Wrocław University of Environmental and Life Sciences

Optimum stochastic modeling for GNSS troposphere delay estimation in real-time

Tomasz Hadaś[1], Felix Norman Teferle[2], Kamil Kaźmierski[1], Paweł Hordyniec[1], Jarosław Bosy[1]

1) Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences
2) Geophysics Laboratory, University of Luxembourg

IAG Commission 4 Positioning and Applications Symposium, September 4-7, 2016. Wroclaw, Poland

Presentation plan

1. Motivation
2. Methodology
3. Results:
   - RWPN global grids
   - Case studies
   - Overall results
4. Conclusion

Motivation

1. IGS-RTS -> Real-time GNSS meteorology
2. Investigations on:
   - elevation dependent weighting (Ning 2012),
   - multi-GNSS solution (Li et al. 2015),
   - relation between clock and ZTD accuracy (Shi et al. 2015),
   - observation model, AR, I2+ effects (Ahmed et al. 2016).
3. Stochastic modeling - **random walk** (RW) with process noise (PN):
   - RWPN=**5mm/√h** for ZWD in PPP (Kouba and Horoux 2001),
   - RWPN=**20mm/√h** for ZWD constraint (Pacione et al. 2009),
   - constraining based on **initial empirical test** (Dousa et al. 2013),
   - RWPN of **about 5-10 mm/√h** (Lu et al. 2015).

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2. Dousa J, Vaclavovic P, Gyori G, Kostelecky J (2013) Development of real-time GNSS ZTD products. Adv Space Res 53:1347-1358
3. Kouba J, Heroux P (2001) Precise Point Positioning Using IGS Orbit and Clock Products. GPS Sol 5(2):12-28
4. Li X, Dick G, Lu C, Ge M, Nilsson T, Ning T, Wickert J, Schuh H (2015) Multi-GNSS Meteorology: Real-Time Retrieving of Atmospheric Water Vapor From BeiDou, Galileo, GLONASS, and GPS Observations. IEEE Transactions On Geoscience And Remote Sensing.
5. Lu C, Li X, Nilson T, Ning T, Heinkelmann R, Ge M, Glaser S, Schuh H (2015): Real-time retrieval of precipitable water vapor from GPS and BaiDou observations. J Geod 89(9): 843-856
6. Ning T (2012) GPS meteorology: with focus on climate applications. PhD thesis, Chalmers University of Technology, ISBN 978-91-7385-675-1
7. Pacione R, Vespe F (2008) Comparative studies for the assessment of the quality of near-real-time GPS-derived atmospheric parameters. J Atmos Ocean Tech 25:701–714
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Random walk theory

ZWD random walk - Markov (memory-less) process:

$$E(|S_n(\varepsilon)|) = \varepsilon\sqrt{n}$$

S - translation distance, *n* – number of steps, **ε** – step length

Adopting for troposhere :

$$E(|\Delta T_{t+\delta t} - \Delta T_t|) = \varepsilon\sqrt{\delta t}$$

ΔT – tropo delay, *δt* – time interval, *ε* = RWPN

To estimate RWPN if a time series of *ΔT* is known:

$$E(\varepsilon) = |\Delta T_{t+\delta t} - \Delta T_t|/\sqrt{\delta t}$$

Data and test campaigns

GNSS data

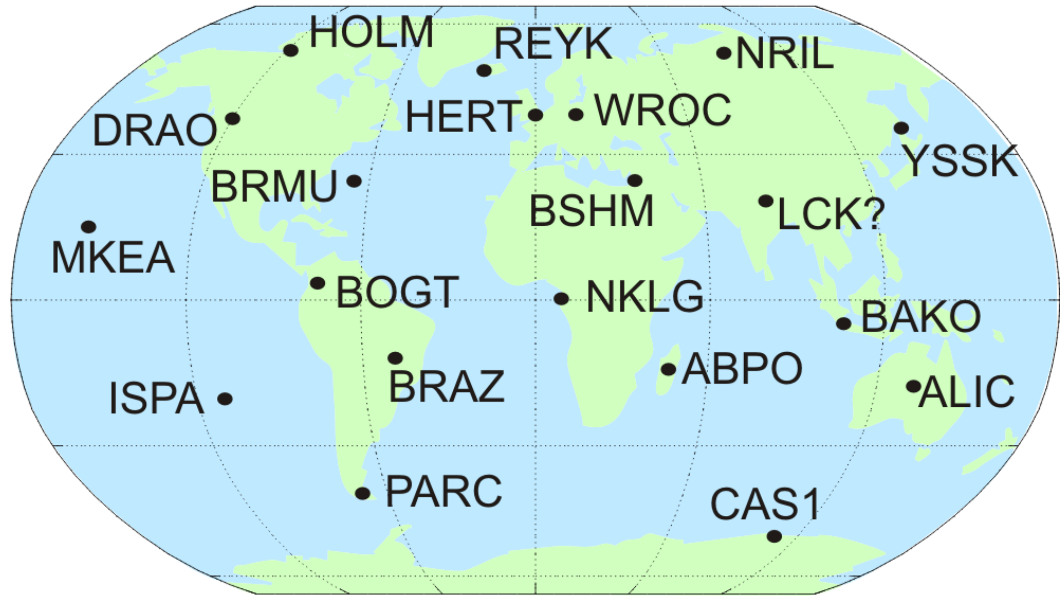
- 20 IGS stations (RINEX)
- RTS IGS03 stream
- reference: IGS Final ZTD (5 min, σ=1-2mm)

