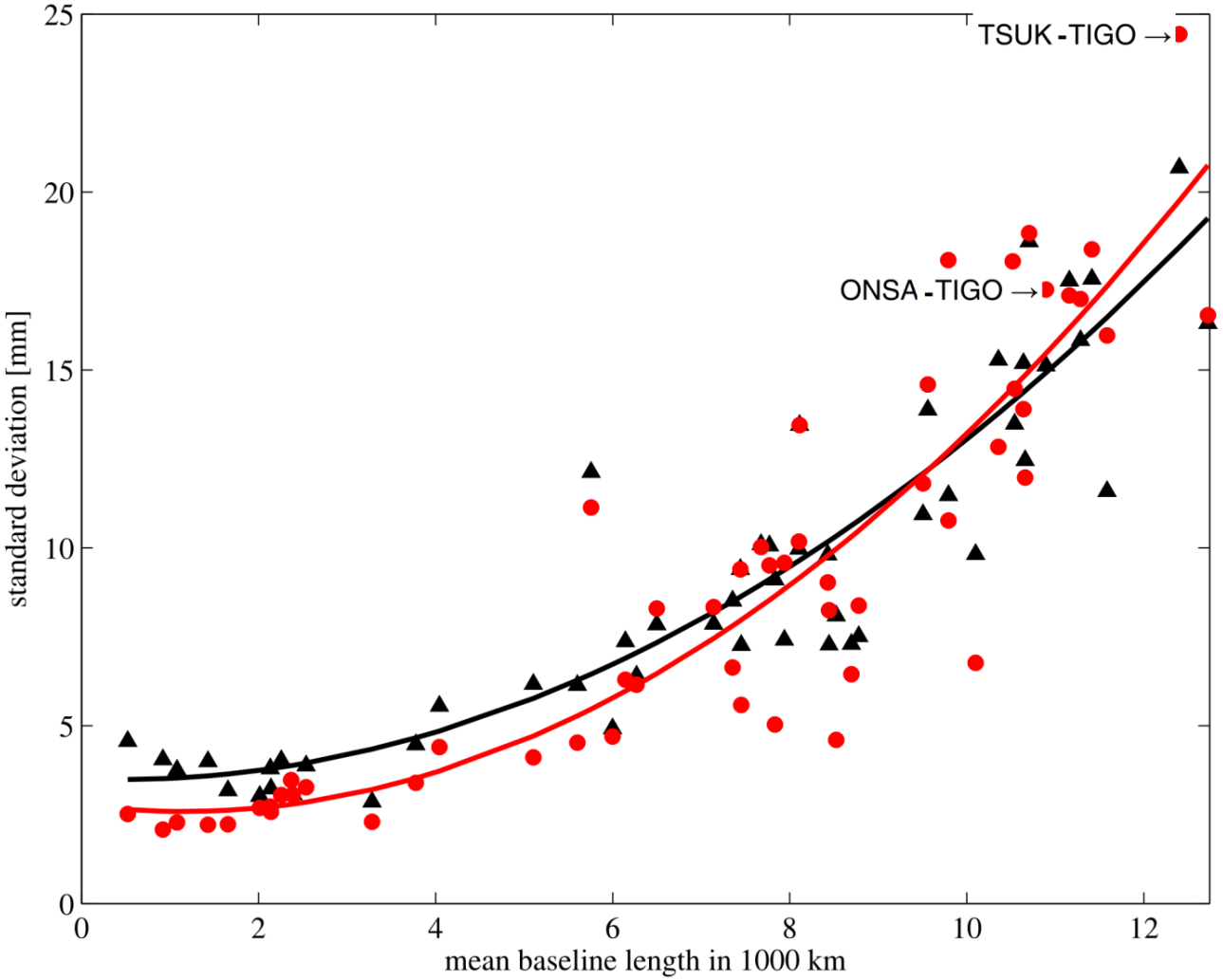
4. VIE ray-tracing system - CONT08 results (2)

Repeatability differences (ray-tracing minus ECMWF/VMF1). Residual zenith delays and gradients are estimated.



4. VIE ray-tracing system - CONT08 results (3)

Baseline length repeatabilities for CONT08 using ray-traced delays (red signs) and delays from ECMWF/VMF1 (black signs) versus baseline lengths. Residual zenith delays were estimated, but no gradients.



