Overview of GNSS Data Processing Methods and Data Quality

J. Douša

(jan.dousa@pecny.cz)

GOP - Geodetic Observatory Pecný
Research Institute of Geodesy, Topography and Cartography
Czech Republic

International Symposium on Data Assimilation 2014
and COST ES1206 Workshop
February, 26-28, 2014, Munich, Germany

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)

Outline

- Brief introduction to GNSS
- Troposphere modelling and estimation in GNSS
- GNSS processing approaches
- Concept of GNSS meteorology
- Example of GNSS ZTD production procedure
- GNSS tropospheric product evaluations
- Summary and outlook

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

GNSS - Global Navigation Satellite Systems

Global navigation systems

- GPS NAVSTAR – NAVigation System using Timing And Ranging

  The United States' military service

- GLONASS – GLObalnaja NAvigacionnaja Sputnikovaja Sistema

  Russian (the Soviet Union's) military service

- GALILEO - European Space Agency (ESA)

  EU civil/commercial service

- BeiDou - Chinese global positioning system (evolving from regional)

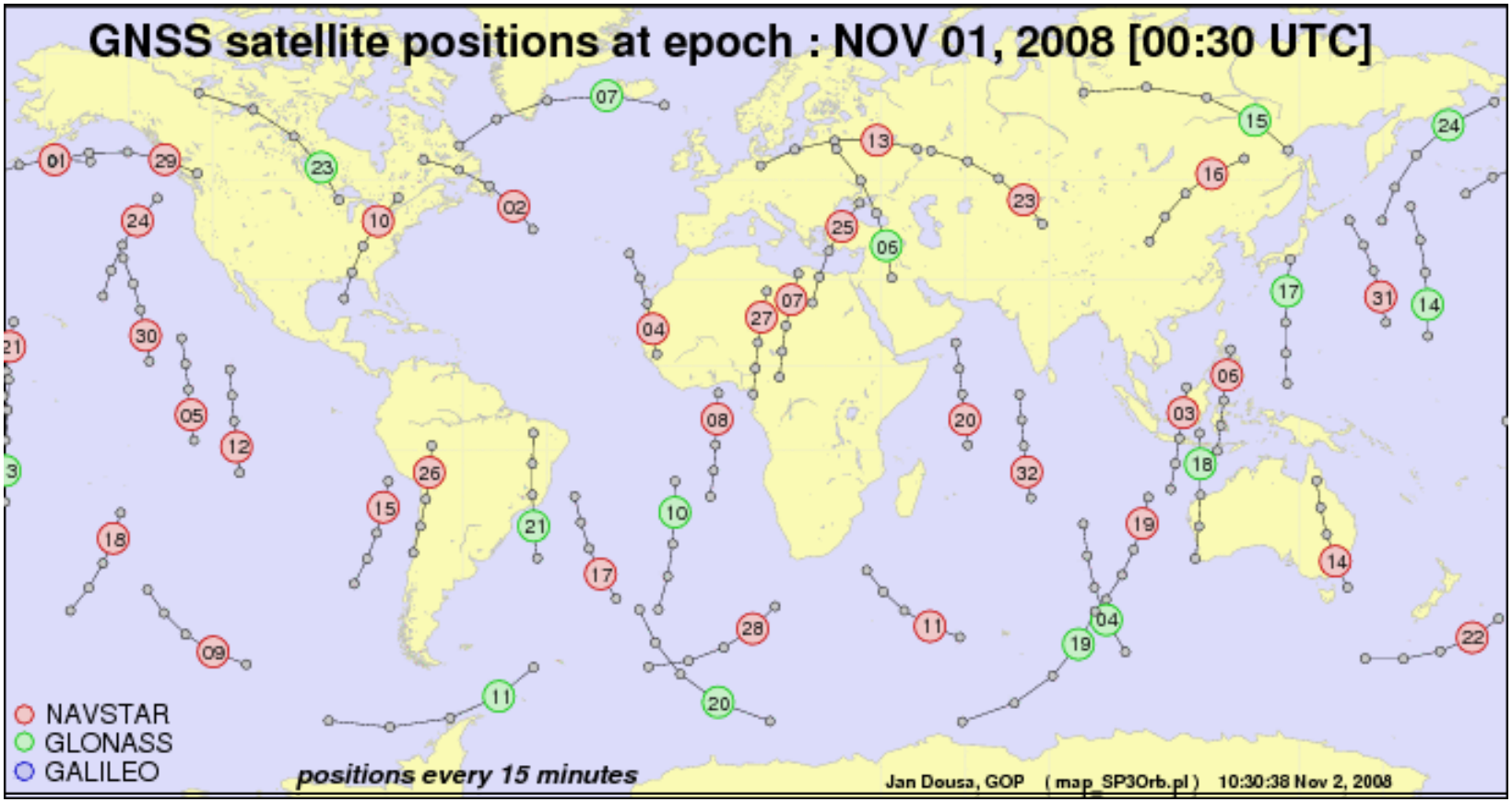
Augmentation systems:

- WAAS (North America), EGNOS (Europe), QZSS (Japan), IRNSS (India)

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

Satellite tracks projected on surface

- GPS – 31 satellites / 6 orbital planes / 11h 58min
- GLONASS – 24 (30) satellites / 3 orbital planes / 11h 15min
- Galileo – 4 (30) satellites / 3 orbital planes
- BeiDou – 5 GEO and 27 MEO/3 IGS0 satellites / 3 orbital planes



Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)

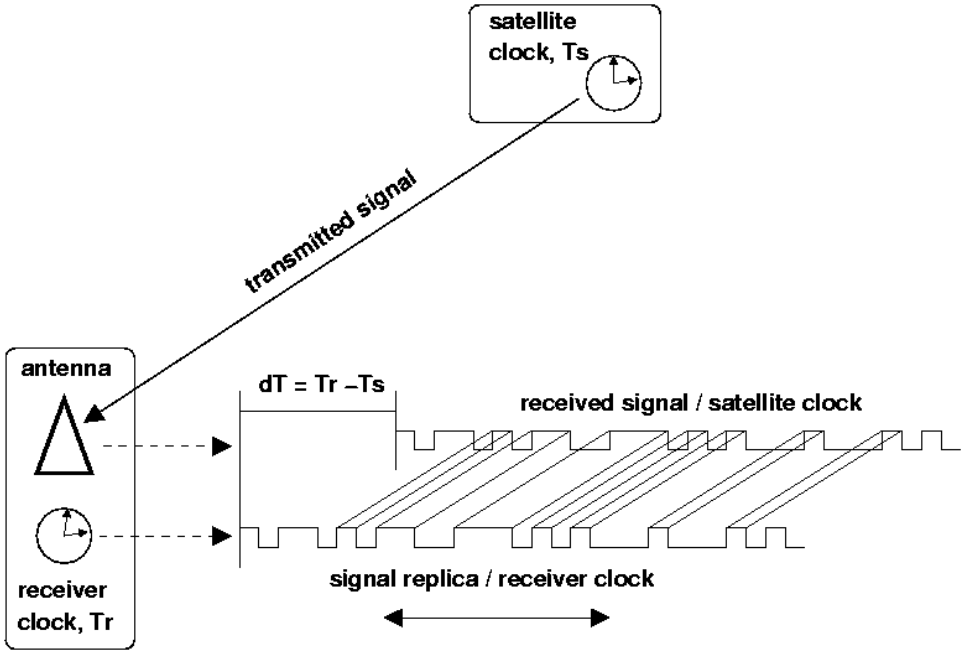
GNSS observables

Satellite oscillator with fundamenta

frequency multiplied by factors

e.g. 154x -> 1575.42 MHz (GPS L1)

120x -> 1227.60 MHz (GPS L2)



Pseudo range (code observation)

the measure of the transit time from satellite to receiver using correlation between received and replicated signal (the time is coded in signal)

absolute positioning with accuracy of a few meters (different for civil & army use)

Carrier phase (phase observation)

the measure of the phase difference btw. received and replicated carrier frequency

sub-centimeter level of relative positioning

Doppler data (phase change rate)

the measure of doppler shift due to a mutual motion of satellite and receiver

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

Error sources for GNSS

satellites: ephemeris, clocks, differential code & phase biases

receivers: clocks, phase center offsets and variations
differential code & phase biases

environment: troposphere, ionosphere, multipath,
Earth's dynamics and crust deformations

processing: cycle-slips (phases), model deficiencies

→ **eliminated**
by observable differences
by linear combinations
by introducing precise models and products

→ **estimated**

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

Observation differences and observation linear combinations

to eliminate some errors in GNSS model, we often use differences of original observables:

- zero-differences (ZD) – original observables
- single-difference (SD) – difference between two stations (baseline generation), which eliminates the satellite clock errors observed at both stations
- double-difference (DD) – difference between two SDs (measurement to two satellites from the single baseline), which eliminates receiver clock errors
- triple-difference (TD) – difference between two DD in two consecutive epochs, which is useful to detect the phase cycle-slips (e.g. when signal from satellite was discontinued)

for reducing/eliminating some errors we usually create specific linear combinations

$$LC = \alpha \cdot \phi_i + \beta \cdot \phi_j + \gamma \cdot \phi_k + \ldots \qquad \text{for i, j, k .. frequencies}$$

➔ ionosphere-free, geometry-free, narrow-lane, wide-lane, Melbourne-Wuebbena,...

