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UNIWERSYTET PRZYRODNICZY WE WROCŁAWIU

Troposphere delay modeling in Satellite Laser Ranging

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Satellite laser ranging - principle

Approximate distance

$$\rho = \frac{1}{2} * c * \tau$$

The total („2-way”) time of flight given by the timing measurements

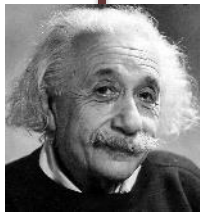
Vacuum speed of light (299 792 458 m/s) *IERS 2010 standards*

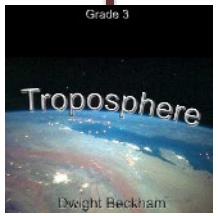
Range measurement may be described by the model:

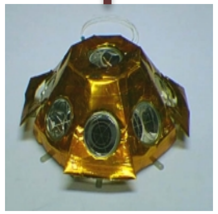
$$\rho = \frac{1}{2}\left(\rho_{up}(t) + \rho_{down}(t)\right) + d_{rel} + d_{atm} + d_{LRA} + \epsilon$$

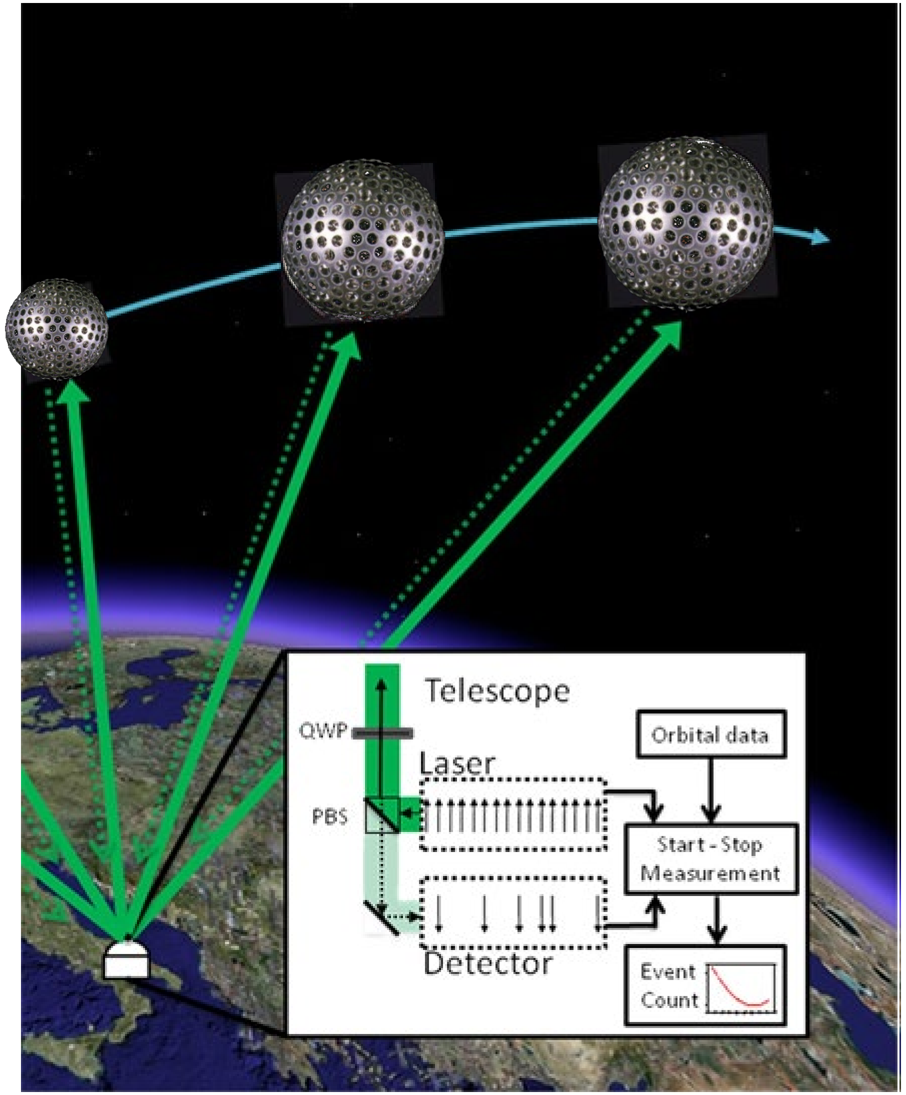
Uplink distance

Downlink distance

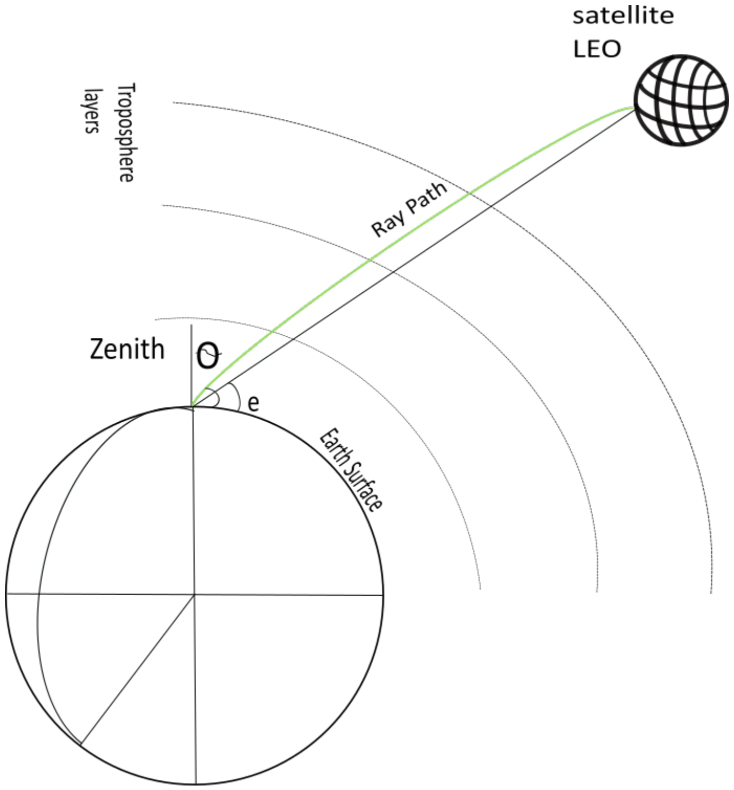








Troposphere delay modeling in SLR solutions



Current model (no tropo parameters are estimated in SLR solutions):

Wet delay: based on water vapor pressure records and the position of an SLR station (latitude, height)

(Mendes and Pavlis, 2004)

$$d_{atm} = m_{fs}(d_h^z + d_{nh}^z)$$

Common mapping function: based on temperature records and the position of an SLR station (latitude, height)

(Mendes et al., 2002)

Hydrostatic delay: based on pressure records and the position of an SLR station (latitude, height)

(Mendes and Pavlis, 2004)

A full symmetricity of the atmosphere over SLR stations is assumed

Troposphere delay modeling in SLR solutions (proposal)

Enhanced model:

$$d_{atm} = m_{fs}(d_h^z + d_{nh}^z) + \tau(\varepsilon) * [G_N cos\alpha + G_E sin\alpha]$$

Mapping function for gradients:
e.g., Chen and Herring (1997)

$$\tau(\varepsilon) = \frac{1}{\sin(\varepsilon)\tan(\varepsilon) + c}.$$

Horizontal gradients:
North and East components representing the delays due to the azimuthal asymmetry

In this model:

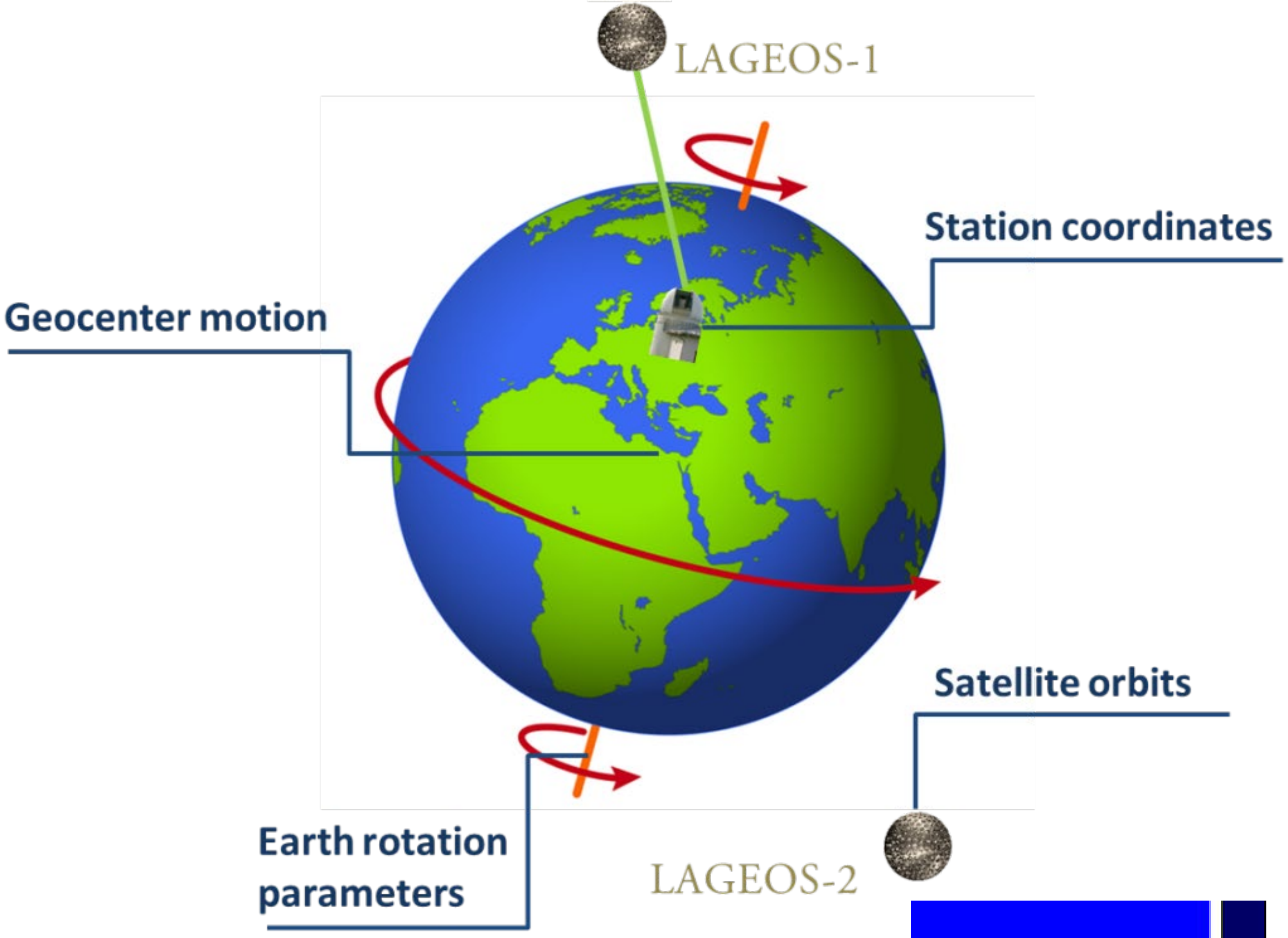
1. **Atmosphere assymetricity is taken into account in SLR solutions,**
2. **SLR solutions become more consistent with GNSS and VLBI where horizontal gradients are modeled.**

SLR solutions

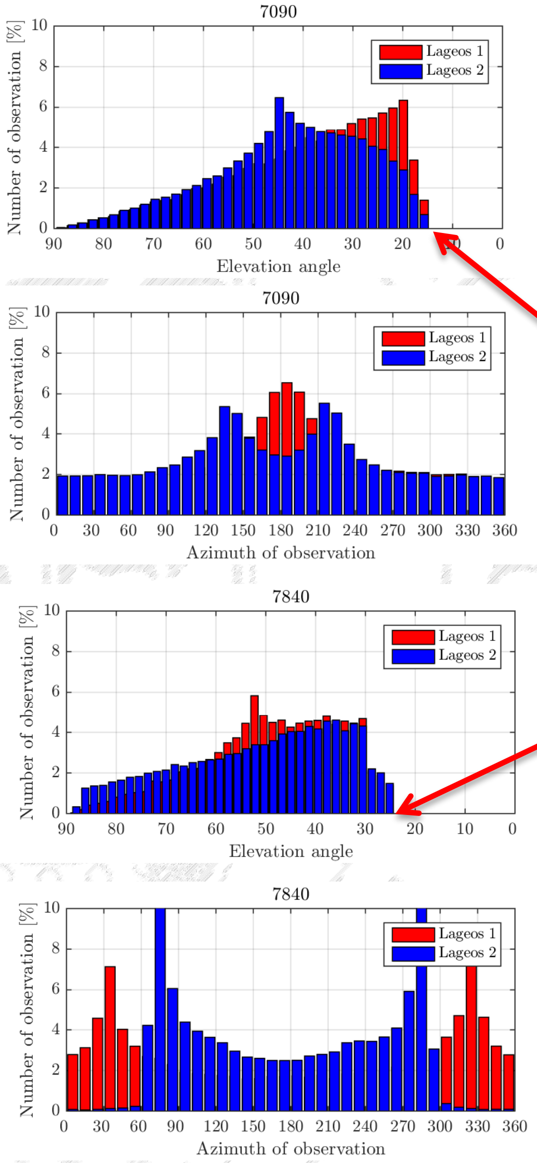
Estimated parameters:

- Station coordinates (7-day)
- Orbit parameters:

  6 Keplerian + 5 empirical (7-day)
- Geocenter coordinates (7-day)
- Range biases for selected stations (1-3 per week)
- X-pole, Y-pole (8 par per 7-day)
- UT1-UTC (8 par per 7-day, 1 parameter fixed)
- Horizontal gradients of troposphere delay.