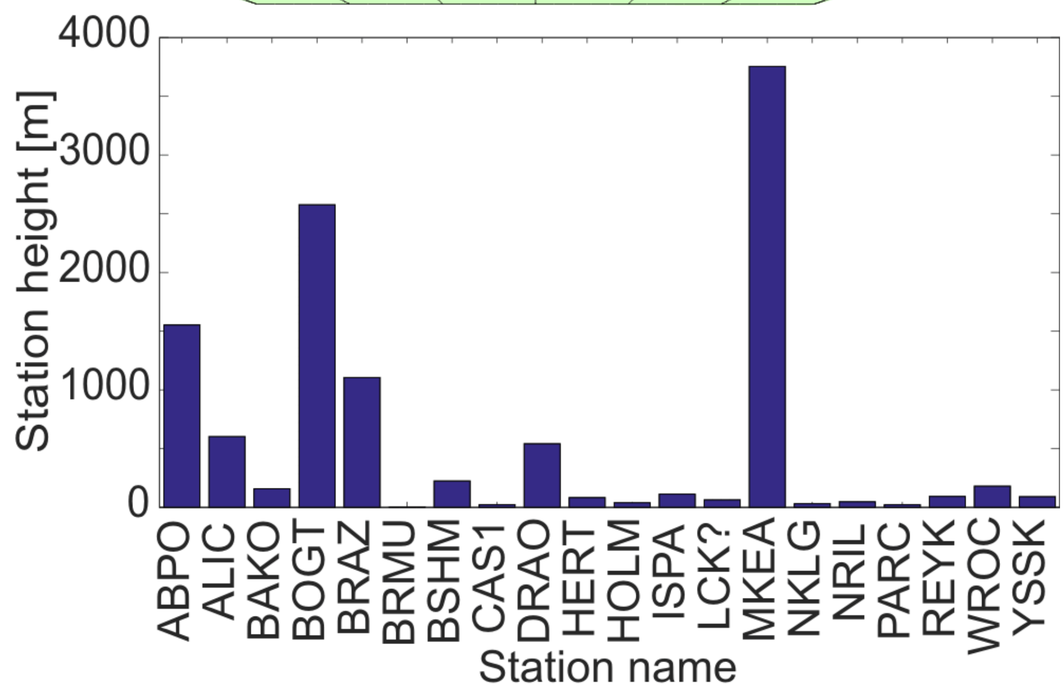
Test campaigns:

- DoY 155-161,2013
- DoY 330-336, 2015

NWP models:

- ECMWF (from VMF1) (2.0 x 2.5 deg grid, 6 hours)
- GFS4 forecast (ray-tracing) (0.5 x 0.5 deg grid, 3 hours)





