On the impact of different mapping functions on geodetic and tropospheric products from VLBI data analysis

Kyriakos Balidakis[1], F. Zus[2], J. Douša[3], T. Nilsson[2], S. Glaser[1], B. Soja[2], M. Karbon[2], R. Heinkelmann[2] and H. Schuh[1,2]

kyriakos.balidakis@tu-berlin.de

[1]Technische Universität Berlin, Institute of Geodesy and Geoinformation Science, Berlin, Germany
[2]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Space Geodetic Techniques, Potsdam, Germaany
[3]Geodetic Observatory Pecný, Research Institute of Geodesy, Topography and Cartography, Czech Republic

The 9th IVS General Meeting – Session 5: Geodetic and Astrometric VLBI Results
Johannesburg, March 17th, 2016

Motivation

- Troposphere is the main random and systematic error source contributor in geodetic VLBI.
- VMF1 is computed from ECMWF operational analysis and the method is 10 years old.
- Utilize our ultra-rapid ray-tracing algorithm (Zus et al., 2012)

Outline

- Investigate the impact of applying different mapping functions in VLBI data analysis on:
  - Zenith wet delays
  - Linear horizontal gradients
  - Station coordinates
  - Network scale
  - Earth orientation parameters

. . . setting the stage

$$T(\varepsilon,\alpha) = mf_h \cdot d_h^{90} + mf_w \cdot d_w^{90} + mf_g \cdot [G_{NS} \cdot \cos(\alpha) + G_{\mathrm{EW}} \cdot \sin(\alpha)$$
$$+ G_{\mathrm{NN}} \cdot \cos^2(\alpha) + G_{\mathrm{NE}} \cdot \cos(\alpha)\, sin(\alpha) + G_{EE} \cdot sin^2(\alpha)]$$

$$mf_i(\varepsilon) = \begin{cases} \dfrac{1 + \dfrac{a_i}{1 + \dfrac{b_i}{1 + c_i}}}{\sin(\varepsilon) + \dfrac{a_i}{\sin(\varepsilon) + \dfrac{b_i}{\sin(\varepsilon) + c_i}}}, i = h \vee w & \text{(Herring, 1992)} \\ \dfrac{1}{\sin(\varepsilon)\tan(\varepsilon) + 0.0032}, i = g & \text{(Chen and Herring, 1997)} \end{cases}$$

Mapping functions

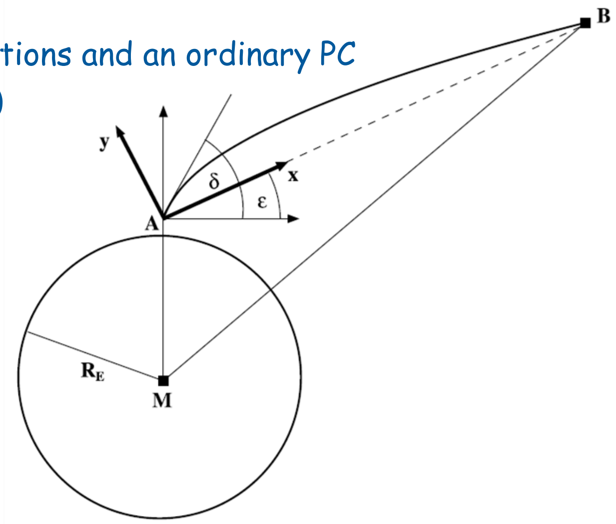
$$mf_i(\varepsilon) = \frac{1 + \cfrac{a_i}{1 + \cfrac{b_i}{1 + c_i}}}{\sin(\varepsilon) + \cfrac{a_i}{\sin(\varepsilon) + \cfrac{b_i}{\sin(\varepsilon) + c_i}}}, i = h \vee w$$

- VMF1 or UNB_VMF1 (Böhm et al., 2006b)
  - a_i estimated,, b_i and c_i from climatology
- GPT2w (Böhm et al., 2015)
  - a_i annual + semi-annual terms,, b_i and c_i from climatology
- PMF (Zus et al., 2012)
  - a_i, b_i and c_i estimated

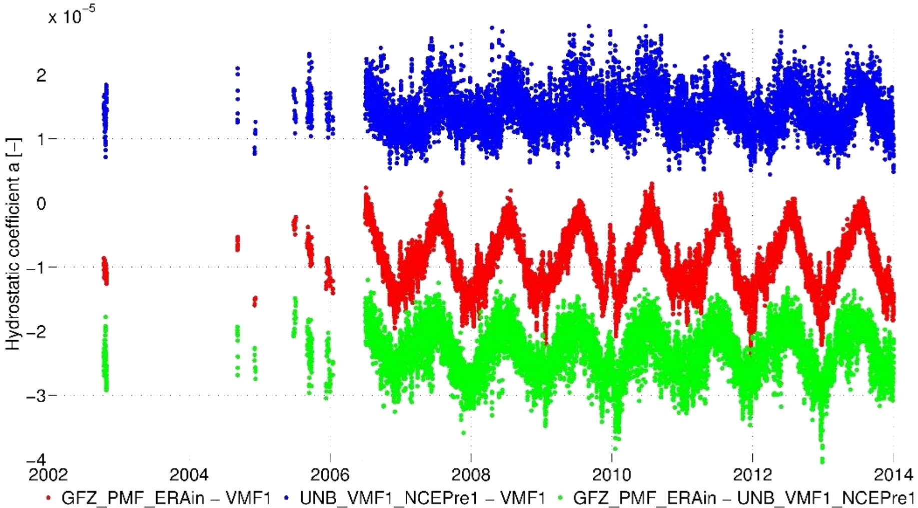
PMF: Potsdam mapping functions

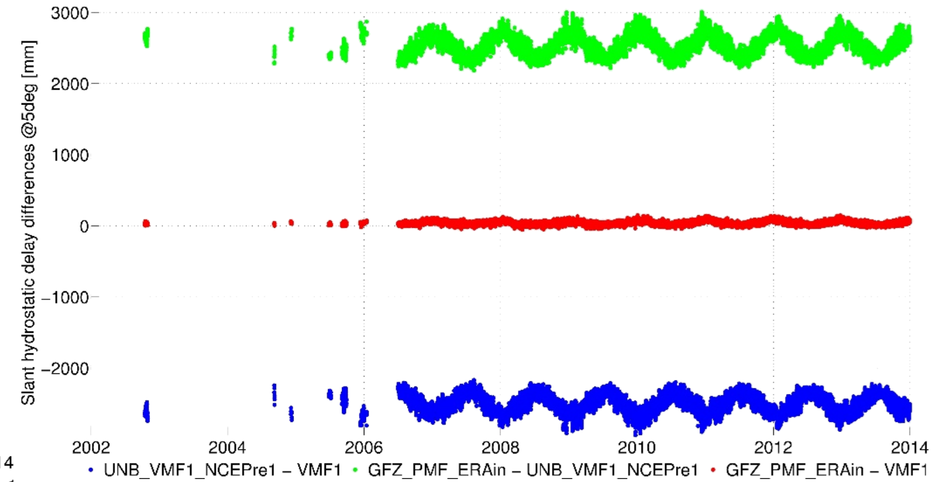
- Ray-trajectory solution with an **implicit finite difference scheme.**
- Structured non-linear system of equations solution with the **Newton-Raphson method**
- We estimate gradient components of 1st and 2nd order
- Ultra-rapid computation
  - using Intel FORTRAN compiler e.g. given 90 stations and an ordinary PC (Core2QuadIntel processor, 2.5 GHz and 2 GB RAM) it takes ~1 sec for 10,800 station-quasar links

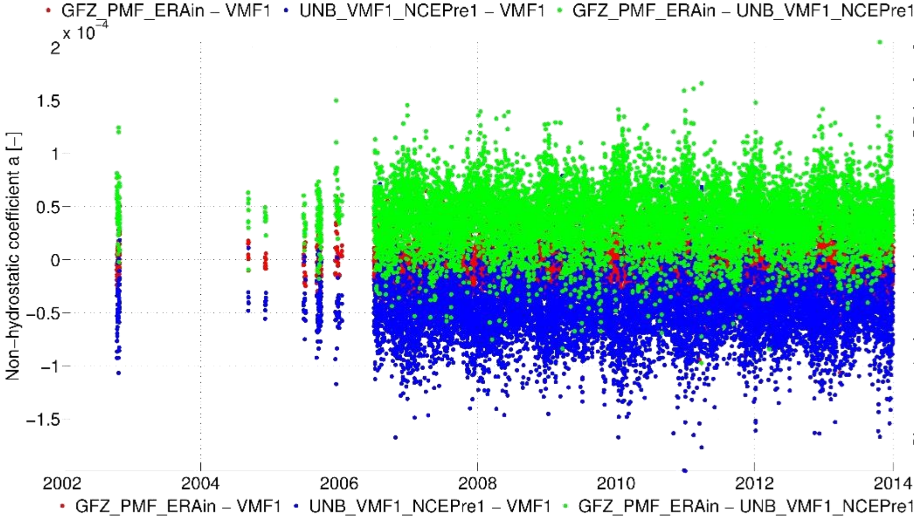
$$\varepsilon = \begin{bmatrix} 3 \\ 5 \\ 7 \\ 10 \\ 15 \\ 20 \\ 30 \\ 50 \\ 70 \\ 90 \end{bmatrix} \qquad \alpha = \begin{bmatrix} 0 \\ 30 \\ 60 \\ 90 \\ 120 \\ 150 \\ 180 \\ 210 \\ 240 \\ 270 \\ 300 \\ 330 \end{bmatrix}$$