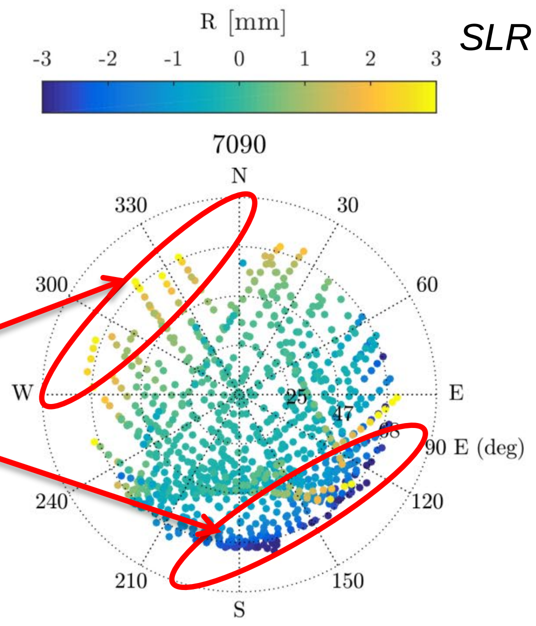
Geometry of observation and systematic effects

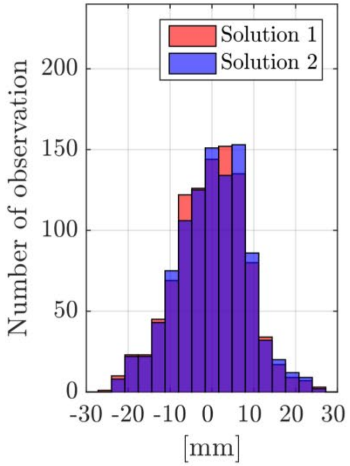


1. For station Yarragadee we see an increasing systematic error for low elevation angles in the north-west and south-east direction
2. Station Yarragadee observes satellites LAGEOS with the elevation angle up to 15 degrees.
3. Station Herstmonceux is located near the airport and it needs to apply for spatial permission for observation lower than 25 degrees

4. For observations at elevation angles above 25 degrees we can also notice systematic errors in the north–south direction and East-west.

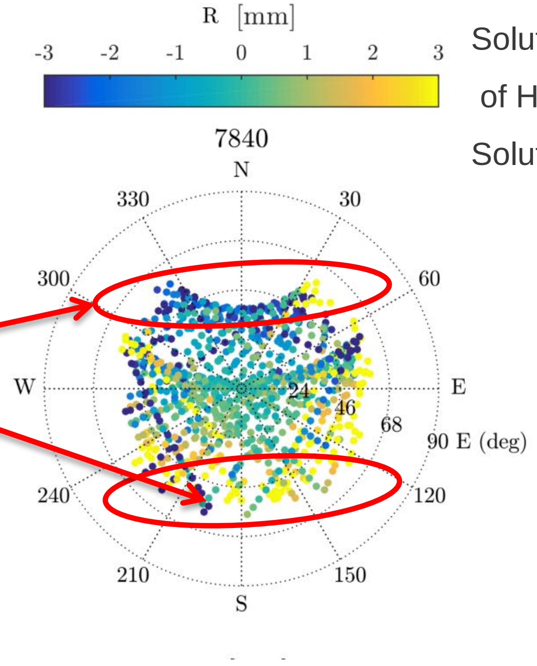
SLR observation residuals

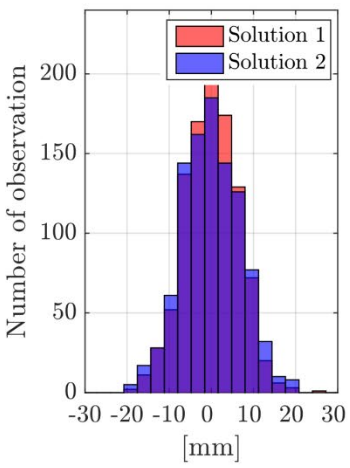




Solution 1 – solution with estimation of Horizontal gradients

Solution 2 – standard solution

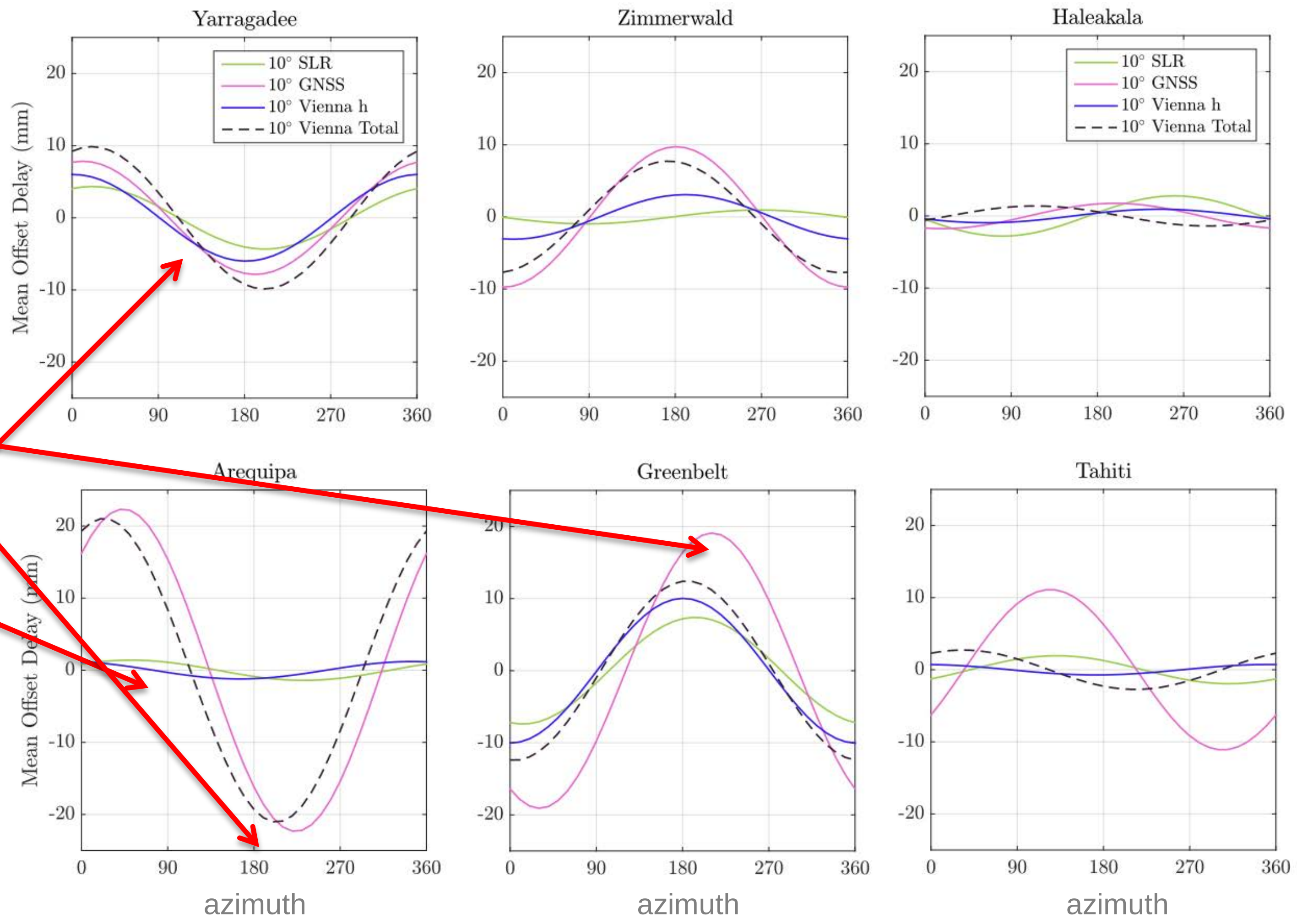




Mean offsets

The mean offset projected on to 10 degree elevation angle using Chen-Herring mapping function for all solutions.

- The horizontal gradients derived for GNSS-SLR co-located stations for the elevation angles 10 degrees achieve values up to 20 mm
- The best consistency of 3 source of gradients we can see for the station Yarragadee and Arequipa
- For a large number of stations we see a consistency to a certain extent.



Values of N and E offsets for selected SLR stations mapped to the elevation angle 10°

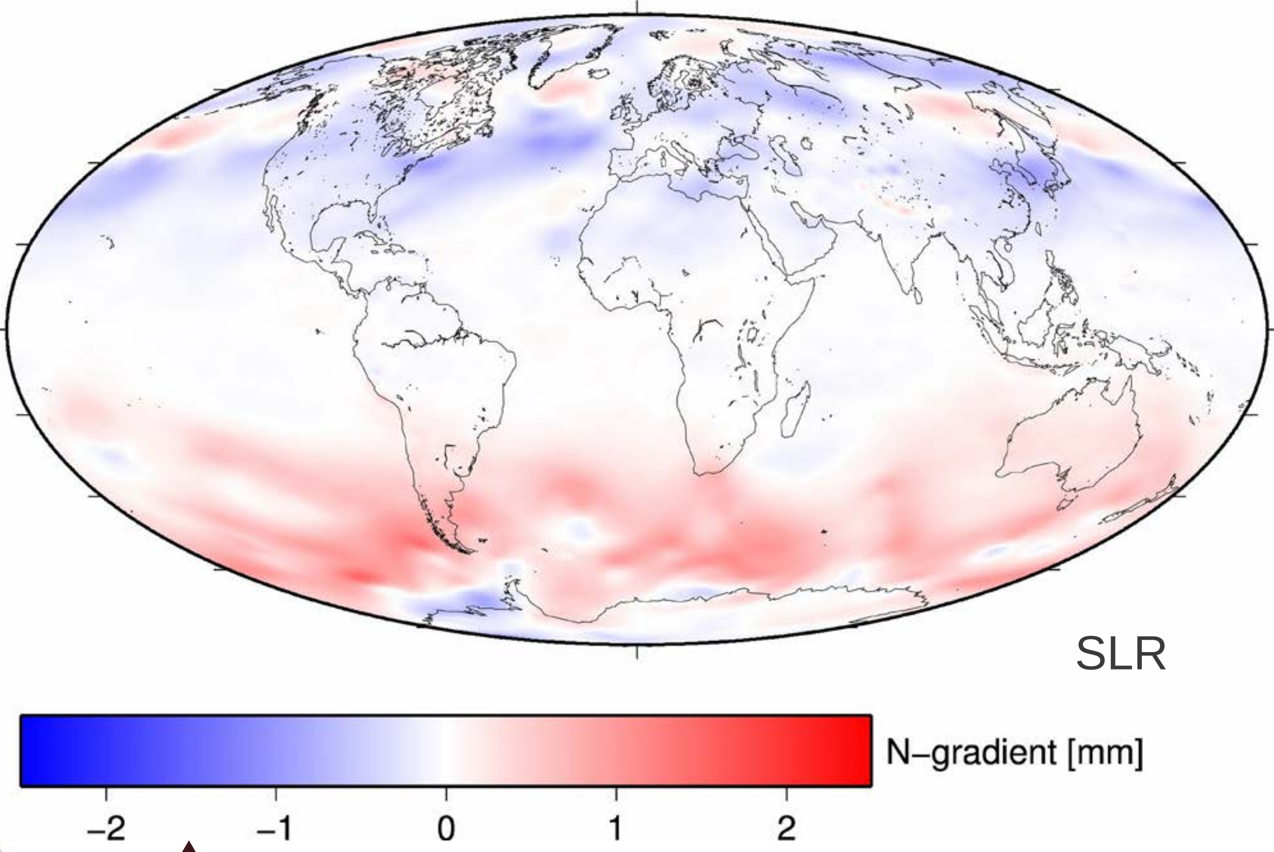
Satellite laser ranging as a tool for the recovery of tropospheric Gradients, Atm. Res. Drożdżewski M., Sośnica K., 2018