GNSS model parameters

- Satellite and receiver positions
- Satellite and receiver clock corrections
- Earth orientation parameters, geocenter coordinates
- Satellite and receiver code/phase biases
- Satellite and receiver phase center offsets and patterns
- Troposphere effect
- Ionosphere effect
- Initial phase ambiguities

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

GNSS observation equation

Basic GPS carrier phase observable (scaled to distance):

$$L_{rec}^{sat} = \sigma_{rec}^{sat} + c \cdot \delta_{rec} - c \cdot \delta^{sat} + \lambda \cdot N_{rec}^{sat} + \Delta_{ion} + \Delta_{tro} + \varepsilon$$

σ_{rec}^{sat} .. receiver-satellite distance in vacuum (receiver and satellite coordinates)

c .. speed of light

δ^{sat}, δ_{rec} .. satellite and receiver clock errors

λ .. wavelength of the carrier phase

n_{rec}^{sat} .. unknown initial phase ambiguity

Δ_{ION} .. ionospheric (slant) delay

Δ_{TRP} .. tropospheric (slant) path delay

← **satellite and receiver position need to be accurately known**

← **eliminated using double-differences (estimated in PPP !)**

← **need to be resolved integer or float**

← **first-order eliminated in the 'ionosphere-free' combination**

→ double difference observations in network solution

$$L_{kl}^{ij} = L_{kl}^{i} - L_{kl}^{j} = \left(L_{k}^{i} - L_{l}^{i}\right) - \left(L_{k}^{j} - L_{l}^{j}\right)$$

Signal propagation & tropospheric path delays

Tropospheric delay is defined as difference between real path and geometric path and consists of signal delay and bending

$$D_T = \int_s \left(n(s)\right) ds - \int_l n dl = \int_s \left(n(s) - 1\right) ds + \left[\int_s ds - \int_l dl \right]$$

Davis (1985) proposed separation of total delay into:

hydrostatic component & wet (non-hydrostatic) component

$$ZHD = 10^{-6} \frac{k_1 R_D}{g_m} P_0$$

Mean value : 2.3 m in zenith
~ 90% of the total path delay

$$ZWD = 10^{-6} \left(k_2^{'} + \frac{k_3}{T_m} \right) \int_{h0}^{\infty} \frac{e}{T} dh$$

Mean value : 0-50 cm in zenith
~ 10% of the total path delay

introducing mean temperature

$$T_m = \frac{\int_{h0}^{\infty} \frac{e}{T} dh}{\int_{h0}^{\infty} \frac{e}{T^2} dh}$$

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

Tropospheric delay for receiver-satellite link

Tropospheric delay correction needs to be known in direction link between each receiver and each observed satellite

Symmetric atmosphere model (elevation dep.)

$$D_T(z_0) = ZHD \cdot mf_H(e_0) + ZWD \cdot mf_W(e_0)$$

Mapping factor

$$mf = \frac{D_T}{D_T^z}$$

Usually mapping function applied a function of elevation angle

Initially defined by Marini (1972), later various modifications:

$$mf(\varepsilon_0) = \frac{1}{\sin(\varepsilon_0) + \frac{a}{\sin(\varepsilon_0) + b}}$$

$$mf(\varepsilon_0) = \frac{1 + \frac{a}{1 + \frac{b}{1 + \frac{c}{\cdots}}}}{\sin(\varepsilon_0) + \frac{a}{\sin(\varepsilon_0) + \frac{b}{\sin(\varepsilon_0) + \frac{c}{\cdots}}}}$$

Asymmetric atmosphere model (azimuth dependent)

Adding horizontal tropospheric gradients for modeling 'tilted' atmosphere

$$D_T(z_0, A) = D_T(z_0) + mf_{AZ}(A)\left[G_N \cos(A) + G_E \sin(A)\right]$$

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

Processing method: Network solution

- Double-differenced observations ➔ baseline(s) ➔ network
- Various error sources reduced or fully eliminated in DD

  ➔ 'Traditional approach'
- Sensing troposphere in 'Relative' sense ➔ long distances
- Large networks needed for 'absolute sensing' (> 500km)
- Short baselines (< 10 km) ➔ troposphere becomes negligible
- Preferably in a batch mode: post-processing/NRT (real-time)
- Complex impact of remaining errors in DD mode

  ➔ absolute and relative ZTD biases can be distinguished

$$\Delta D^{ji}_{T,BA} = \Delta D^{i}_{T,BA} - \Delta D^{j}_{T,BA} = \left[\Delta D^{i}_{T,A} - \Delta D^{i}_{T,B}\right] - \left[\Delta D^{j}_{T,A} - \Delta D^{j}_{T,B}\right] =$$

$$ZHD_A \cdot \left[mf_{H,A}\left(z^i_A\right) - mf_{H,A}\left(z^j_A\right)\right] - ZHD_B \cdot \left[mf_{H,B}\left(z^i_B\right) - mf_{H,B}\left(z^j_B\right)\right] +$$

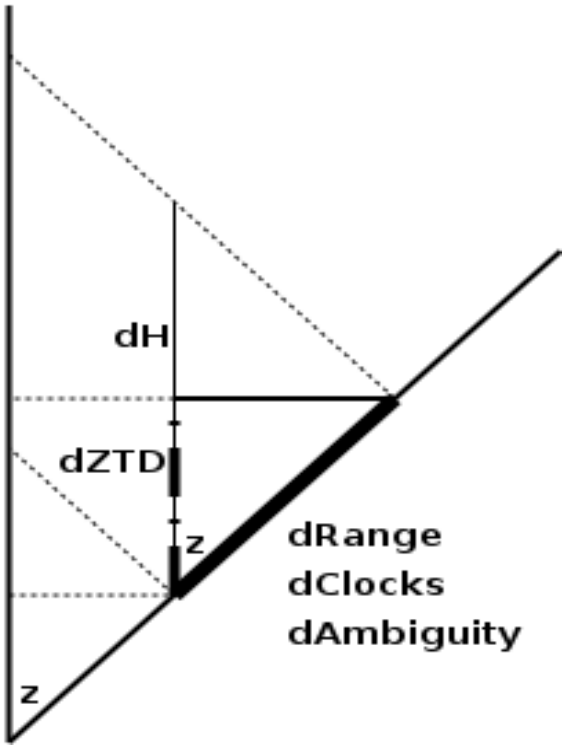
$$ZWD_A \cdot \left[mf_{W,A}\left(z^i_A\right) - mf_{W,A}\left(z^j_A\right)\right] - ZWD_B \cdot \left[mf_{W,B}\left(z^i_B\right) - mf_{W,B}\left(z^j_B\right)\right]$$

Processing method: Precise Point Positioning

- Raw (not differenced) observations ➔ autonomous solution!
- Sensing troposphere in 'Absolute' sense
- Strongly depend on quality of all precise model and products
- Ambiguities and receiver clocks are capable of absorbing various remaining errors

$$\delta_{OBS} = \delta_{CLOCK} = \sec(z) \cdot \delta_{HEIGHT} = \cos(z) \cdot \delta_{ZTD}$$

- Code observation required
- Difficulties with ambiguity resolution
- Various adjustments (LSQ, filters,…)
- Real-time/NRT/final processing mode



Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

Parameters of GNSS model – PPP vs. DD

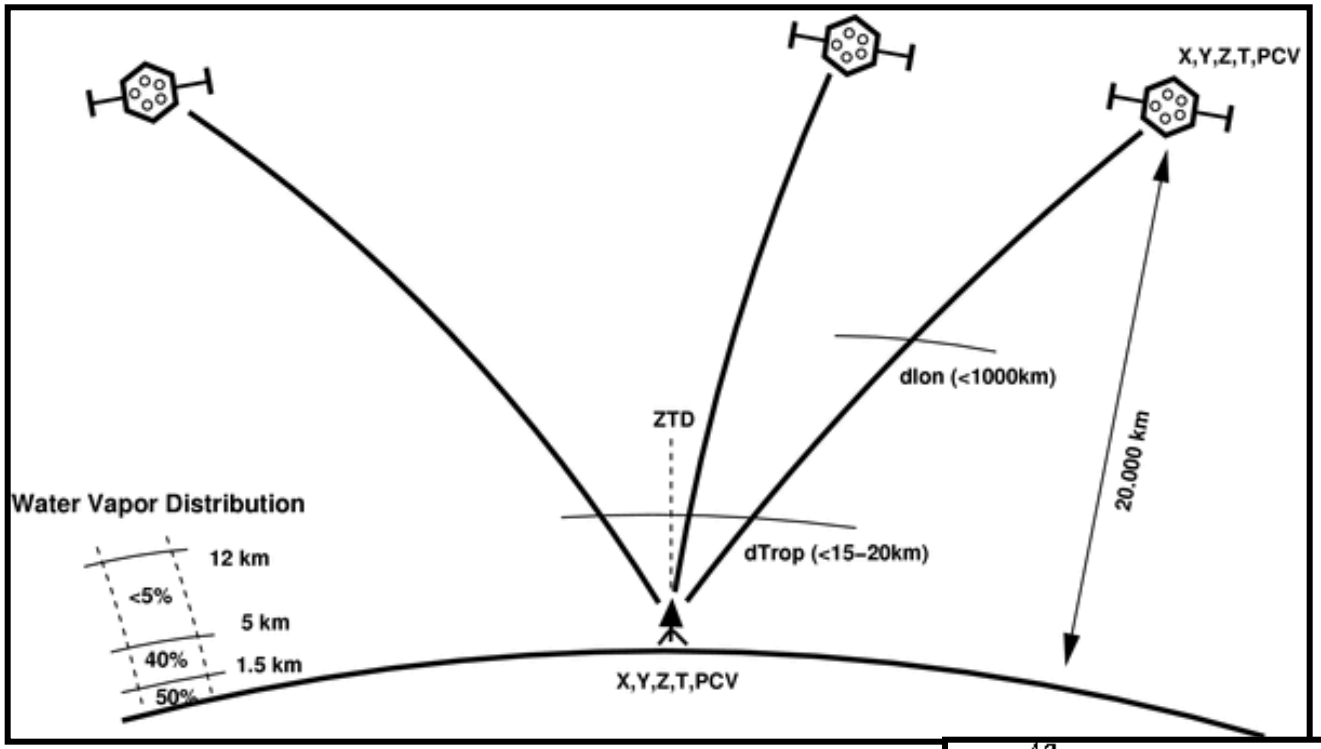
- satellite and receiver positions
- satellite and receiver clock corrections
- Earth orientation parameters and geocenter coordinates
- satellite and receiver code/phase biases
- satellite and receiver phase center offsets and patterns
- troposphere effect
- ionosphere effect
- initial phase ambiguities

Precise Point Positioning (PPP)

Network solution (DD)