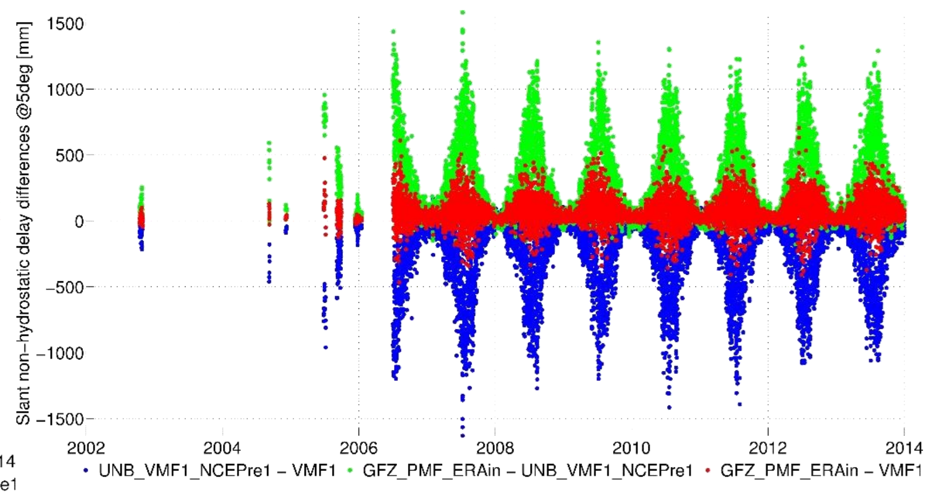


Badary, Russia

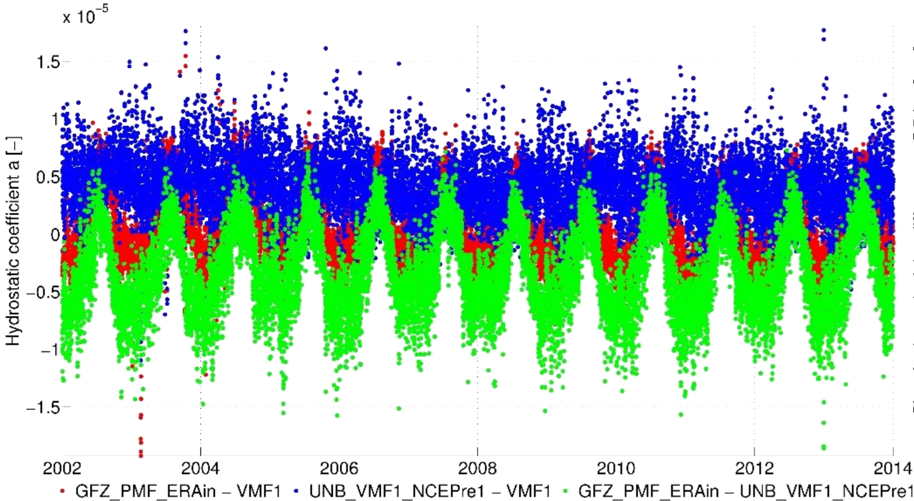


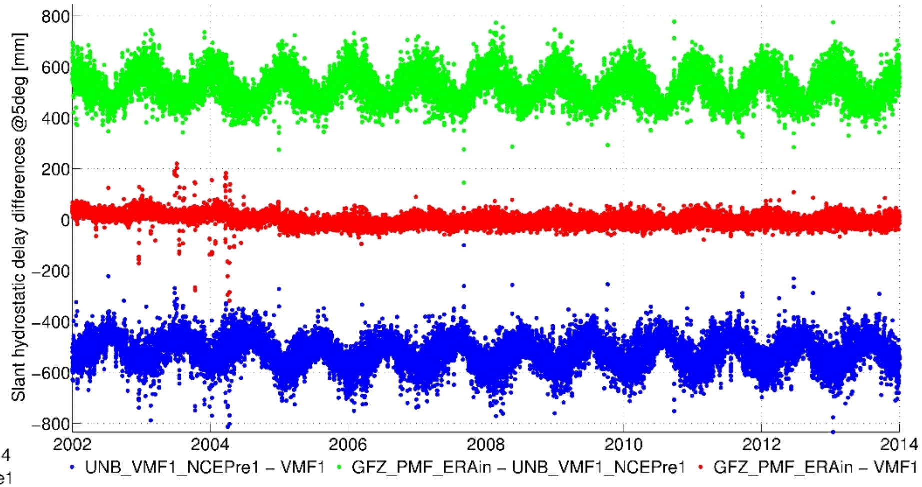


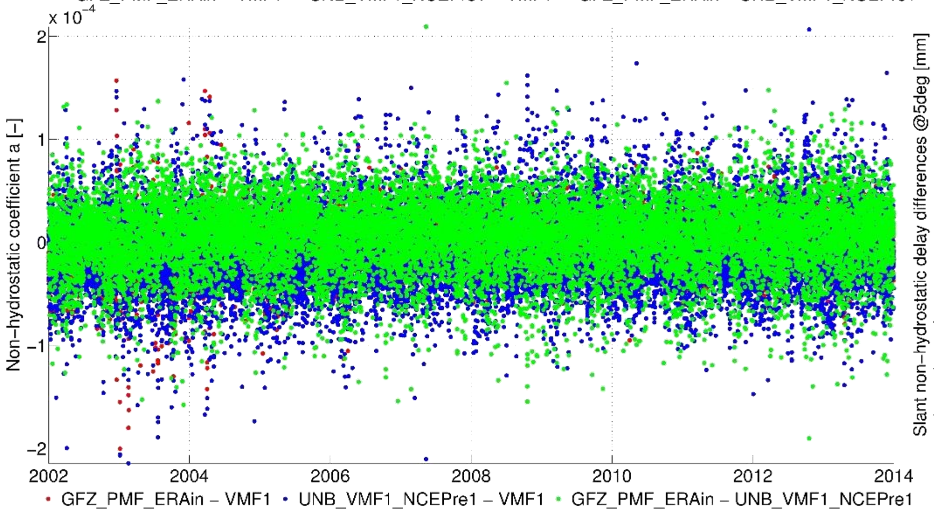


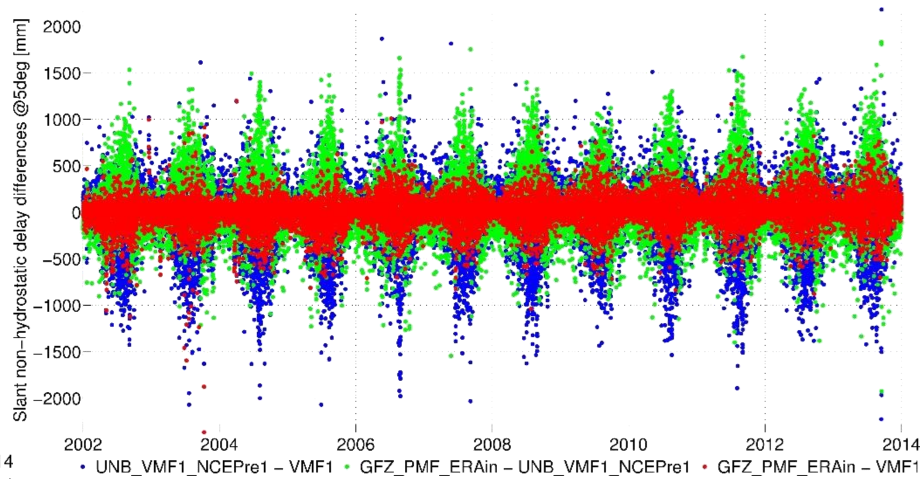


Tsukuba, Japan



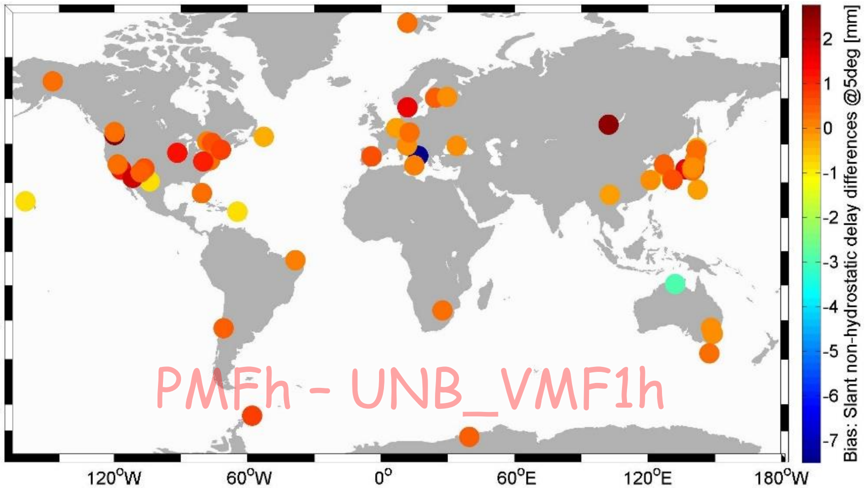


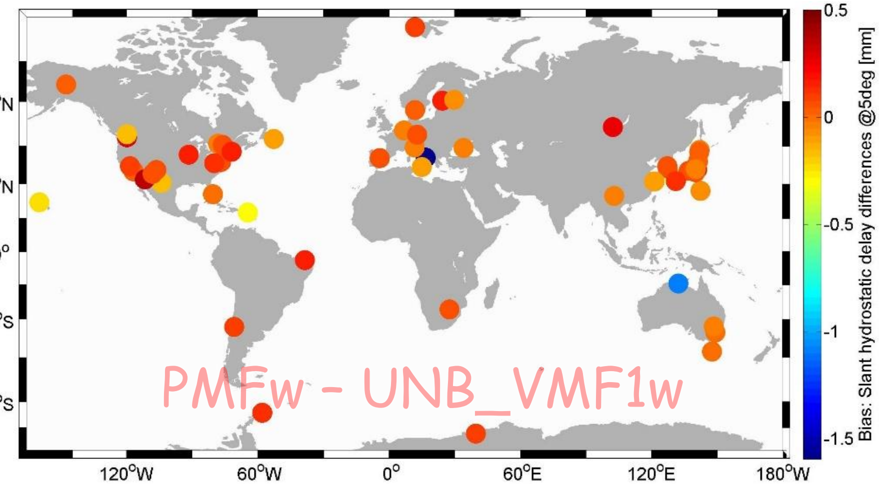


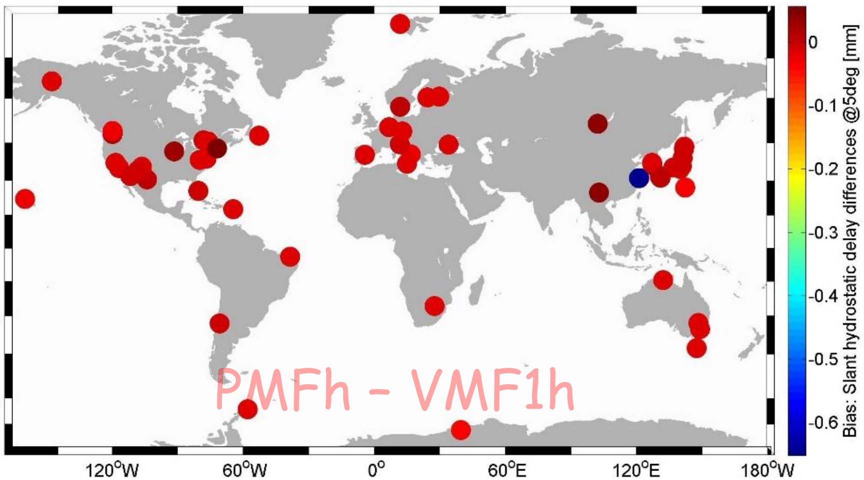


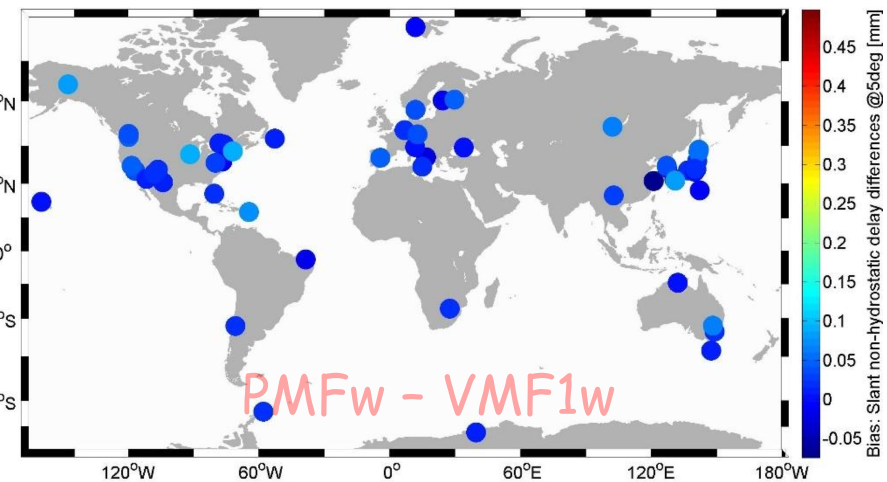
. . . comparisons

$\delta d_i^{5^\circ}, i = h \vee w$









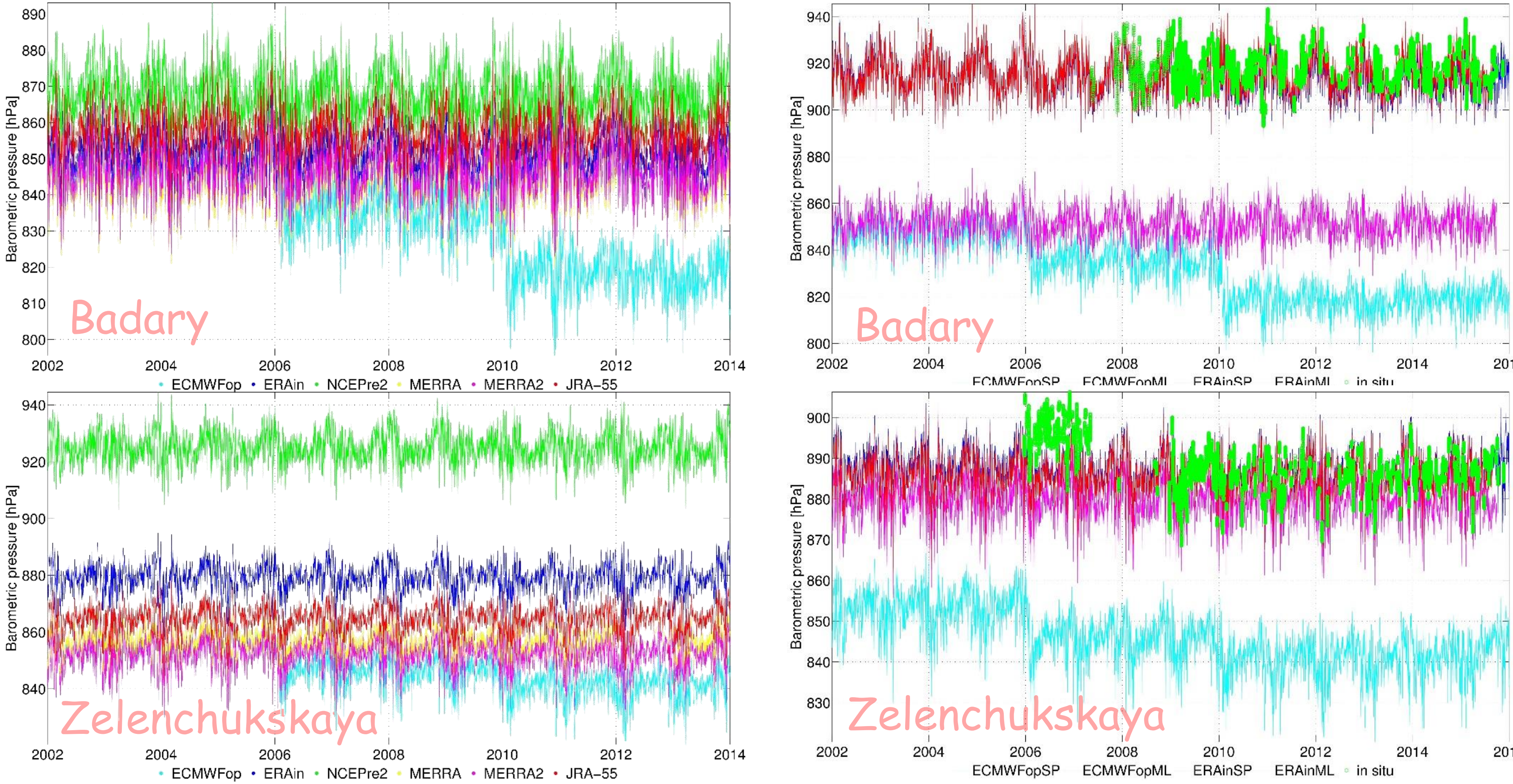
VLBI data analysis

- Vienna VLBI Software, VieVS@GFZ (Gauß-Markov model)
- Group delay data from IVS-R1 and IVS-R4 from 2002 until 2015 (1326 sessions) featuring a 32 station network
- We produced 3 solutions:
  - **VMF1** (Böhm et al., 2006b)
  - **GPT2w** (Böhm et al., 2015)
  - **PMF** (Zus et al., 2012)

- All solutions determined w.r.t. ITRF2008 and USNO Finals EOP series, using the homogenized meteorological dataset and accounting for geophysical loading at the observation level.
- Daily estimates of station positions and EOPs, hourly ZWDs, 6-hourly gradients, ...