Horizontal gradients dedicated for optical measurements

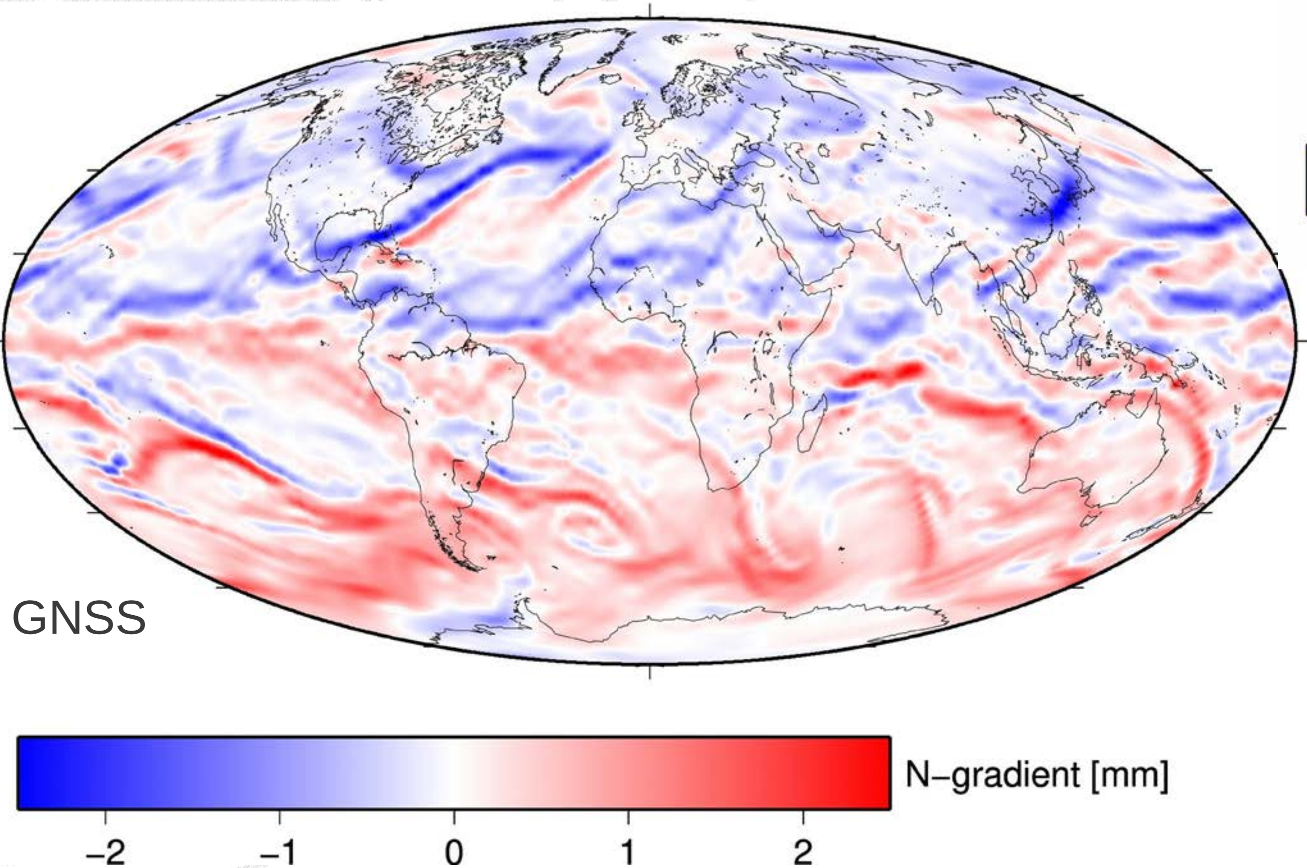
Horizontal gradients comparison

GFZ
Helmholtz Centre
POTSDAM

- *Time resolution: 6h*
- *Spatial resolution 0.5x0.5 degree*



North component for SLR (wave length 530 nm)



North componenent for GNSS

PMF troposphere delay model

Common mapping function: based on temperature records and the position of an SLR station (latitude, height)

(Mendes et al., 2002)

Hydrostatic delay: based on pressure records and the position of an SLR station (latitude, height)

(Mendes and Pavlis, 2004)

Wet delay: based on water vapor pressure records and the position of an SLR station (latitude, height)

(Mendes and Pavlis, 2004)

$$d_{atm} = m_f(d_h + d_w)$$

Potsdam Mapping Function: derived from NWM

$$d_{atm} = m_{PMF}(d_h + d_w)$$

O1: Linear horizontal gradients derived from NWM

$$d_{atm} = m_{PMF}(d_h + d_w) + m_{CH-H}(G_N \cos A + G_E \sin A)$$

O1+O2: Nonlinear horizontal gradients: derived from NWM

$$d_{atm} = m_{PMF}(d_h + d_w) + m_{CH-H}(G_N \cos A + G_E \sin A + G_{NN} \cos^2 A + G_{EE} \sin^2 A + G_{NE} \cos A \sin A)$$

New troposphere delay model PMF

a_{ij}	FCULa
a_{10}	$(12100.8 \pm 1.9) \times 10^{-7}$
a_{11}	$(1729.5 \pm 4.3) \times 10^{-9}$
a_{12}	$(319.1 \pm 3.1) \times 10^{-7}$
a_{13}	$(-1847.8 \pm 6.5) \times 10^{-11}$
a_{20}	$(30496.5 \pm 6.6) \times 10^{-7}$
a_{21}	$(234.6 \pm 1.5) \times 10^{-8}$
a_{22}	$(-103.5 \pm 1.1) \times 10^{-6}$
a_{23}	$(-185.6 \pm 2.2) \times 10^{-10}$
a_{30}	$(6877.7 \pm 1.2) \times 10^{-5}$
a_{31}	$(197.2 \pm 2.8) \times 10^{-7}$
a_{32}	$(-345.8 \pm 2.0) \times 10^{-5}$
a_{33}	$(106.0 \pm 4.2) \times 10^{-9}$

Mendes et al., 2004

Mean values of coefficients derived

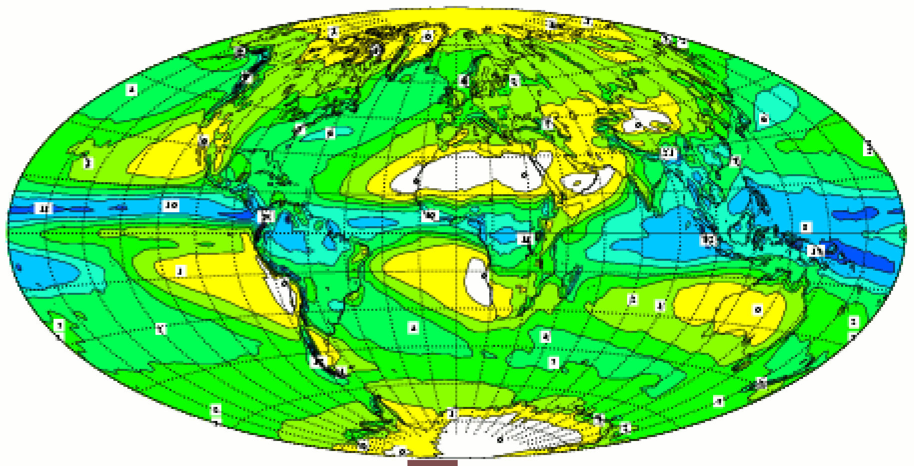
From 2 years of radiosonde data

$a_{i;j} = a_{1,2,3;0,1,2,3}$

Temperature records at the site

$a_i = a_{i0} + a_{i1} t_s + a_{i2} \cos\varphi + a_{i3} H$

Potsdam Mapping Function



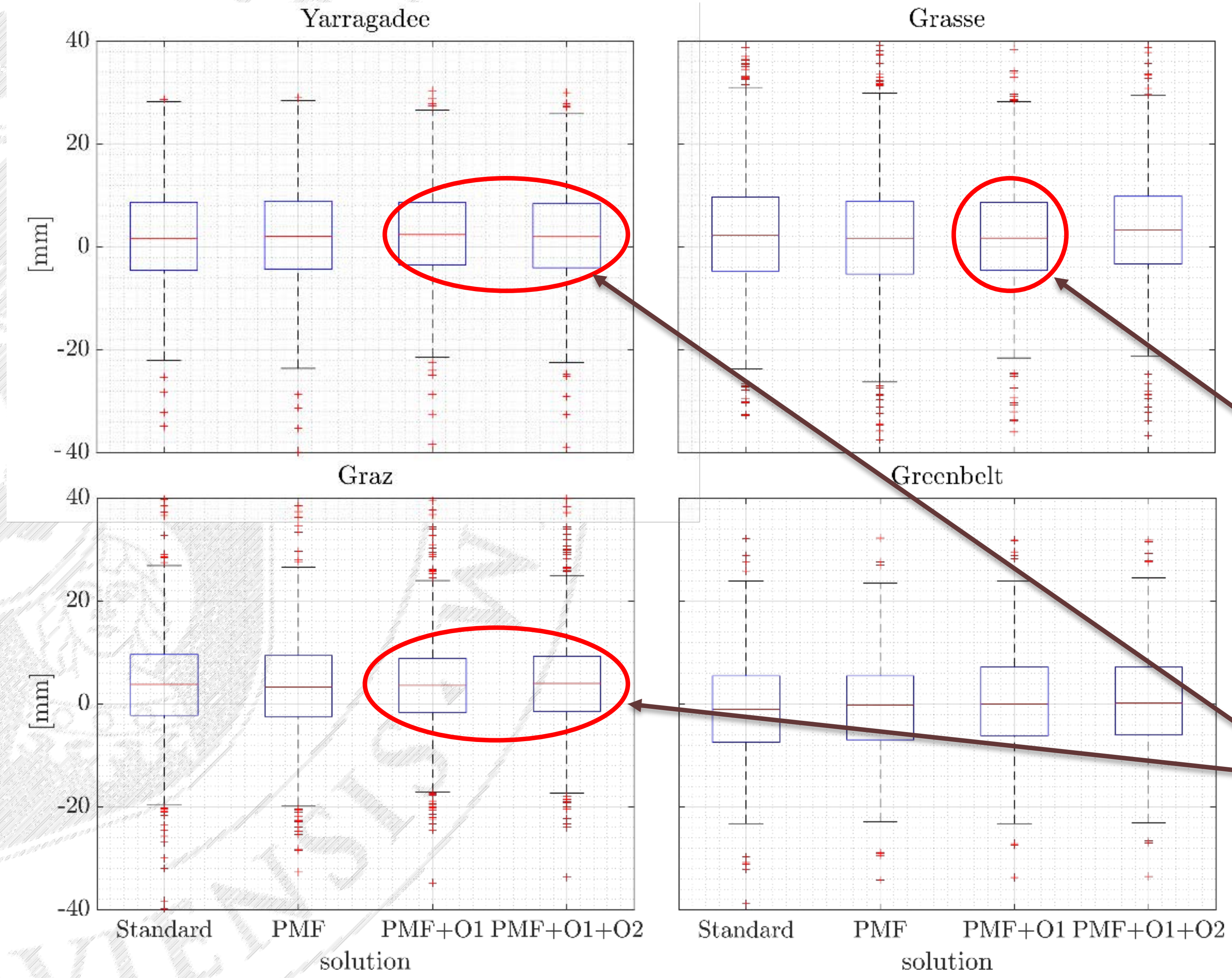
$X = [a_1, a_2, a_3, zh, zw, G_N, G_E, G_{NN}, G_{NE}, G_{EE}]$

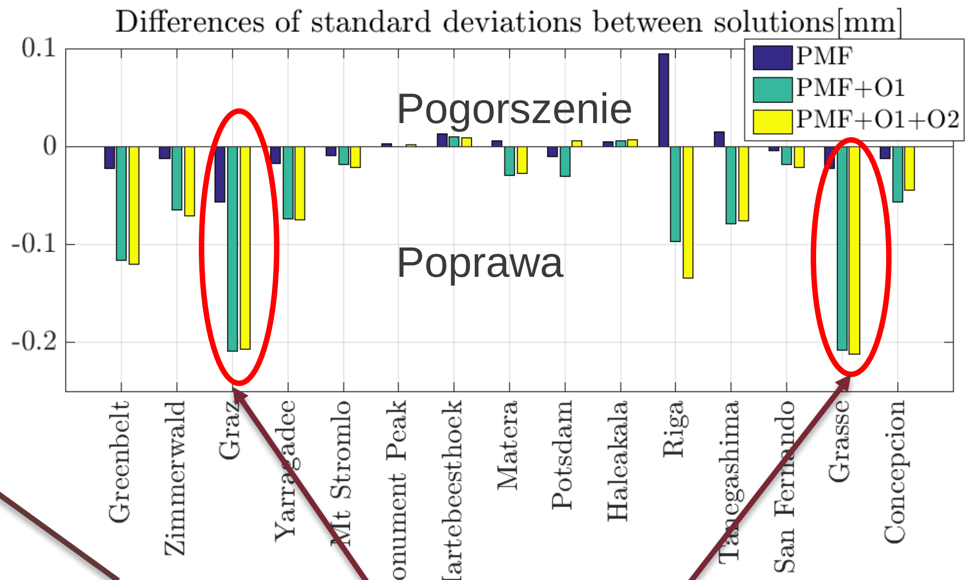
$$m(e) = \frac{1 + \frac{a_1}{1 + \frac{a_2}{1 + a_3}}}{\sin e + \frac{a_1}{\sin e + \frac{a_2}{\sin e + a_3}}}$$

Marini and Murray, 1972

How can we examine the impact of horizontal gradients on SLR observations ?

