Real-time troposphere monitoring at GOP

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Standard ground-based GNSS troposphere monitoring

Production in near-real time (NRT):

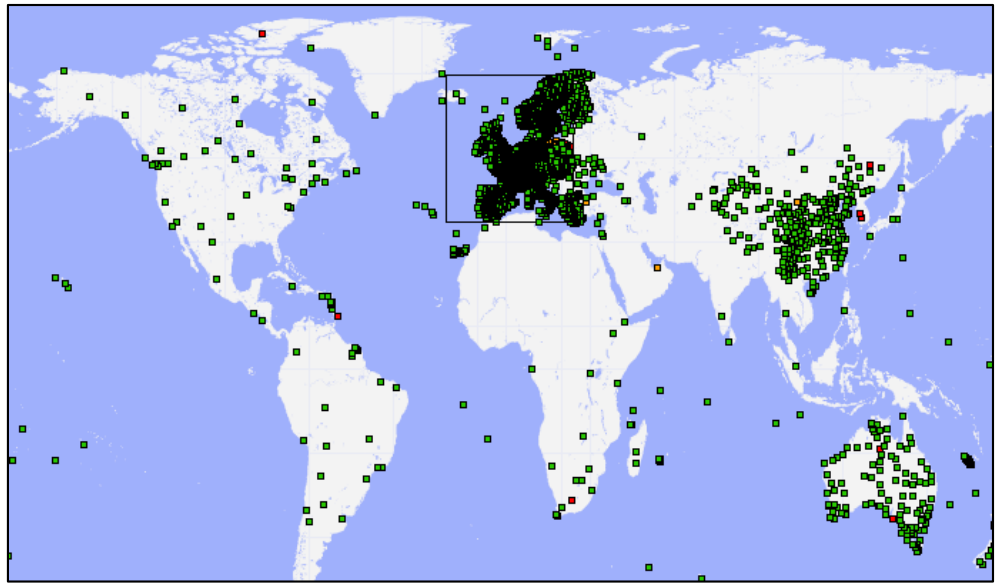
- E-GVAP – the EUMETNET EIG GNSS Water Vapour Programme (I-IV, 2004-…)
- **Dominant strategy**: network (DD) solution based on ultra-rapid precise orbits
- **Exploitation**: GNSS ZTD assimilated into Numerical Weather Model
- **Requirements:** latency < 90 min, σZTD < 10 mm (IWV < 1.5kg/m^2)

https://egvap.dmi.dk

… NRT operational products satisfy requirements

… ground-based GNSS is considered well-established method for sensing troposphere

… new challenges towards advanced troposphere productions (fast, autonomous, anisotropy) …