Input meteorological data

cf. poster S5P9 by Balidakis et al.



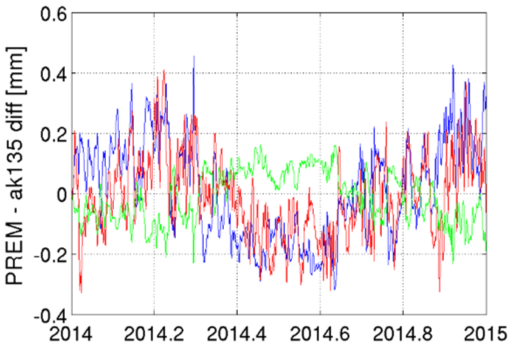
GFZ Helmholtz Centre Potsdam

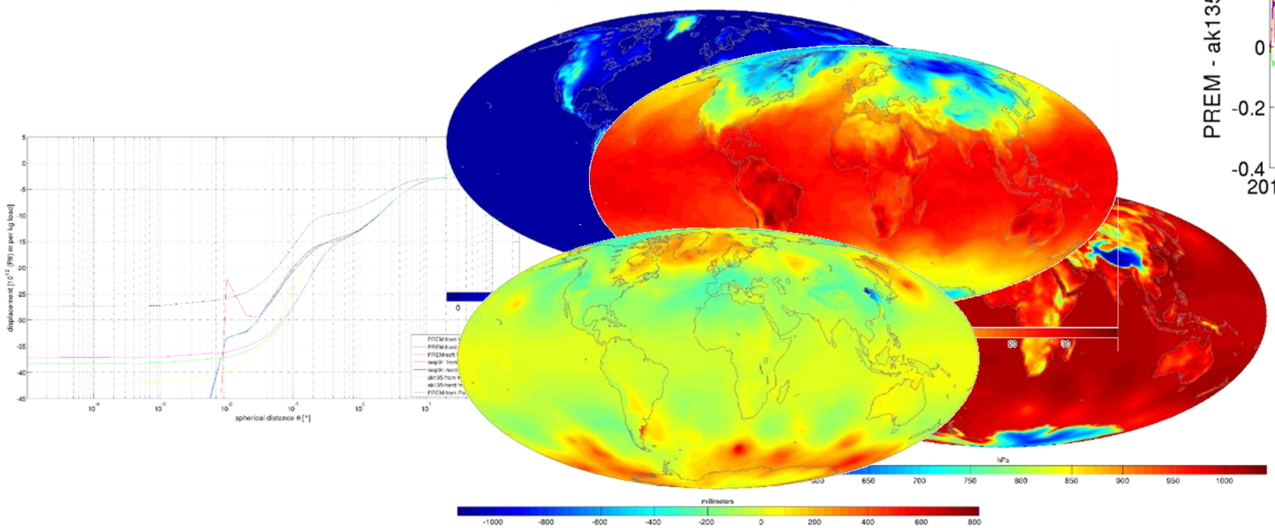
HELMHOLTZ ASSOCIATION

Geophysical loading

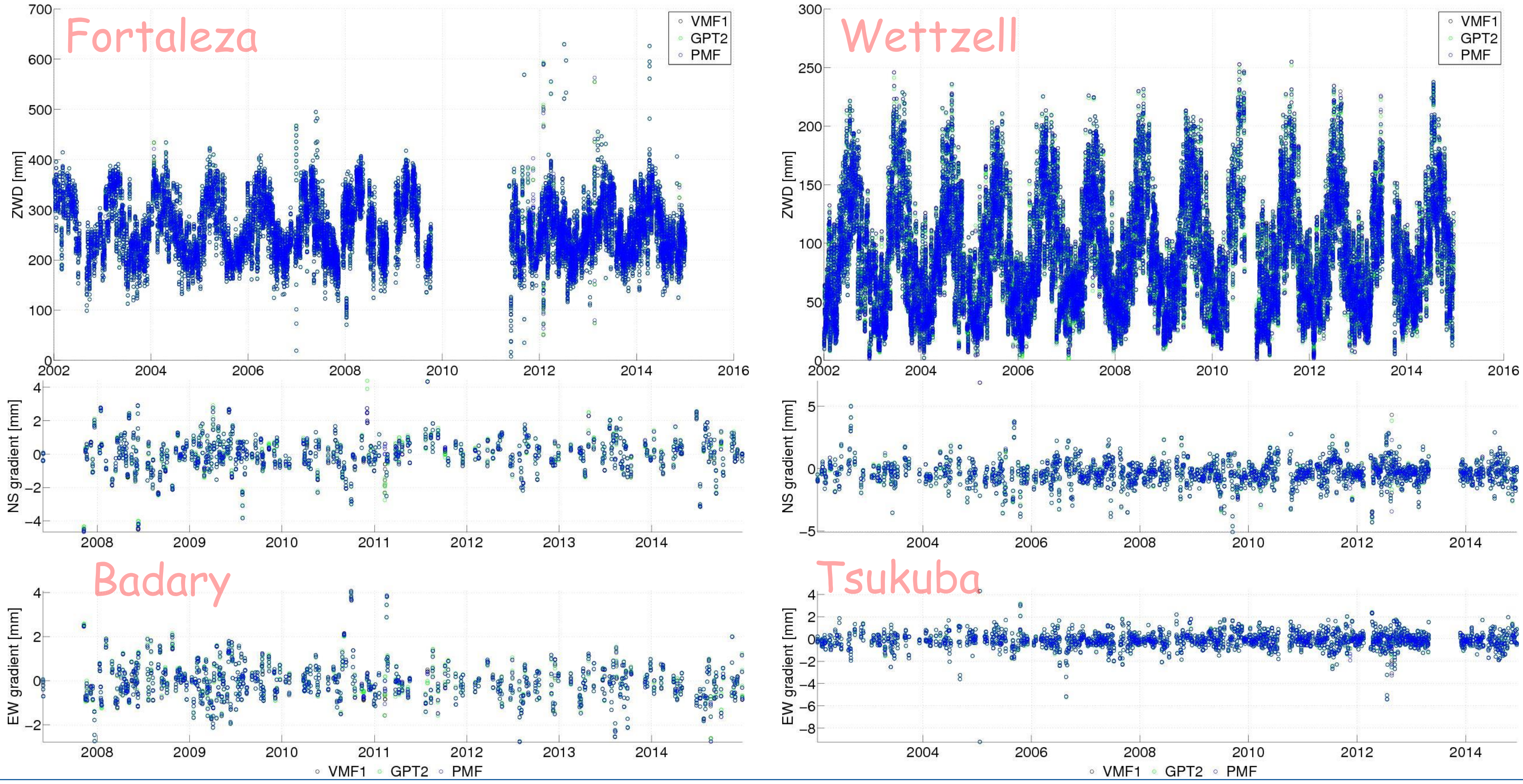
- Non-tidal atmospheric pressure loading (Balidakis et al., 2015)
  - Patched Green's function approach
  - ak135 Earth model until $n = 46340$
  - Dynamic atmospheric correction (MOG2D-G/IB)
  - Pressure anomalies from ECMWF operational analysis model level data (temperature, specific humidity, surface pressure, geopotential)

- Continental hydrological loading (Dill and Dobslaw, 2013)
  - Soil moisture, snow, surface water and water in rivers and lakes from LSDM, forced by ECMWF operational analysis





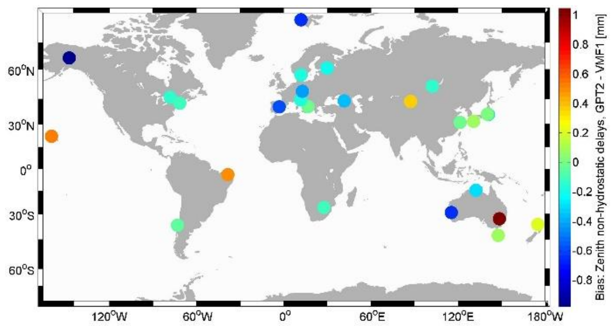
VLBI analysis
(ZWDs and linear horizontal gradients)