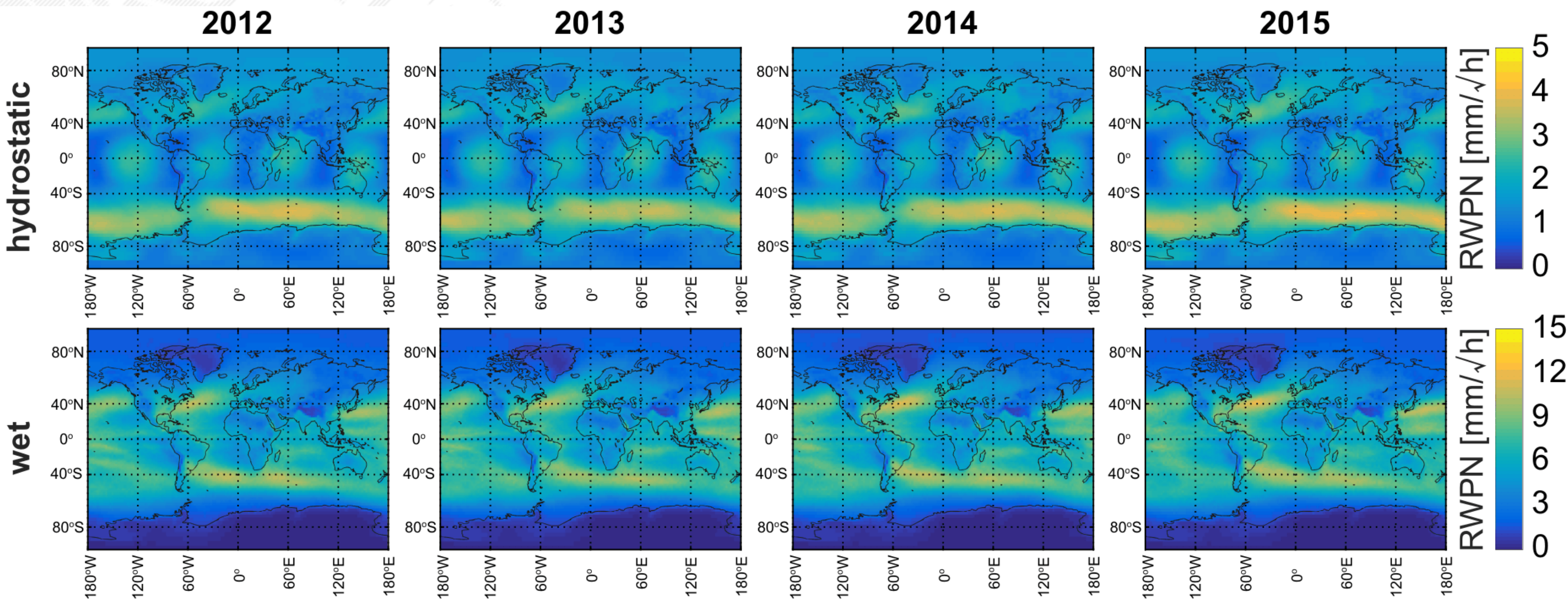
Processing variants

Simulated real-time mode in GNSS-WARP software:

1. **Fixed** – initial empirical testing
   - RWPN: from 1 mm/√h to 10 mm/√h (with 1 mm/√h step)
2. NWP based **yearly** mean RWPN
   - use ZWD time-series from the past year
3. NWP based **seasonal** mean RWPN
   - use 30-day window of corresponding season, last year
4. NWP forecast based **dynamic** RWPN
   - use NWM forecast to estimate RWPN in real-time

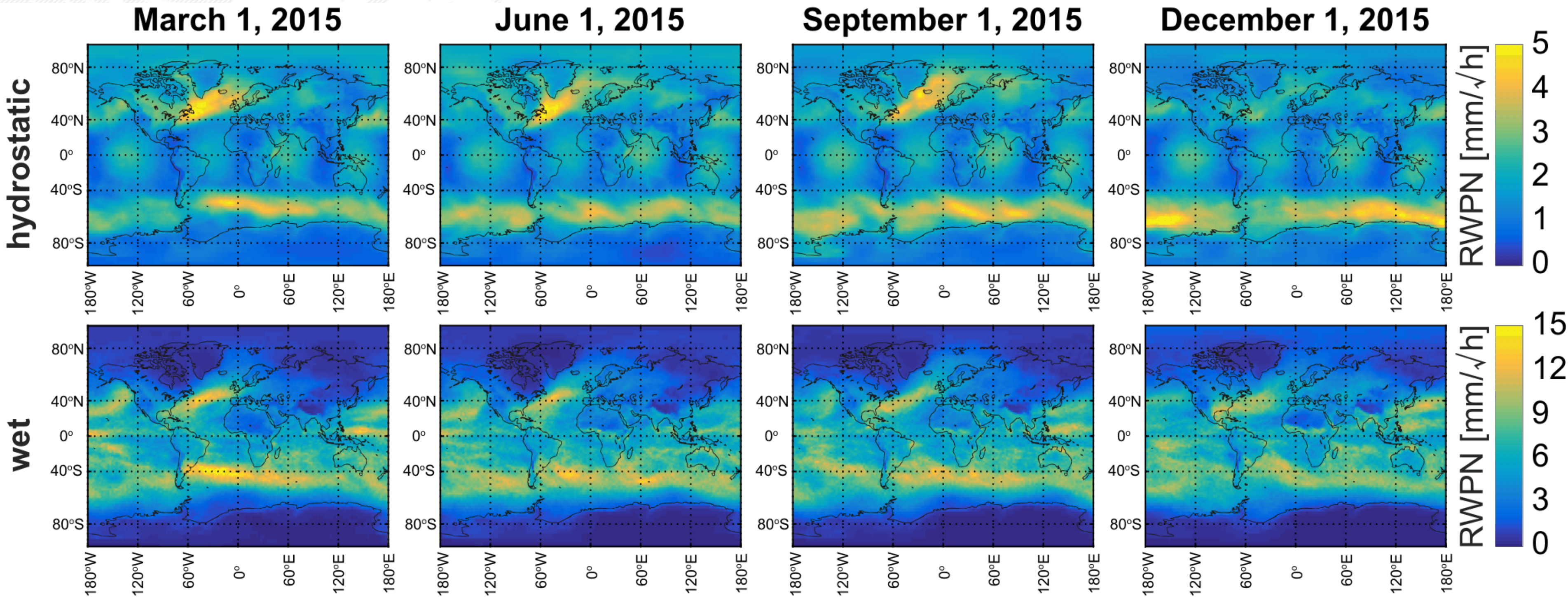
Objective: Provide optimum RWPN setting without initial empirical tests.