Observation residuals for elevation angle below 15 degrees





Improvement of IQR distance at the level of

2.0 mm

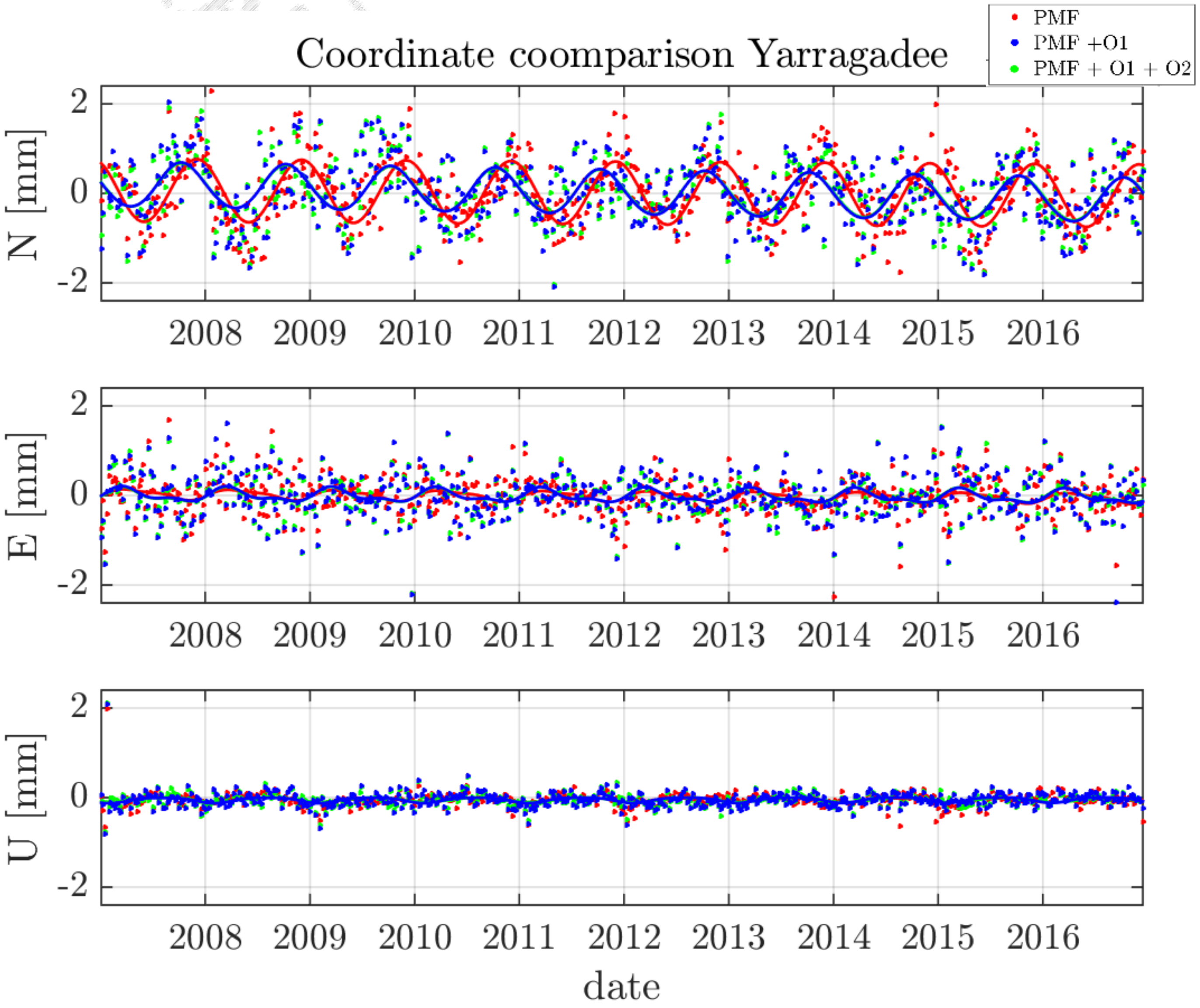
Improvement of observation STD for low elevation angles

For solutions with horizontal gradients

Improvement of IQR distance between first

And third quartile at the level of 1.5 mm

Impact of horizontal gradients on station coordinates repeatability

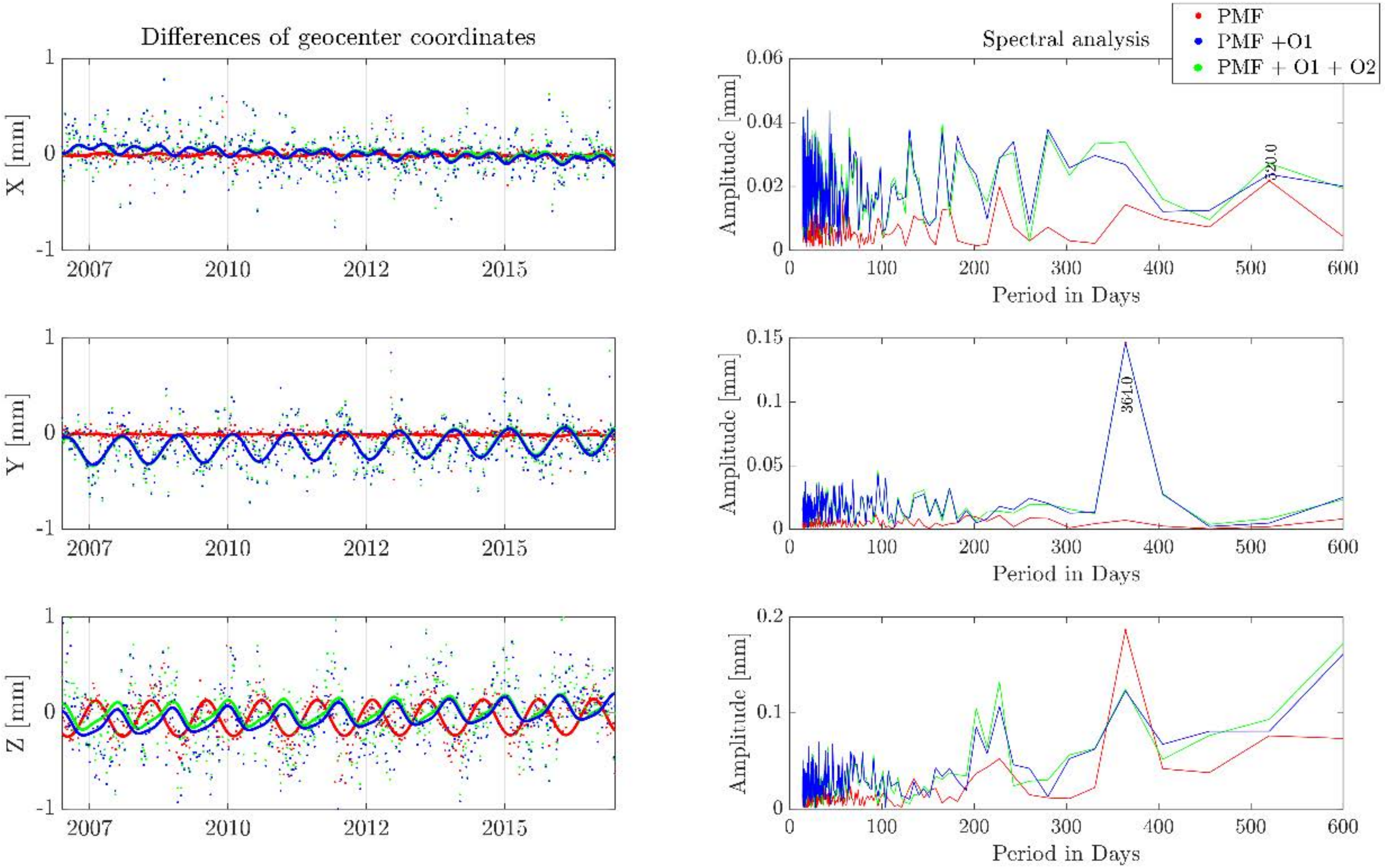


1. The main impact of station coordinates is caused by PMF (red dots, signal red line). The amplitude of annual signal is equal to 0.7 mm for solutions with horizontal gradients.
2. The differences of the estimated station coordinates reach the level of 2 mm, 1.2 and 0.2 for the North, East and Up component.
3. We observe phase shift of annual signal between PMF and PMF+O1.

Geocenter coordinates

Mean offset at the level of 0.12 mm for Y component for solutions with horizontal Gradients.

Occurrence of periodic components At the level of 0.16 mm for Y and Z Component.



	Średnie wartości różnic współrzędnych geocentrum [mm]					
	X [mm]		Y [mm]		Z [mm]	
	Średnia	σ	Średnia	σ	Średnia	σ
PMF	-0.003	0.004	-0.010	0.003	-0.056	0.008
PMF+ O1	0.039	0.013	-0.122	0.009	0.006	0.017
PMF+O1+O2	0.035	0.013	-0.126	0.009	-0.038	0.017