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK

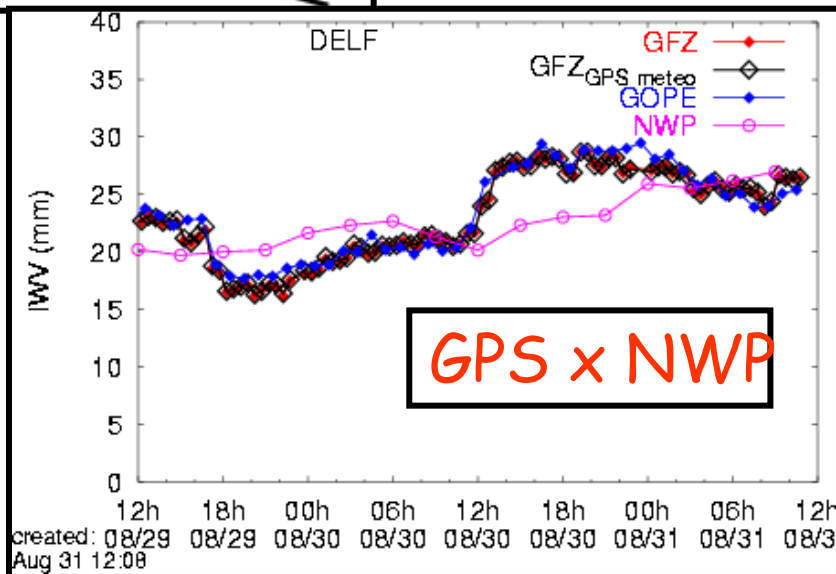
GNSS meteorology concept



we introduce: receiver and satellite positions *(satellite clocks)* and precise models (PCVs, loading effects, mapping functions ...),

we eliminate: ionospheric effect *(receiver and satellite clock error)*,

we estimate: troposphere, ambiguities *(receiver clocks)*



Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VUGTK

Products of tropospheric estimations

Availability/timelines:

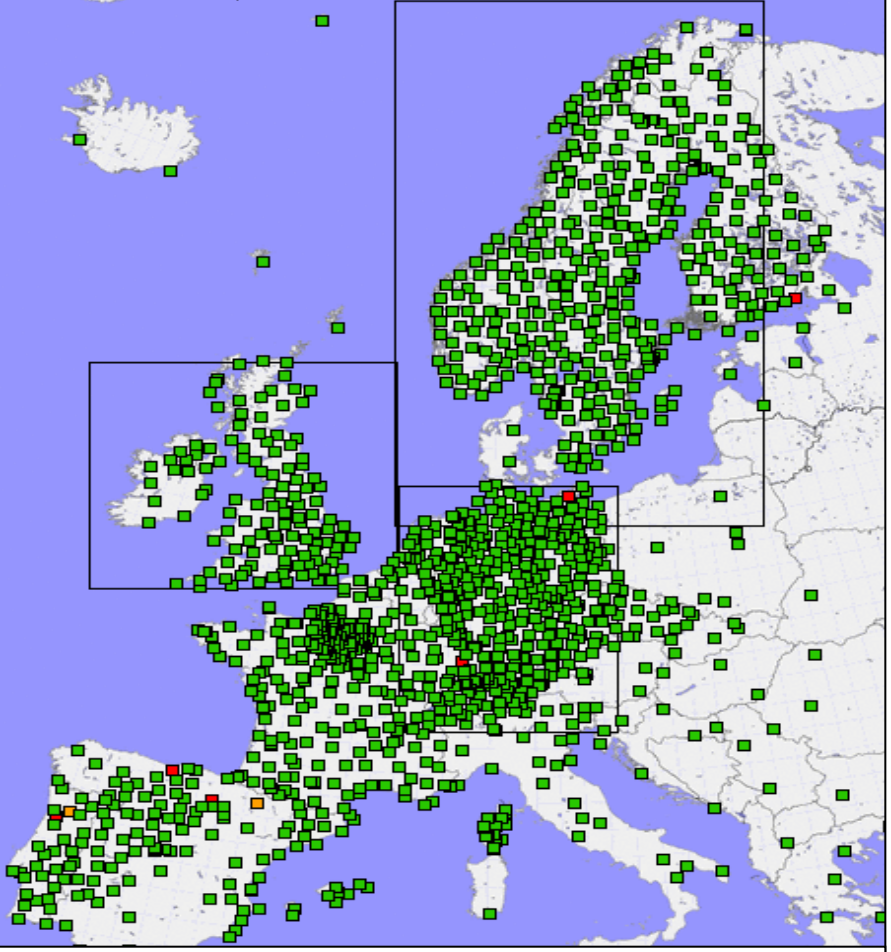
- post-processing (reference products, climatology, …)
- near real-time (GNSS-meteorology, …)
- sub-hourly/real-time (NWP nowcasting, severe weather monitoring, …)

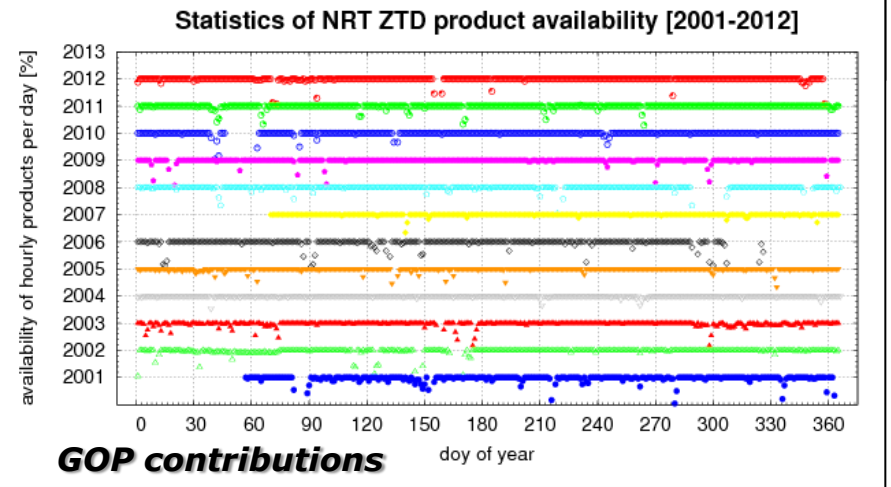
Adjustment models:

- LSQ adjustment (batch processing)
- Filtering approach (epoch-wise processing)

Processing techniques:

- Network mode (often using double-difference observations)
- Precise Point Positioning (autonomous, but external clock products)





GOP contributions

GNSS-meteorology in Europe

COST-716 Action (1998-2003): *"Exploitation of Ground-Based GPS for Operational Numerical Weather Prediction and Climate Applications"*

- **15 institutions, 7 ACs, > 200 GPS sites**

TOUGH (2003-2006): *„Targeting Optimal Use of GPS Humidity Measurements in Meteorology"*

- **15 institutions, 12 ACs, > 400 GPS sites**

E-GVAP I, II, III (2006-2016)

„The EUMETNET GPS Water Vapor Programme"

- **15 institutions, 15 ACs, > 1800 GNSS sites**

GNSS4SWEC - COST Action (2013-2016)

„Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate "

- **> 37 institutions (25 EU countries)**
- **Kick-off meeting in May 17, Brussels, 2013**

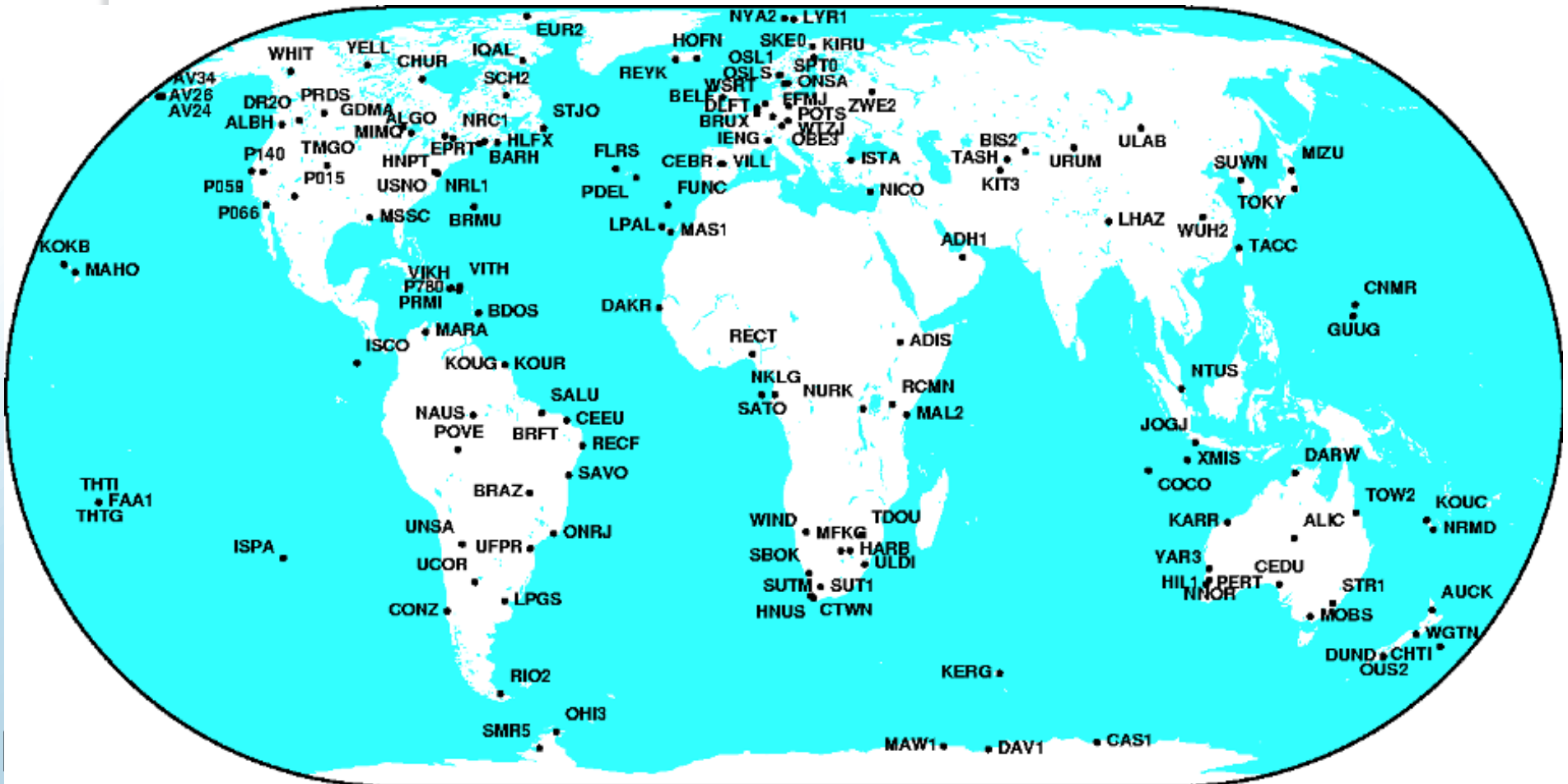
IGS: International GNSS Service (since 1994)

➔ global GNSS data and products for scientific community (> 300 agencies)

Data: real-time, high-rate, hourly, daily high-rate, multi-GNSS (M-GEX) etc.