Yearly mean RWPN grids



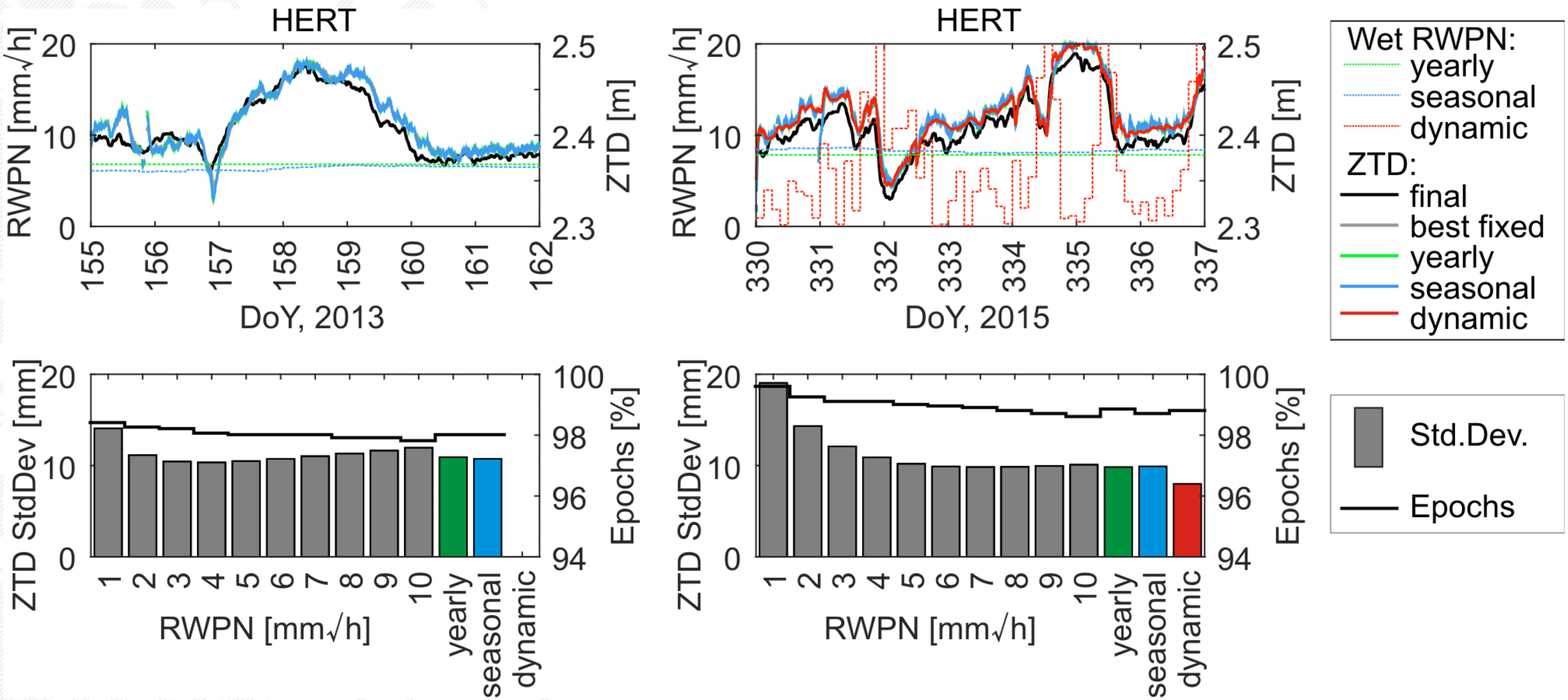
- Hydrostatic and wet RWPN are geographically dependent
- RWPN repeats year by year
- Wet RWPN: 0.1 – 12.0 mm/√h, mean – 5.0mm/ √h, Europe ~ 5mm√h