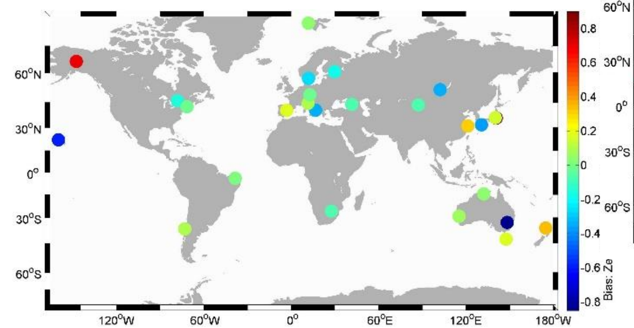


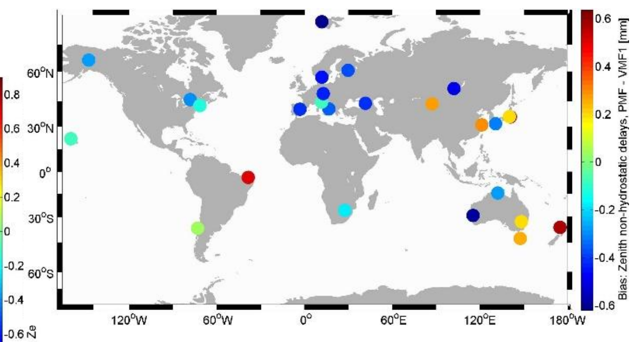
Balidakis et al.: On the impact of different mapping functions on products from VLBI data analysis

VLBI analysis (ZWDs)

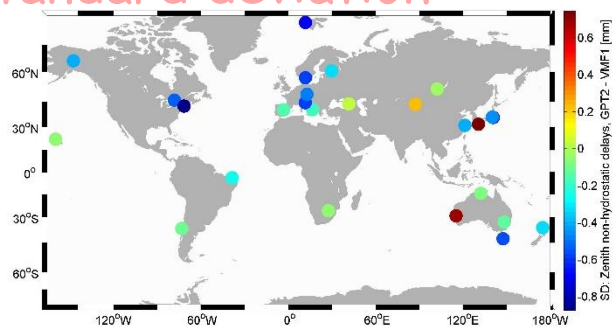
Bias

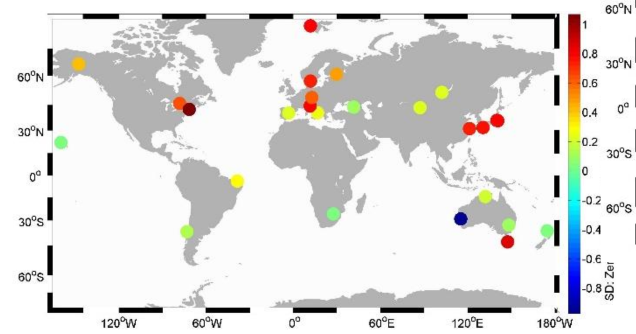


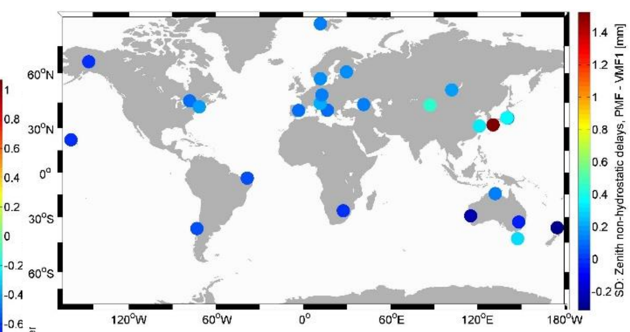




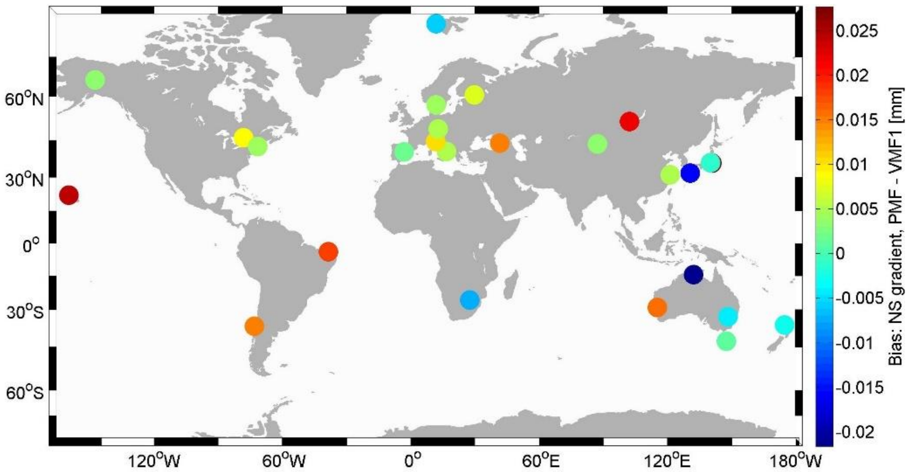
Standard deviation

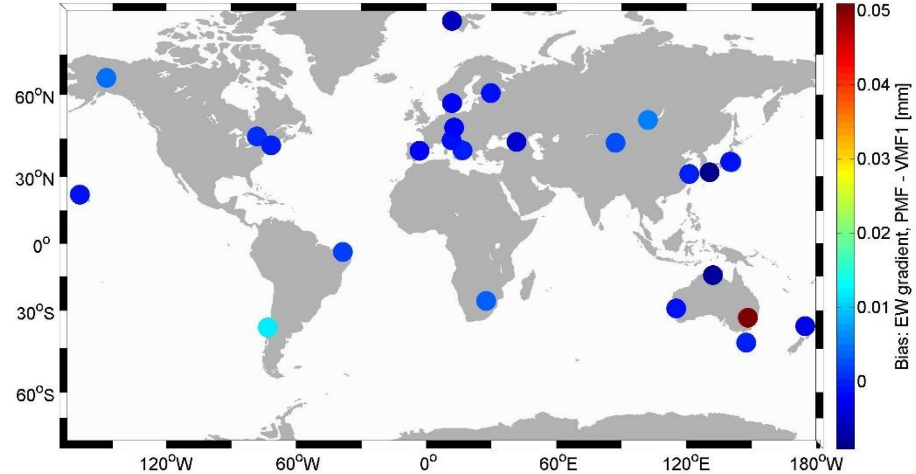


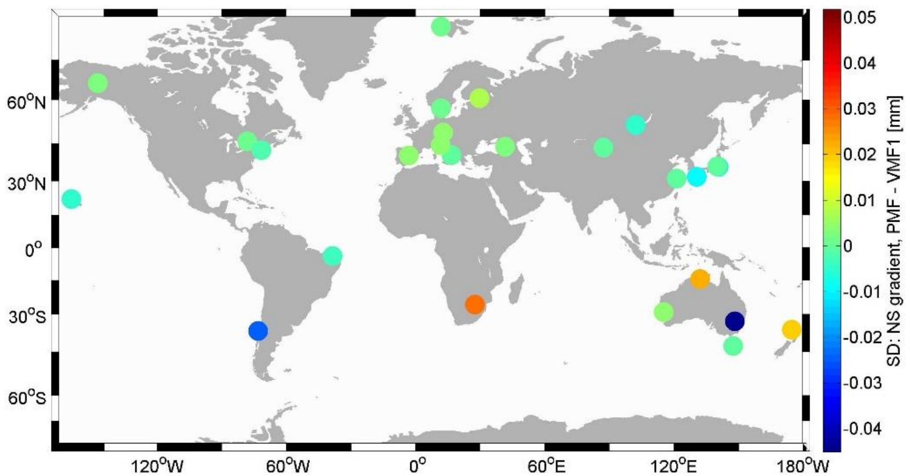


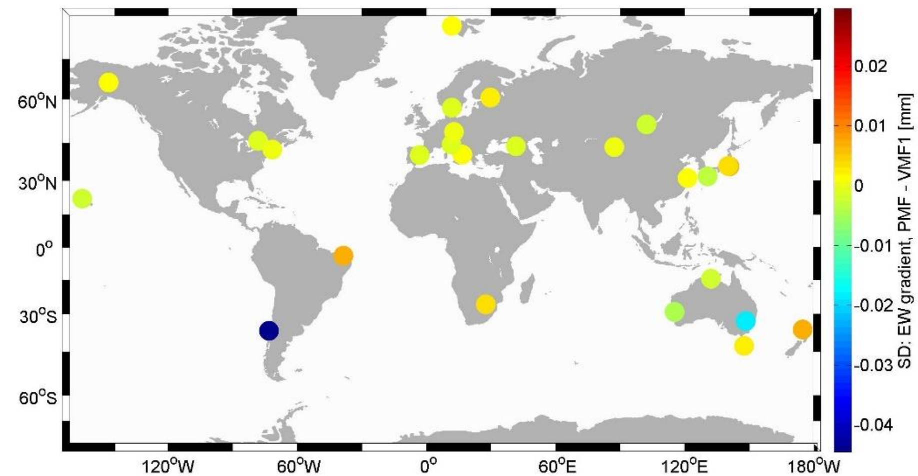


VLBI analysis (linear horizontal gradients)

