

Global Navigation Satellite System (GNSS) research and services at the Geodetic Observatory Pecný

Jan Douša,

Pavel Václavovic, Michal Eliaš, Petr Bezděka, Lewen Zhao

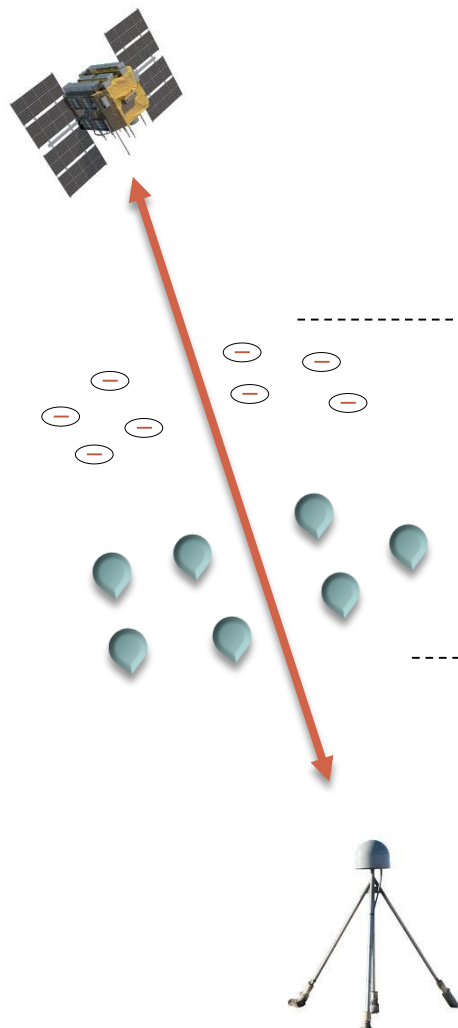
**Geodetic Observatory Pecný (GOP)
Research Institute of Geodesy, Topography and Cartography (RIGTC)
Czech Republic**

Prague, November 14, 2018



GNSS data analysis – models/errors

GNSS: Global Navigation Satellite Systems – GPS, GLONASS, Galileo, BeiDou



Satellite orbits (positions)

Satellite clock corrections

Satellite antenna models

Phase wind-up correction

Satellite hardware delays

Satellite-specific effects

Ionosphere delay

Atmospheric effects

Troposphere delay

Multipath effect

Receiver clock corrections

Receiver antenna models

Receiver hardware delays

(Terrestrial reference frame)

Site-specific effects

G-Nut/Anubis for GNSS data QC

Open-source software for multi-GNSS data quality control

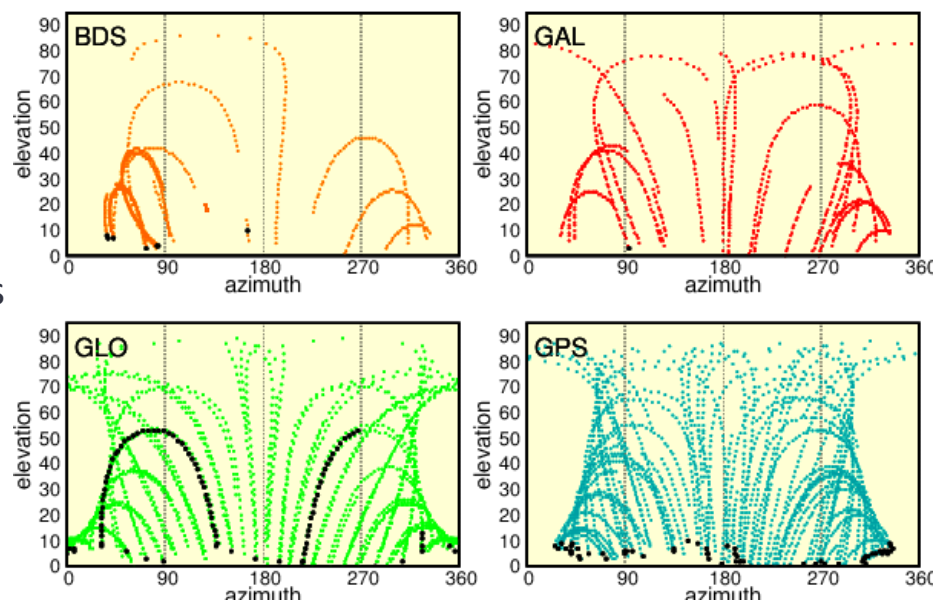
<http://software.pecny.cz/anubis>

→ GOP contribution to the **European Plate Observing System (EPOS)**
GNSS data and products **Thematic Core Service (TCS)**

Key functionalities:

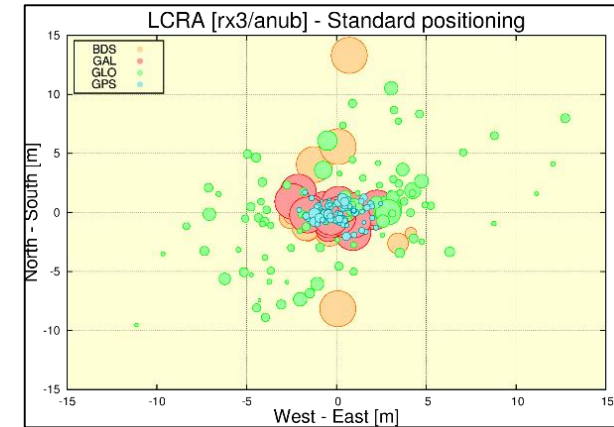
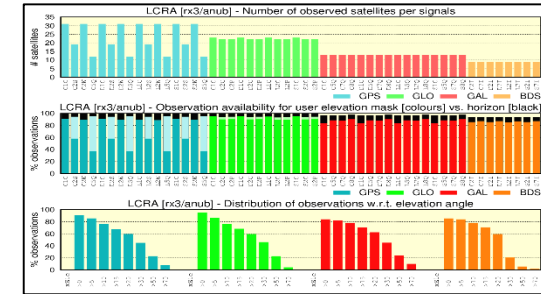
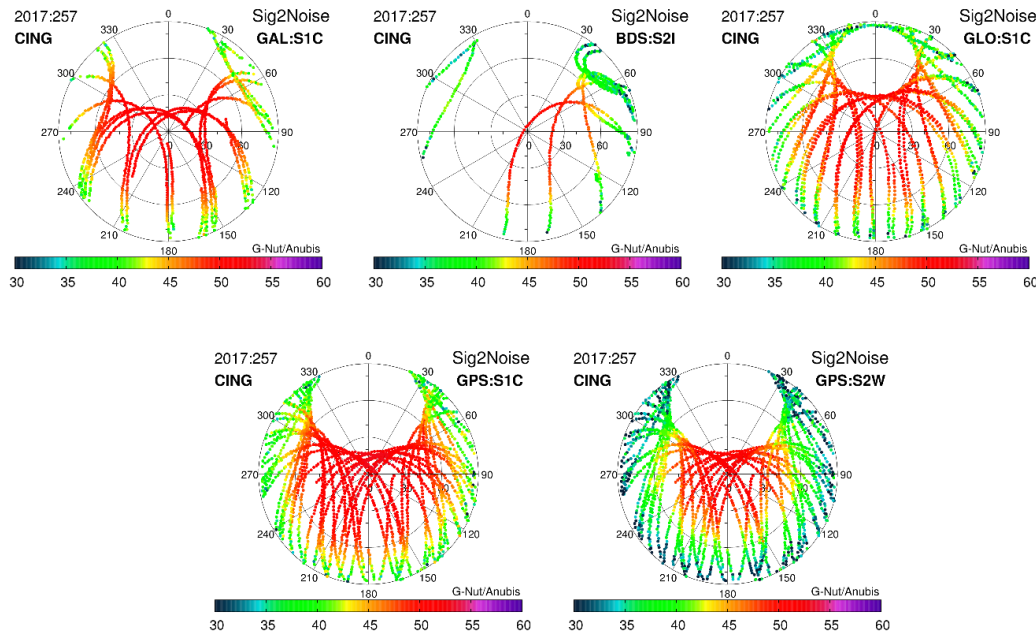
- Summary statistics over key parameters
- Data availability – data gaps, small pieces
- Observation-specific statistics
- Phase processing (cycle slips, clock jumps)
- Azimuth/elevation information for sky plots
- Pseudo-range multipath, signal noise
- Standard positioning, repeatability, GDOP
- Consolidation of navigation messages
- Format and metadata control

GOP7 - Satellite sky tracks (azimuth-elevation plot)



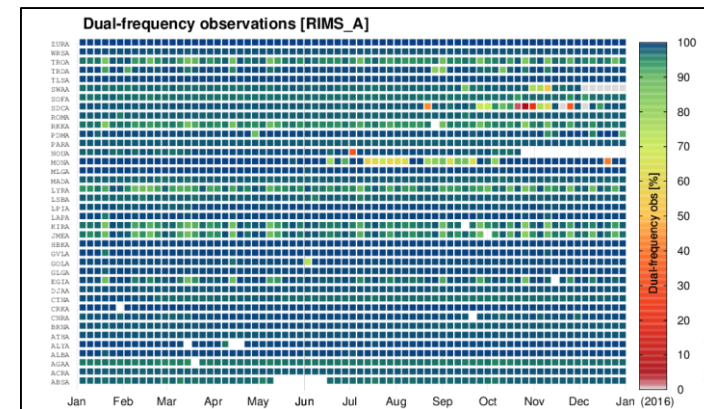
New GNSS Reference Network in Italy

Full multi-constellation data processing, consultation for location/environment new 32 fiducial stations