Pole coordinates

Improvement of mean offset value

At the level of 20 µas for X component

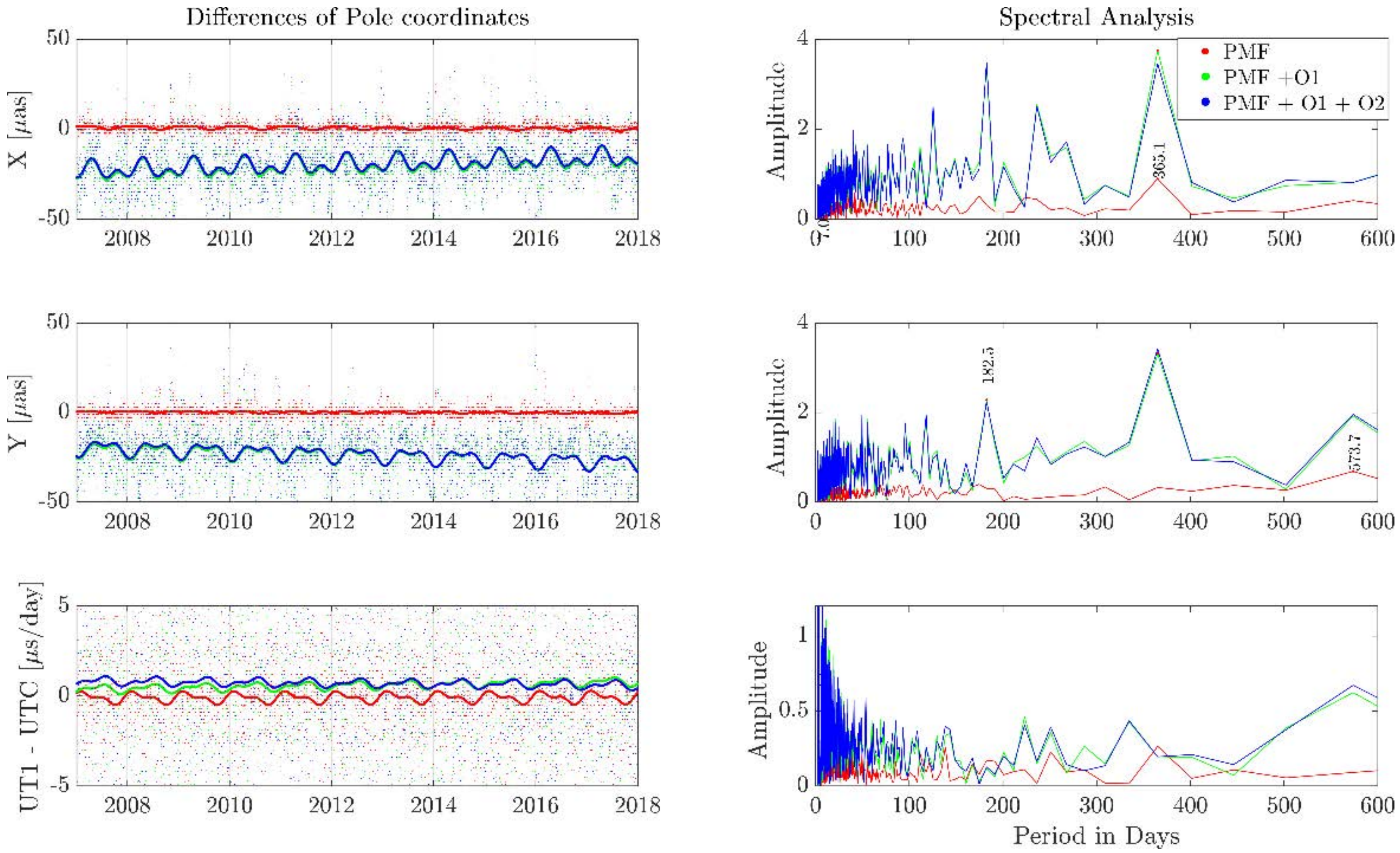
Improvement of mean offset between

combined solution C04 and SLR

at the level of 24 µas for Y component

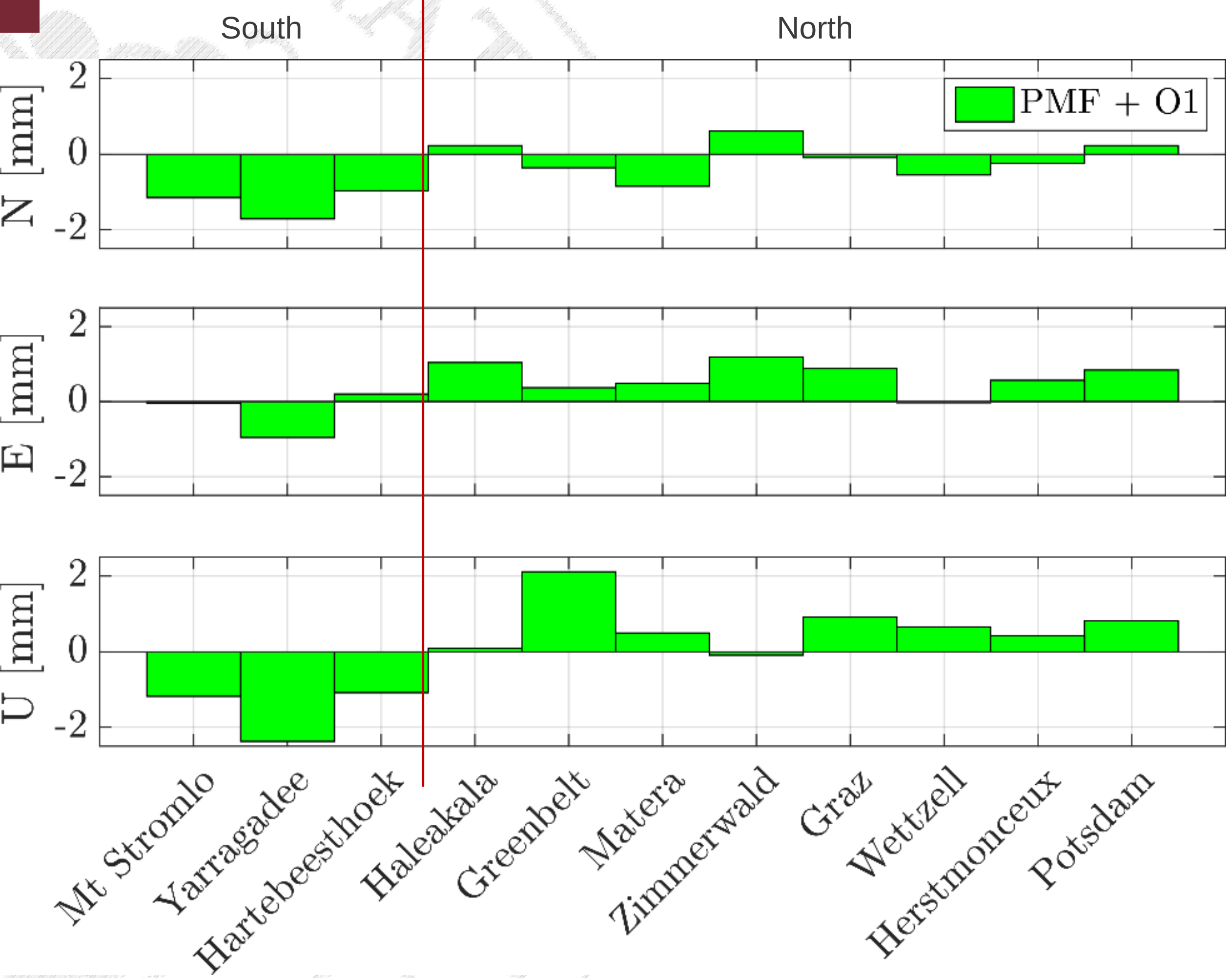
30 µas = 1 mm

On the Earth surface

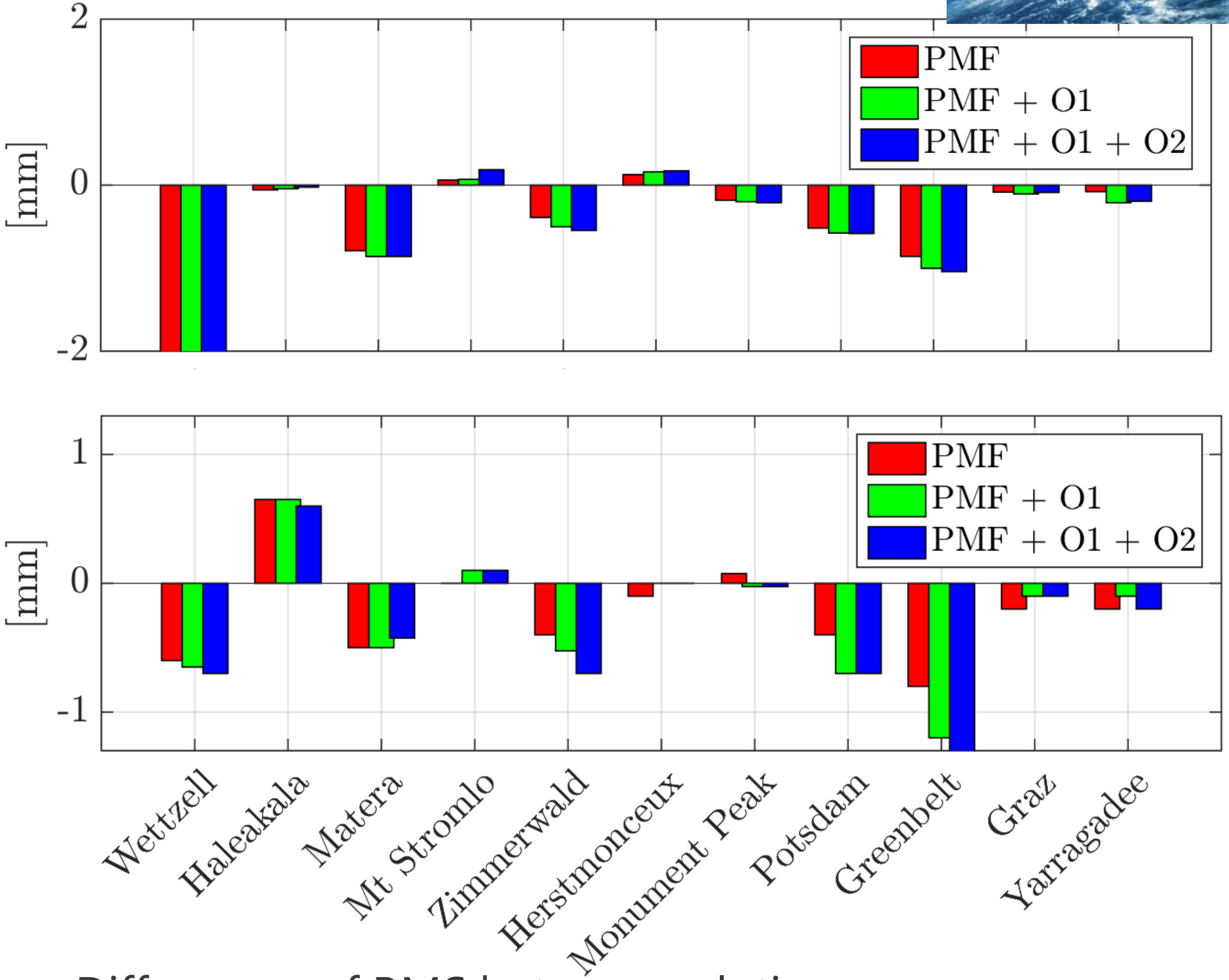


	X-POLE (µas)		Y-POLE (µas)		LOD (µs/day)		Number of epoch
	OFF	SIG	OFF	SIG	OFF	SIG	
Standard sol.	22	7.5	38	7.6	-77	5.2	574
PMF	23	7.5	38	7.6	-77	5.2	574
PMF O1	2	7.5	14	7.6	-76	5.2	574
PMF O1+O2	2	7.5	14	7.6	-75	5.2	574

Observations to LEO with horizontal gradients



Impact of first degree horizontal gradients on selected station Coordinates. Station are sorter w.r.t. increasing latitude



Differences of RMS between solutions.

Differences of IQR between standard solution and PMF

Conclusions

1. Modelling troposphere delay with horizontal gradients in SLR solutions improves observation residuals, especially for low elevation angles. (small effect for LAGEOS, large effect for Sentinel 3a)

2. SLR solutions become more consistent with the IERS-14-C04 combined series, which means that SLR solutions become more consistent with other techniques of space geodesy.

3. Second order gradients can be neglected in SLR solutions.

Next step:

1. VMF3o (impelementations ready in Bernese GNSS Software, tests ongoing)

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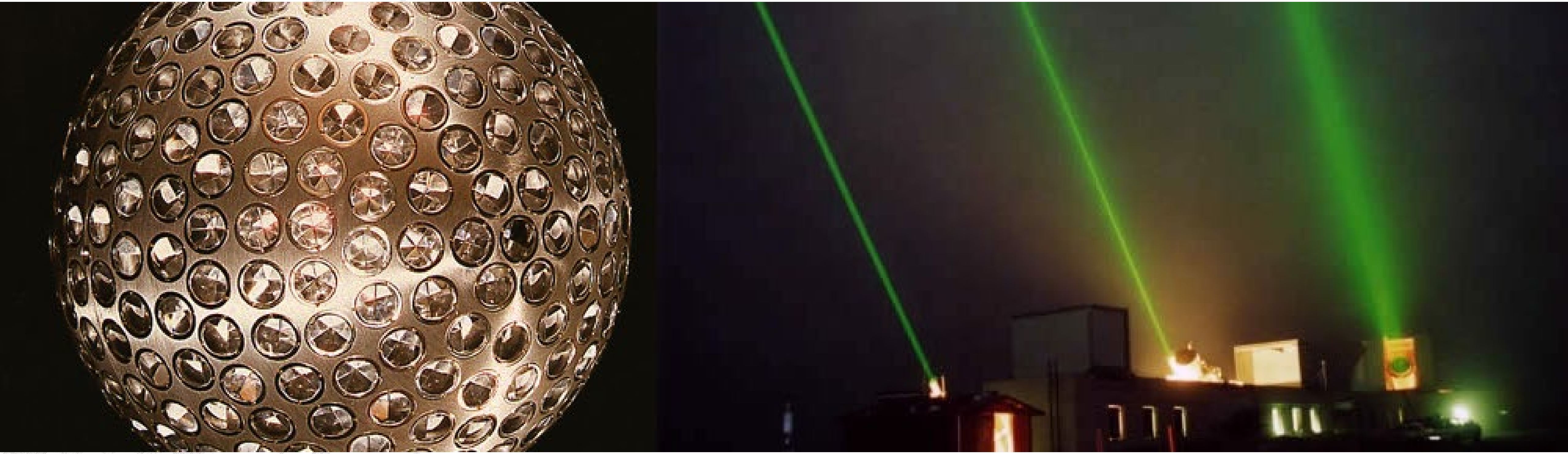
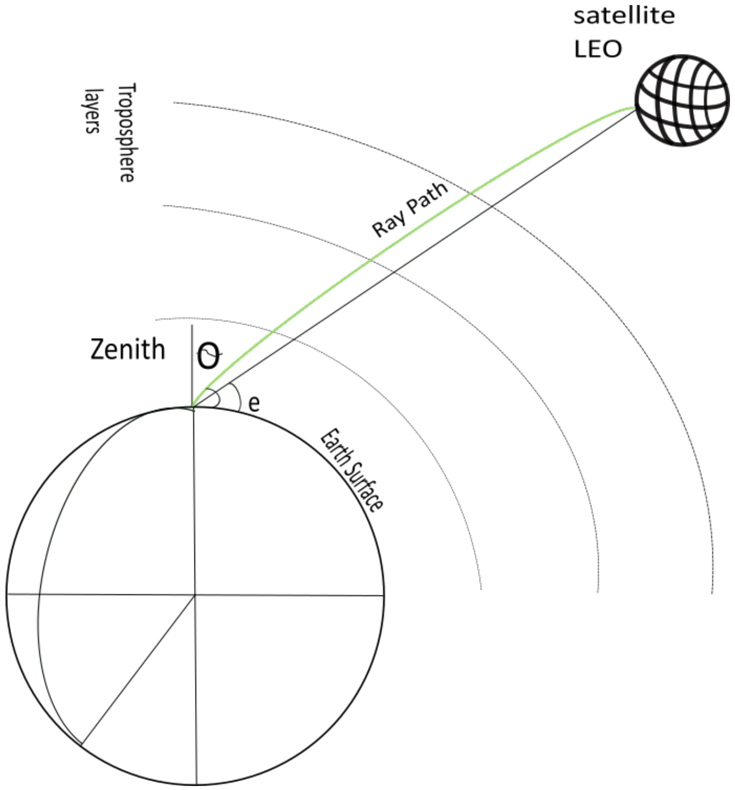