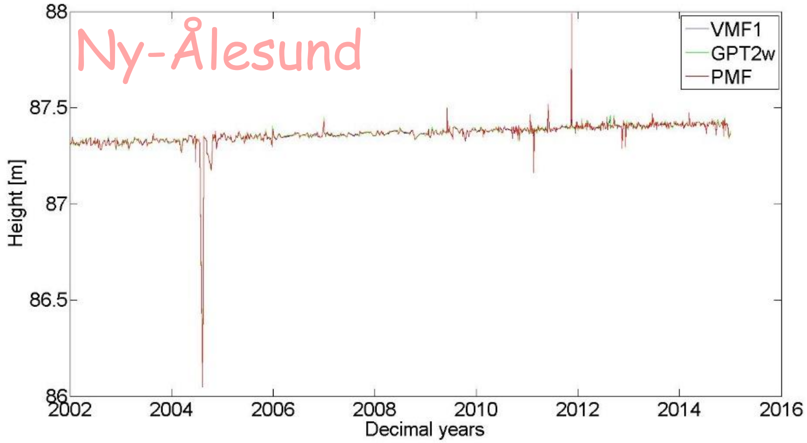


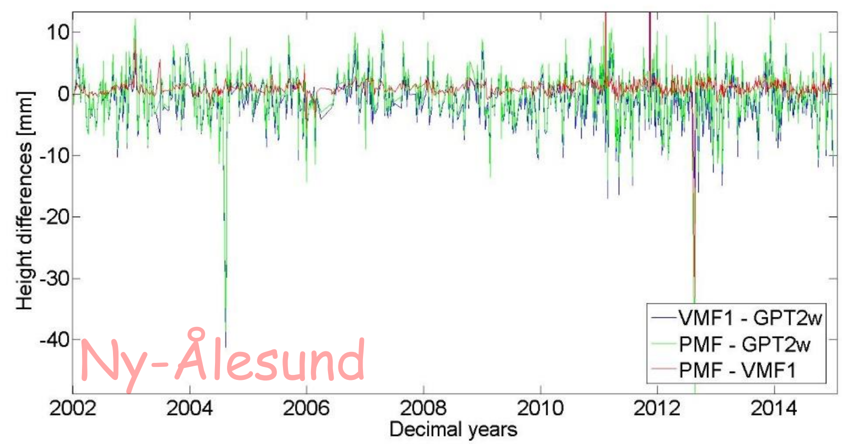


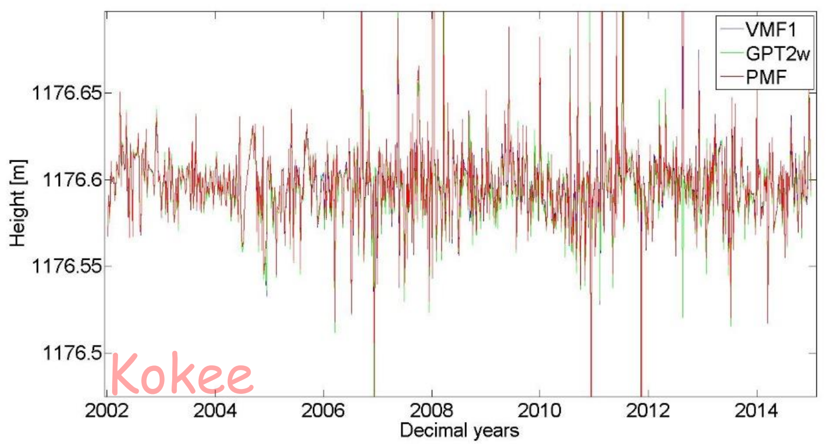


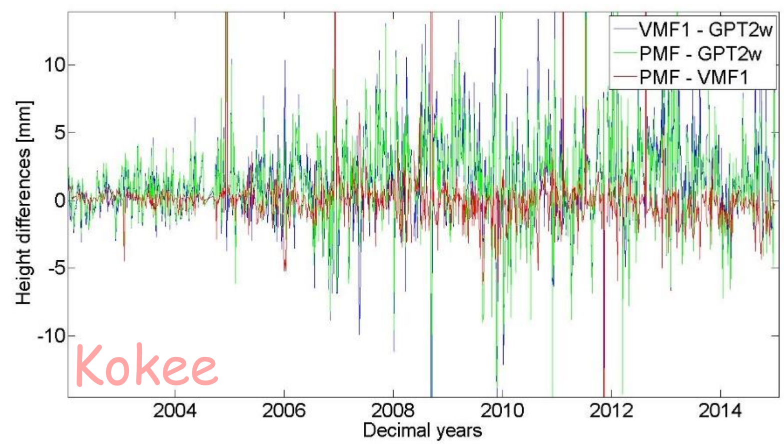


VLBI analysis (station ellipsoidal heights)