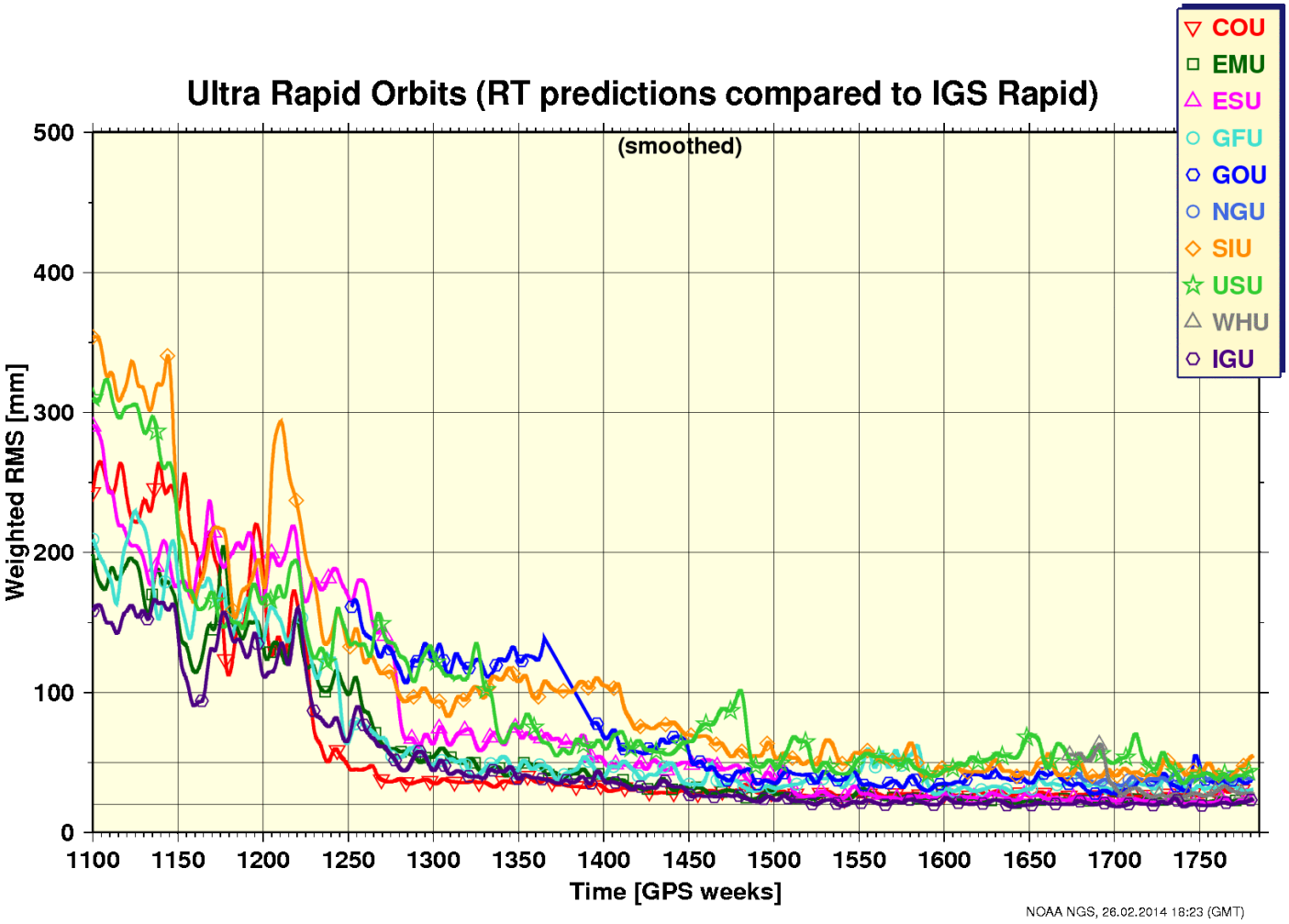
Products: satellite orbit & clock, precise models (PCVs,...), reference frame etc.

http://www.igs.org



Precise orbit quality monitoring

	orbits	clocks	Y,X pole	X,Y pole rates	length of a day
observed	~3 cm (1D)	~1.50 / ~3.00 ns	0.1 mas	0.2 mas/day	0.03 ns
predicted	~5 cm (1D)	~0.15 / ~0.05 ns	0.3 mas	0.3 mas/day	0.07 ns
real-time	~5 cm (1D)	~0.15 ns	-	-	-

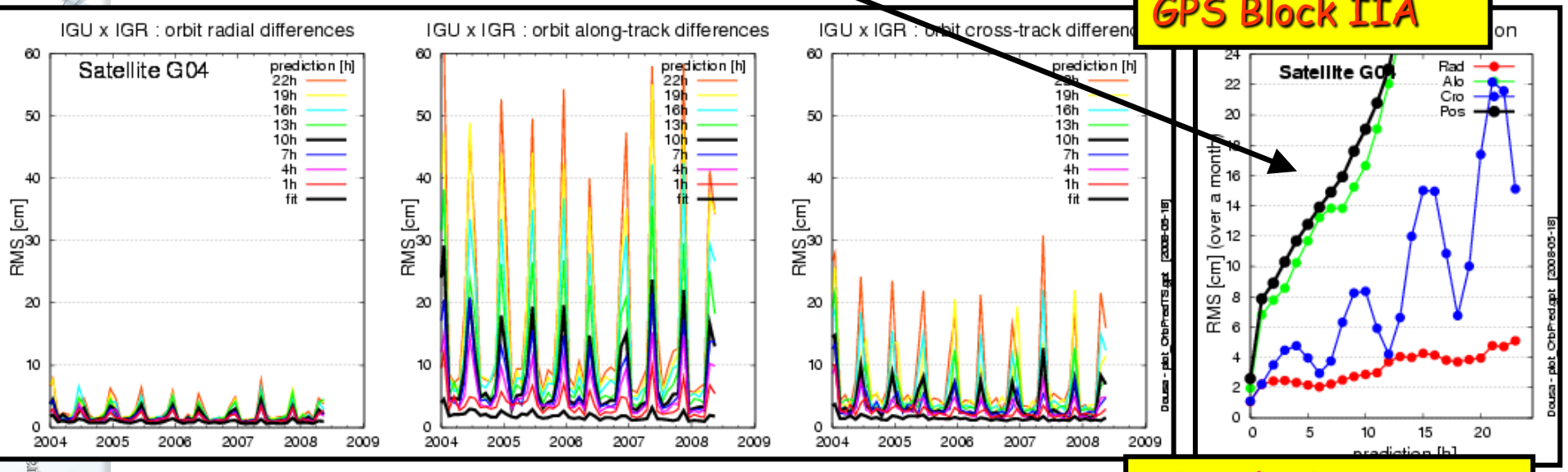


Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VUGTK

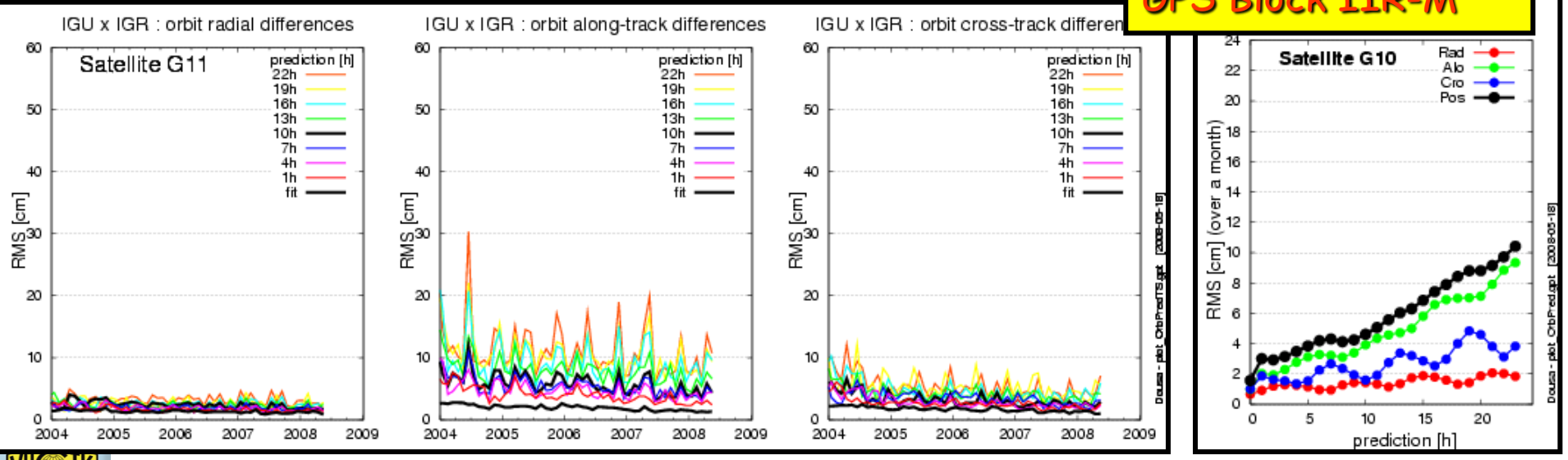
IGS precise orbit quality assessment

Normal situation vs. eclipsing period (satellite-specific)

GPS Block IIA



GPS Block IIR-M



PPP processing strategy – two step approach

1. PPP Service → can be shared in a community

- Determination of global precise products - satellite orbits & clocks
- Global network processing
- Updated in 1-6 hours, predicted orbits used up to 10 hours