EGNOS Service Performance Monitoring Support (SPMS)

Goal: EGNOS RIMS site environment monitoring
European GNSS Agency (GSA)
(2016-2020)



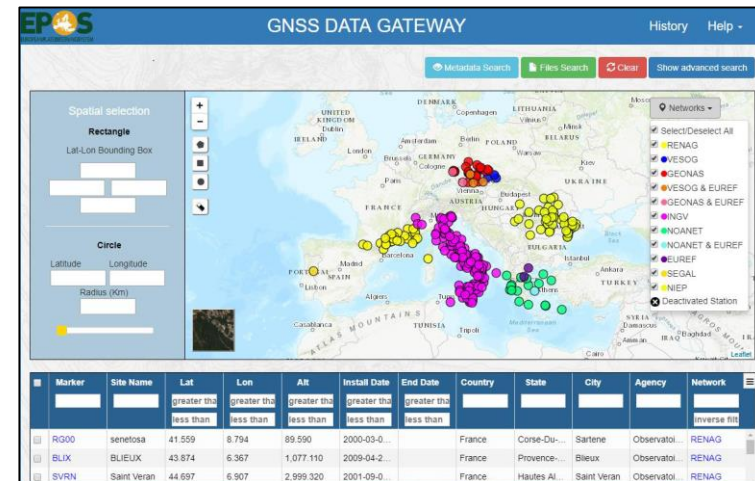
EPOS: European Plate Observing System

<http://www.epos-ip.org>

Contribution to the Solid Earth Science (SED)

- European Large Research Infrastructure for SED following the EU roadmap of *European Strategic Forum for Research Infrastructures (ESFRI)*
- Coordinating development of **new way of GNSS data dissemination (GLASS software)**

- **Preparatory phase**
FP7: 2012-2013
- **Implementation phase**
H2020: 2016-2019
- **Operational phase**
ERIC: since 2020



CzechGeo: Czech National Research Infrastructure

National RI for geophysical observations

- GNSS observations, data dissemination and analyses
→ *EUREF Densification and Reprocessing, GNSS Meteorology*
- **Liaison to the EPOS project – maintenance of national EPOS node**

<http://www.czechgeo.cz>

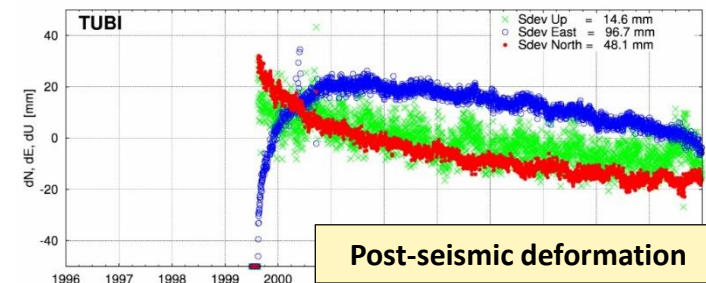
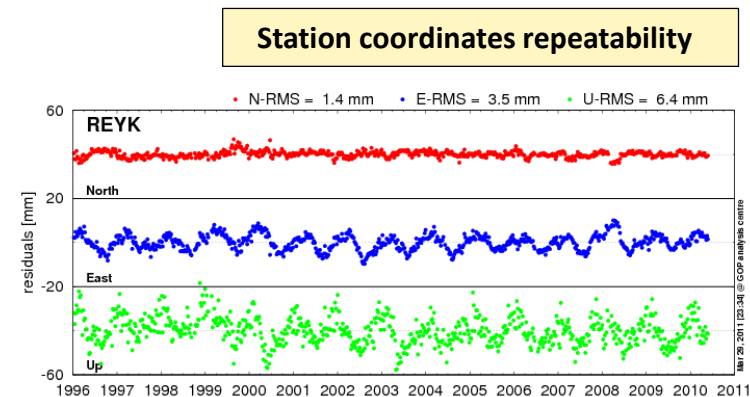
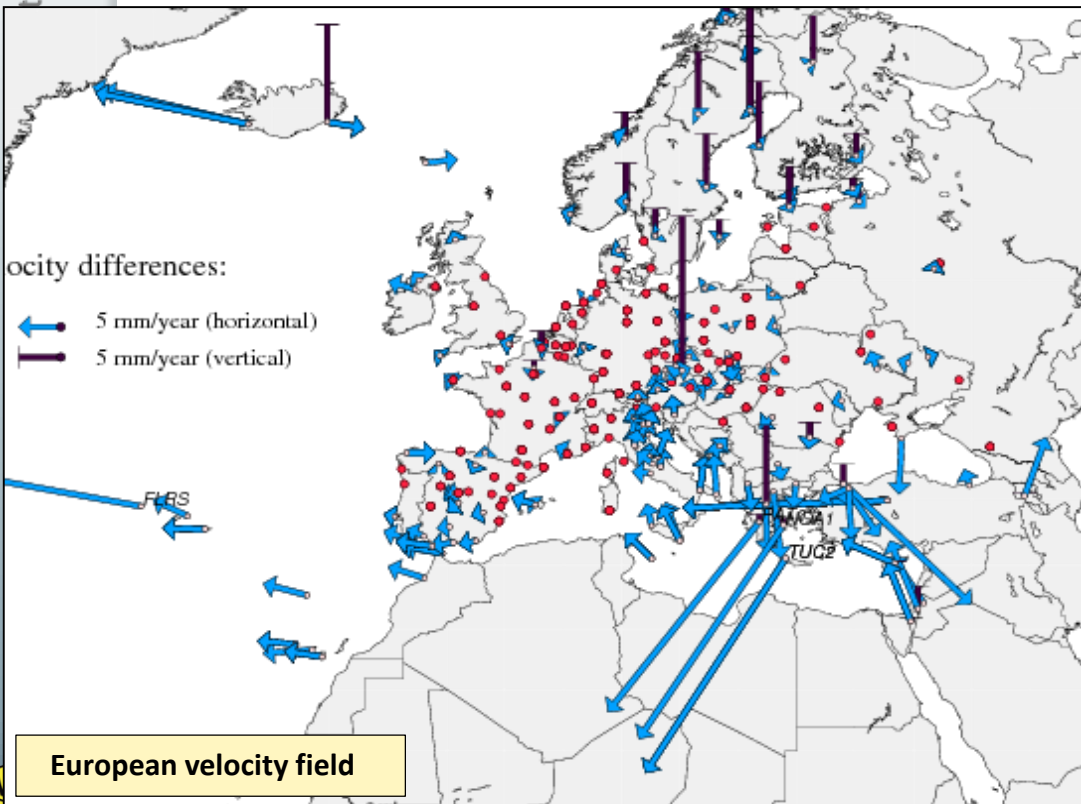
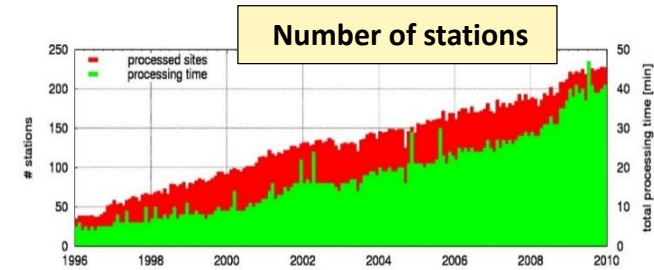
EUREF: European Reference Frame (IAG sub-commission)