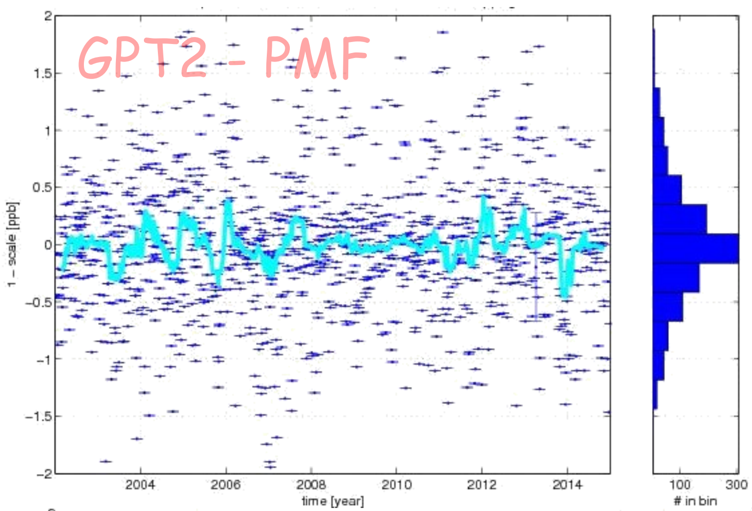


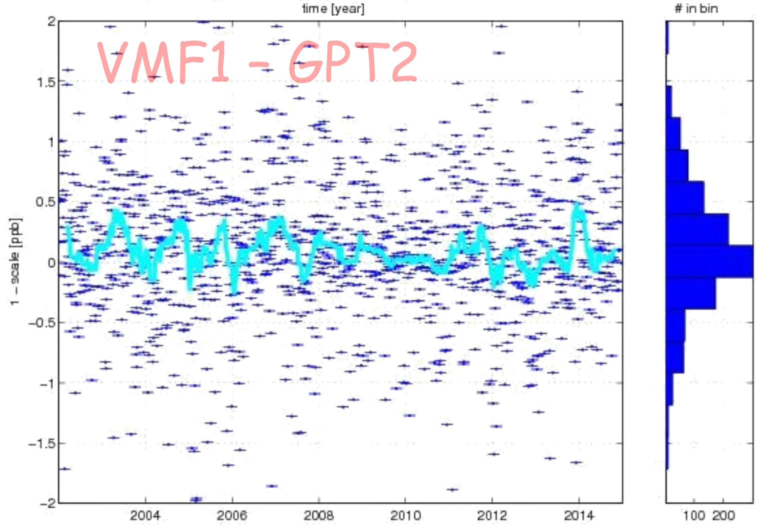


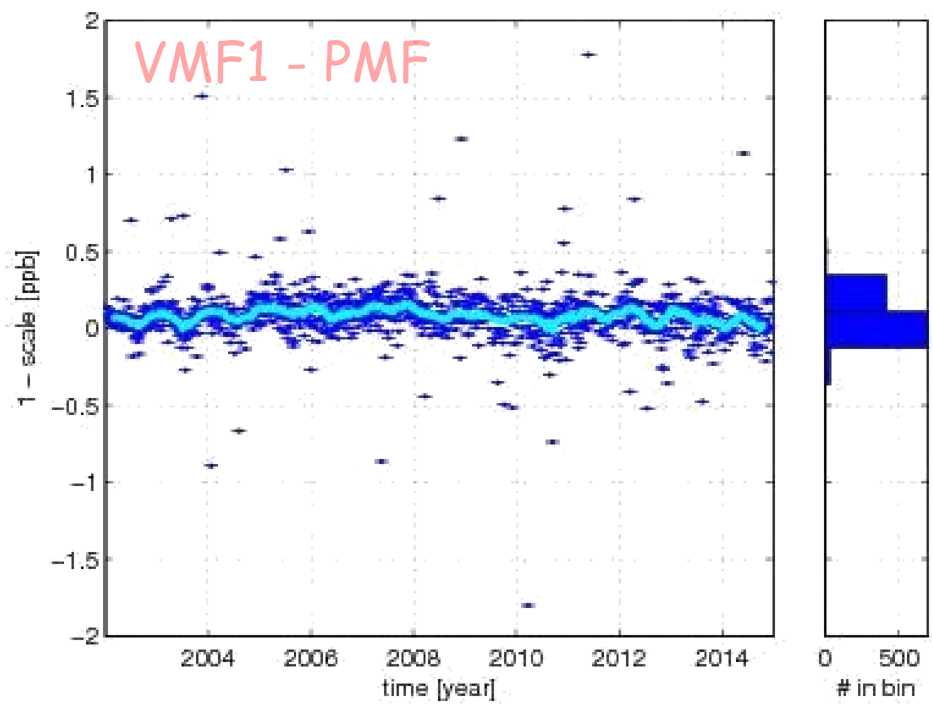




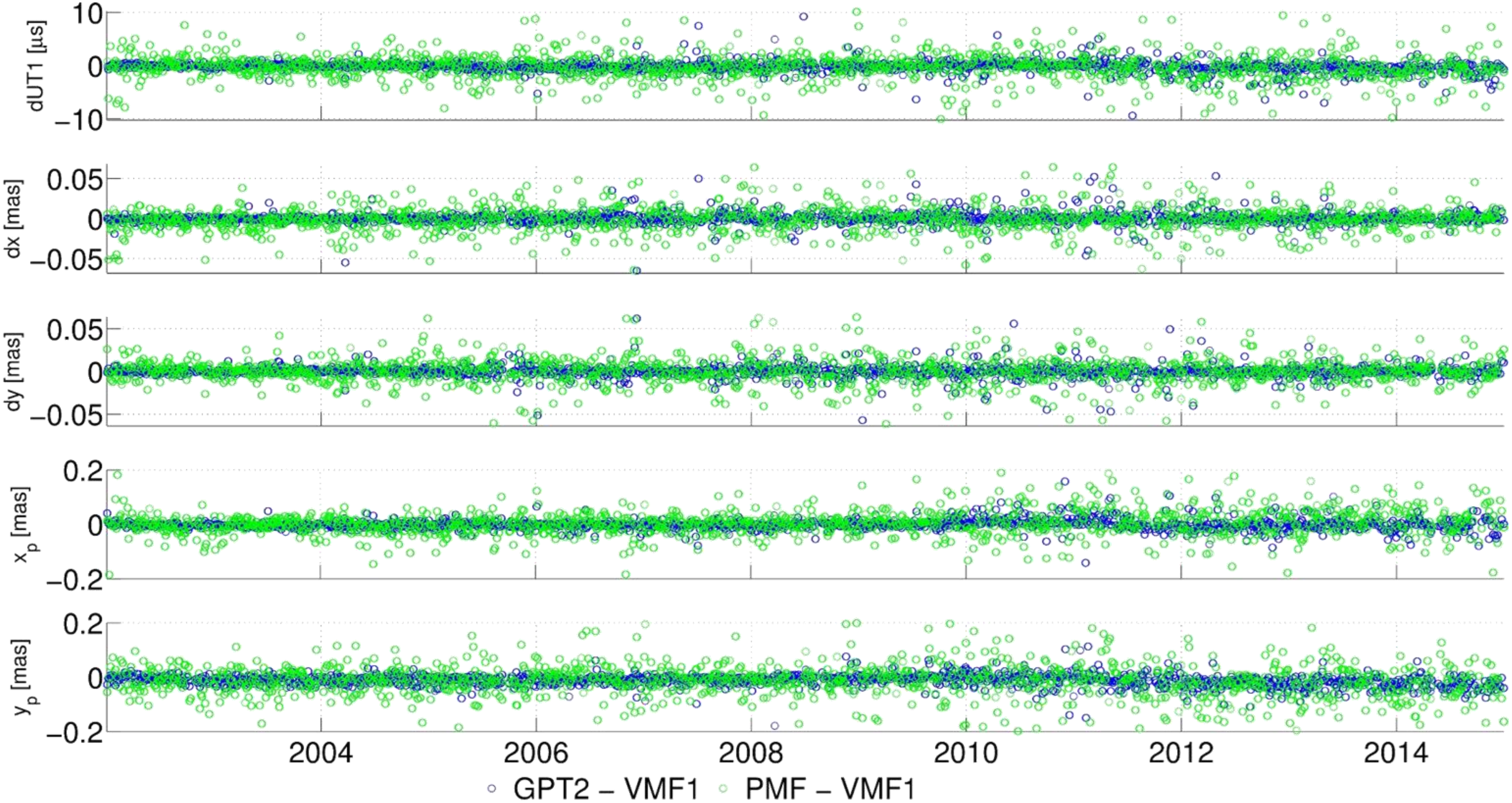
VLBI analysis (network scale)



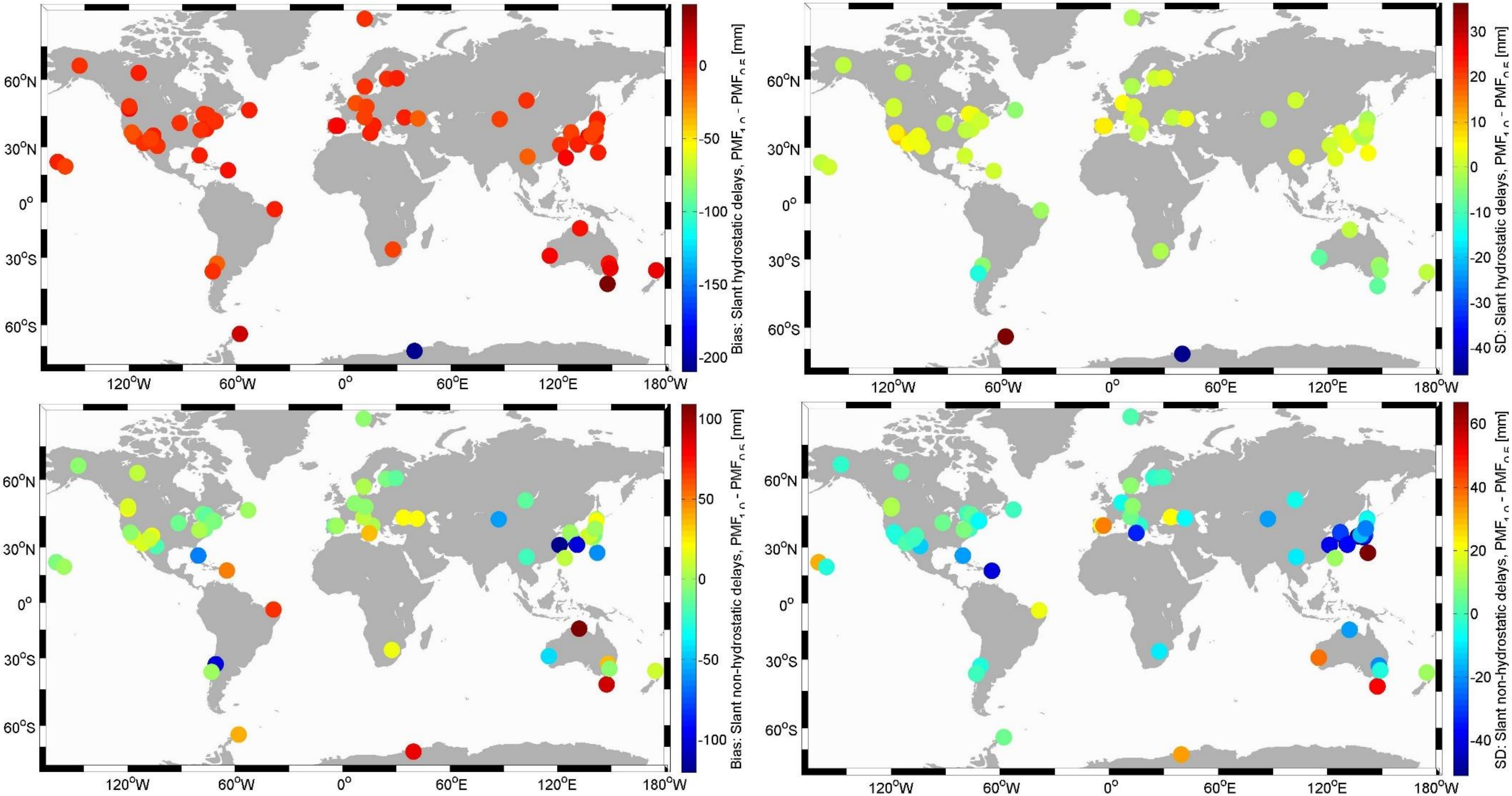




VLBI analysis (δEOPs)