Thank you

Back up SLIDES

Characteristic of PMF troposphere delay model

Parametr	Opis
Software	GFZ direct numerical simulation (DNS) tool
Ray-traicing method	2D
Model:	ERA-Interim
Spatial resolution	0.5° x 0.5°
Vertical resolution NWM	60 layers
Elevation angle	3, 5, 7, 10, 15, 20, 30, 50, 70, 90
Horizontal resolution	0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 360



Models derived by:

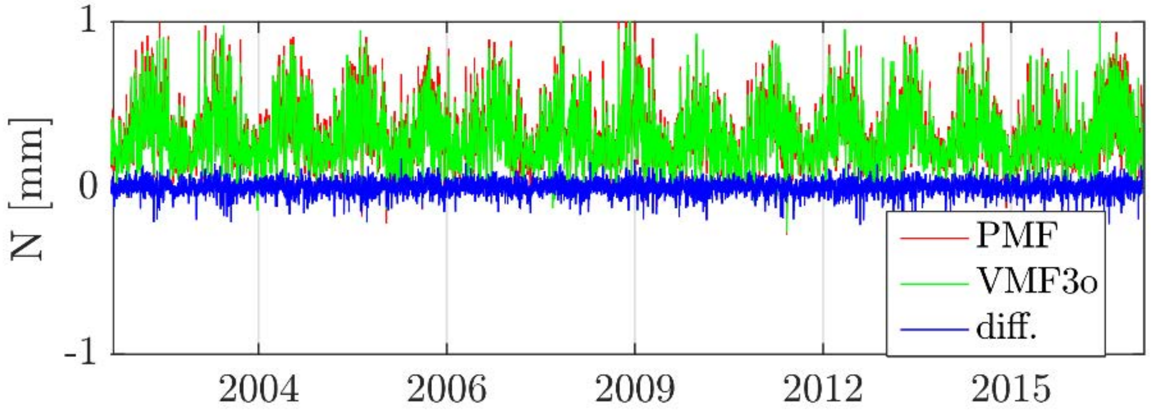
Dr dipl Ing. Florian Zus,

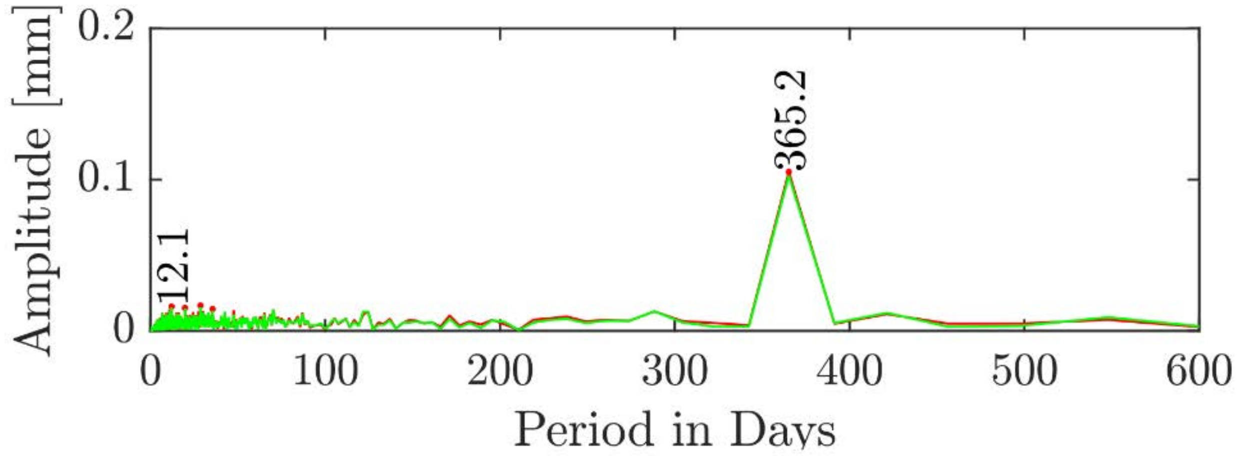
Dipl Ing. Kyriakos Balidakis

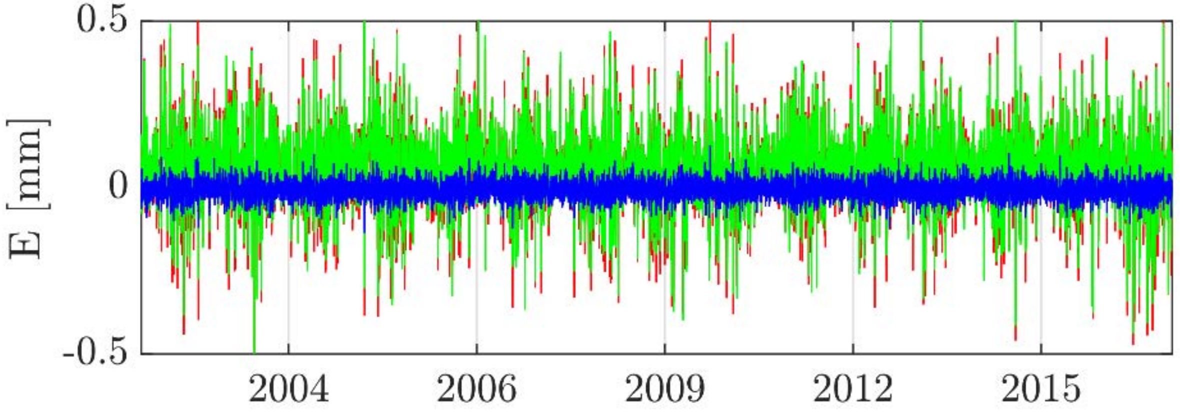
ECMWF

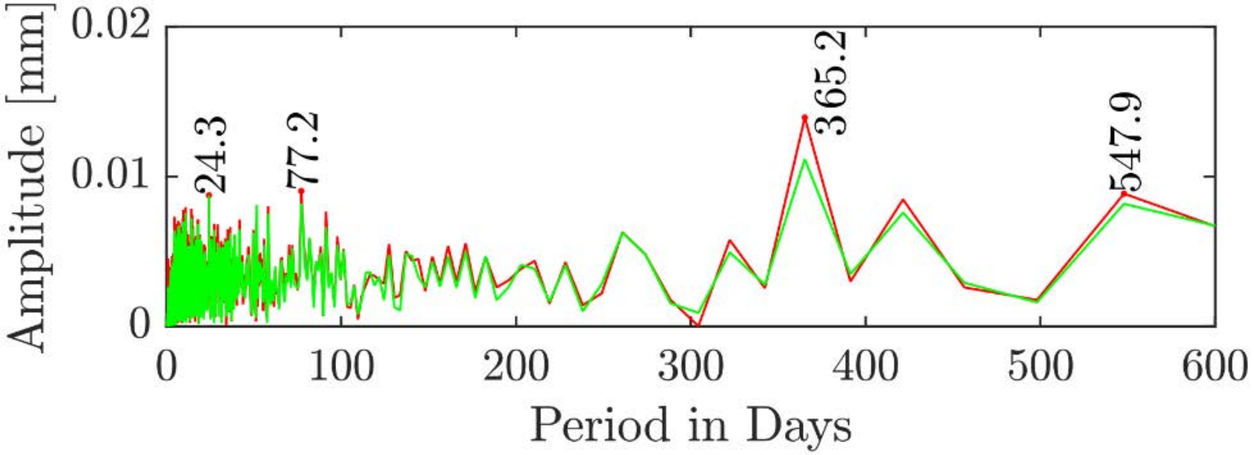
GFZ Helmholtz Centre Potsdam

Comparison of horizontal gradients data time series: PMF & VMF3o station: Yarragadee