<http://www.euref.eu>

Activities since 1996

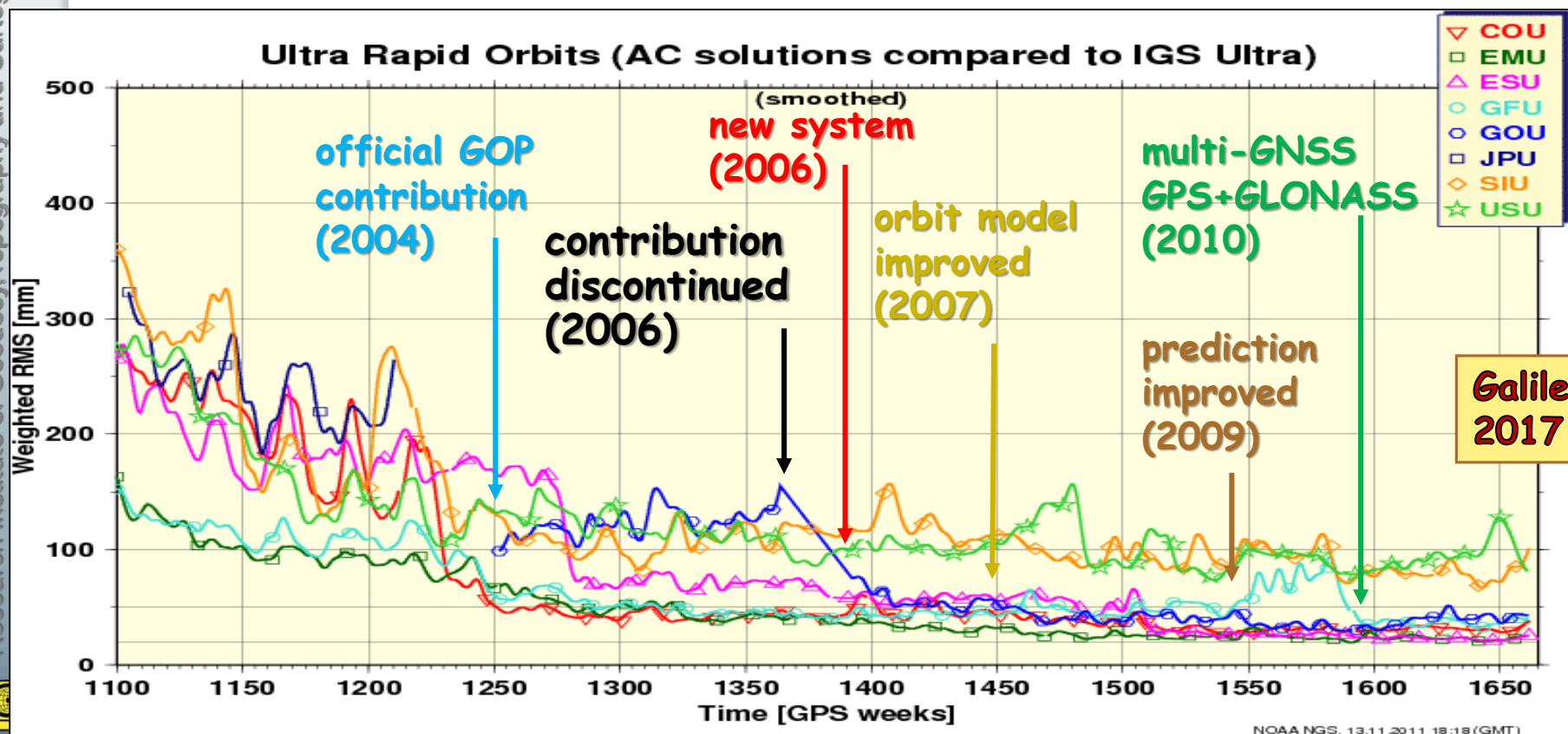
- GOP Analysis and Data Centers
- Membership in the EUREF Governing Board (GB)
 - **Reprocessing:** homogeneous analysis 1996-2014
 - **Troposphere:** estimates and validation
 - **Multi-GNSS:** data QC, multi-GNSS processing
 - **Real-time:** real-time processing, data dissemination



IGS: International GNSS Service (IAG service)

Contributions to **global precise products and services** (since 2004)

- GOP Analysis Center for precise ultra-rapid orbits (GPS+GLONASS)
 - Czech-US (US Naval Observatory) bilateral project (2013-2016)
- **Troposphere**: inter-technique parameter comparisons (GOP-TropDB)
- **Multi-GNSS**: data quality control, consolidated navigation data
- **Real-time**: real-time GNSS analysis – troposphere, positioning, clock corrections
- **GNSS SISRE / performance monitoring**: IGMA (UNOOSA-ICG) and IGS trial project



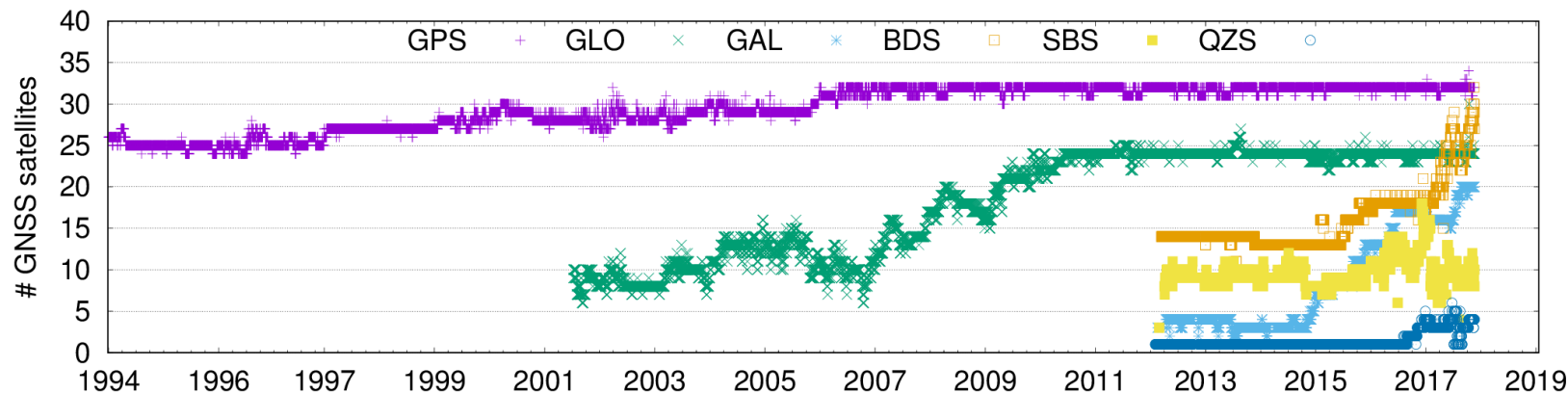
Consolidated multi-GNSS navigation messages

➔ supporting multi-GNSS data QC, POD, signal-in-space monitor, etc.

In-house developed strategy without need of external data

- *range checks and data pre-filtering (conservative approach)*
 - *time-series parameter analysis (for pre-selected parameters)*
 - *header consolidation (RINEX 3)*
 - *healthy status consolidation (statistical)*
 - *total group delays consolidation (statistical)*
 - *identification of problematic receivers (health status, TGDs etc.)*
- ✓ G-Nut/Aset software (in-house)
- ✓ collection over 300 data files worldwide from IGS network
- ✓ multi-step procedure using RINEX2, RINEX3, hourly, real-time
- ➔ full archive since 1994 (consistent for both RINEX2 and RINEX3)
- RINEX3 daily files:** http://ftp.pecny.cz/LDC/orbits_brd/gop3

GOP GNSS navigation data historical archive [1994-present]

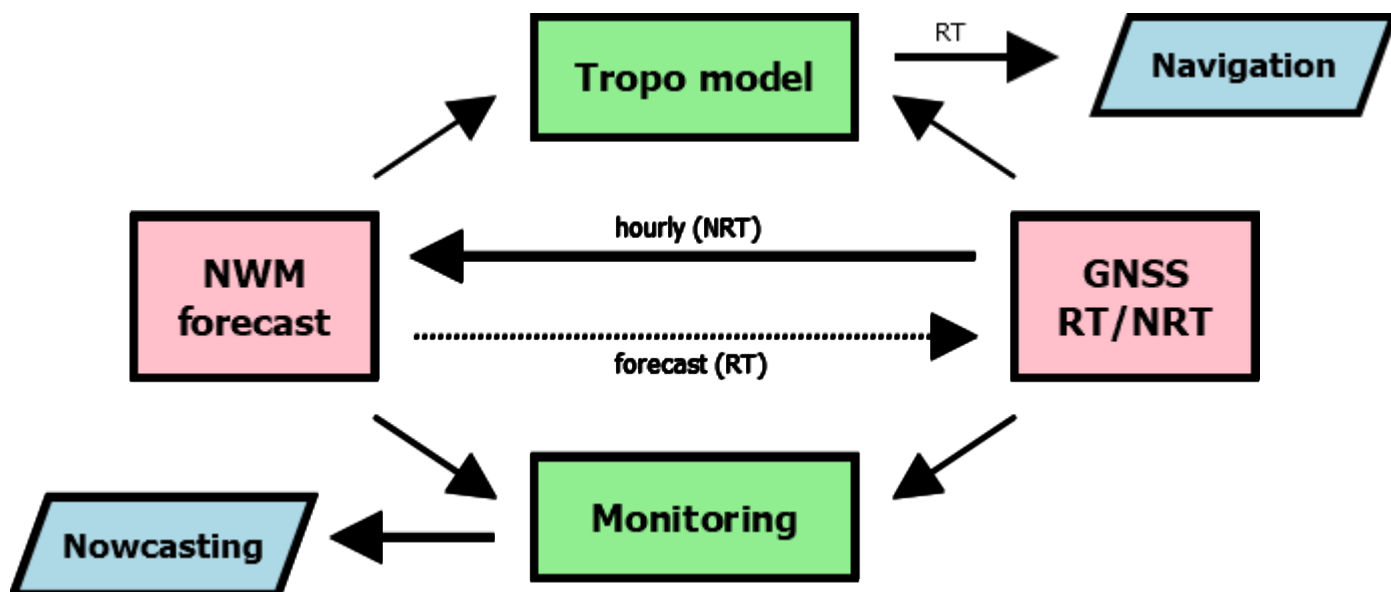


GNSS, Troposphere & Meteorology

(synergy in troposphere monitoring/modelling)

Tropospheric parameters from GNSS are **side products** along with estimating geodetic parameters of main interest, and need to be estimated if high-accuracy geodetic products are of interest.