Seasonal mean RWPN grids



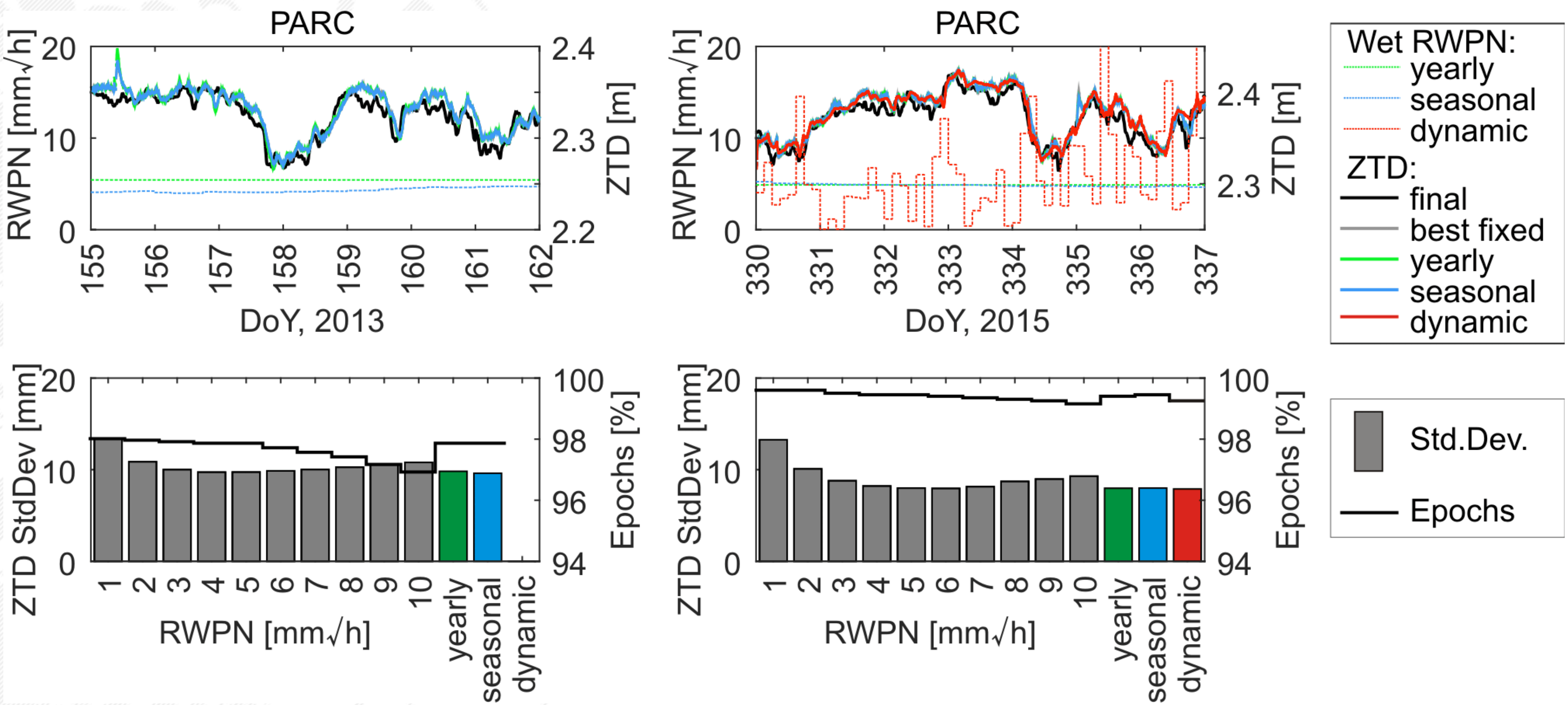
- Hydrostatic and wet RWPN vary over seasons
- Wet RWPN varies slightly over lands, significantly over oceans
- Wet RWPN: 0.1 – 16.5 mm/√h, mean – 4.8mm/ √h, Europe ~ 5mm√h

Case study – station HERT



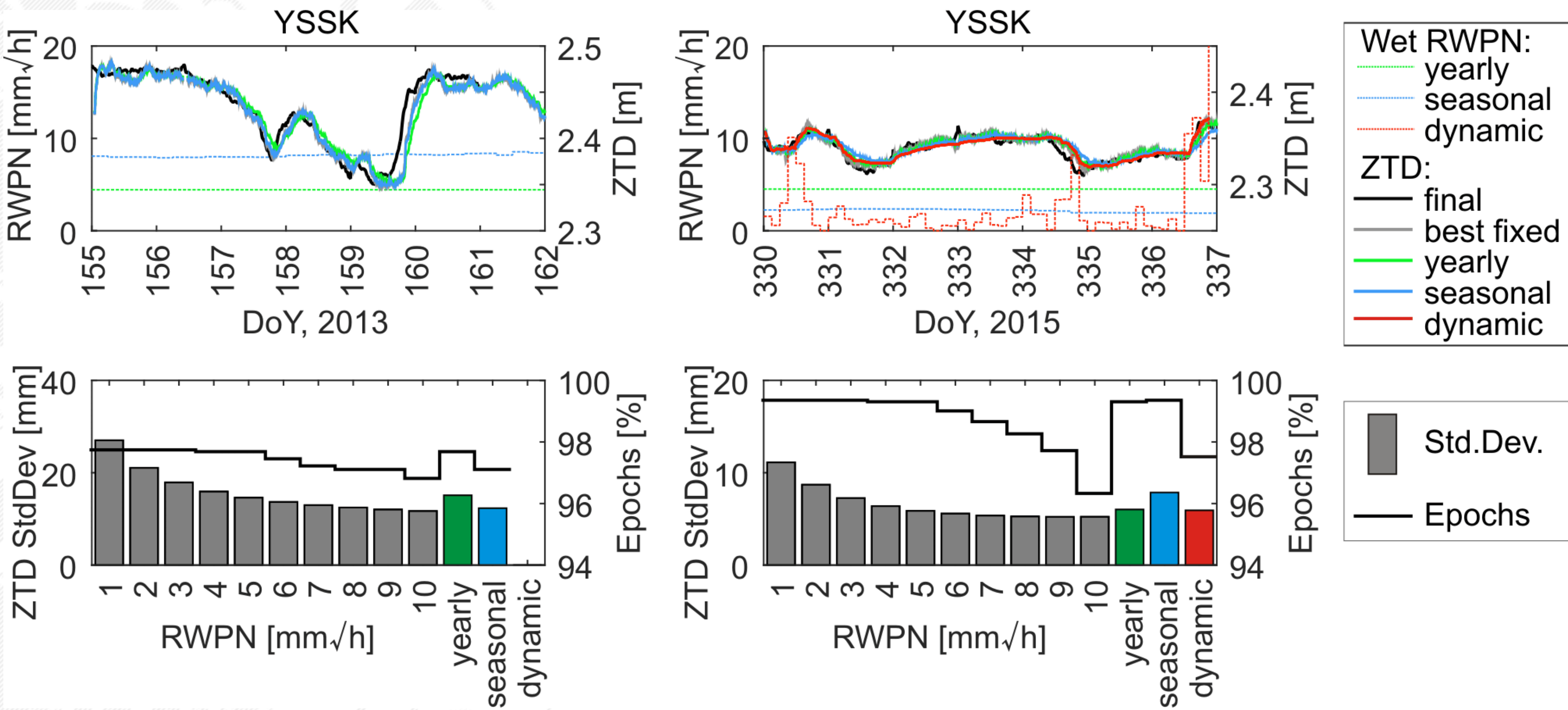
- good agreement of RT solutions with the the Final solution
- small differences among RT solutions
- the larger the RWPN, the smaller % of epochs, best fixed =3 in 2013, =7 in 2015
- yearly and seasonal approach are almost as good as the best fixed (StdDev & %)
- dynamic approach reduced StdDev (18%!), % of epochs is high