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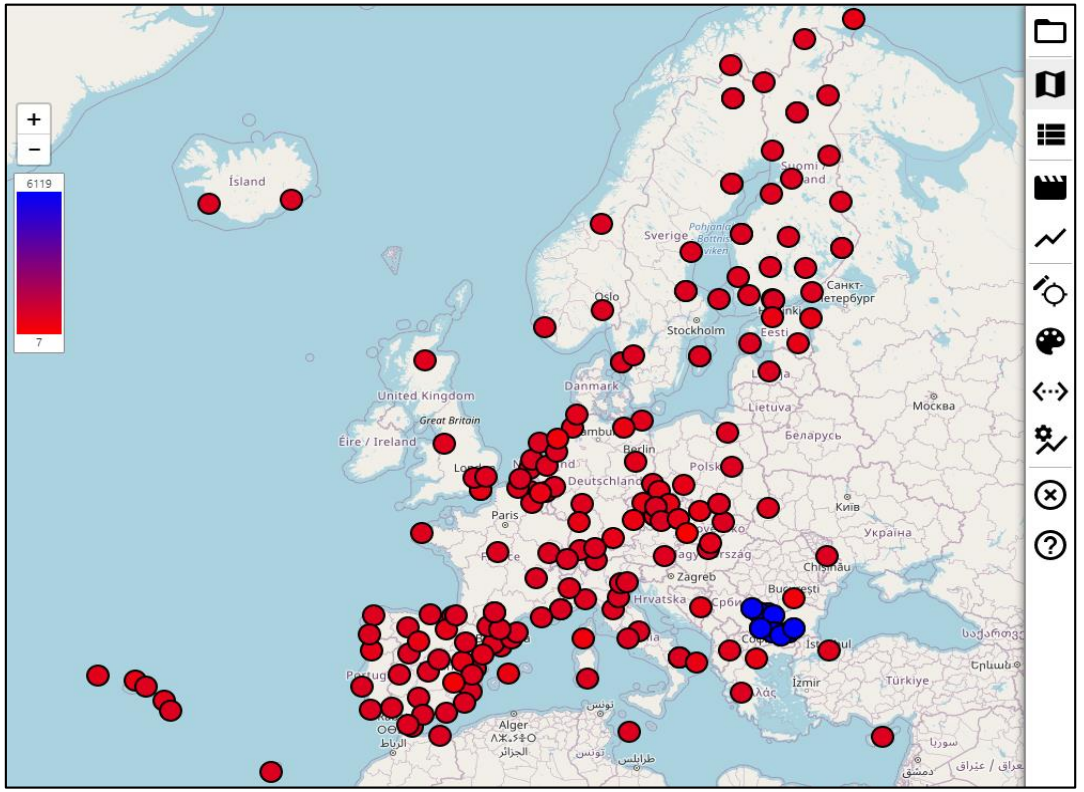
Real-time troposphere production at GOP

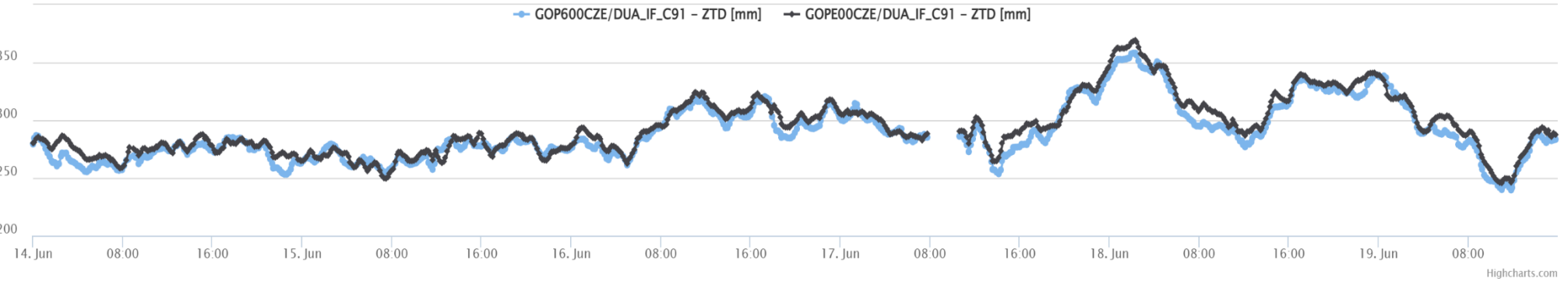
Software: G-Nut/Tefnut RT [a)]
Strategy: PPP (IF / UU model)
Method: Kalman filter
Inputs: 1Hz observations in RTCM streams
Estimates: ZTD + GRD + SLT (5min) + CRD (static)
Outputs: TRO_SINEX v2 files (every 5-60 min)
Constellations: GPS+GLONASS+Galileo (or individual)
Scope: 250+ European/global stations (no limit)