- **Geodesy: *assessing/improving*** tropospheric modelling for geodetic applications
- **Geodesy: *exploiting*** external tropo corrections for RT positioning/navigation
- **Meteorology: *improving*** numerical weather prediction, weather nowcasting
- **Climatology: *monitoring*** of long-term trends in water vapor content/variation



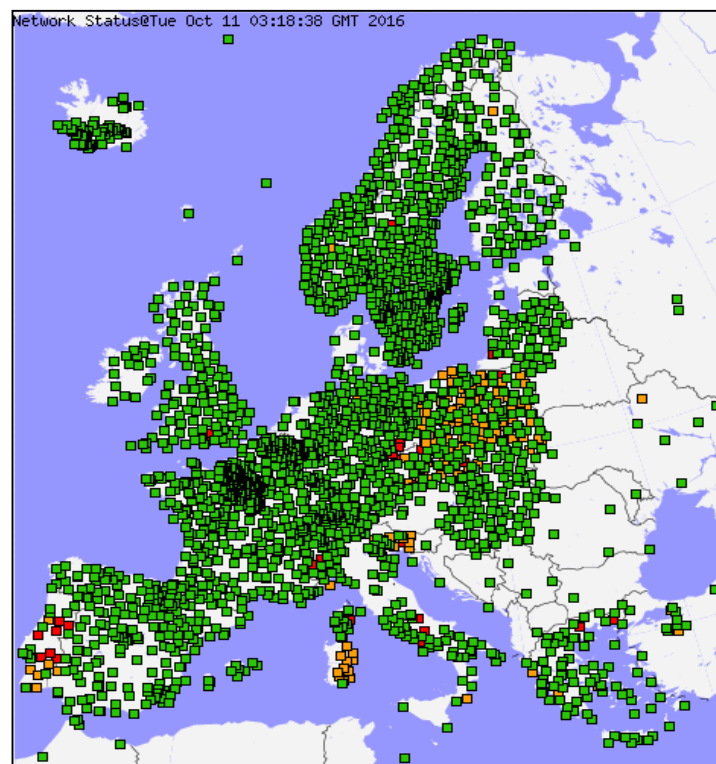
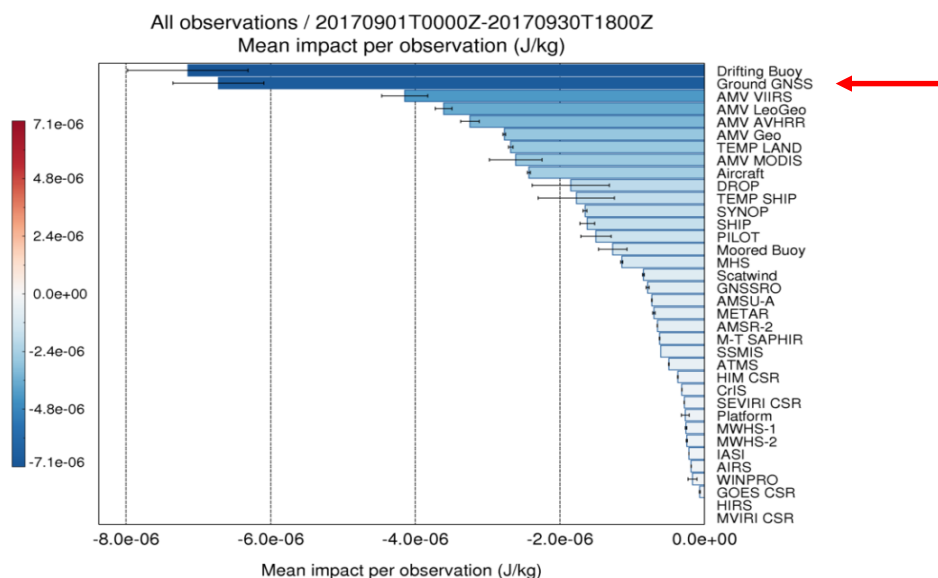
Standard near-real time processing

The EIG EUMETNET GNSS Water Vapour Programme, E-GVAP I-III (2005-2019)

- Focus is on **hourly processing** for ZTDs near real-time processing for results **within 90 min**
- In support of operational dissemination, quality control and assimilation of GNSS ground-based ZTD
- Contributions of **20 analysis centres**
- Project coordinating the **near real-time** delivery of data from ~2600 GPS sites



<http://egvap.dmi.dk>



courtesy of Data Assimilation, UK Met Office

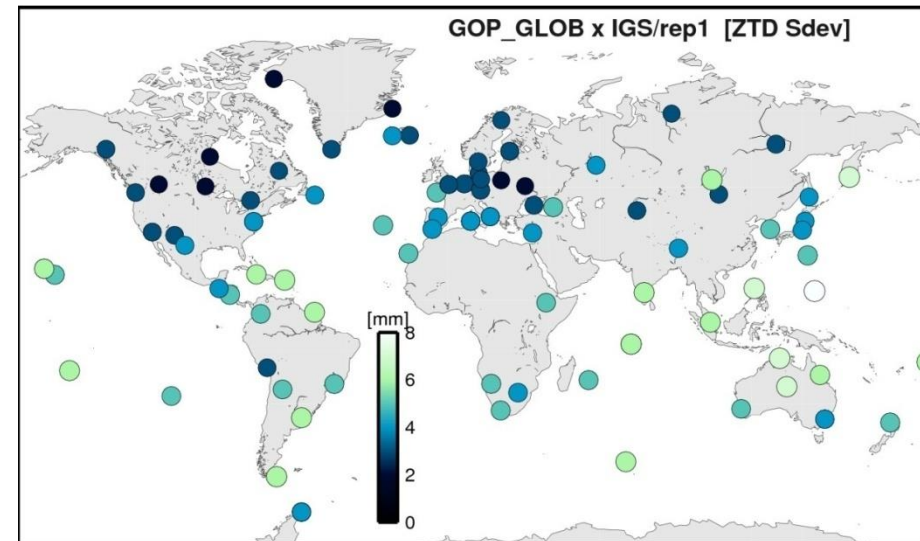
GOP tropospheric solutions (2001-present)

(Near) real-time solutions:

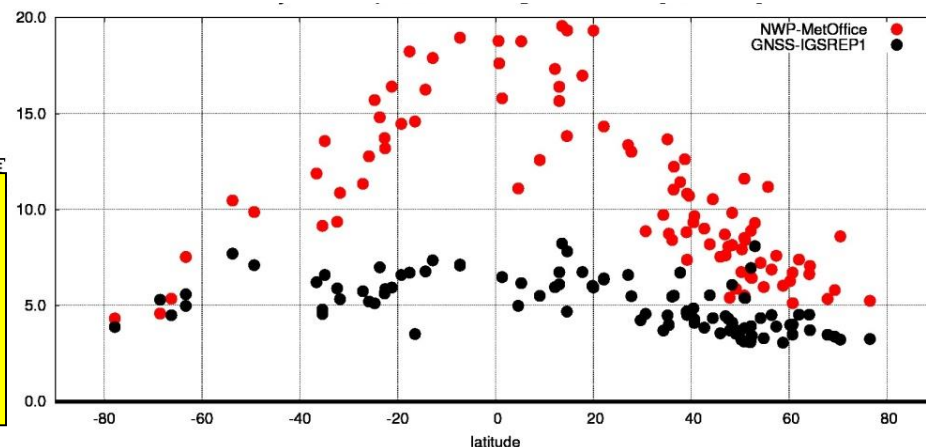
- Regional (since 2000)
- GPS+GLONASS (since 2008)
- Global (since 2010)
- Real-time (since 2014)
- Support to partners (since 2015)

Software/strategy

- Bernese GNSS Software V52
network solution (DD)
- G-Nut/Tefnut
Precise Point Positioning (PPP)

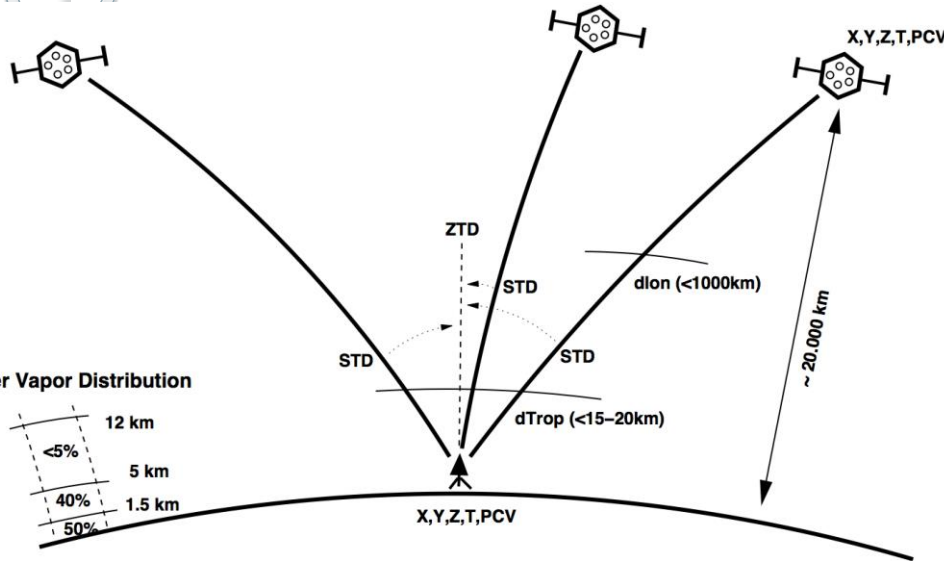


Comparison to UK MetOffice global NWM



ZTD × ZTD/final	Bias	StdDev
regional	< ±1 mm	< 5 mm
global	< ±3 mm	< 8 mm
real-time	< ±5 mm	< 10 mm

PPP for troposphere monitoring



Precise Point Positioning (PPP)

- ✓ absolute estimates
- ✓ autonomous method
- ✓ optimal in multi-GNSS
- ✓ highly efficient
 - real-time processing
 - high-temporal resolution
 - asymmetry modelling
 - stochastic modelling