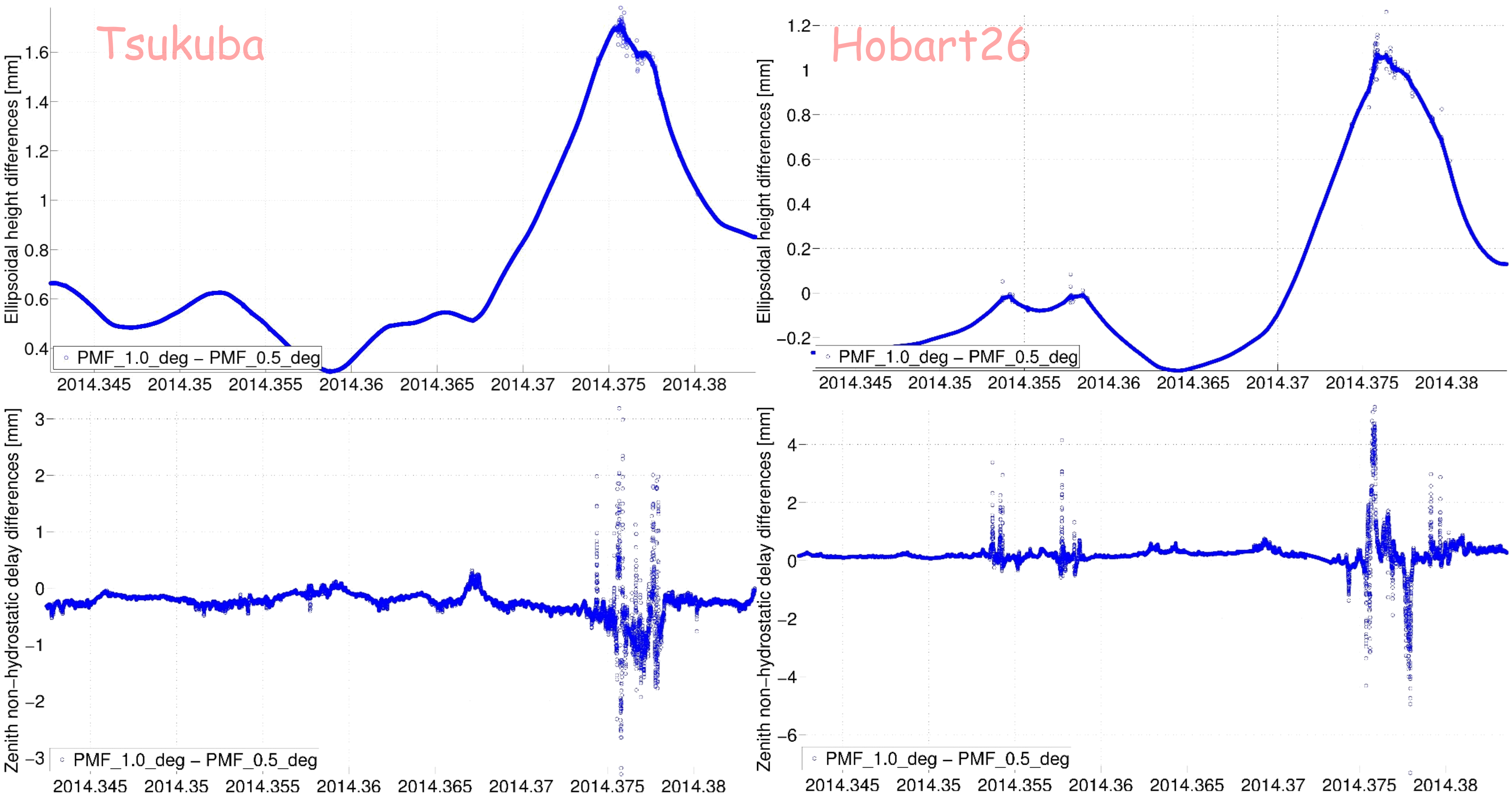
PMF
Spatial resolution of NWM: 1.0^0 vs 0.5^0



VLBI data analysis with Kalman Filtering

- Vienna VLBI Software, VieVS@GFZ, VIE_KAL (Nilsson et al., 2015)
- Group delay data from CONT14 featuring a 17 station network
- We produced 2 solutions:
  - **PMF 1.0^0 spatial resolution**
  - **PMF 0.5^0 spatial resolution**
- Both solutions determined w.r.t. ITRF2008 and USNO Finals EOP series, using the homogenized meteorological dataset and accounting for geophysical loading at the observation level.
- Scan-wise estimates of station positions and EOPs, ZWDs, gradient components, . . .

Some results



GFZ Helmholtz Centre POTSDAM

HELMHOLTZ ASSOCIATION

Recapitulation

- Estimating b_i and c_i in addition to a_i does not affect the estimated coordinates, zenith delays, gradients or EOPs appreciably, given the grid spacing. E.g., the height difference rarely exceeds 1 mm.
- Utilizing a finer resolution of the same NWM and the same ray-tracing algorithm, results in an offset at the mm level in the height time series during severe weather events.

$$mf_i(\varepsilon) = \frac{1 + \frac{a_i}{1 + \frac{b_i}{1 + c_i}}}{\sin(\varepsilon) + \frac{a_i}{\sin(\varepsilon) + \frac{b_i}{\sin(\varepsilon) + c_i}}}, i = h \vee w$$

Outlook

- More tests with even finer resolution.
- Both VMF1 and PMF suffer from systematics, so we should replace the parametrized mapping approach by the rapid direct mapping concept (e.g. Eriksson et al., 2014; Zus et al., 2015).
- Implement ultra-rapid direct mapping in VieVS@GFZ as the default option.
- . . . . more tests

Selected References

- Balidakis K., S. Glaser, D.D. Wijaya, B. Soja, M. Karbon, T. Nilsson, R. Heinkelmann, H. Schuh (2015) ***Geophysical loading effects on station positions and Earth orientation parameters from VLBI data analysis.*** Oral presentation at Geodätische Woche 2015, Stuttgart
- Böhm, J., S. Böhm, T. Nilsson, A. Pany, L. Plank, H. Spicakova, K. Teke and H. Schuh (2012) ***The new Vienna VLBI Software VieVS***, in Proceedings of IAG Scientific Assembly 2009, International Association of Geodesy Symposia Series Vol. 136, edited by S. Kenyon, M. C. Pacino, and U. Marti, pp. 1007-1011, 2012, doi:10.1007/978-3-642-20338-1_126
- Böhm, J., B. Werl and H. Schuh (2006b) ***Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data***, J. Geoph. Res., Vol. 111, B02406, doi:10.1029/2005JB003629
- Böhm, J., G. Möller, M. Schindelegger, G. Pain and R. Weber (2015) ***Development of an improved blind model for slant delays in the troposphere (GPT2w)***, GPS Solutions, doi: 10.1007/s10291-014-0403-7
- Chen, G. and T. A. Herring (1997) ***Effects of atmospheric azimuthal asymmetry on the analysis of space geodetic data***, J. Geophys. Res., 102(B9), pp. 20,489{20,502, doi: 10.1029/97JB01739
- Dill, R. and H. Dobslaw (2013) ***Numerical simulations of global-scale high-resolution hydrological crustal deformations***, J. Geophys. Res. Solid Earth, 118, 5008–5017, doi: 10.1002/jgrb.50353
- Eriksson, D., D. S. MacMillan, and J. M. Gipson (2014) ***Tropospheric delay ray tracing applied in VLBI analysis***, J. Geophys. Res. Solid Earth, 119, 9156–9170, doi: 10.1002/2014JB011552
- Herring, T. A. (1992) ***Modeling atmospheric delays in the analysis of space geodetic data,*** in Proceedings of refraction of transatmospheric signals in geodesy, Netherlands Geodetic Commission Series, 36, The Hague, Netherlands, pp. 157-164
- Lagler, K., M. Schindelegger, J. Böhm, H. Krásná and T. Nilsson (2013) ***GPT2: empirical slant delay model for radio space geodetic techniques***. Geophys. Res. Lett., 40, 1069–1073, doi:10.1002/grl.50288
- Nilsson T., B. Soja, M. Karbon, R. Heinkelmann and H. Schuh (2015) ***Application of Kalman filtering in VLBI data analysis***. Earth, Planets and Space 67(136):1 – 9, doi:10.1186/s40623-015-0307-y
- Schuh, H. and D. Behrend (2012) ***VLBI: A fascinating technique for geodesy and astrometry***, Journal of Geodynamics, Vol. 61, pp. 68–80, October 2012. doi:10.1016/j.jog.2012.07.007
- Zus, F., M. Bender, Z. Deng, G. Dick, S. Heise, M. Shang-Guan and J. Wickert (2012) ***A methodology to compute GPS slant total delays in a numerical weather model***, Radio Sci., 47, RS2018, doi:10.1029/2011RS004853
- Zus, F., G. Dick, J. Douša, S. Heise and J. Wickert (2014) ***The rapid and precise computation of GPS slant total delays and mapping factors utilizing a numerical weather model***, Radio Sci., 49, 207–216, doi:10.1002/2013RS005280
- Zus, F., G. Dick, J. Dousa and J. Wickert (2015) ***Systematic errors of mapping functions which are based on the VMF1 concept***, GPS Solutions, 19, 2, 277-286, doi:10.1007/s10291-014-0386-4

Thank you for your attention!

kyriakos.balidakis tu-berlin.de

Acknowledgements

IVS for coordinating the VLBI experiments used in this work.
ECMWF for making publicly available the ERA interim reanalysis data sets.
KB is supported by **IAG International Travel Award** and the DFG project **ECORAS** (HE 5937/2-1)

Deutsche Forschungsgemeinschaft