a) https://www.gnutsoftware.com

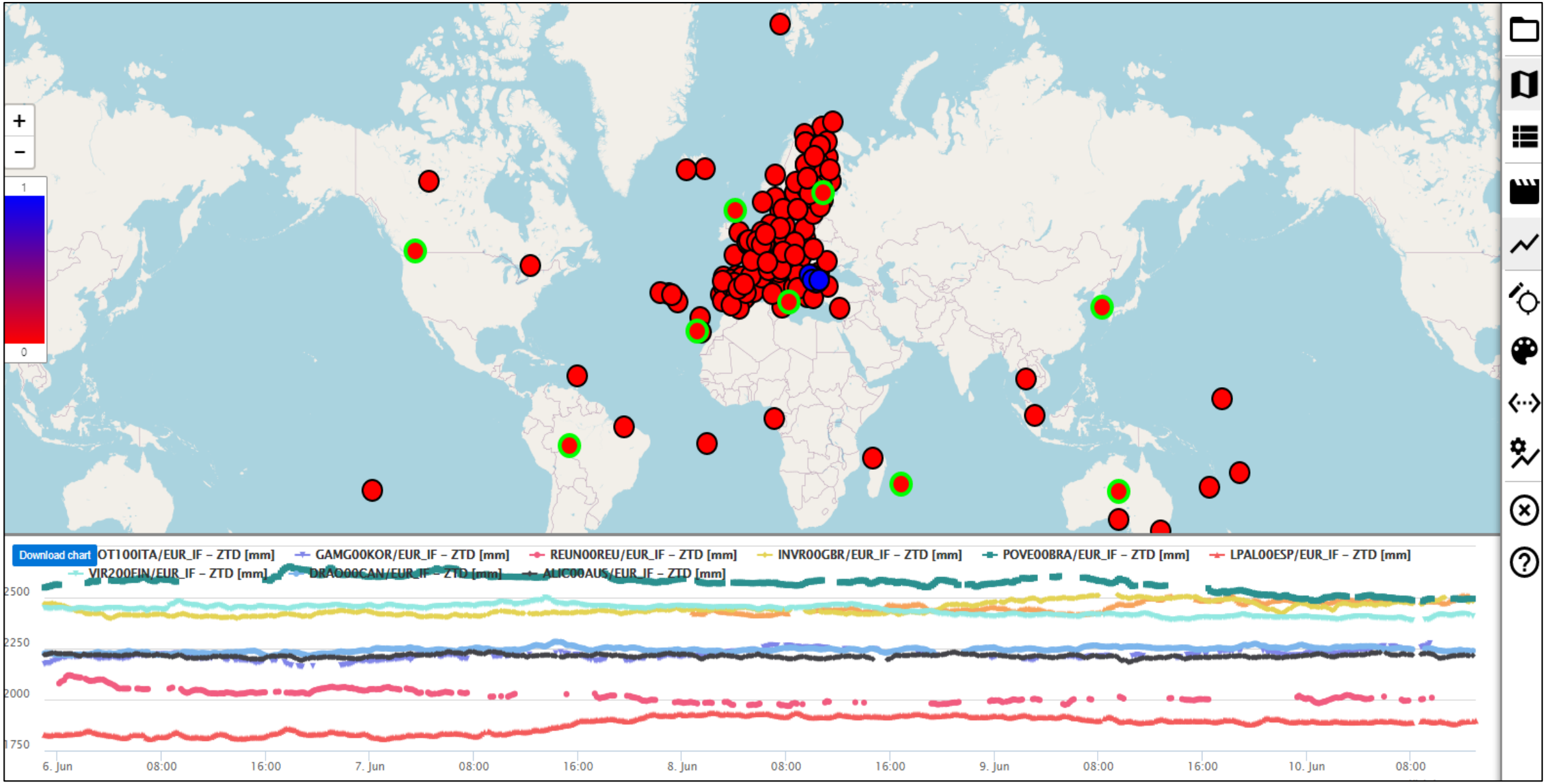
Collocation stations:

ZTD from collocation stations @GOP:



GOP real-time GNSS tropospheric portal

https://www.pecny.cz/RT-TROPO



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Real-time ZTD vs Final ZTD (EUREF)

Evaluations (2019-2021):