2. Client PPP processing → possible for individual utilization in 'black-box ' approach

- Estimation of tropospheric parameters
- Large set of parameters possible when keeping very efficient
  – supporting high sampling rate, tropospheric gradients, slant delays

Additional notes:

PPP in several aspects interesting for a future extensive utilization

PPP possible for utilization mainly thanks to IGS precise products

PPP not widely used in NRT so far due to the lack of precise clock products in IGS

-> recently changed with real-time products by IGS

Summary of method comparison characteristics

Precise Point Positioning

- Autonomous (absolute) method
- Efficient for a high resolution
  (unlimited number of parameters)
- Requires precise products & models
- Implicitly ready for a global scale
- Easy to support slant delays
- Easy to support real-time
- All observations can be directly used
  (including multi-GNSS observations)
- Absolute tropospheric estimates
- Correlation via global products
- Possible production at receiver
  (if precise products available)

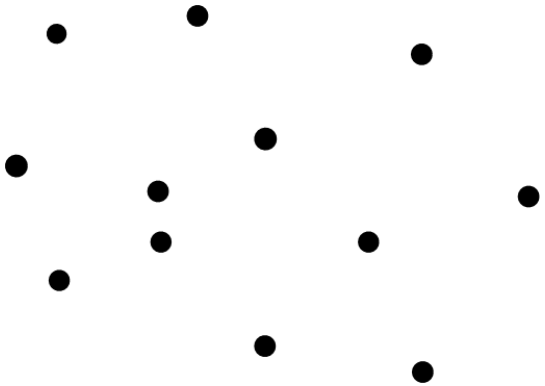
…

Network solution (double-differences)

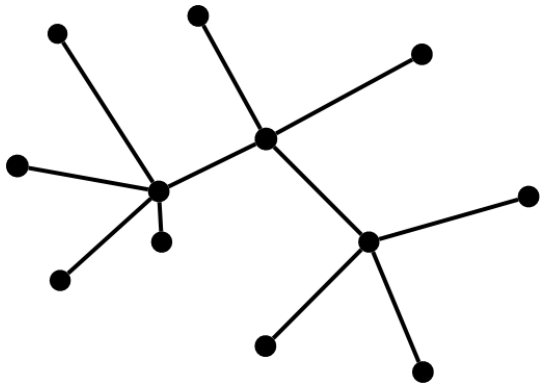
- Relative method
- Differences in short ×Long baselines processing
- Limited to common observations in baseline
- Independent of satellite clock product
- Reduction of various error sources
- No direct access to undifferenced slant delays
- Large matrix inversions when full correlations
  (limits for # of parameters)
  (CPU demanding ➔ clustering)
- Complex error propagation ➔ 'network biases'
  (different impact of orbit errors)
- Possible ambiguity resolution
  (*without additional products)*

…

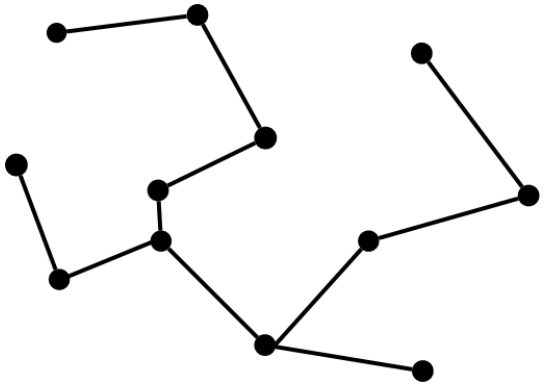
GNSS stations – PPP vs. DD (network)



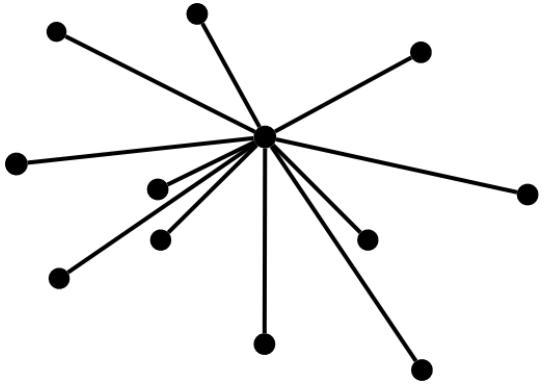
Precise Point Positioning



Maximum observations (DD)



Shortest (DD)



Star (DD)

→ *various impacts on the tropospheric estimations*

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)

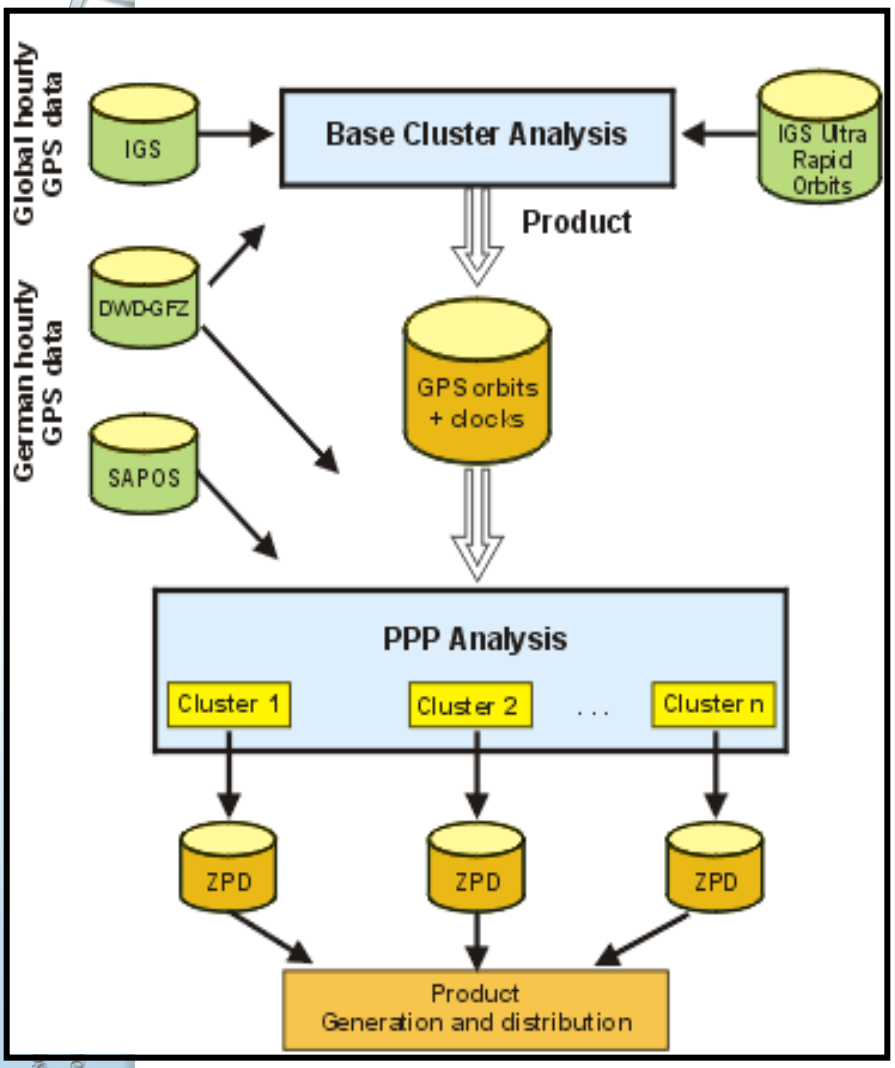
VÚGTK

Batch GNSS processing scenario

- creating data batches (hourly or in a sliding window)
- data quality check
- single point positioning for rough receiver clock synchronization
- network design/baseline definition using double differencing
- data screening (clock jumps, phase cycle slips, new ambiguities)
- iterative site & satellite quality checking and outliers rejection
- ionosphere product & ambiguity resolution
- coordinate fixing/estimating & reference frame definition
- ZTD product generation, QC & filtering

** Specific features of network (double-difference) solution*

PPP processing strategy (example GFZ)



Part 1 – Network for global products

➔Adjustment of precise orbits & clocks

Global network : IGS+German sites

Input orbits: GFZ 3h Ultra-rapid (prediction)

CPU time: 2-3 min

Part 2 - PPP troposphere analysis:

➔ Estimation of tropospheric parameters

Large set of parameters possible, i.e. supports of high rate ZTDs, tropospheric gradients, slant delays

CPU time: approx. 8 min for 350 stations

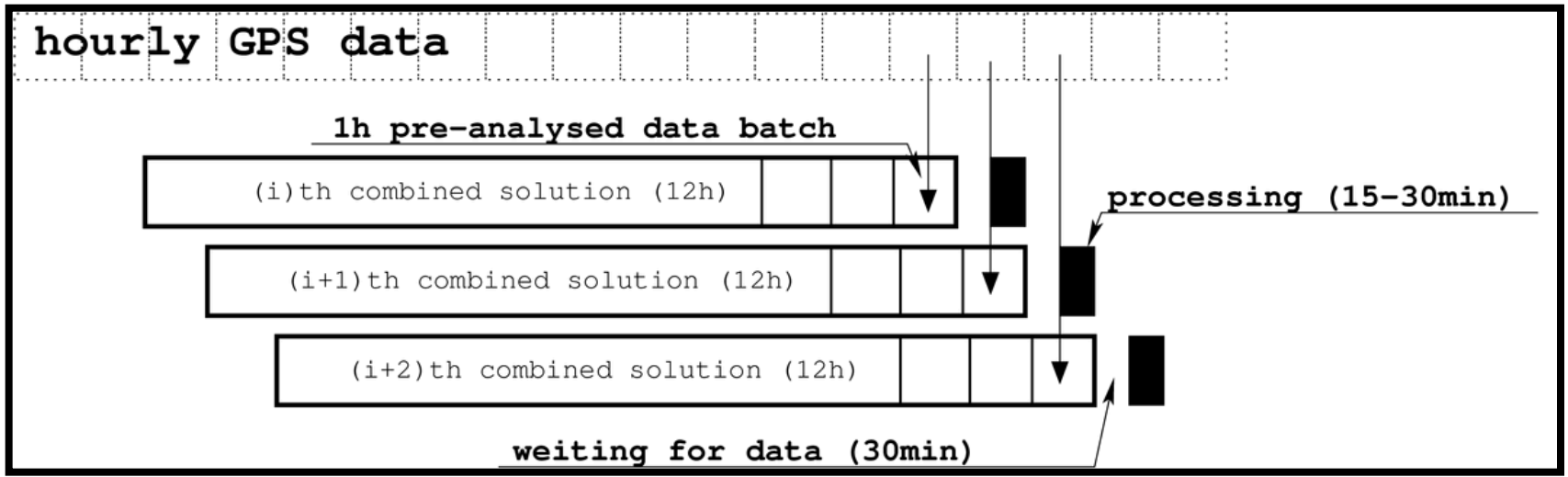
courtesy of Galina Dick (GFZ)