Case study – station PARC



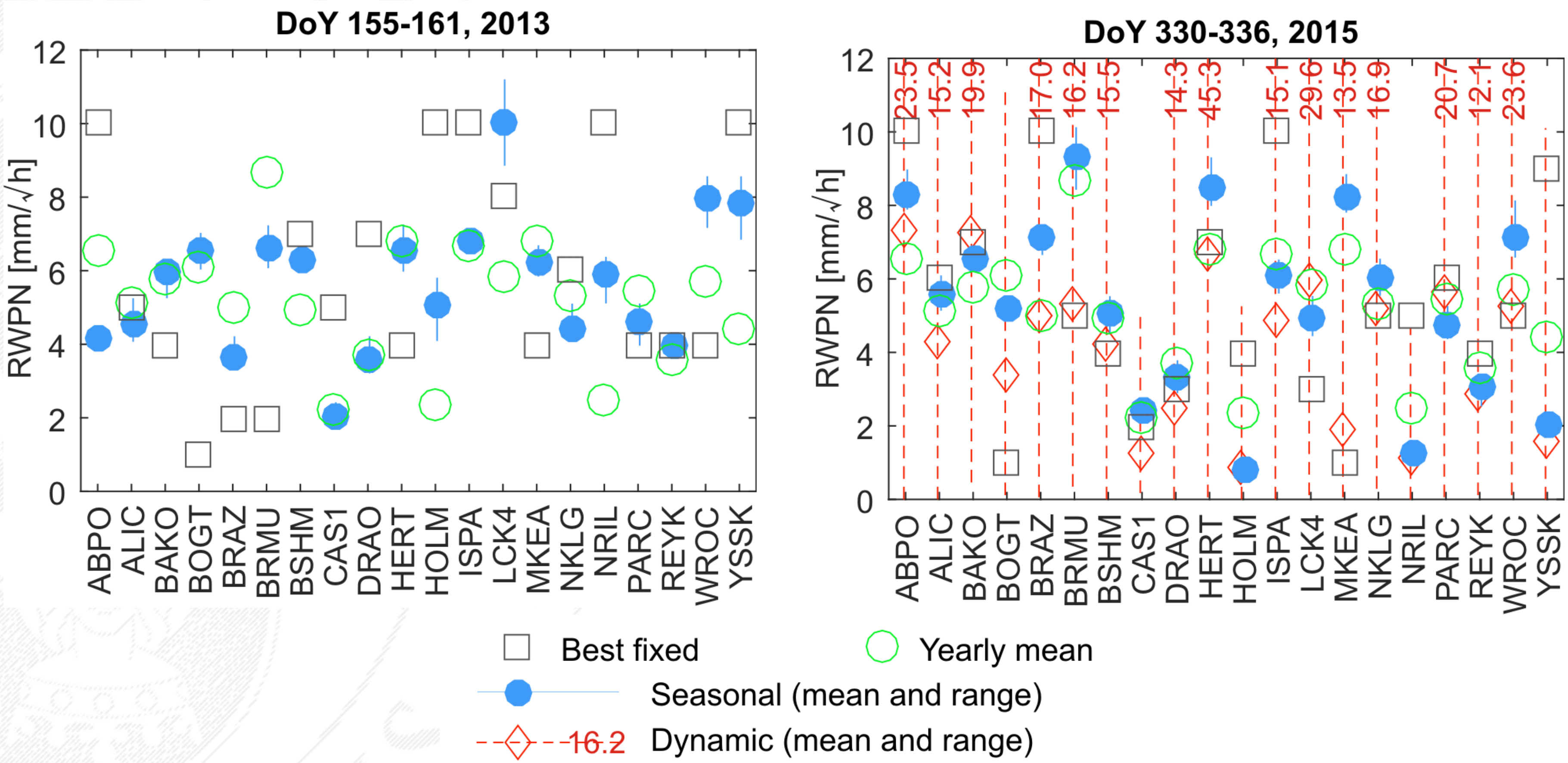
- best fixed RWPN: 5mm/√h in 2013 and 2015
- yearly and seasonal – equally good
- dynamic variant – more accurate, less available

Case study – station YSSK



- best fixed RWPN: 10mm/√h in 2013 and 2015, but significant loss of availability!
- optimum RWPN: 5mm/√h
- yearly and seasonal – unambiguous among years
- dynamic variant – more accurate, less available

Comparison of wet RWPN among variants



No single globally optimum value of RWPN!