➔ implemented in G-Nut/Tefnut

GNSS model (ZTD + gradients)

$$d_{trp} = m f_h \boxed{ZHD} + m f_w \boxed{ZWD} + m f_g [\boxed{G_N} \cos A + \boxed{G_E} \sin A]$$

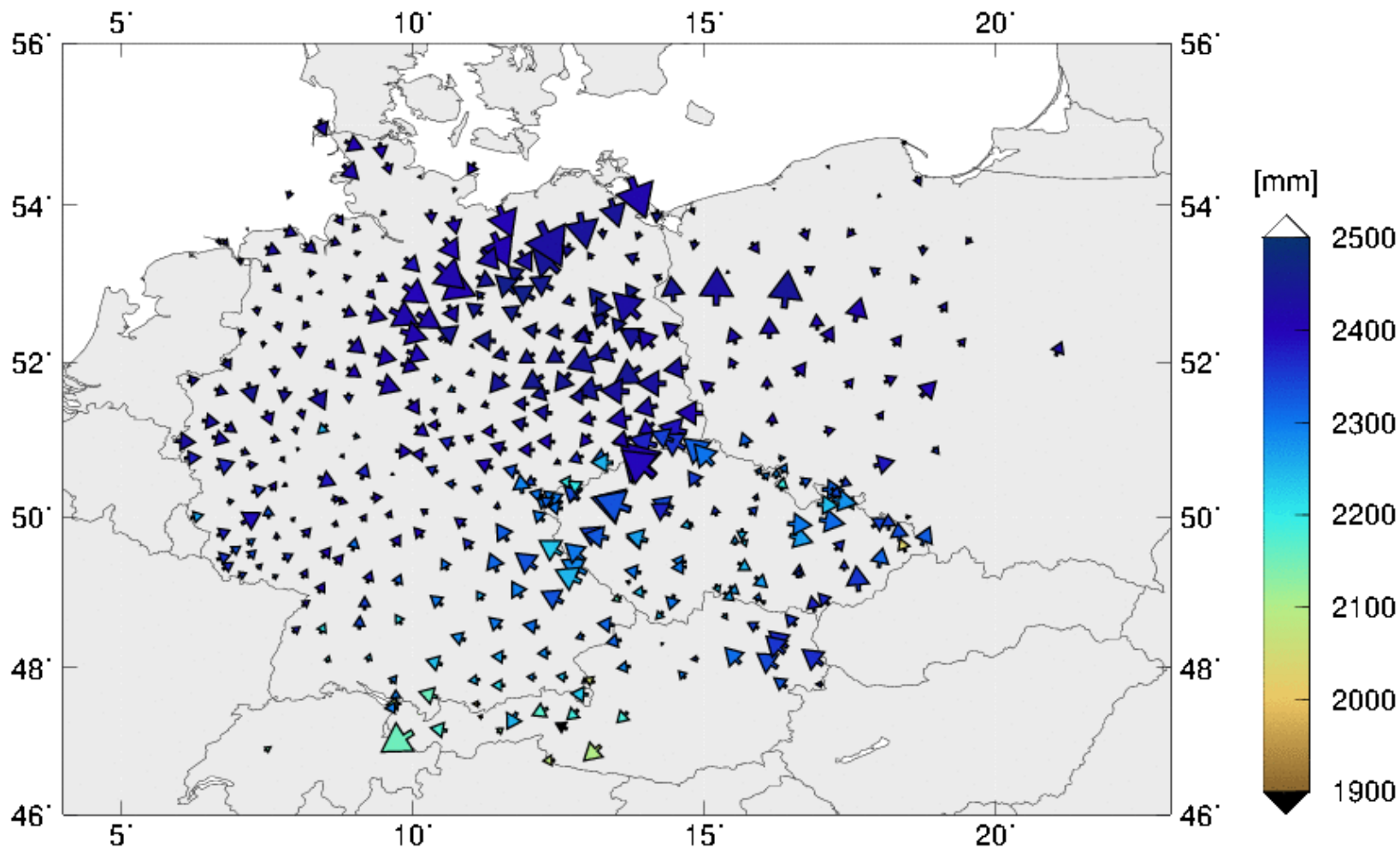
Slant retrievals (using clean post-fit carrier-phase residuals)

$$d_{trp} = m f_h ZHD + m f_w ZWD + m f_g [G_N \cos A + G_E \sin A] + \boxed{res - mpt}$$

Troposphere horizontal 1st order gradients

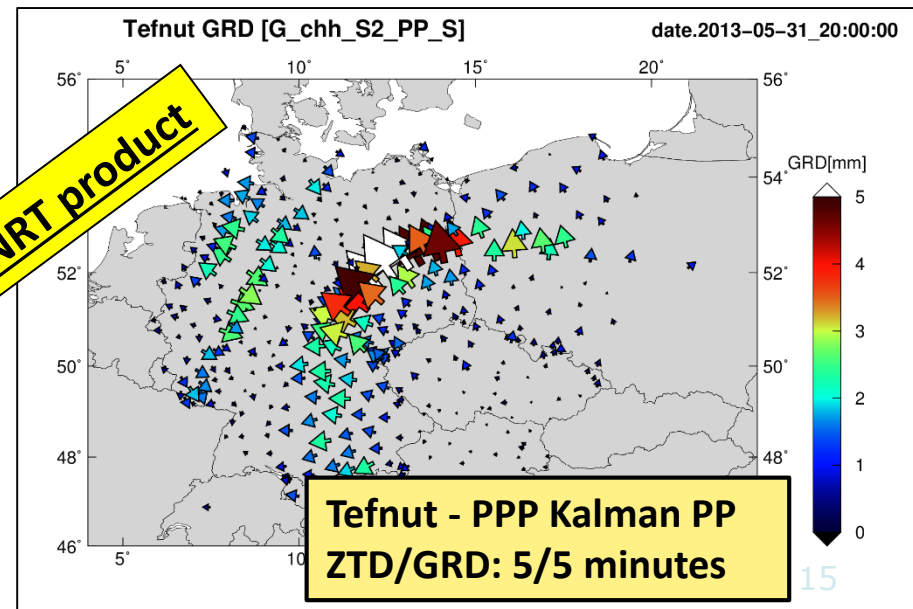
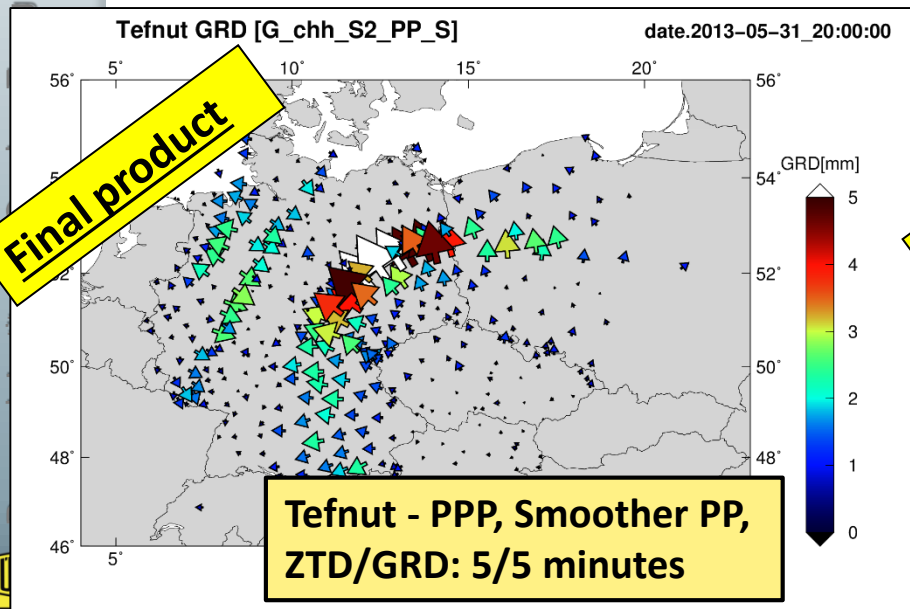
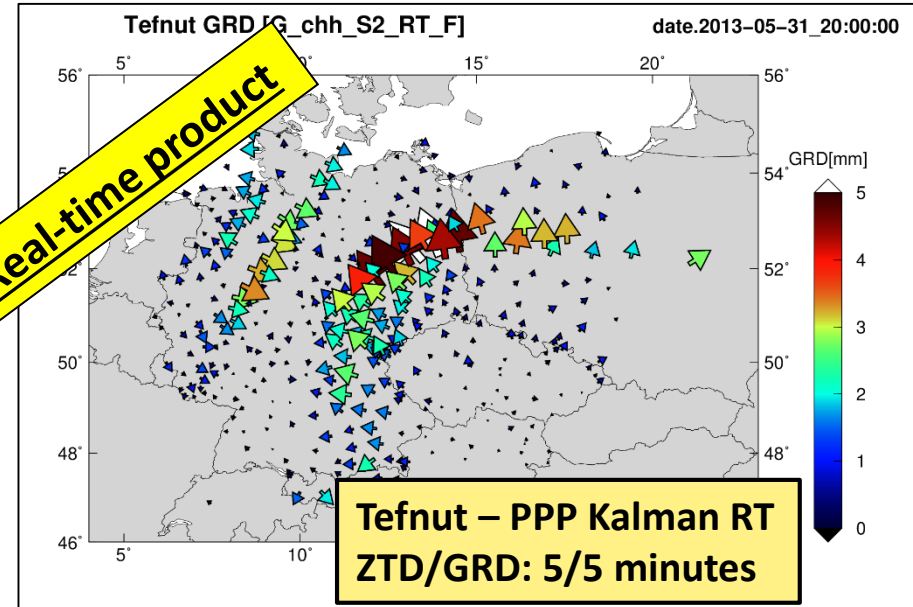
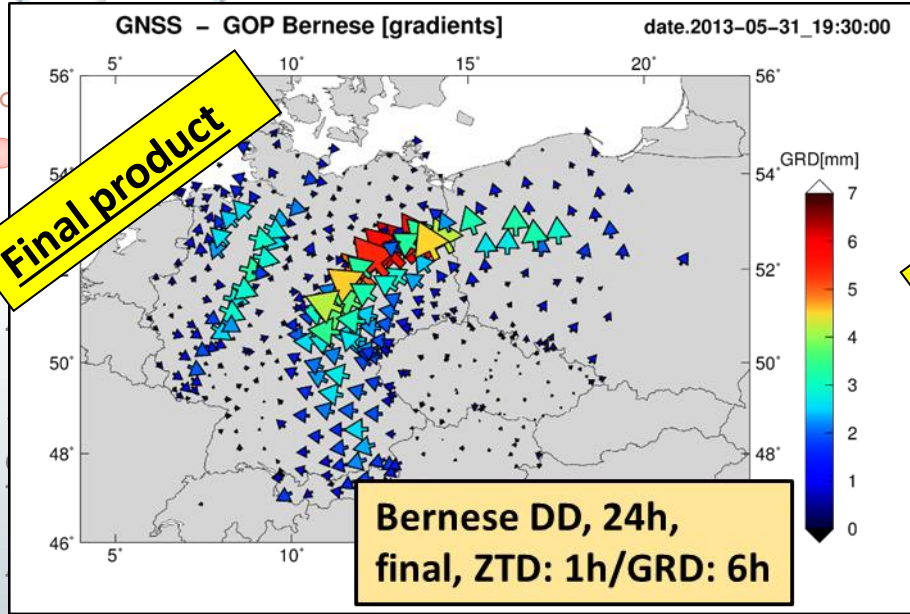
→ Exploiting dense Benchmark campaign for monitoring horizontal anisotropy