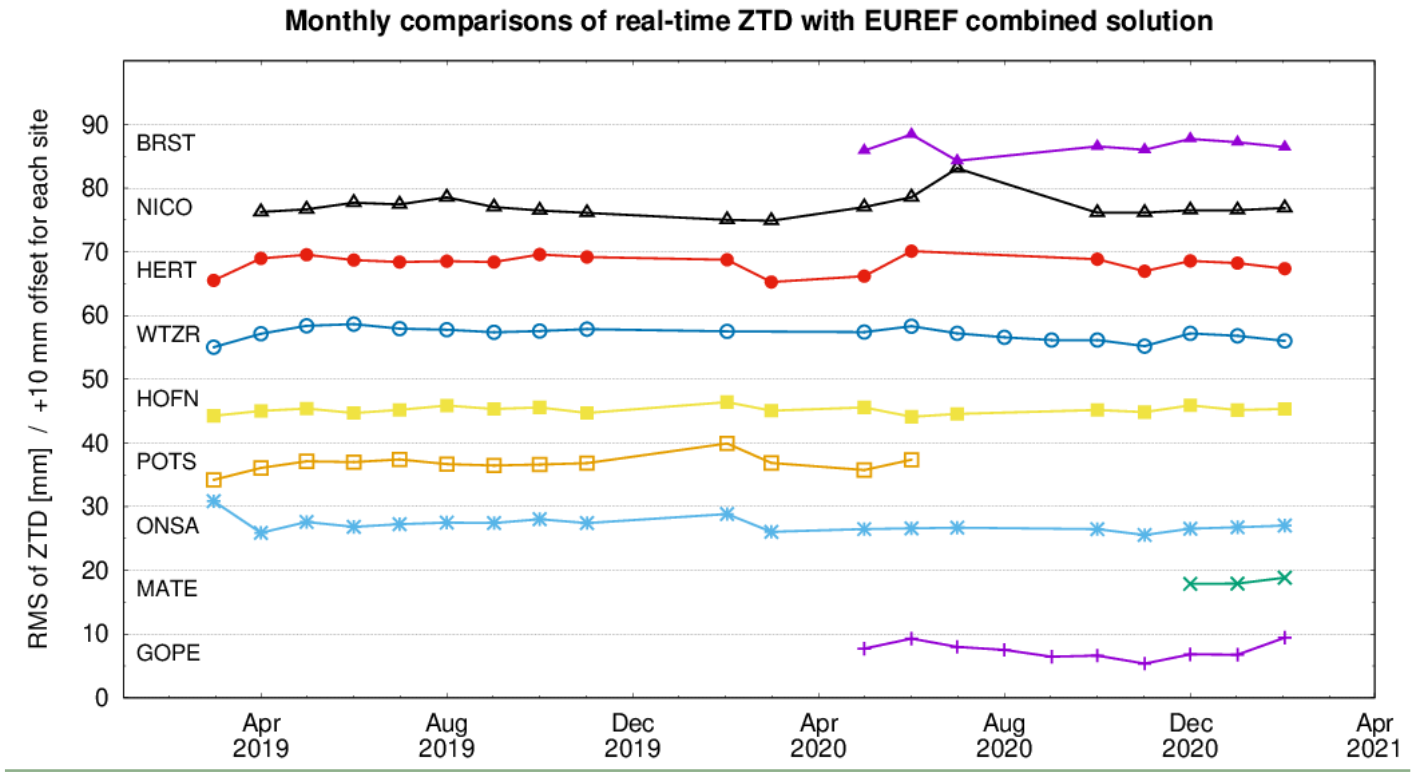
- 9 selected EUREF stations
- ZTD only (!GRD @ EUREF)
- common epochs (1 hour)
- period: 2019-2021

Solutions:

- GOP real-time (PPP)
- EUREF (final, combined)

Results:

- Figure: monthly RMS
  - ➔ **ZTD: 6-10 mm**
- Table: mean statistics
  - ➔ **ZTD RMS: 5-8 mm**