Optimum RWPN is time and location dependent

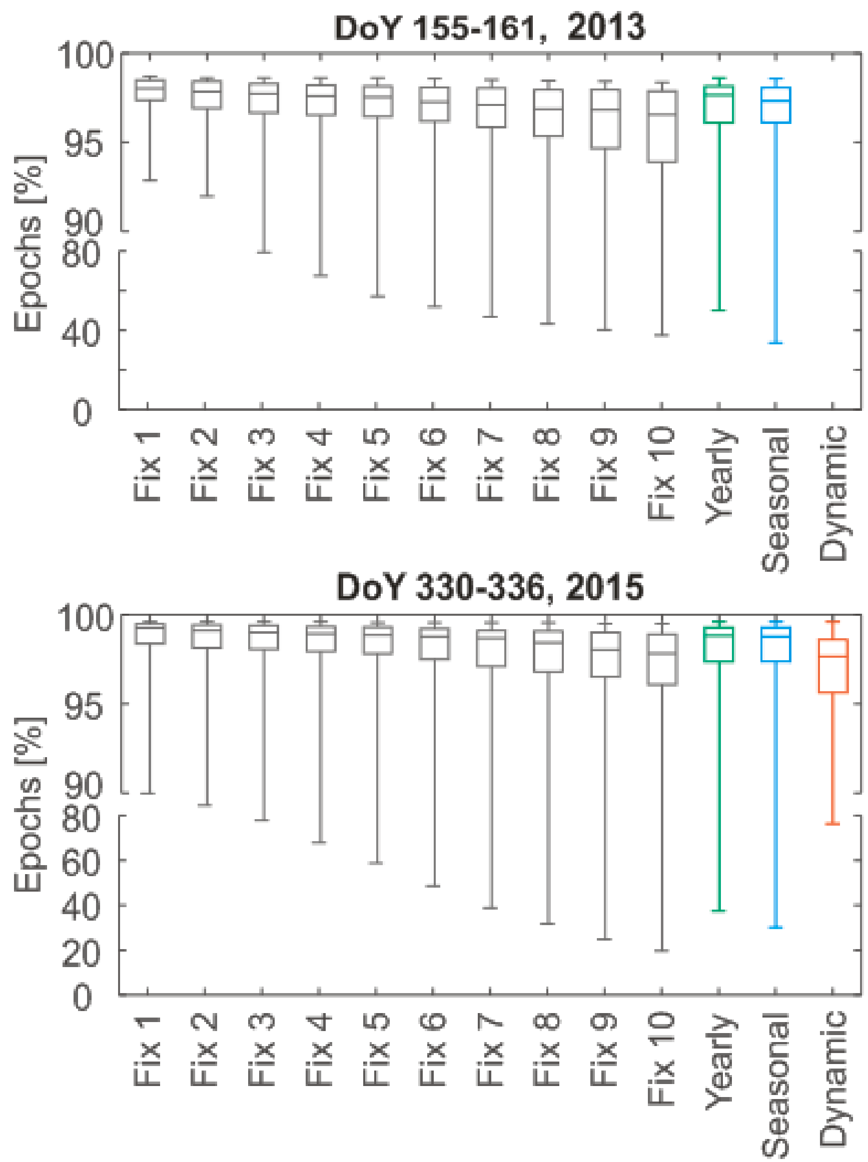
Solution availability

2013:
- >95% epochs for 17/20 stations
- worse stations – BOGT, LCK4, MKEA

2015:
- >95% epochs for 19/20 stations
- worse stations – MKEA

Yearly apporach similar to Fix 6
Seasonal appraoch < Yearly apporach

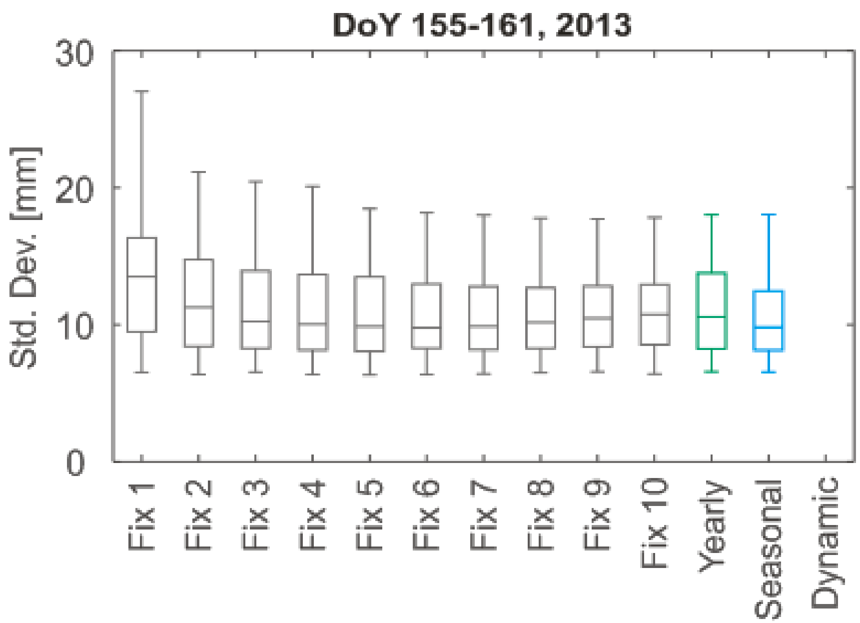
Dynamic appraoch:
- 76% epochs for MKEA!
- slighlty less epochs for other stations

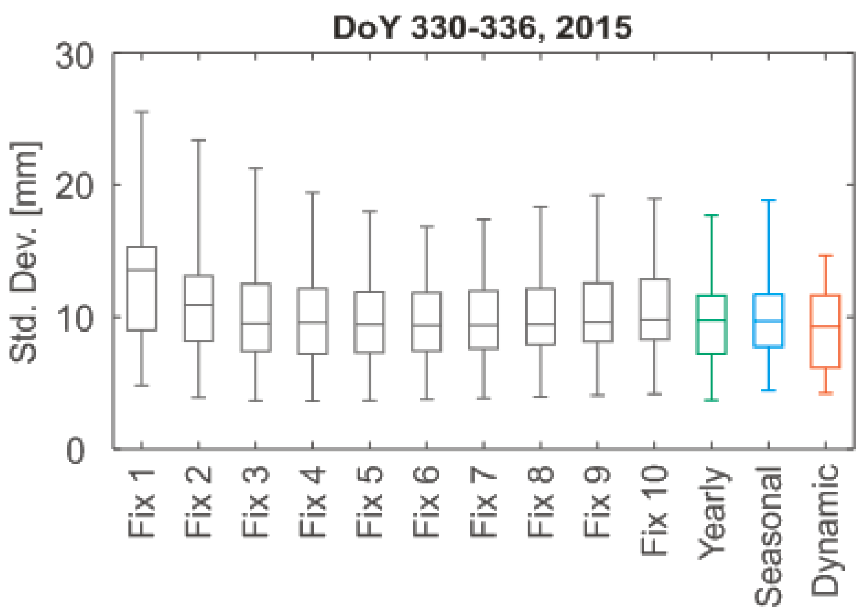


Solution accuracy

2013:
- For Fix 5-10, yearly and seasonal:
    - error: average=10mm, max<20

2015:
- Fix 6 is the best empirical value:
    - mean:9.7mm
    - range:3.8mm – 16.8mm
- Yearly slightly better than Fix 6
- Seasonal slightly worse than Yearly
- Dynamic better than Fix 6:
    - mean:9.2
    - range:4.2mm – 14.7mm





Overall evaluation

2013

	RWPN		Epochs			StdDev		
	[mm/√h]		[%]			[mm]		
	Min	Max	Avg	Min	Max	Avg	Min	Max
Indiv. Fixed	1.0	10.0	93.8	43.3	98.5	10.3	6.3	17.4
Yearly	2.2	8.6	93.5	**50.0**	98.6	11.1	6.6	18.0
Seasonal	1.8	11.2	92.8	**33.7**	98.6	10.9	6.6	18.0

2015