GNSS – GOP Final product [2013-05-31 00:30:00]



GNSS tropospheric gradients

offline and simulated real-time processing (Bernese DD & G-Nut/Tefnut PPP)



Carrier-phase post-fit residuals

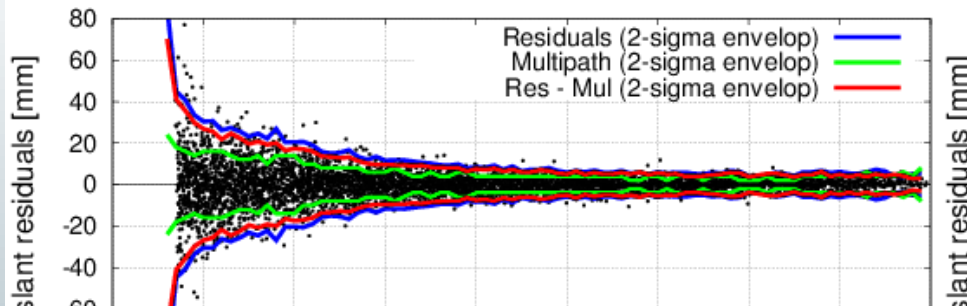
Dual station: POTS/POTM (June 19-20, 2013)

- Slant residuals from the day with normal (left) and variable (right) conditions
- 2-sigma envelopes for multipath, raw and clean residuals at dual stations displayed

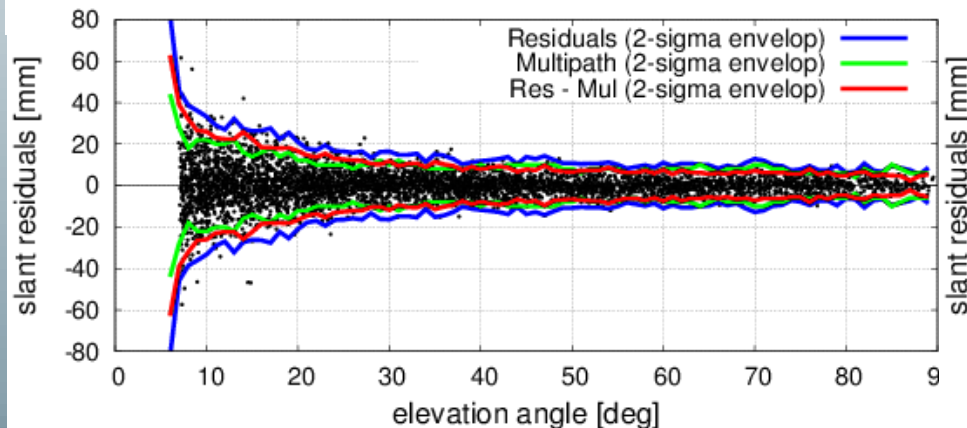
Normal day (June 19, 2013)

× Severe day (June 20, 2013)

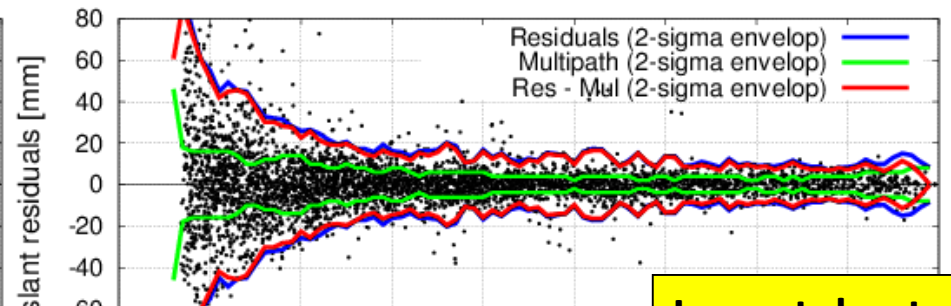
POTS [GFZ] - slant residuals (clean) 2013:170



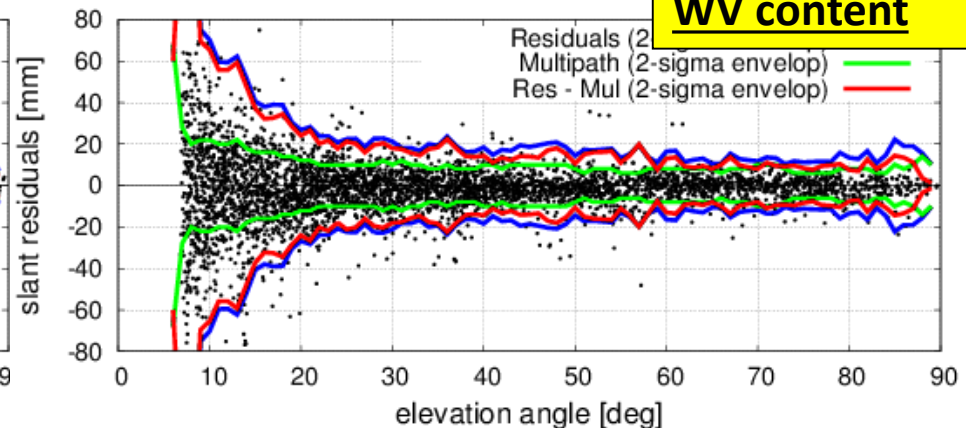
POTM [GFZ] - slant residuals (clean) 2013:170



POTS [GFZ] - slant residuals (clean) 2013:171



POTM [GFZ] - slant residuals (clean) 2013:171

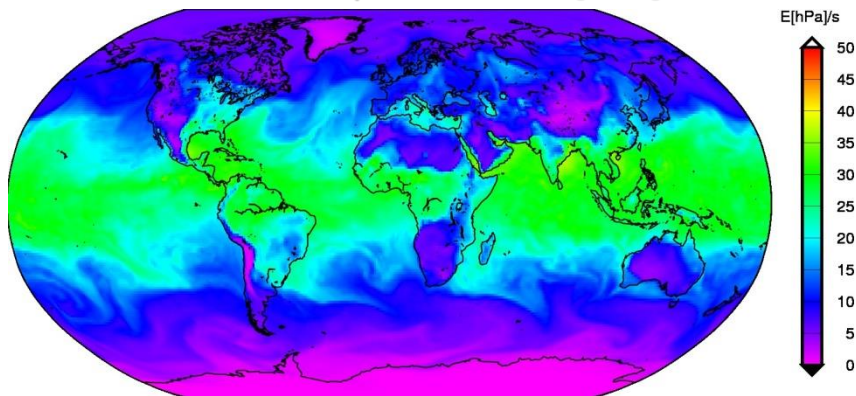


**Impact due to
WV content**

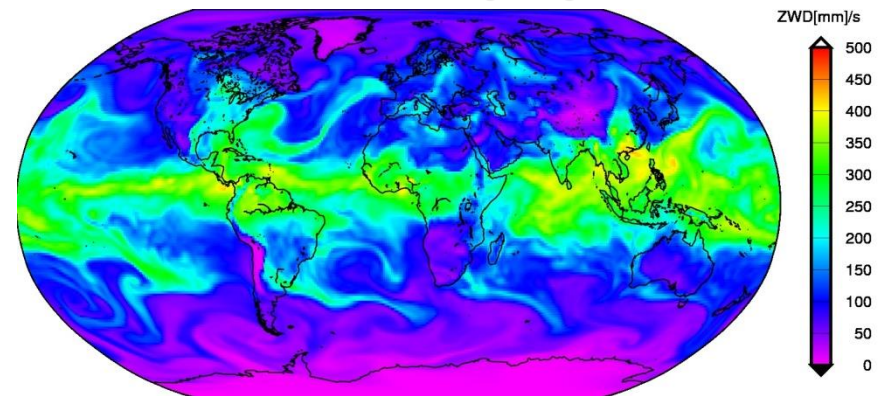
Characteristics of troposphere corrections