Station	Mean [mm]	Std Dev [mm]	RMS [mm]
BRST	2.58	5.95	**6.43**
NICO	3.15	6.04	**6.53**
HERT	5.42	6.02	**8.53**
WTZR	4.82	5.12	**7.20**
HOFN	2.34	4.64	**5.16**
POTS	4.28	5.08	**6.82**
ONSA	4.91	4.66	**6.76**
MATE	2.58	7.55	**7.91**
GOPE	4.14	5.43	**6.81**

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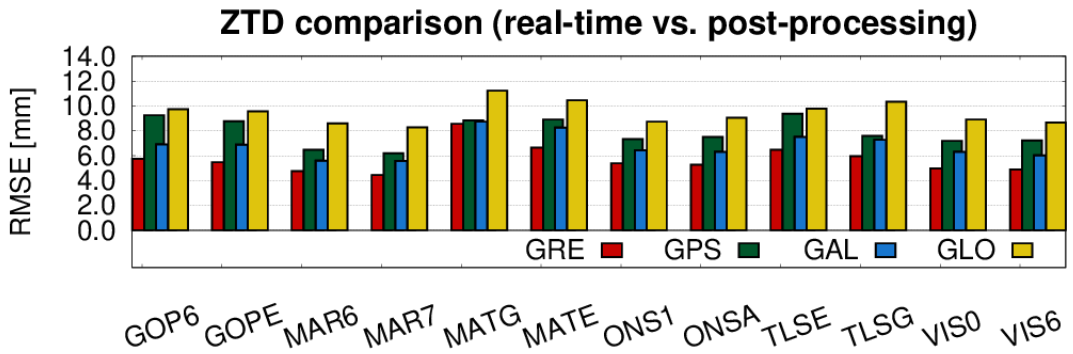
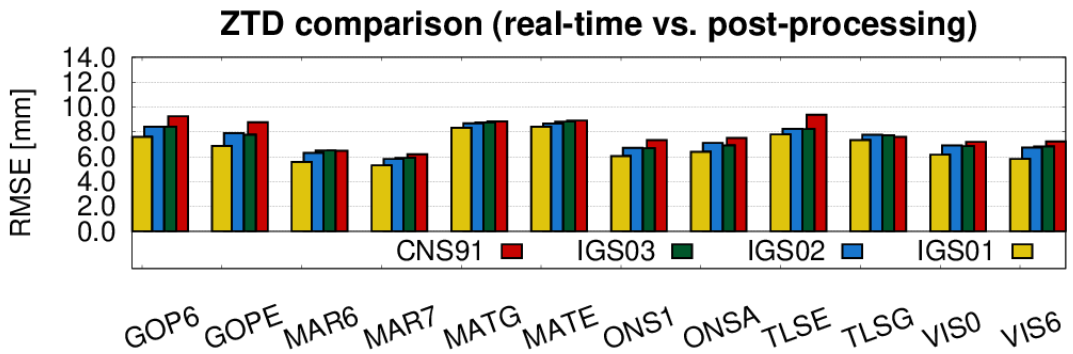
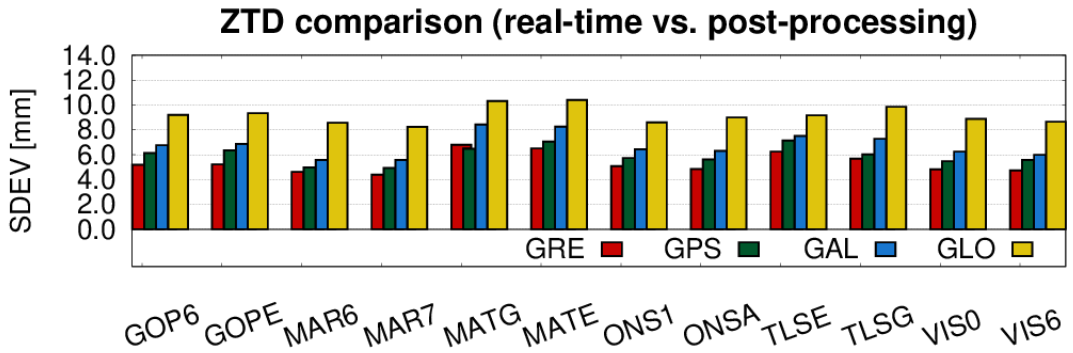
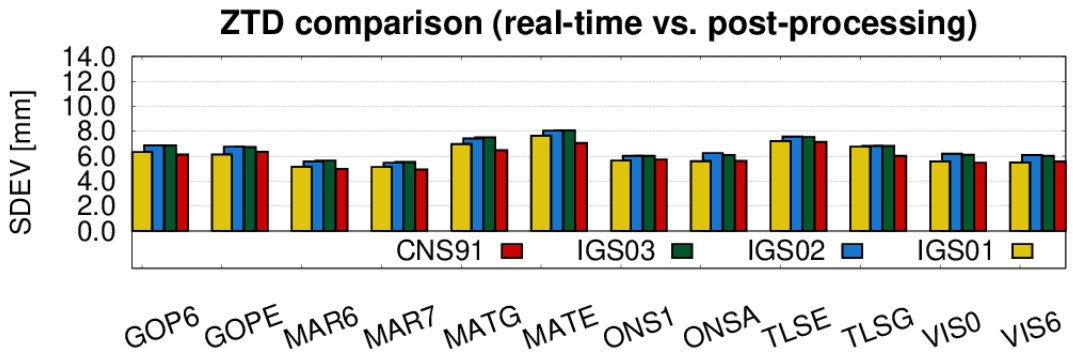
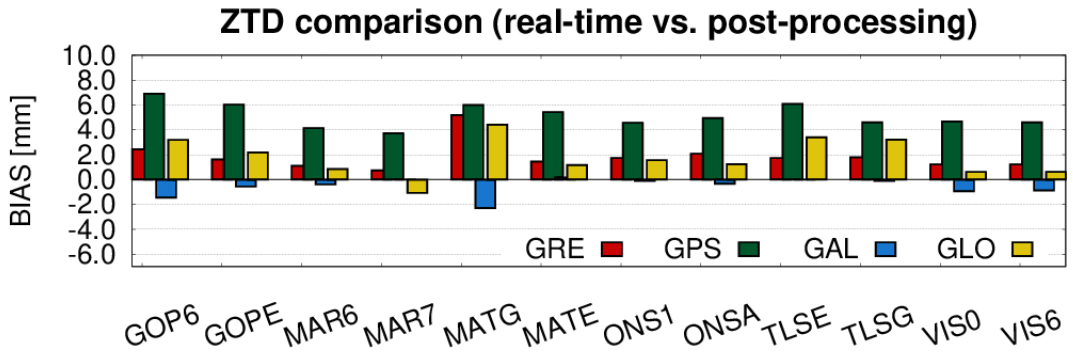
Constellation/product benchmark (July/August 2021)