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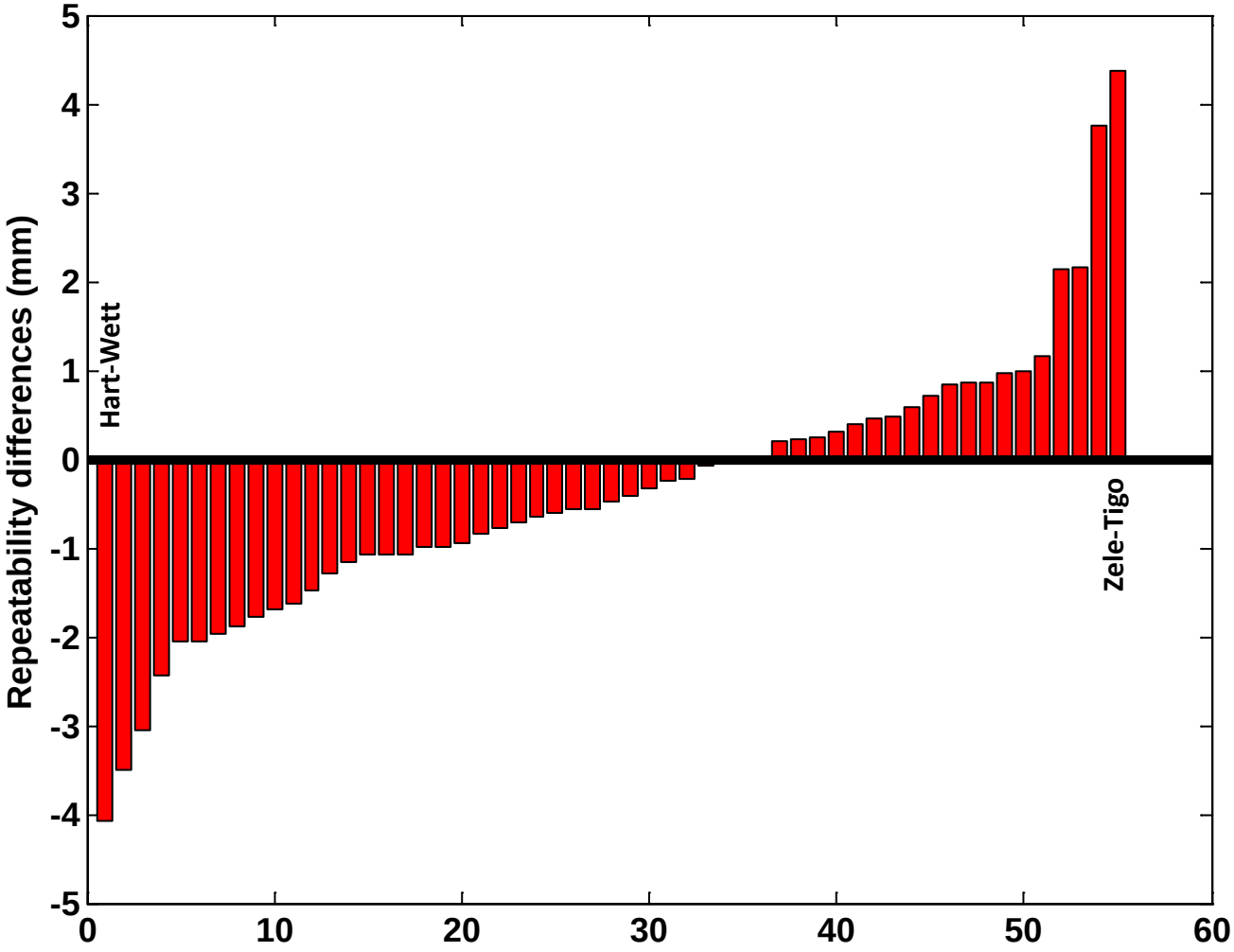
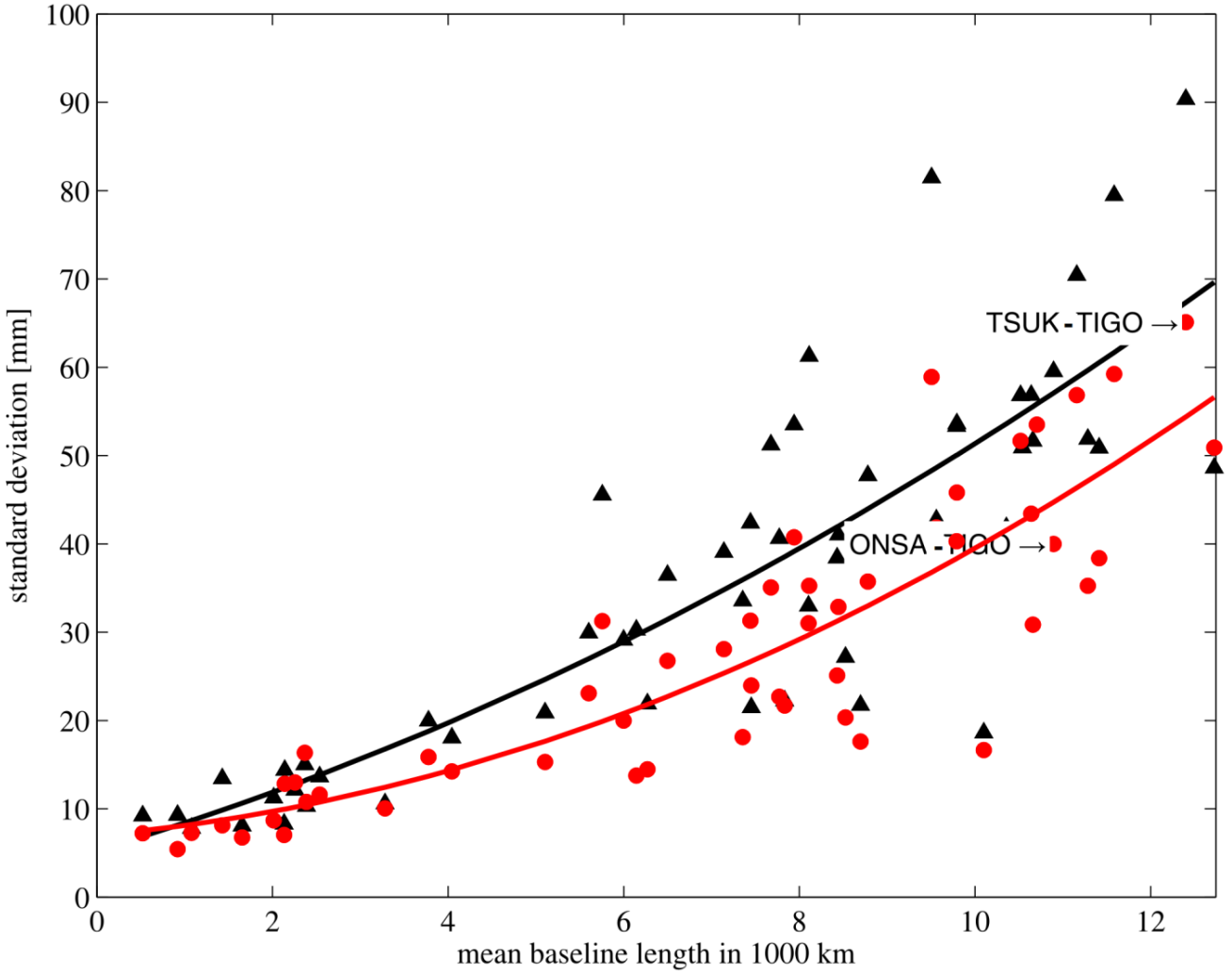