Characteristics of tropospheric parameters: Global ERA-Interim data (2005-06-05:00)
Water Vapour (WV), Pressure (P), Zenith Wet Delay (ZWD), Zenith Total Delay (ZTD)

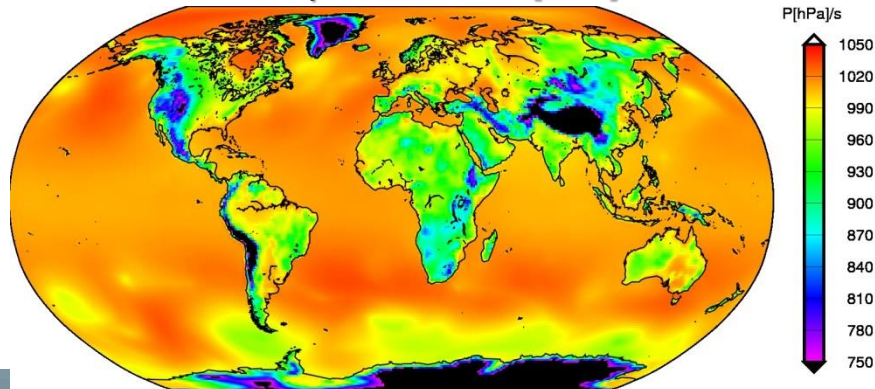
Surface WV pressure – E [hPa]



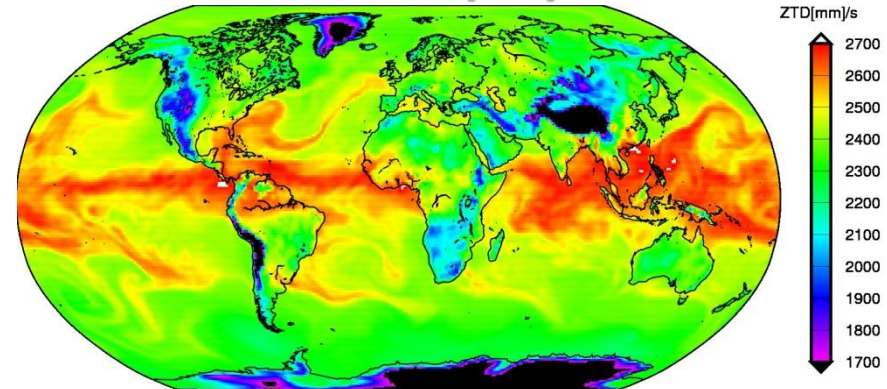
Surface ZWD [mm]



Surface pressure – P [hPa]



Surface ZTD [mm]



Troposphere correction models for positioning

ESA ITT project

ITT AO 7076

partners: Netherlands Aerospace Center (NLR)

Royal Netherlands Meteorological Institute (KNMI)

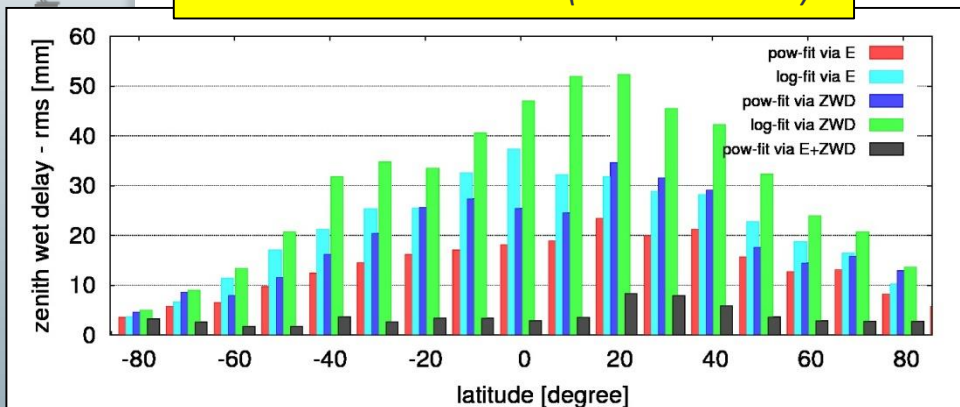
Enhanced modelling of Zenith Wet Delay (ZWD)

- Improved ZWD physical model of Askne and Nordius (1987)
- Improved ZWD vertical scaling

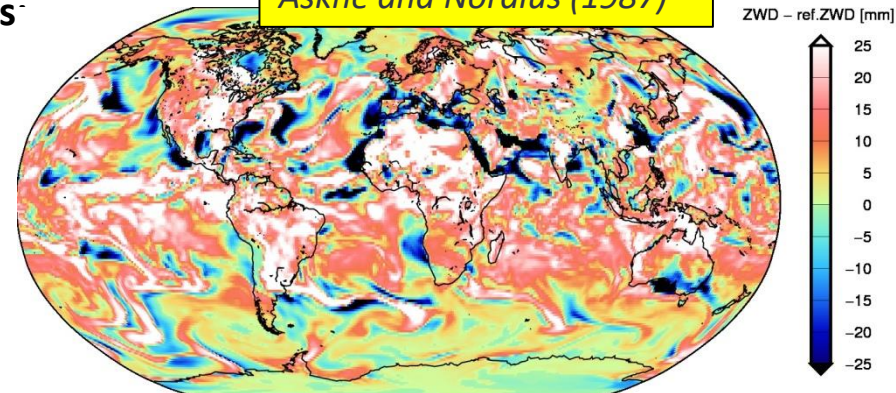
Model developments for different user modes

- Blind, Augmentation, Site and Combined

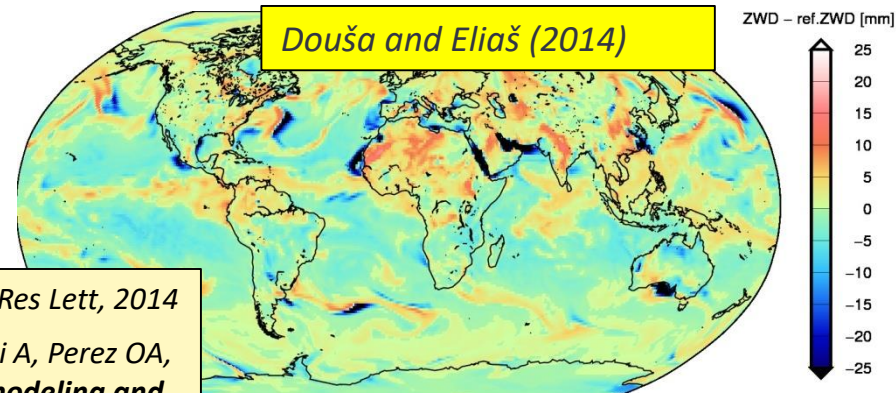
Global ERA-Interim data (2005-06-05:00)



Askne and Nordius (1987)



Douša and Eliaš (2014)



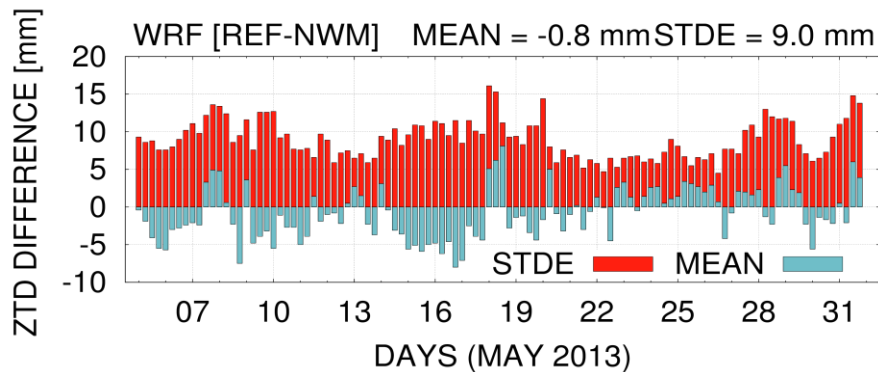
Douša and Eliaš, *An improved model for tropospheric wet delay*, Geophys Res Lett, 2014

Douša J, Eliaš M, Veerman H, van Leeuwen S, Zelle H, de Haan S, Martellucci A, Perez OA, *High accuracy tropospheric delay determination based on improved modeling and high resolution Numerical Weather Model*, Proceedings of ION GNSS, 2015