	RWPN		Epochs			StdDev		
	[mm/√h]		[%]			[mm]		
	Min	Max	Avg	Min	Max	Avg	Min	Max
Indiv. Fixed	1.0	10.0	97.7	89.9	99.6	8.9	3.6	14.2
Yearly	2.2	9.3	95.4	**37.5**	99.6	9.7	3.7	**17.7**
Seasonal	0.8	10.1	95.0	**30.2**	99.6	9.8	4.4	18.8
Dynamic	0.0	45.3	96.1	**76.3**	99.6	**9.2**	**4.2**	**14.7**

Conclusions and recommendations

1. Optimum RWPN is **location and time dependent** parameter.
2. There is no single globally optimum value of RWPN.
3. The best results are obtained where RWPN is determined empirically, but:
   - it is very time consuming (# station, time series length),
   - it may still varies depending on the test-period.
4. Instead of using empirical apporach, one can:
   - use global yearly RWPN grid (static, look-up table)
   - perform NWP ray-tracing using short-term forecast data to apply dynamic RWPN

Thank You!

Tomasz Hadaś
Kamil Kaźmierski
Paweł Hordyniec
Jarosław Bosy

Université du Luxembourg
Norman Teferle

Presenting & corresponding author:
Tomasz Hadaś
Institute of Geodesy and Geoinformatics
Wroclaw University of Environmental and Life Sciences