Network processing strategy (GOP example)

- pre-processing is based on two-hours data batches

  1 hour redundancy with the previous run - easier ambiguity resolution,

  - coordinates also for regularly 'late' RINEX (> 30min)
- normal equations (NEQ) – 1h for ZTD and 2h for coordinates
- processing in clusters of the network
- coordinates are combined from last 28 days using 4h-NEQs with ambiguity fixed, free-network solution, up-to-date reference frame
- ZTD product based on last 12h stacking of 1h-NEQs
- ionosphere product for ambiguity resolution



Ambiguity resolution (GOP example)

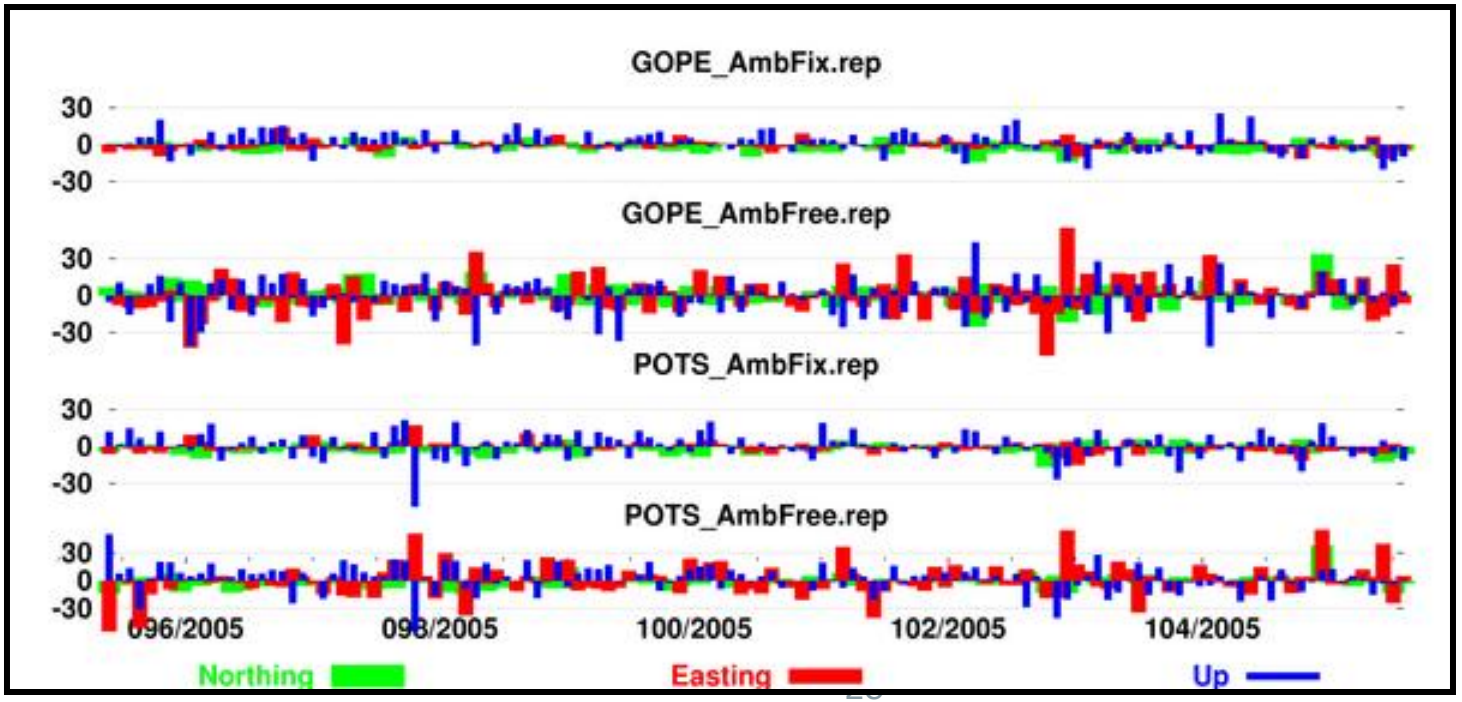
- initial phase ambiguities represent a huge number of additional parameters in the solution (> 90% of total number!)
- ambiguity resolution depends on time-window, baseline length, availability of a precise ionospheric product
- typically, in near real-time ambiguities are resolved from 60-80% by applying a dual step procedure (first wide-lane, second narrow-lane)
- in a network solution, they can be resolved for integer numbers, which has strong impact for coordinate estimation in a short-time data-span
- resolved ambiguities should be introduced for coordinate estimation - →*North/East/Up coordinate repeatability improved by a factor of 2*
- resolved ambiguities are not necessarily used in final estimation of ZTD

NRT coordinate solutions (GOP example)

The coordinates, which are 'fixed' or 'tightly constrained' in (near) real-time ZTD solution should be as good as possible although the rule-of-thumb ratio between UP : ZTD is about 1:3 (i.e. 3 mm in CRD → 1 mm in ZTD)

The coordinates are usually based on 'ambiguity-fixed' solution stacking normal equations from previous days, i.e. solution is updated every hour

The coordinates are expressed in a 'verified' datum that is very close to the up-to-date realization of the International Terrestrial Reference System

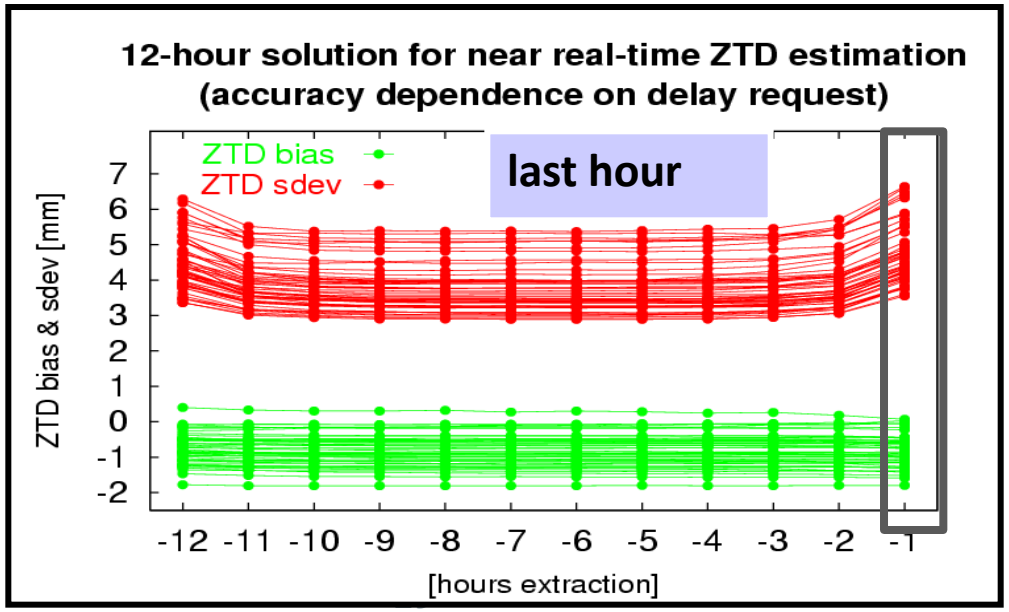


Tropospheric product (GOP example)

- Updated every hour (near real-time), available at HH:25
- *piece-wise linear function* for station ZTDs (HH:00 + HH:59)
- final coordinates constrained and written to the COST 716 format
- ZTD product filtering prior submission:
  - *Sites with less than 4 hours of data in a ZTD solution are excluded.*
  - *Sites with less than 2 days of data in a coordinate solution are excluded.*
  - *Sites with ZTD formal errors exceeding standard values are excluded.*
- ZTD constraints in NRT

  Absolute / relative: - / loose
- Last ZTD estimated at the end of observation window

  ➔ new solution update could replaces last end values



GOP tropospheric products - summary

Near real-time products - traditional approach

NRT regional product (GPS) - Bernese GPS V5.0 (2001-today)

NRT global product (GPS) – Bernese GPS V5.0 (2010-today)

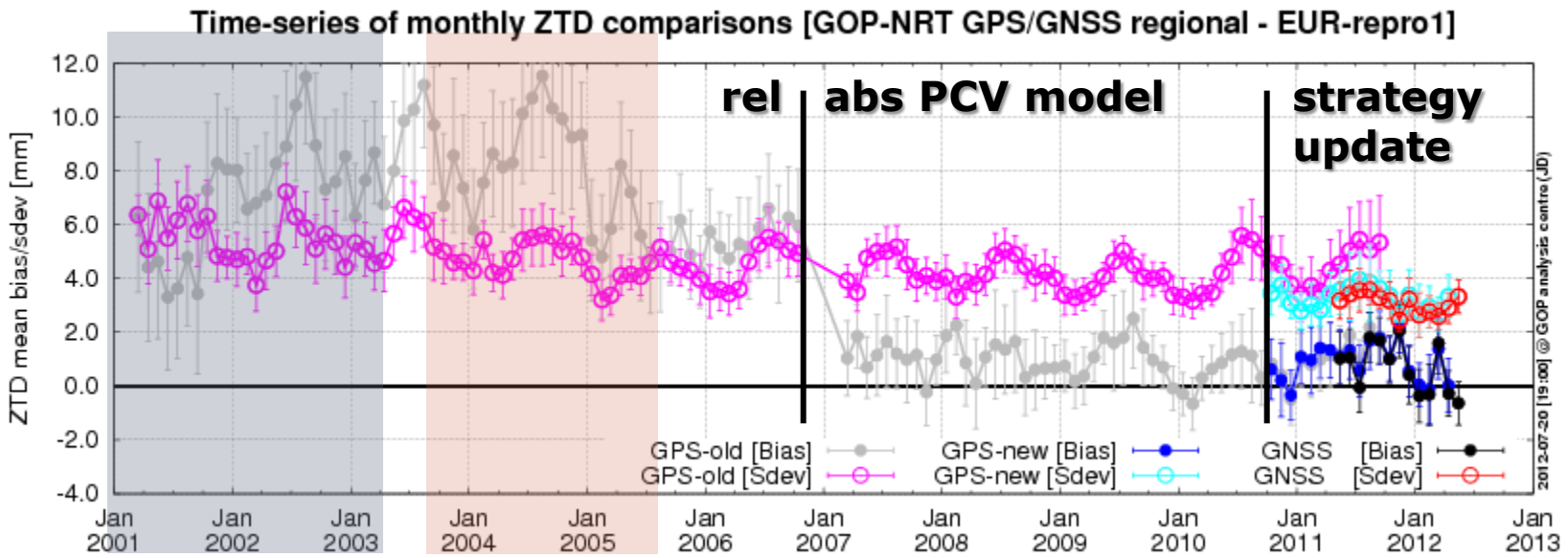
NRT regional product (GPS+GLONASS) – Bernese GPS V5.0 (2011-today)