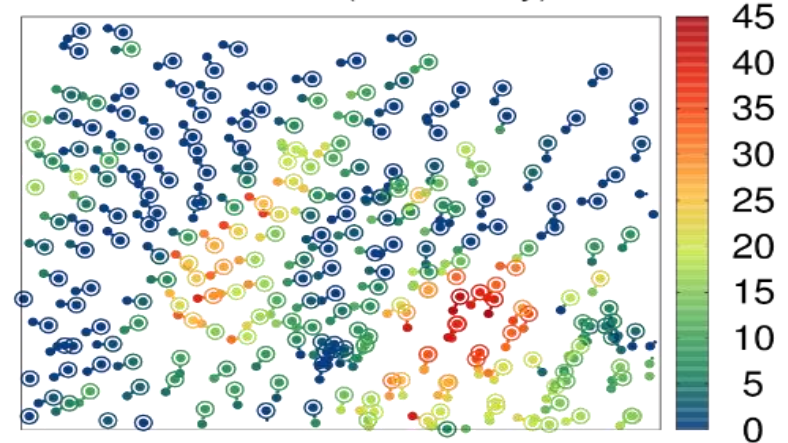
Troposphere modeling for GNSS RT applications

New **2-stage troposphere modelling** combining hydrostatic delays from Numerical Weather Model (NWM) forecast and wet delays from (near) real-time GNSS

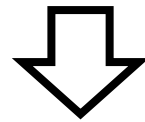
NWM-only ZTD prediction



REF - WRF (NWM-only)

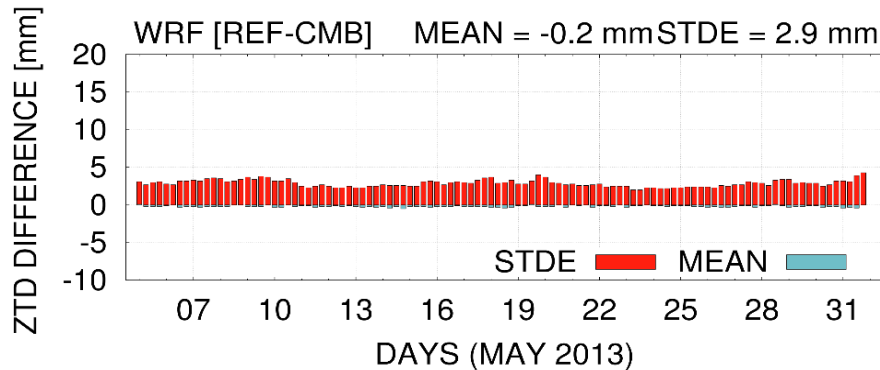


Improvement in
by a factor of 2-4
in ZTD accuracy

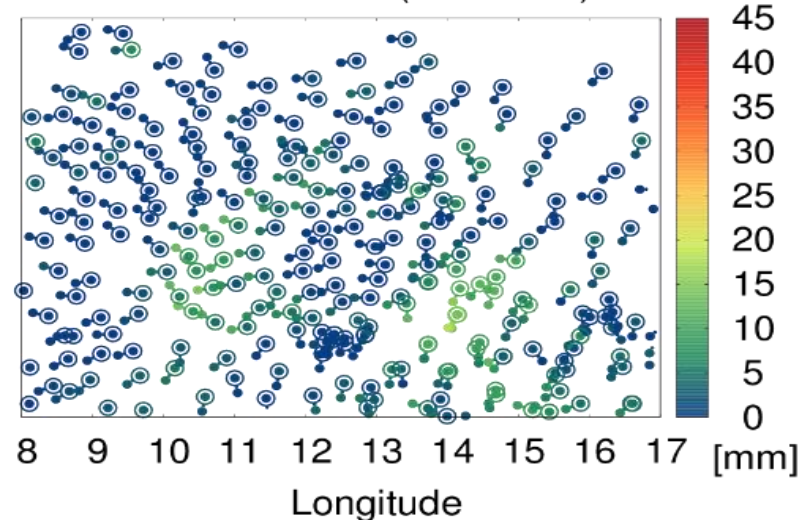


NWM+GNSS

by a factor of 2.5
in ZTD stability



REF - WRF/GPS (combined)



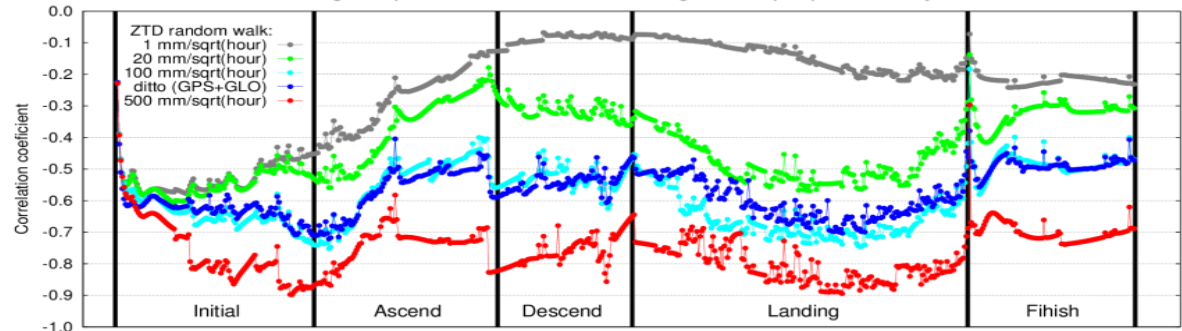
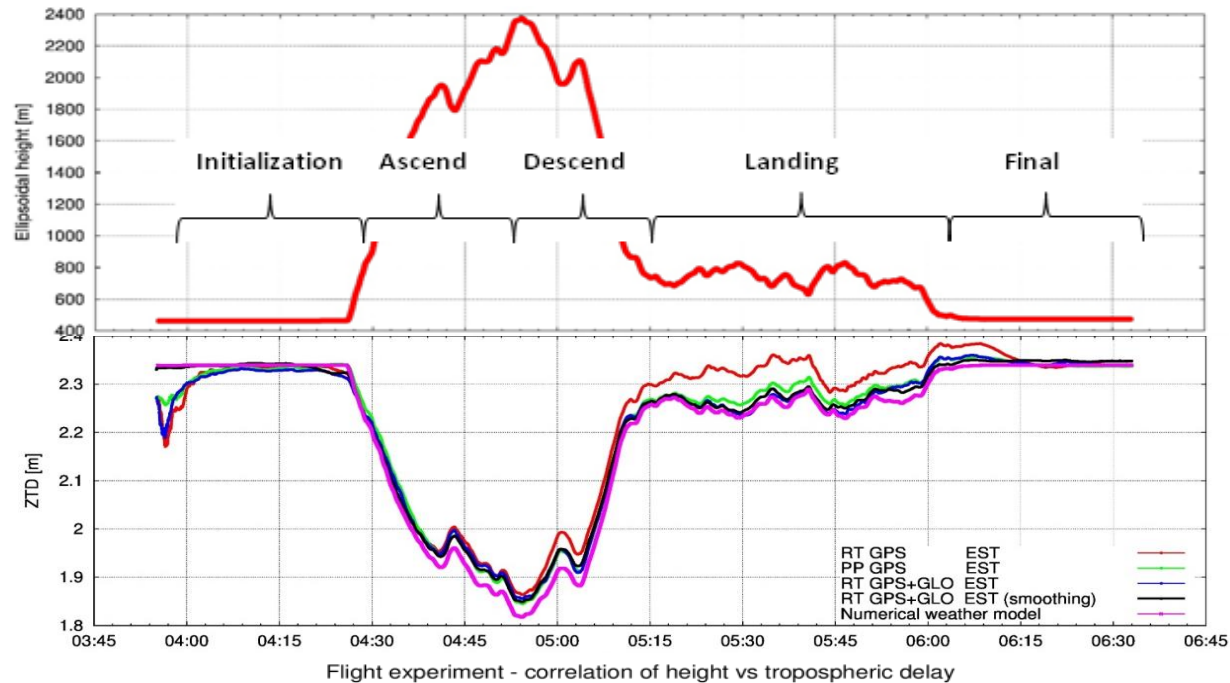
GNSS Real-Time kinematic positioning

ESA EGEP project, RIGTC/GOP (prime), Institute of Computer Science ASCR (partner)

- Hot-air balloon positioning with GNSS
- 2.4 km above ellipsoid $\approx$ 2 km above earth surface
- 12th August 2015 (5:45 – 8:45) initial + final phase: 30+30min



Václavovic P, Douša J, Eliaš M, Kostecký J (2017) - Vertical kinematic GNSS positioning supported by external tropospheric corrections, GPS solutions,



Summary

Multi-GNSS data collection and dissemination

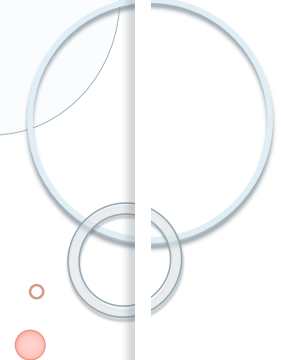
- **GNSS observations** – operating stations in the Czech Republic and Greece
- **GNSS data flow** – daily/hourly and real-time data centers, historical archives
- **GNSS data quality control** – monitoring data quality

High-precision multi-GNSS analysis

- **GNSS global products** – GNSS orbit and clock ultra-fast production/monitoring
- **GNSS reference frame** – long-term reference station coordinates and velocities
- **GNSS positioning** – offline/real-time PPP and kinematic applications
- **GNSS meteorology** – troposphere monitoring in (near) real-time
- **GNSS climatology** – homogeneous re-analysis of tropospheric parameters

GNSS modelling and software development

- **GNSS modeling** – augmentation tropospheric corrections for precise positioning
- **GNSS software** – development of high-precision in-house multi-GNSS software



Thank you for your attention

jan.dousa@pecny.cz