4. VIE ray-tracing system - CONT08 results (5)

Baseline length repeatabilities for CONT08 using ray-traced delays (red signs) and delays from ECMWF/VMF1 (black signs). No gradients and no wet zenith delays were estimated in the analysis.



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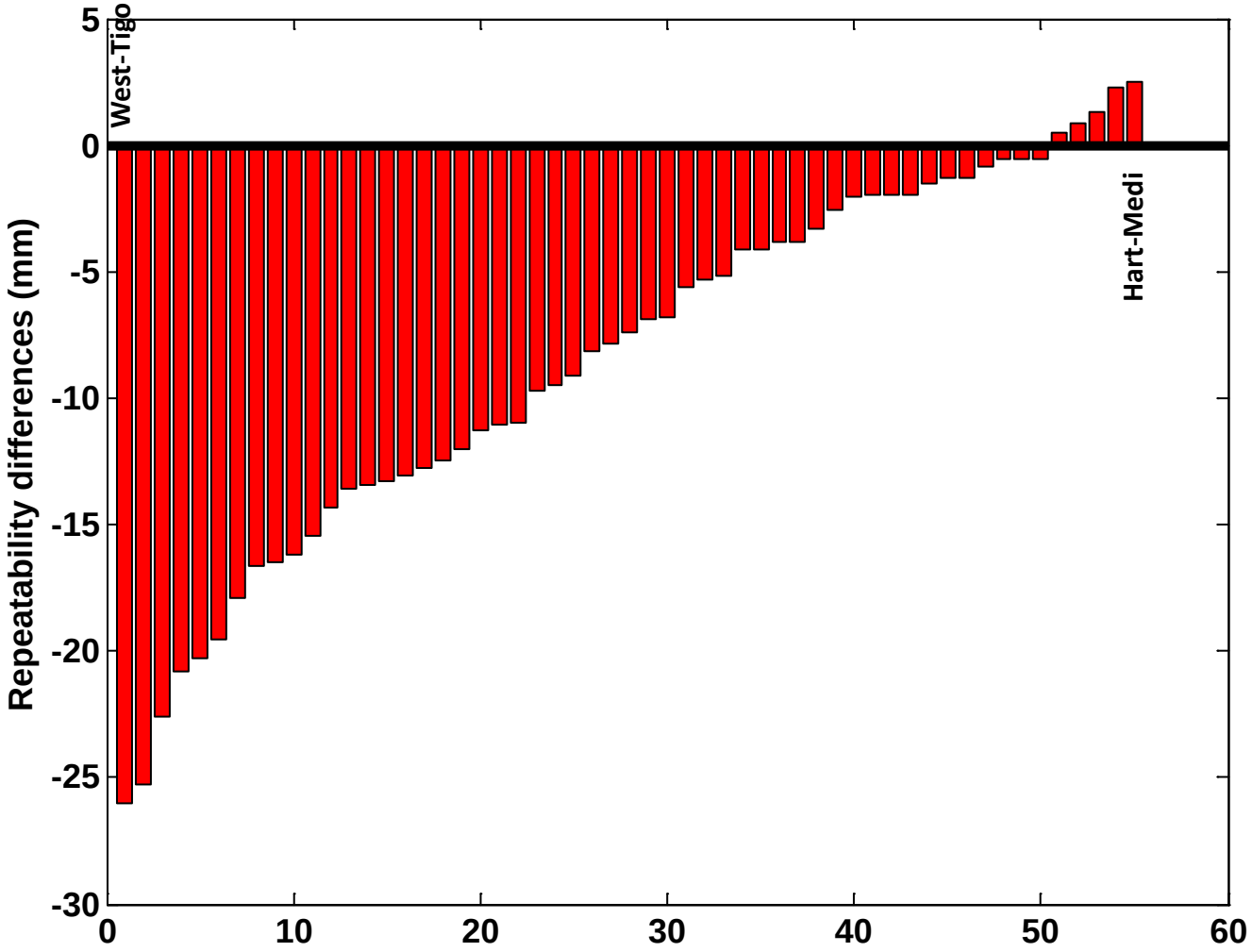
Repeatability differences (ray-tracing minus ECMWF/VMF1). No gradients and no wet zenith delays were estimated in the analysis.



4. VIE ray-tracing system - CONT08 results (7)

- On average, ray-traced delays yield an accuracy similar to the standard approach. However, taking a closer look, at some stations ray-traced delays provide better tropospheric corrections

- In any case the additional estimation of gradients and residual zenith delays improves the results.