New products - PPP

Real-time product (2013, demonstration)

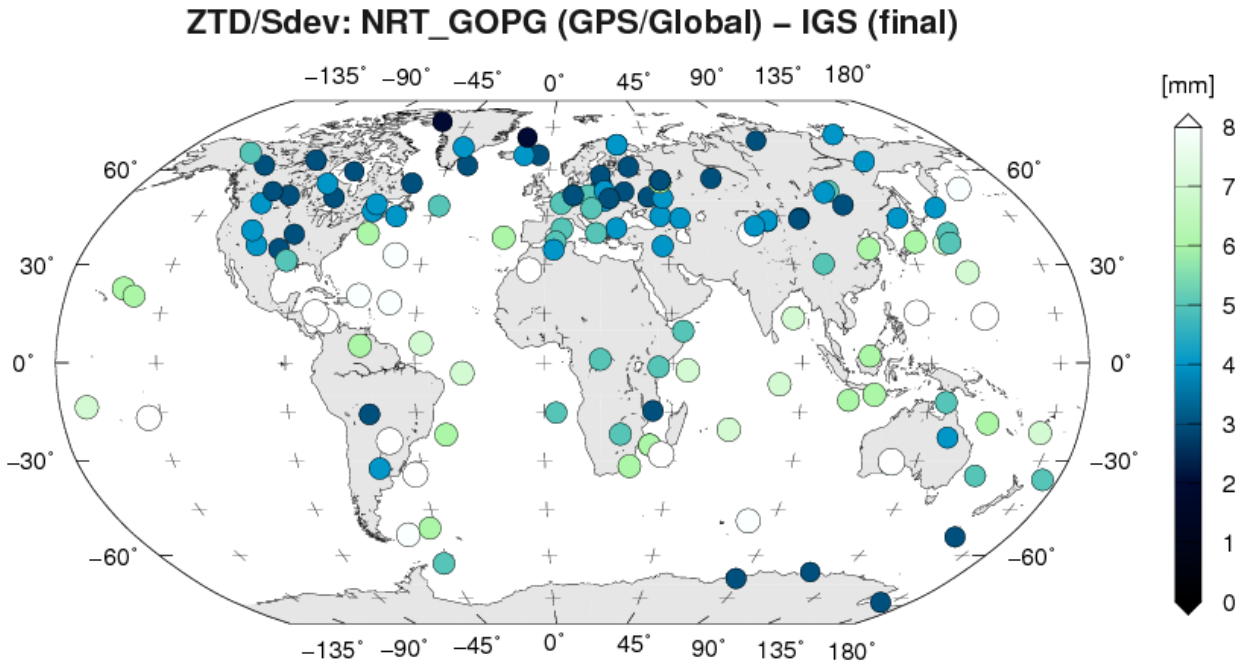
Sub-hourly product (2014, development)

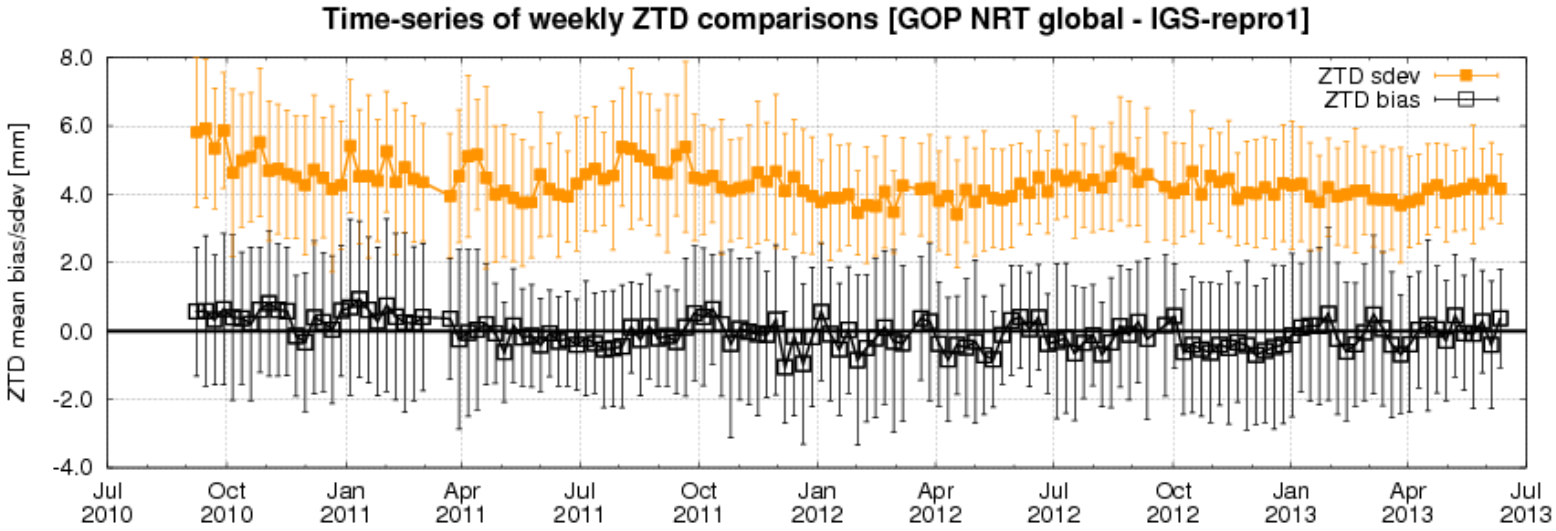
vs. final ZTD	AbsBias	StdDev
ZTD regional	0-3 mm	3-6 mm
ZTD global	0-1 mm	3-9 mm
ZTD real-time	~0-20 mm	5-10 mm



Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VUGTK

GOPG - global hourly ZTD solution

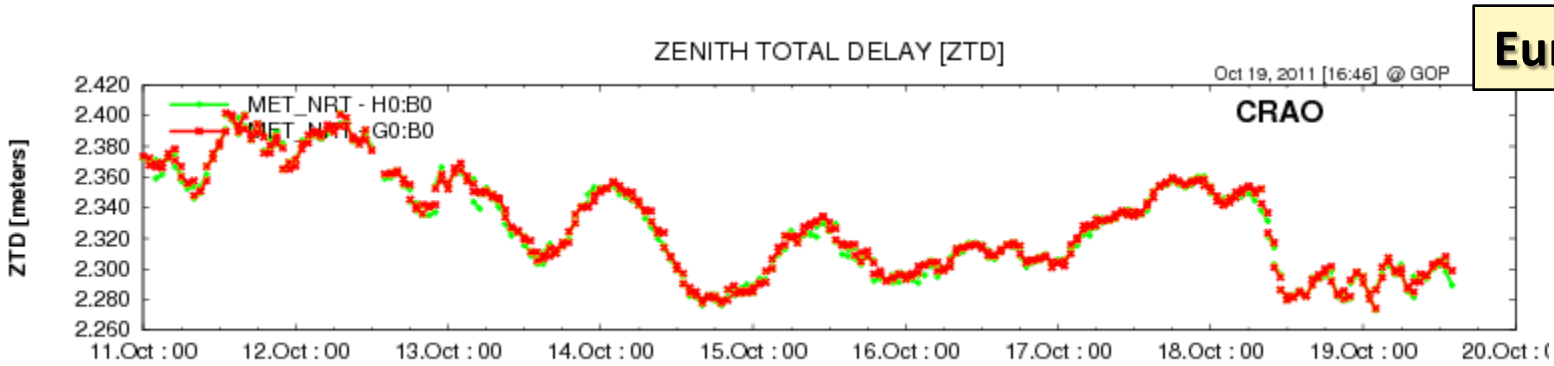




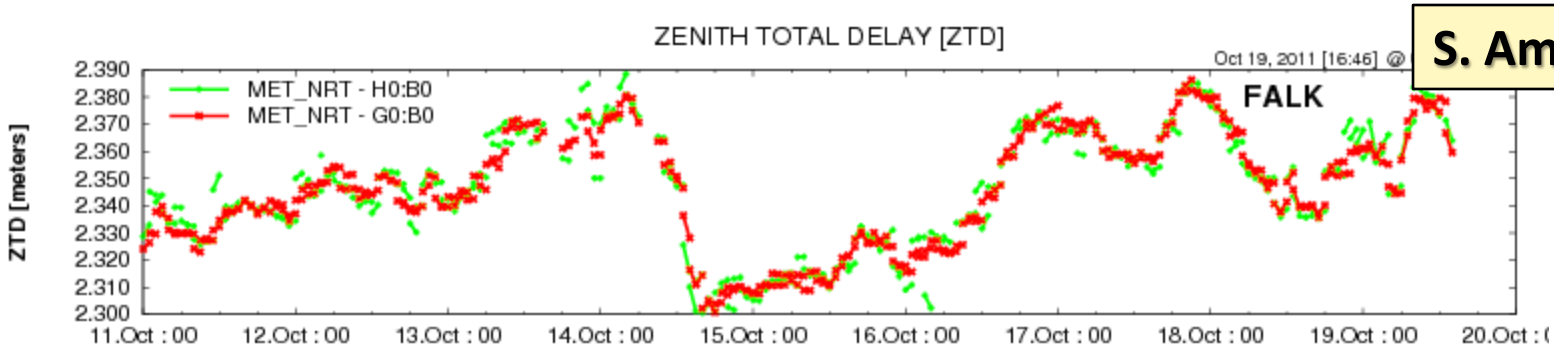
w.r.t. IGS final solution

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)