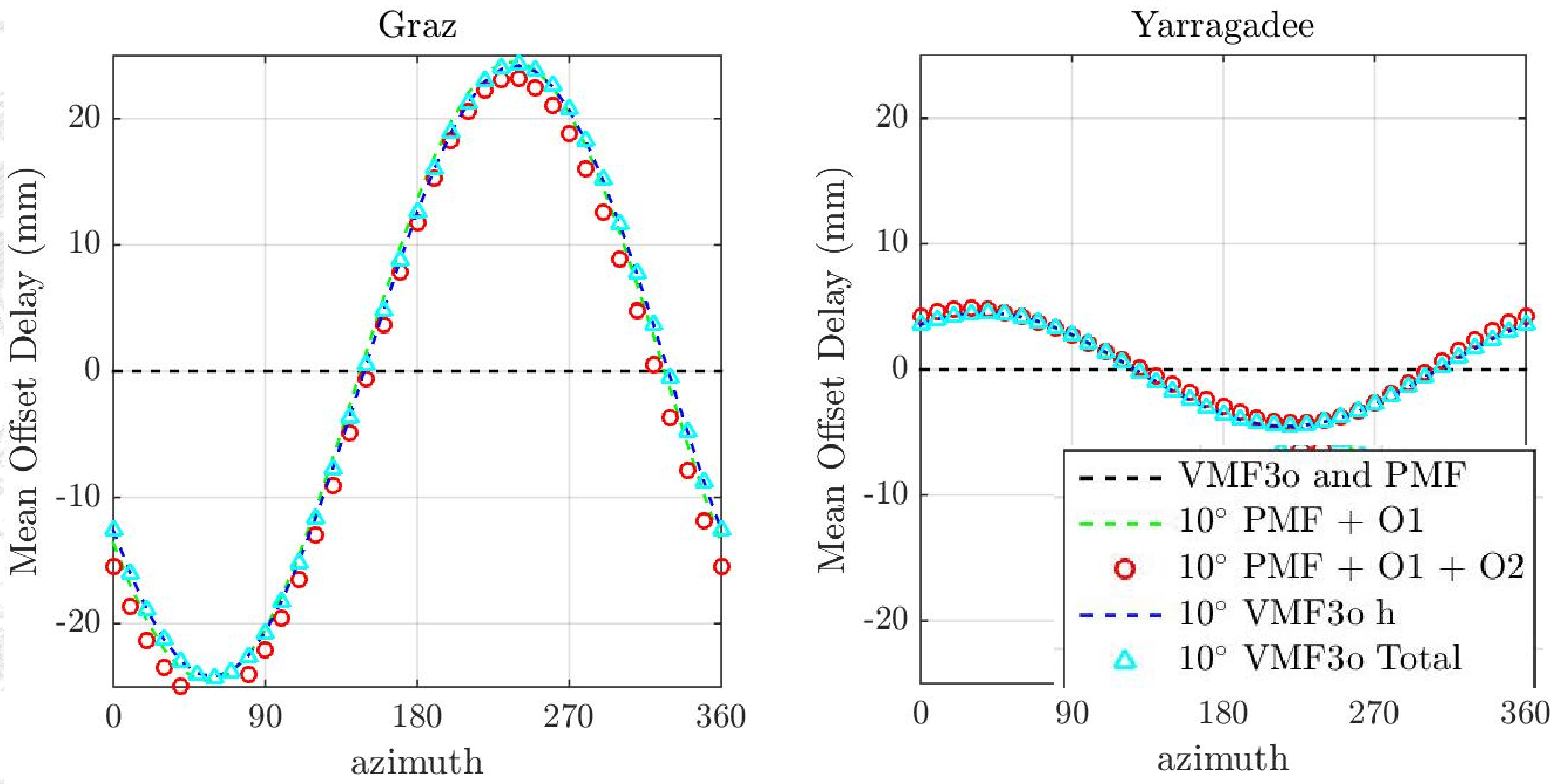




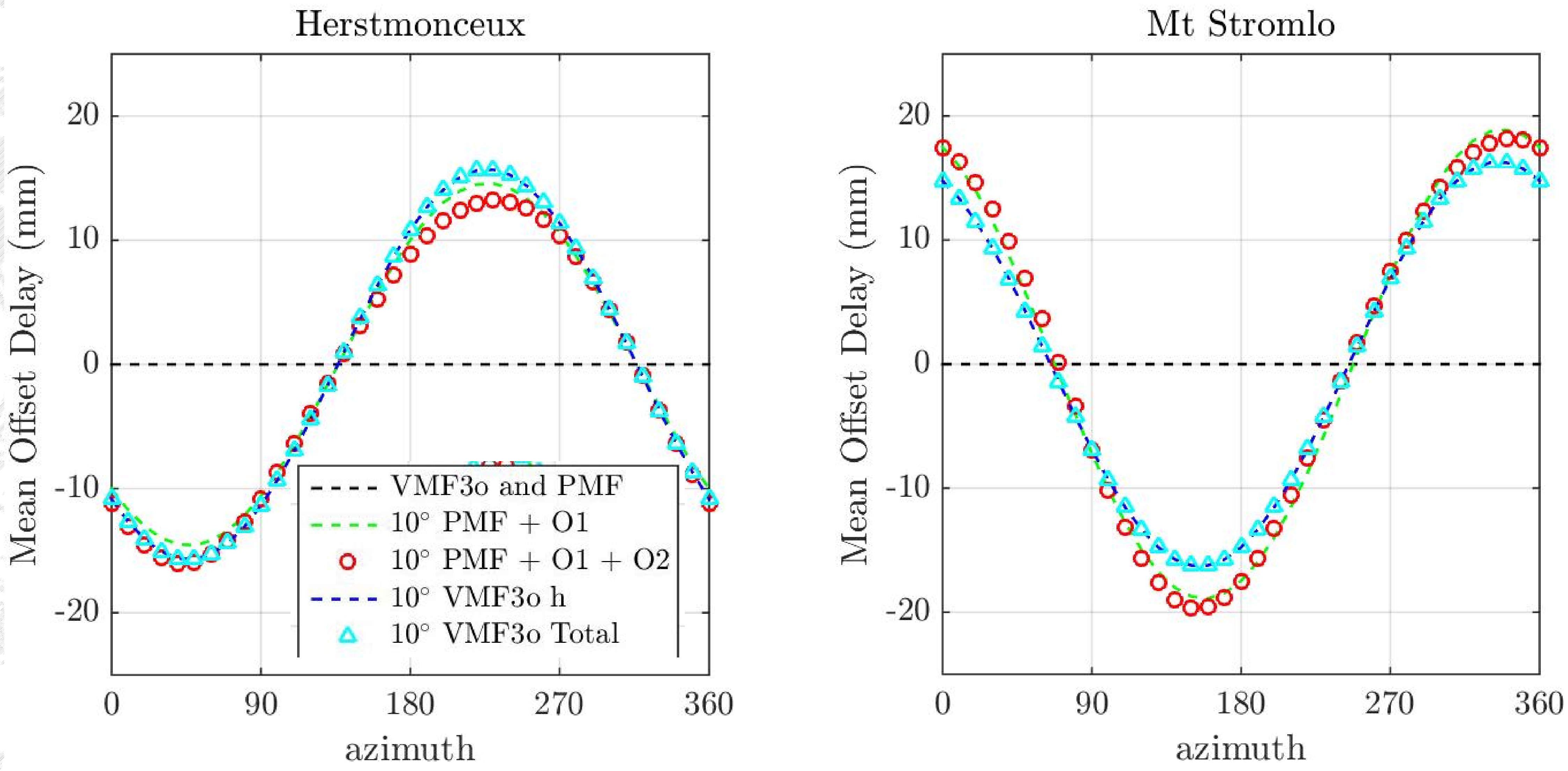
Horizontal gradients derived from PMF are more scattered

Gradienty horyzontalne PMF wykazują większe amplitudy roczne i szum nisko częstotliwościowy

Impact of horizontal gradients derived from PMF & VMF3o

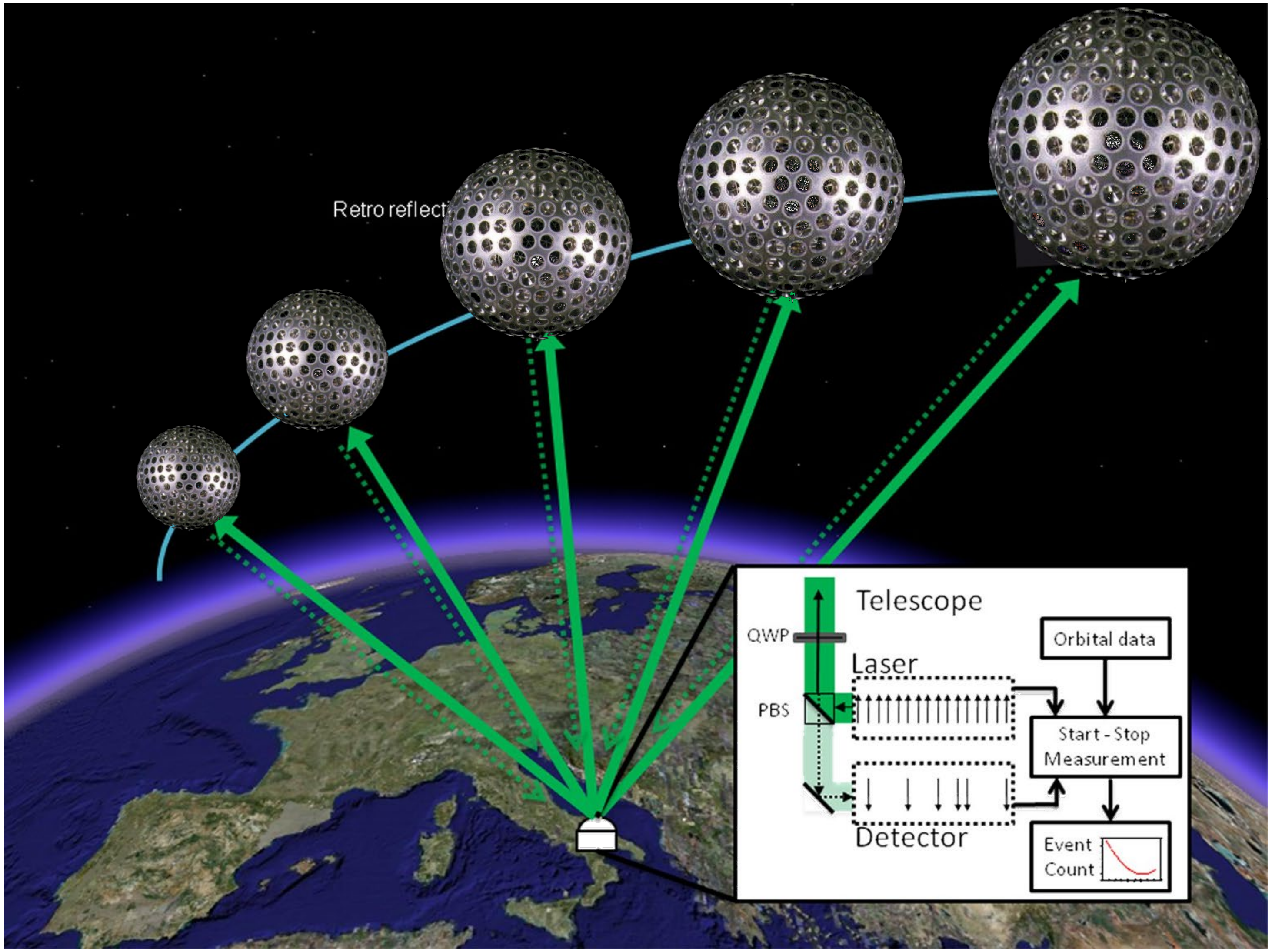


Impact of horizontal gradients derived from PMF & VMF3o

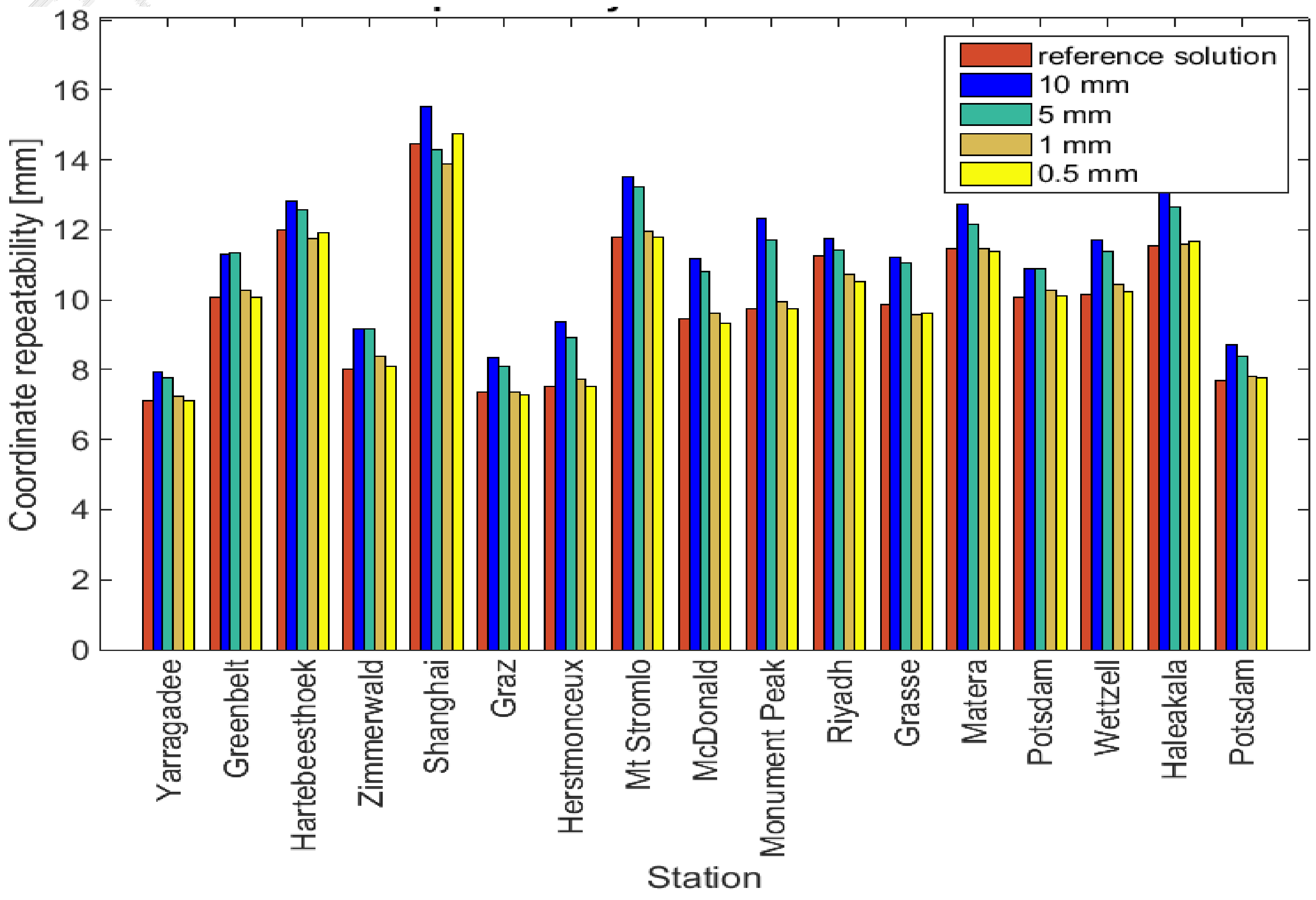


Podstawy pomiarów SLR

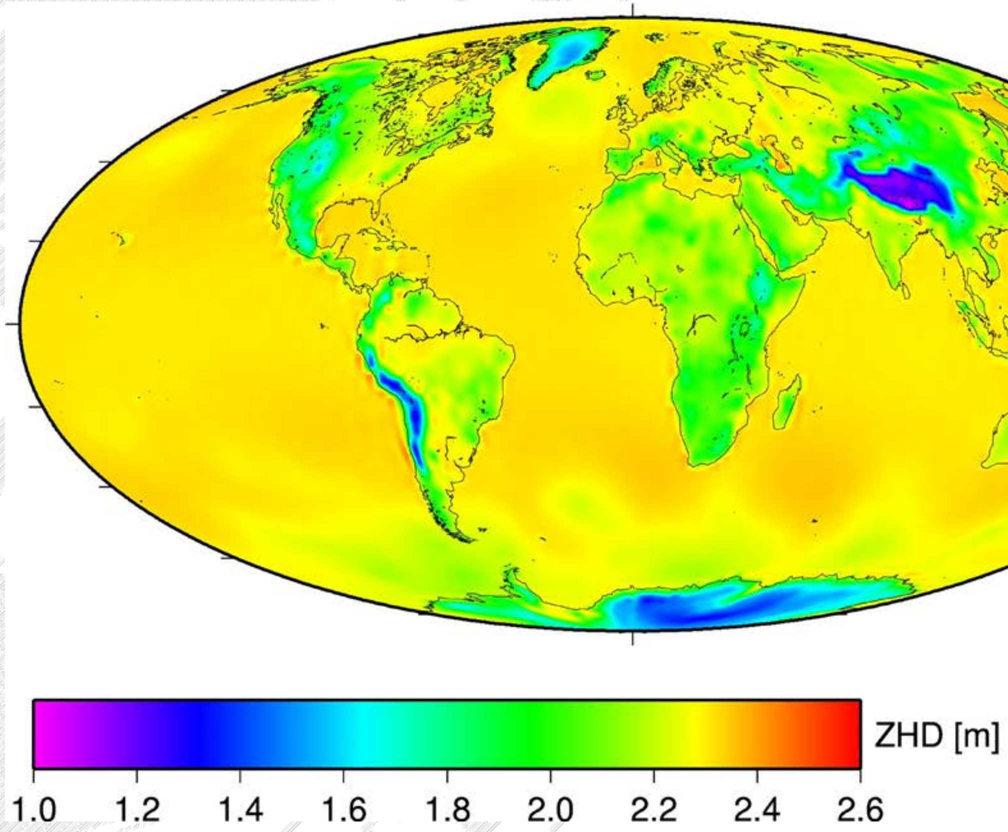
	LAGEOS-1	LAGEOS-2
Waga:	406.96 kg	405.38 kg
Sponsor:	United States	United States and Italy
Reflektory:	426 corner cubes	426 corner cubes
kształt:	Kulisty	Kulisty
RRA Średnica:	60 cm	60 cm
Zastosowanie:	Geodezja	Geodezja
Okres obiegu:	225 minut	223 minut
Perygeum:	5,860 km	5,620 km
Orbita:	Kołowa	kołowa
Data wystrzelenia:	Maj 4, 1976	Październik 22, 1992
Inklinacja:	109.84 stopni	52.64 stopni
Czas eksploatacji:	Wiele dekad	Wiele dekad
Ekscentryczność:	0.0045	0.0135
COSPAR ID:	7603901	9207002