- Improvement with respect to the results from the classical approach with mapping functions if no additional gradients are estimated

5. Concluding remarks and future works (1)

- **A ray-tracing package based on Eikonal equation has been developed at IGG/TU Wien**

- **Computational aspects must be considered**

5. Concluding remarks and future works (2)

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

- **Validation of results obtained by VIE ray-tracing system, using VLBI intensive session observations (baseline Tsukuba-Wettzell)**

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

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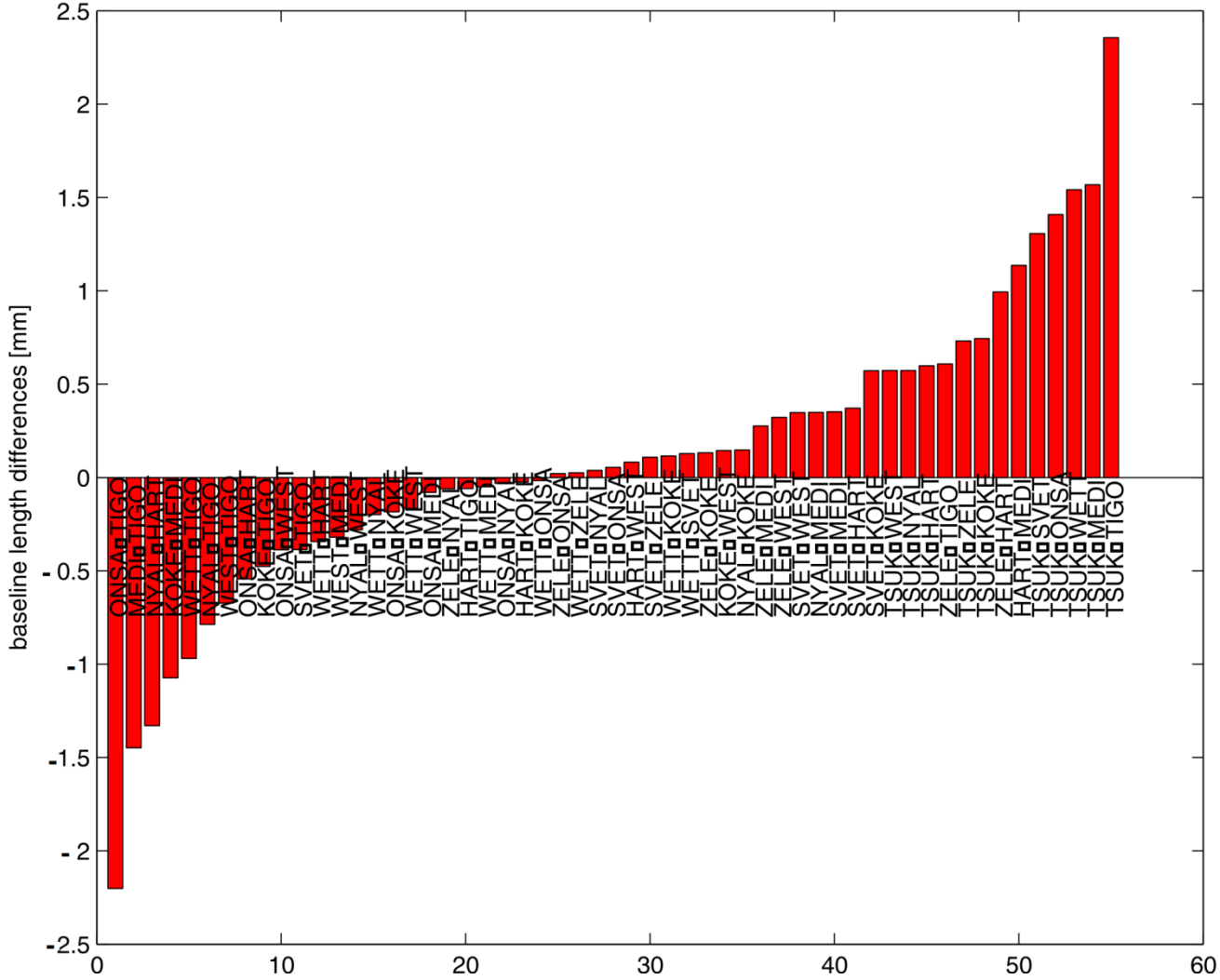
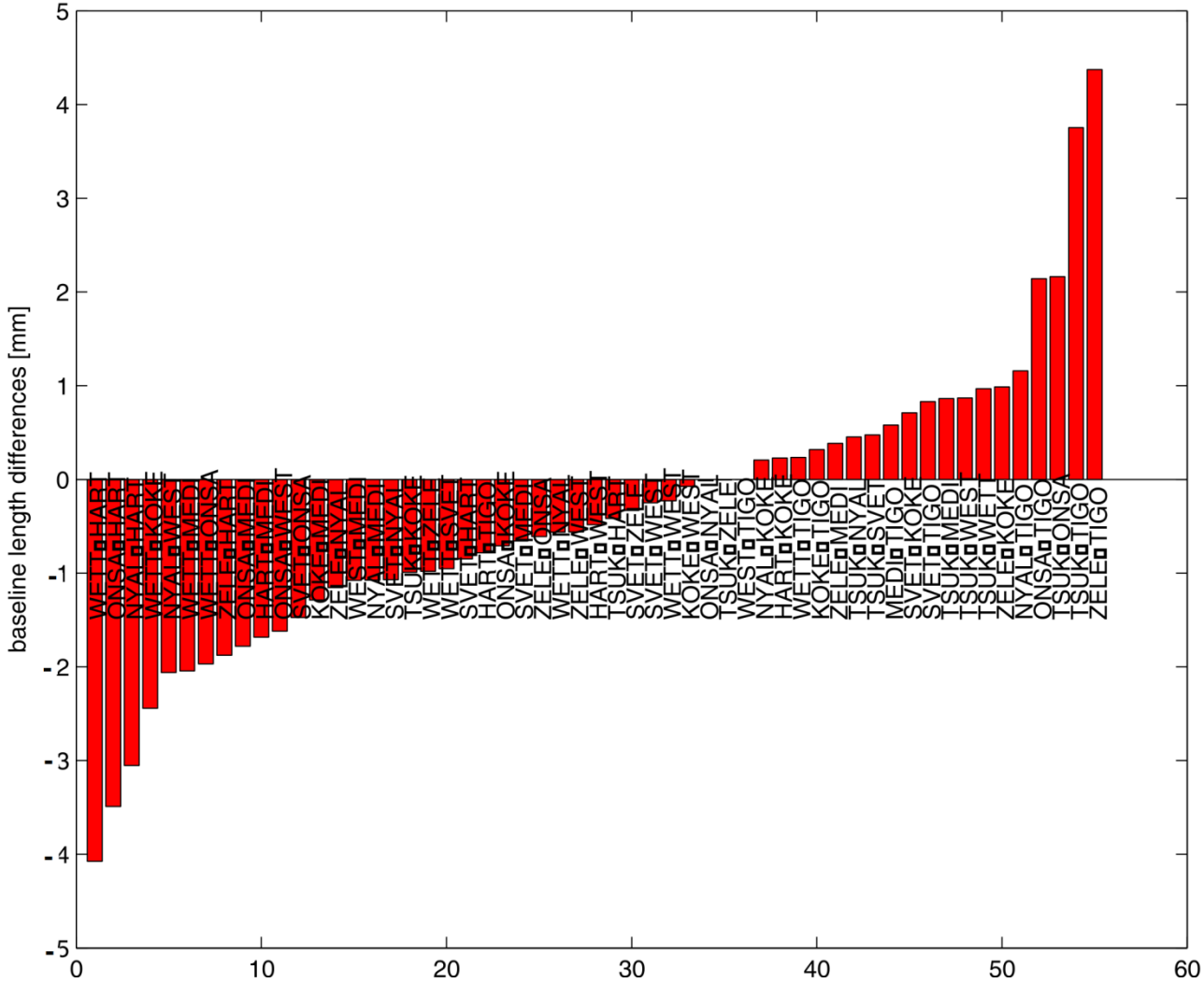
- Iran Ministry of Science, Research and Technology (MSRT) and the University of Isfahan for funding part of this research in Vienna University of Technology.