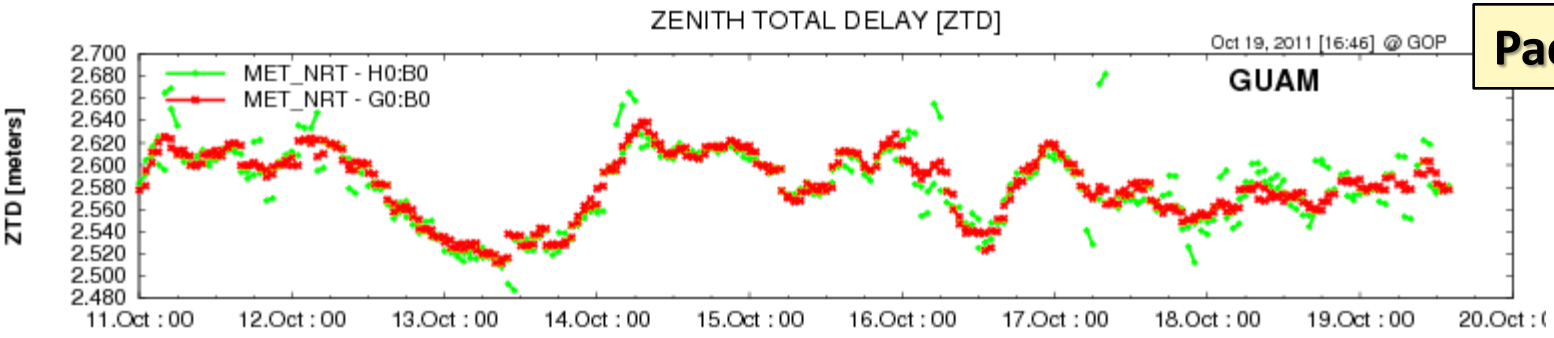
Global near real-time ZTDs – sample time-series



Europe

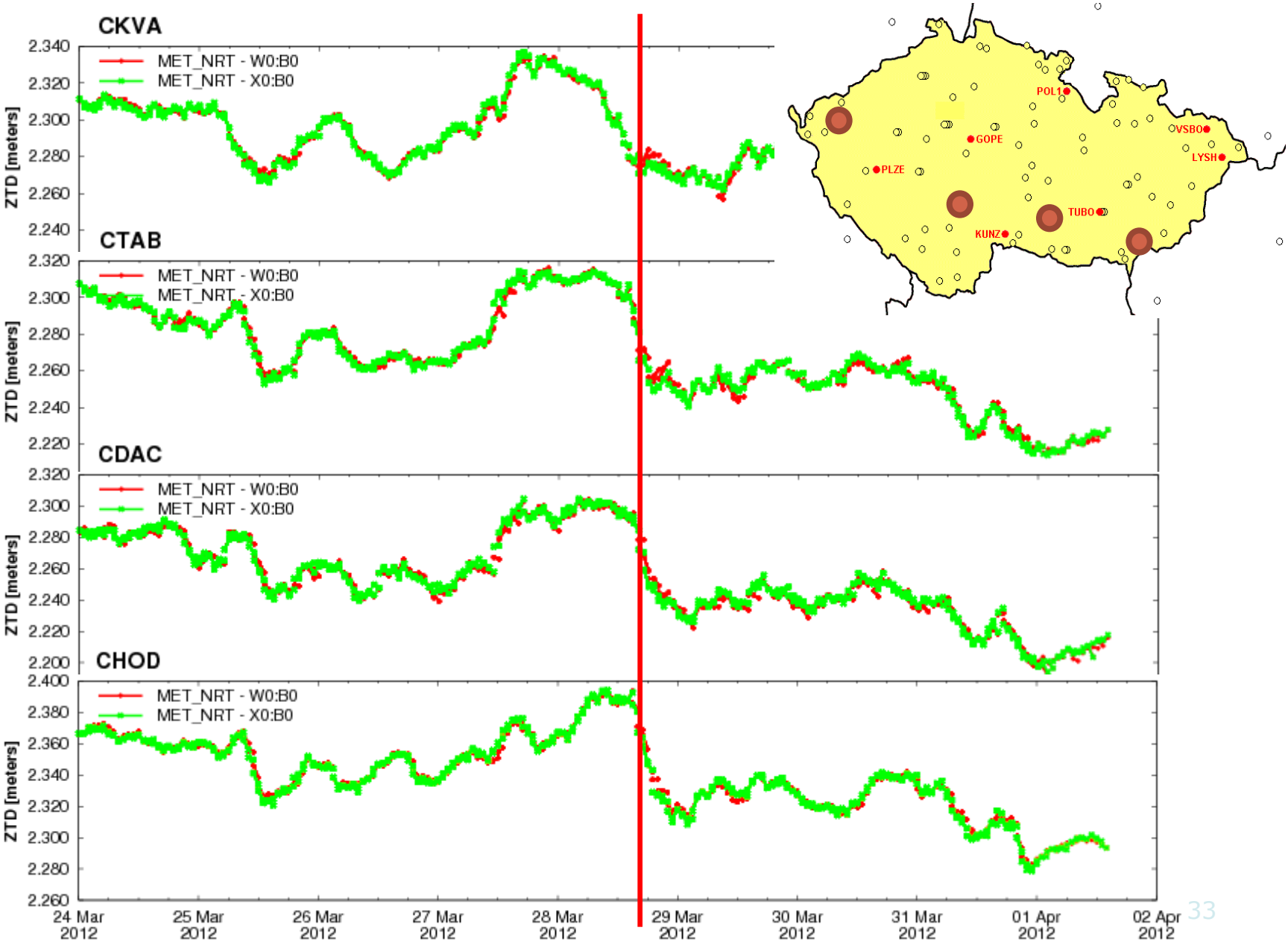


S. America



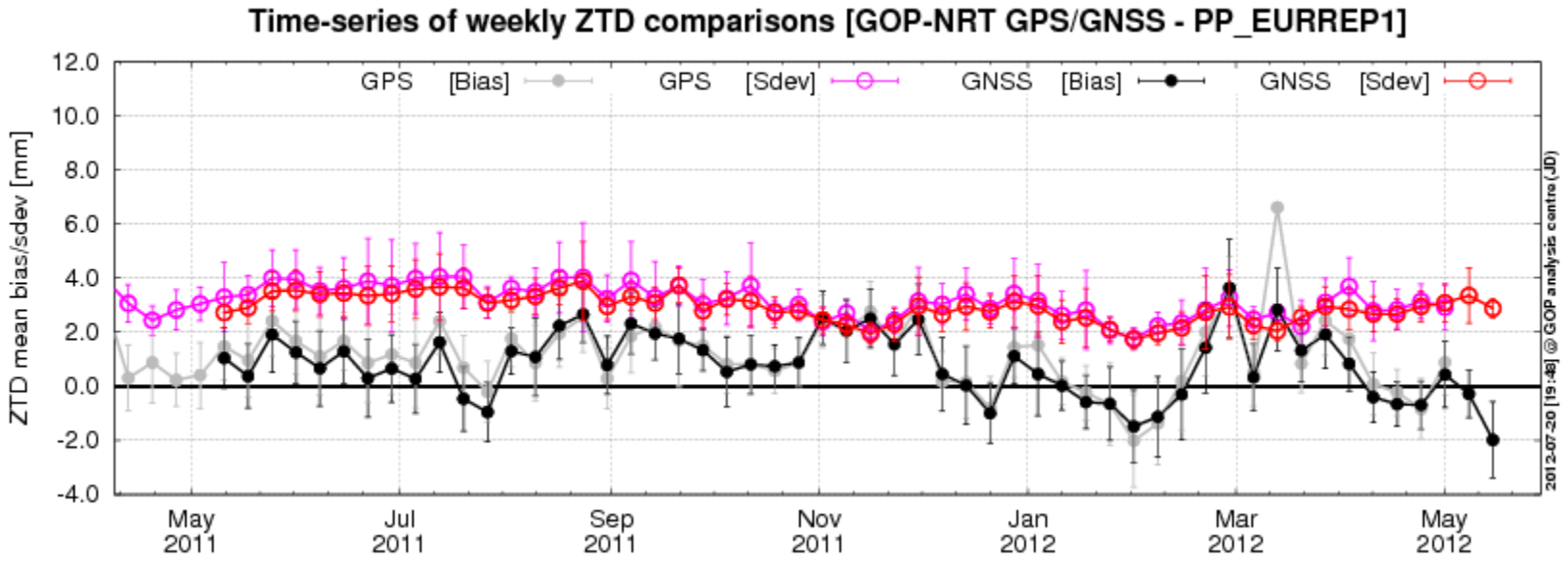
Pacific

ZTD evolution in time and space



Multi-GNSS – a few notes

- 'GPS world' dramatically changing into the 'GNSS world'
- Satellites: 28 (GPS) ➔ 56 (GPS+GLONASS) ➔ more than 100 in 2020
- Full integration will require a lot of effort ➔ consistent models, products …
- Progress in capabilities of ground-based networks to observe all systems
- Development of new methods for optimal exploitation of many new signals
- GPS+GLONASS ZTD ok! since GPS week 1632 (new IGS08 PCV+PCO models)



Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)

Summary & outlook

- GPS-meteorology well established in Europe (2001-today)
  -> E-GVAP: about 2000 stations with improving coverage
- GNSS coming soon
  -> more satellites & better geometry
- Two different approaches: PPP vs. network solution
  -> more attention on PPP in future
- New challenges
  - Multi-GNSS (global products, models consistency, various observations)
  - Real-time/ultra-fast processing for up-to-date meteorological applications
  - Asymmetry troposphere monitoring – horizontal gradients, slant delays,

- COST ES1206 Action aims at covering the above challenges

Research Institute of Geodesy, Topography and Cartography
Geodetic Observatory Pecný (GOP)
VÚGTK