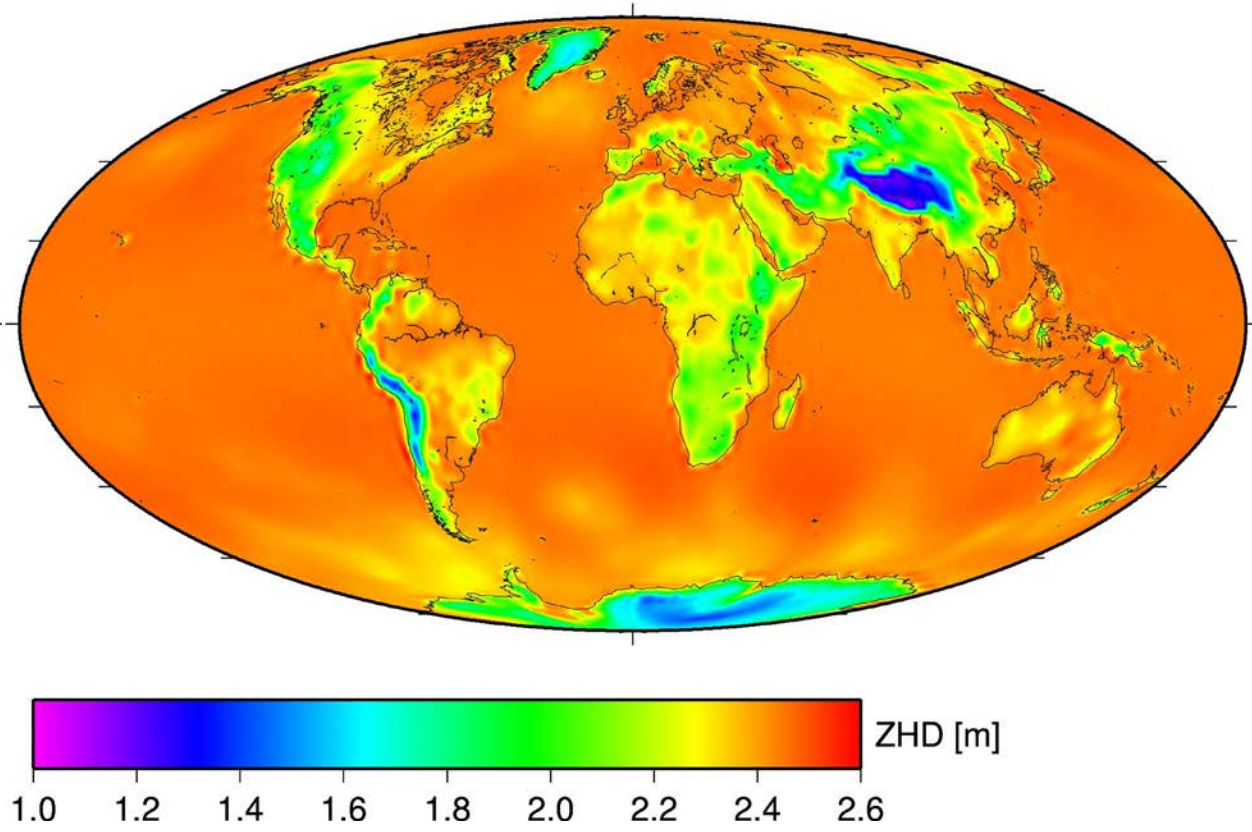


Station coordinates repeatability

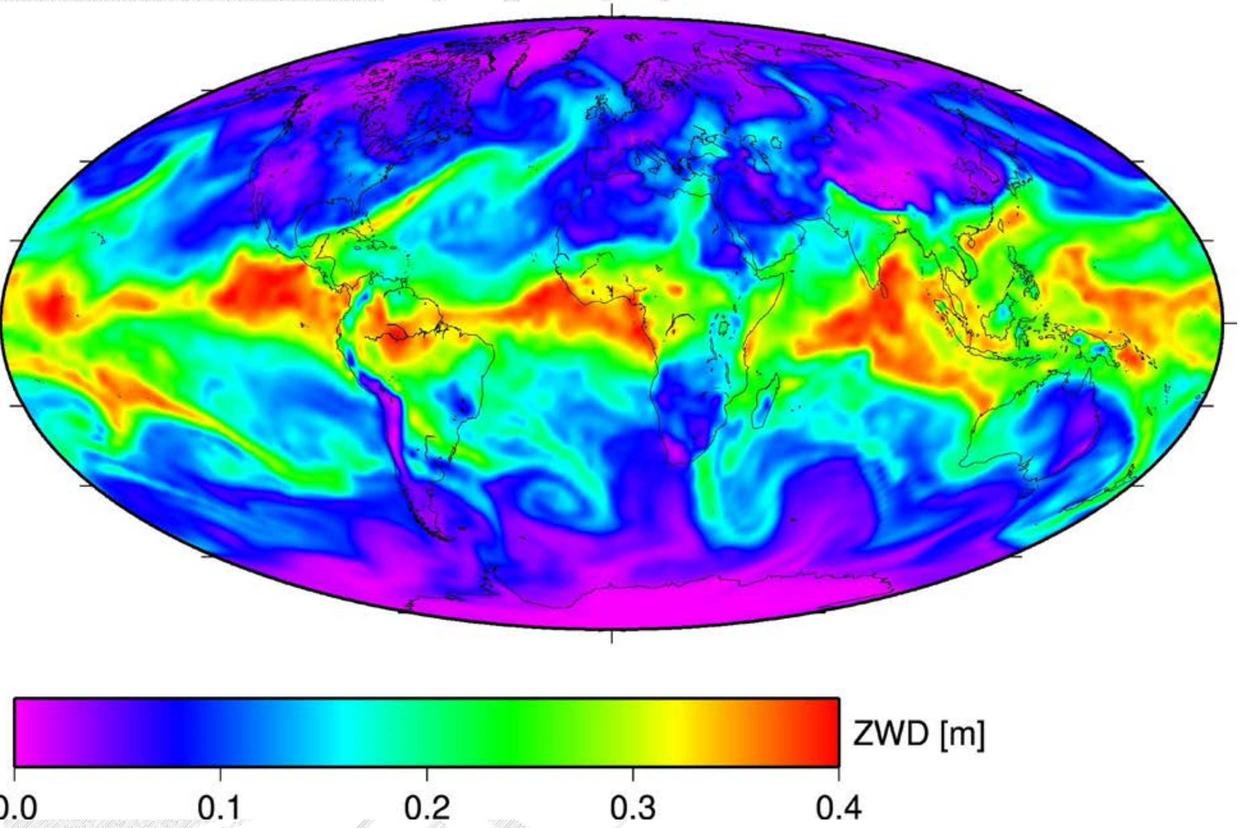


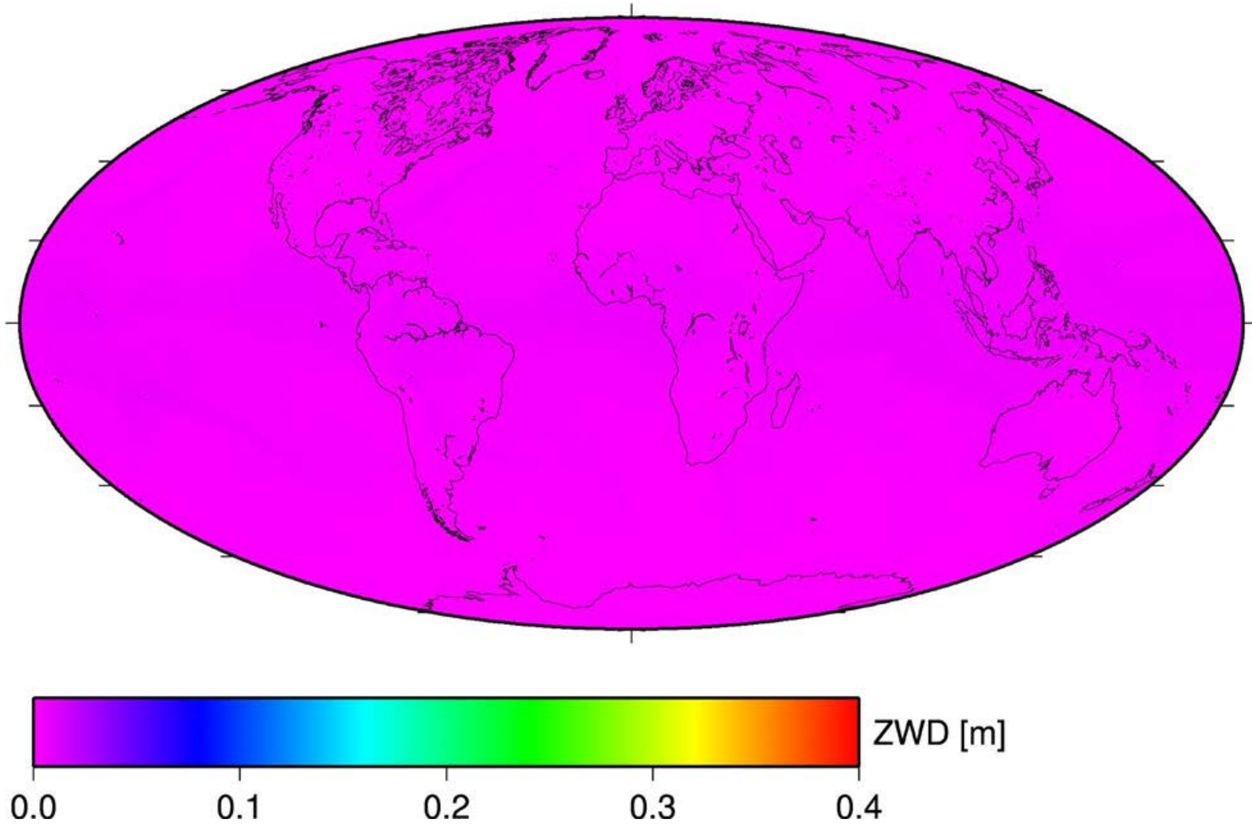
ZHD GNSS & ZHD SLR





ZWD GNSS & ZWD SLR





Publikacje

Publikacje wyróżnione w JCR (lista „A" MNiSzW):

Sośnica K, Prange L, Kaźmierski K, Bury G, **Drożdżewski M**, Zajdel R, Hadaś T (2018) *Validation of Galileo orbits using SLR with a focus on satellites launched into incorrect orbital planes*, Journal of Geodesy 92(2), pp. 131-148. doi:10.1007/s00190-017-1050-x, **pkt. 40; IF 4.633**

Drożdżewski M, Sośnica K, (2018) *Satellite laser ranging as a tool for the recovery of tropospheric gradients*, Atmospheric Research 212 pp. 33-42, https://doi.org/10.1016/j.atmosres.2018.04.028 **pkt. 30; IF 3.817**

Publikacje w czasopismach recenzowanych:

Drożdżewski M. (2017) *TROPOSPHERE DELAY MODELING WITH GRADIENTS FOR SLR:*

FIRST RESULTS, 19th Professional Conference of Postgraduate Students "JUNIORSTAV 2017", Brno, Czech Republic, 26.01.2017