baseline length differences [mm]
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
10
20
30
40
50
60
ONSA TIGO
MEDI TIGO
NYAL HART
KOKE MEDI
WETT TIGO
NYAL TIGO
WEST TIGO
ONSA HART
KOKE TIGO
ONSA WEST
SVET TIGO
WETT HART
WEST MEDI
NYAL WEST
WETT NYAL
ONSA KOKE
WETT WEST
ONSA MEDI
ZELE NYAL
HART TIGO
WETT MEDI
ONSA NYAL
HART KOKE
WETT ONSA
ZELE ONSA
WETT ZELE
SVET NYAL
SVET ONSA
HART WEST
SVET ZELE
WETT SVET
ZELE KOKE
KOKE WEST
NYAL KOKE
ZELE MEDI
ZELE WEST
SVET WEST
NYAL MEDI
SVET MEDI
SVET HART
SVET KOKE
TSUK WEST
TSUK NYAL
TSUK HART
ZELE TIGO
TSUK ZELE
TSUK KOKE
ZELE HART
HART MEDI
TSUK SVET
TSUK ONSA
TSUK WETT
TSUK MEDI
TSUK TIGO


baseline length differences [mm]
5
4
3
2
1
0
-1
-2
-3
-4
-5
0
10
20
30
40
50
60
WETHART
ONSAHART
NYALHART
WETTKOKE
NYALWEST
WETTMEDI
WETTONSA
ZELEHART
ONSAMEDI
HARTMEDI
ONSAWEST
SVETONSA
KOKEMEDI
ZELENYAL
WESTMEDI
NYALMEDI
SVETNYAL
TSUKKOKE
WETTZELE
WETTSVET
SVETHART
HARTTIGO
ONSAKOKE
SVETMEDI
ZELEONSA
WETTNYAL
ZELEWEST
HARTWEST
TSUKHART
SVETZELE
SVETWEST
WETTWEST
KOKEWEST
ONSANYAL
TSUKZELE
WESTTIGO
NYALKOKE
HARTKOKE
WETTTIGO
KOKETIGO
ZELEMEDI
TSUKNYAL
TSUKSVET
MEDITIGO
SVETKOKE
SVETTIGO
TSUKMEDI
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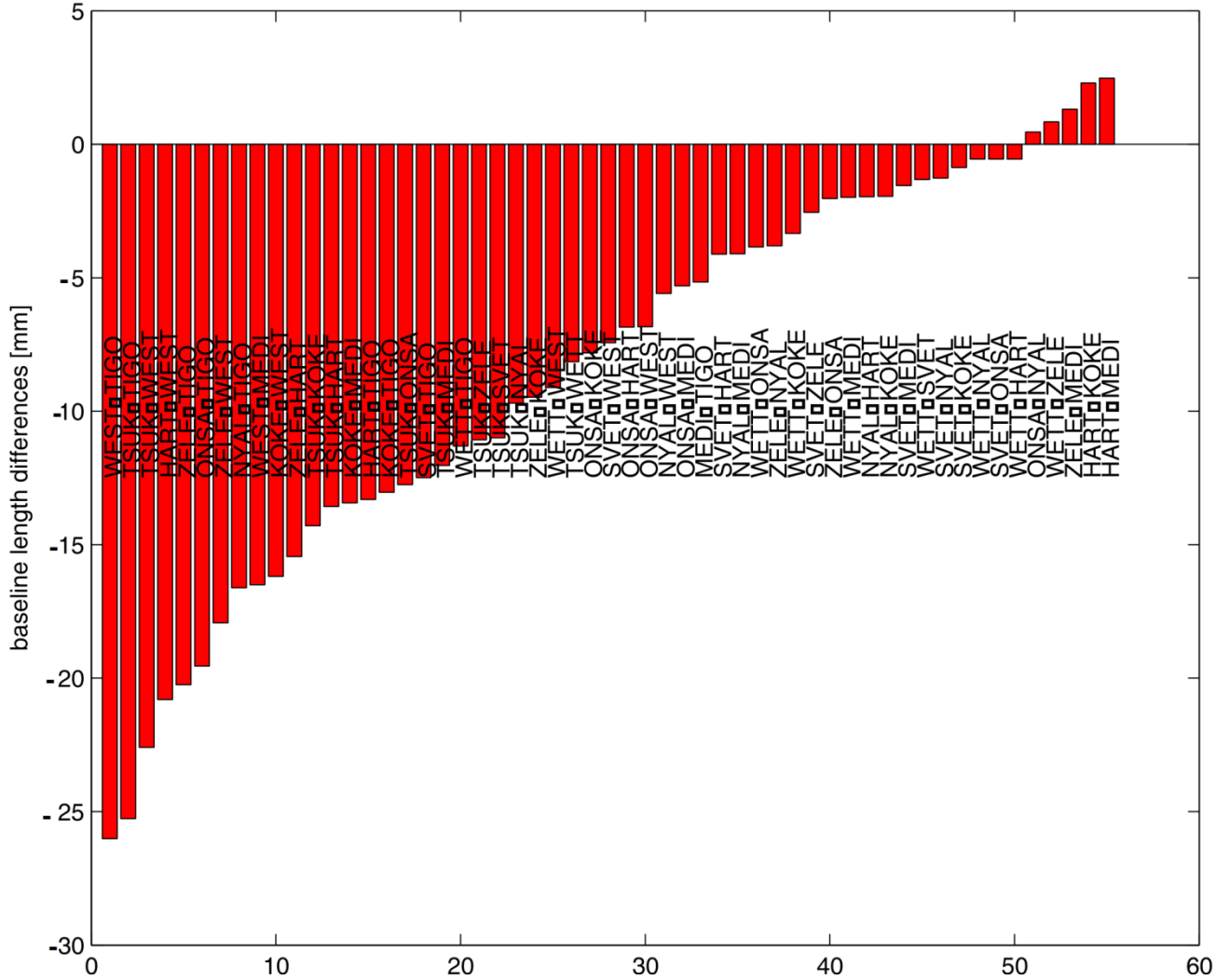
TSUKWETT
ZELEKOKE
NYALTIGO
ONSATIGO
TSUKONSA
TSUKTIGO
ZELETIGO


baseline length differences [mm]
5
0
-5
-10
-15
-20
-25
-30
0
10
20
30
40
50
60
WEST TIGO
TSUK TIGO
TSUK WEST
HART WEST
ZELE TIGO
ONSA TIGO
ZELE WEST
NYAL TIGO
WEST MEDI
KOKE WEST
ZELE HART
TSUK KOKE
TSUK HART
KOKE MEDI
HART TIGO
KOKE TIGO
TSUK ONSA
SVET TIGO
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MEDI TIGO
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NYAL MEDI
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ZELE NYAL
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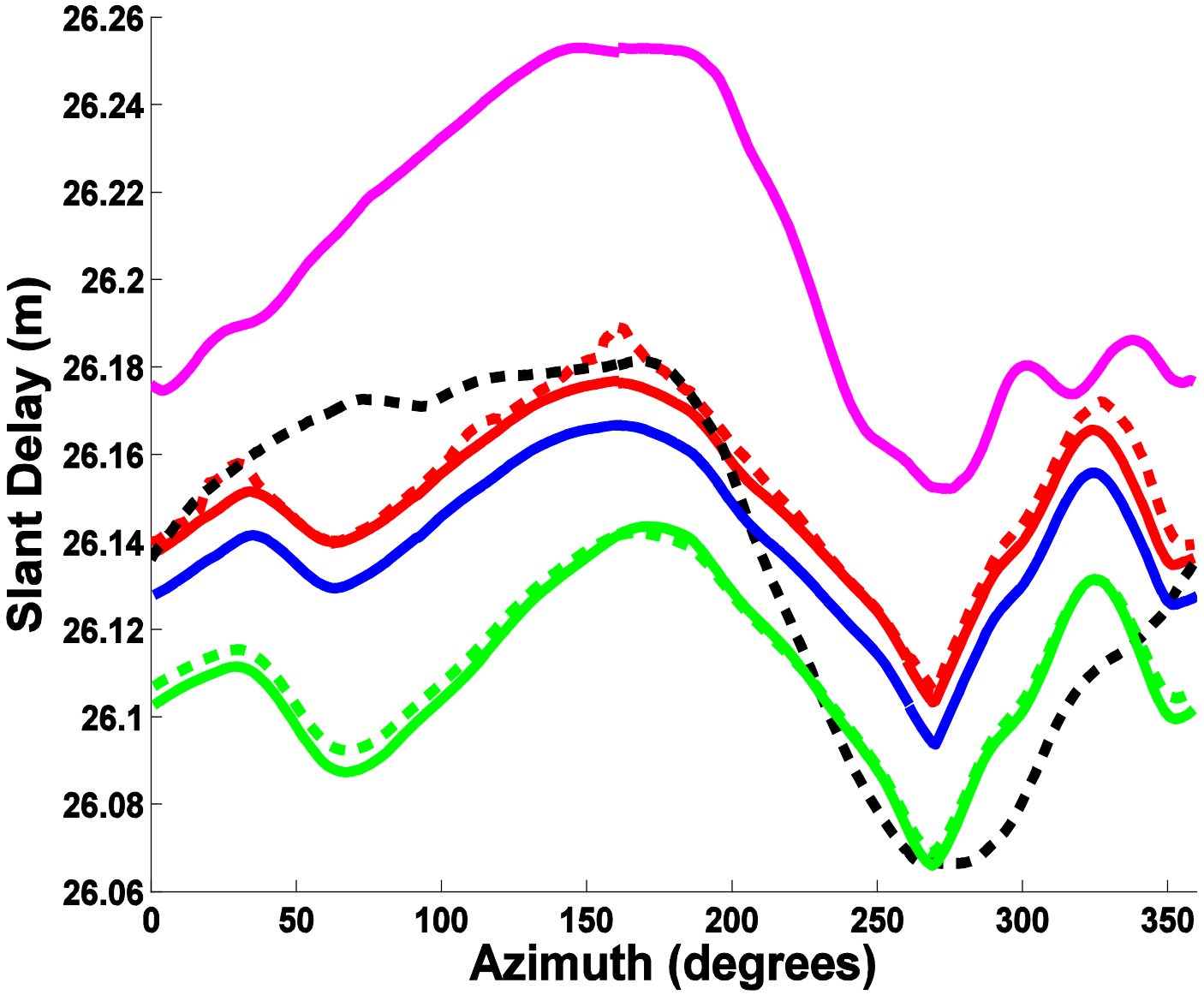
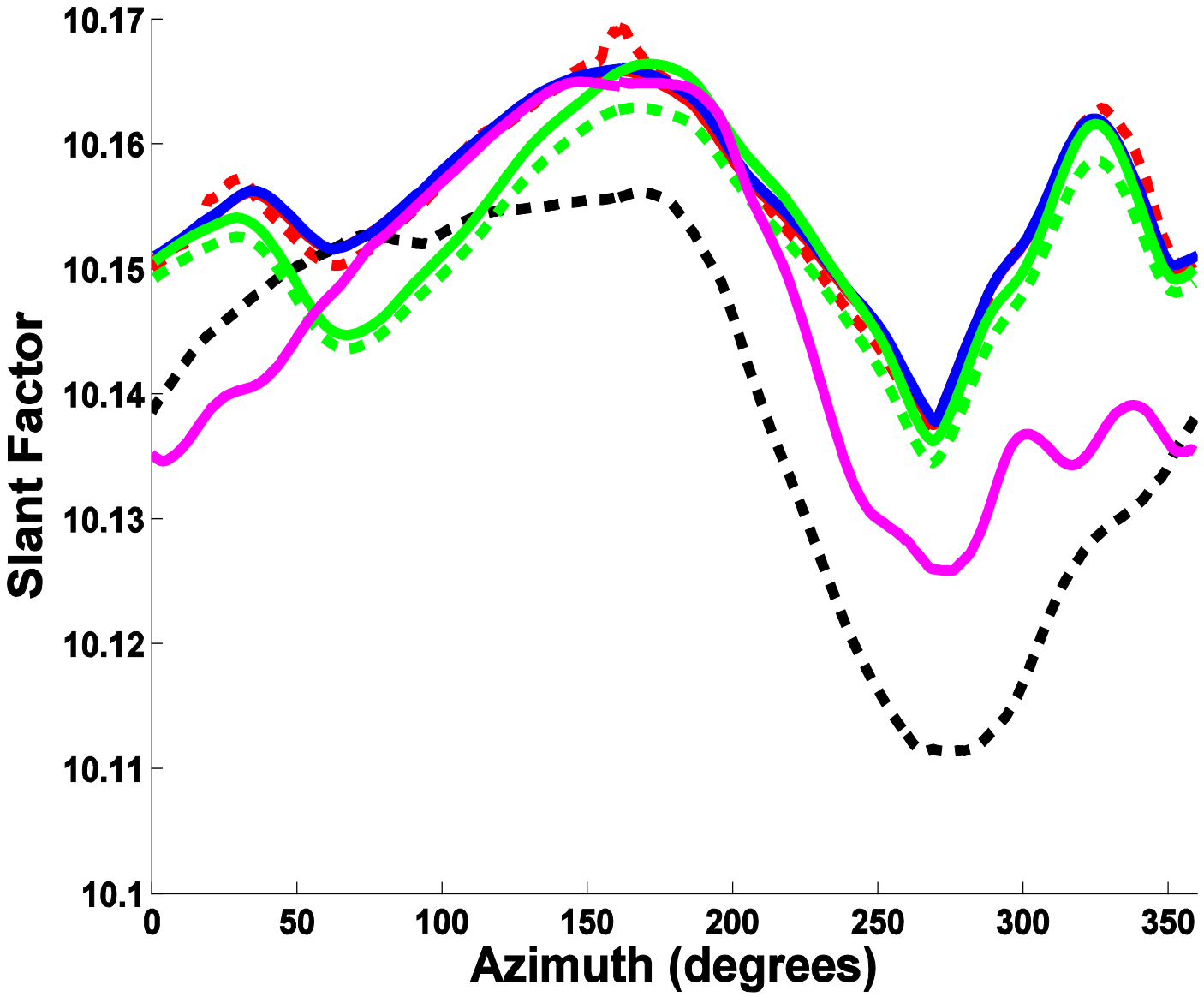
SVET ONSA
WETT HART
ONSA NYAL
WETT ZELE
ZELE MEDI
HART KOKE
HART MEDI

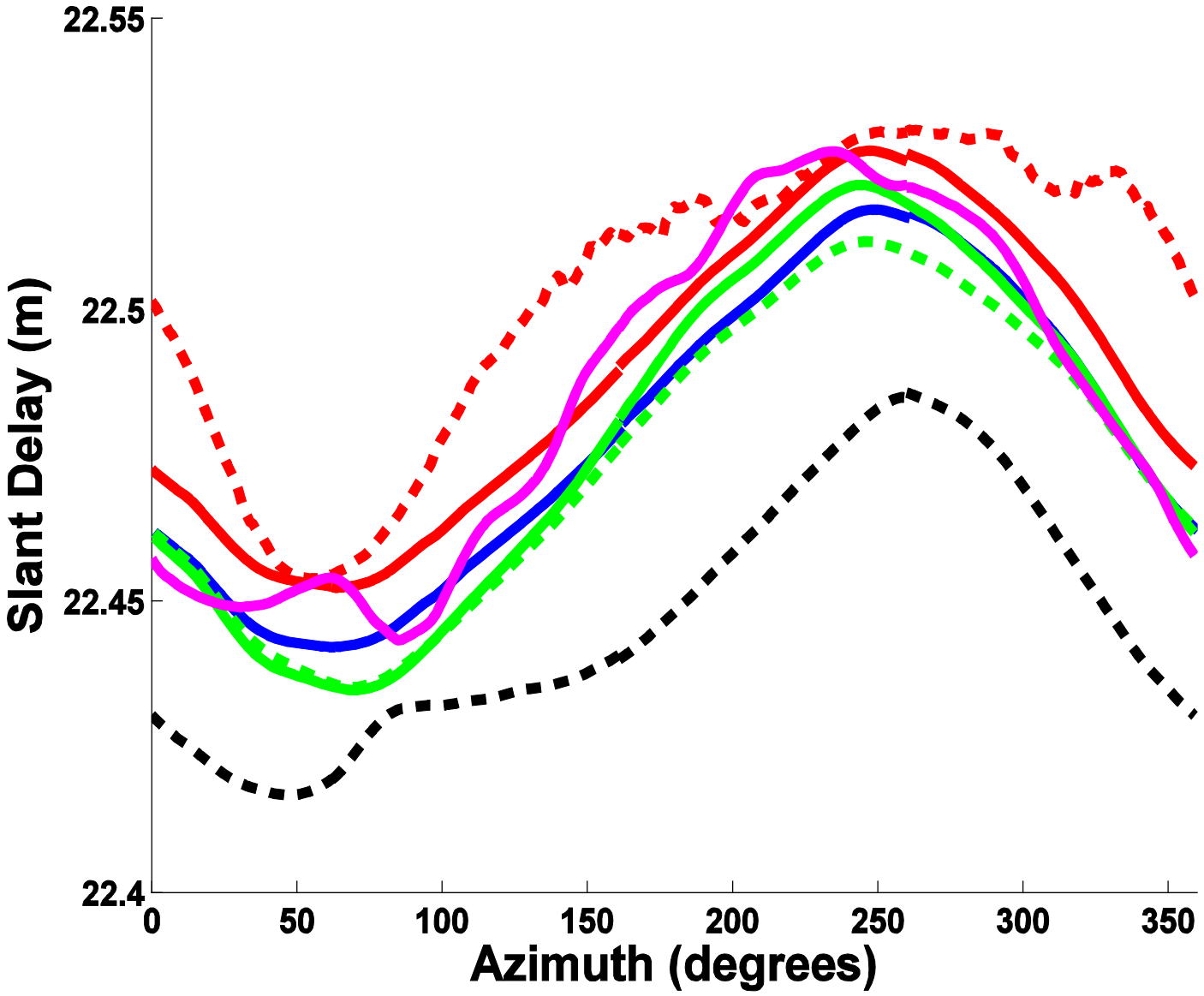
Results of ray-tracing campaign – Tsukuba, 5 deg. Elevation angle



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



Results of ray-tracing campaign – Wettzell, 5 deg. Elevation angle



Results of ray-tracing campaign – Wettzell, 5 deg. Elevation angle