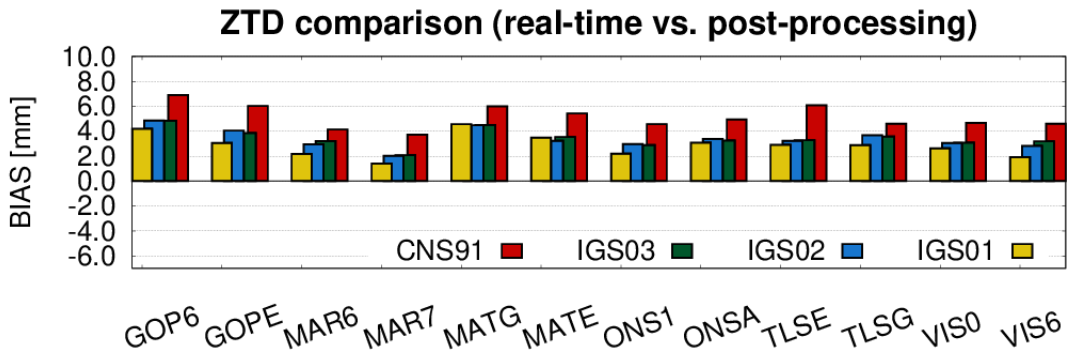












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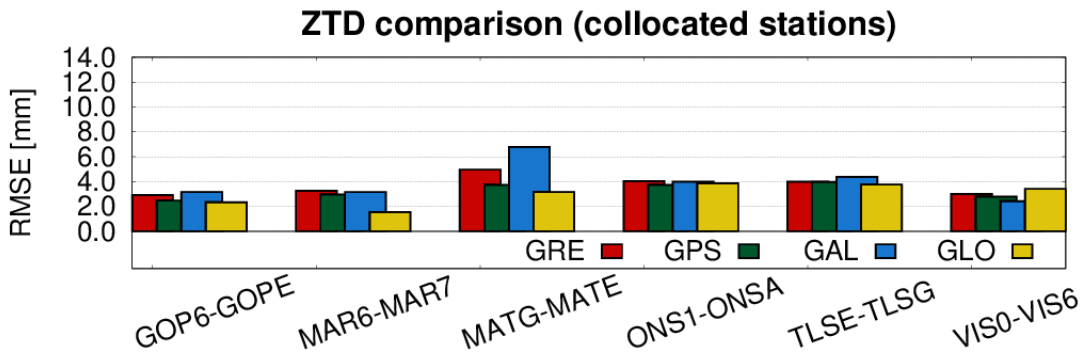
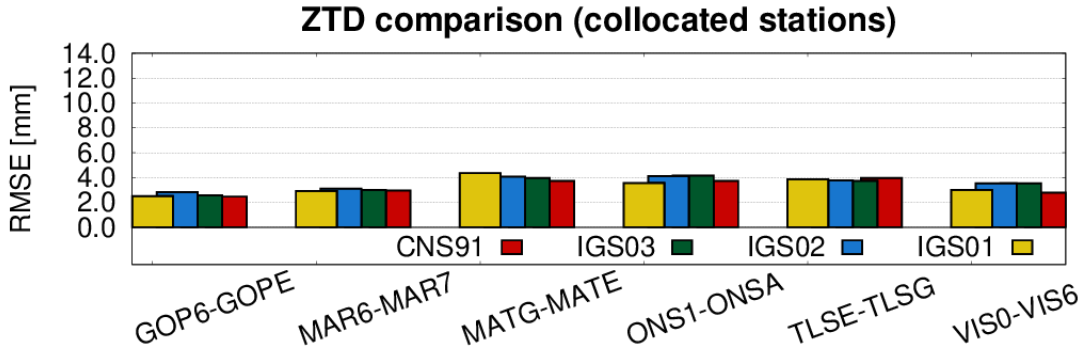
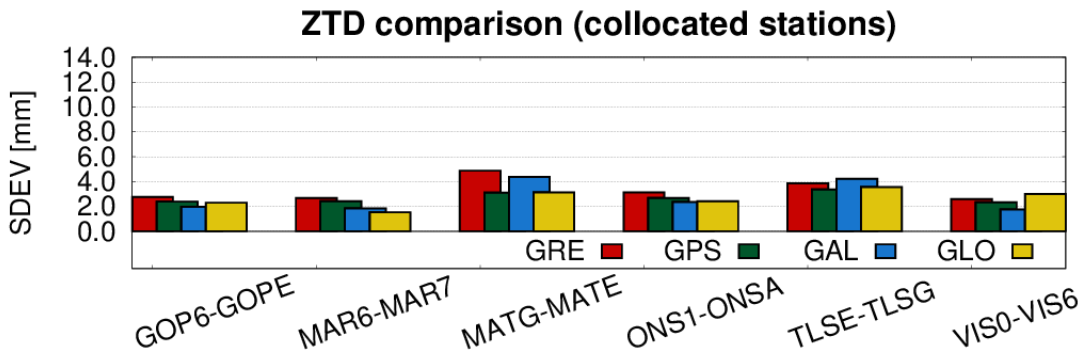
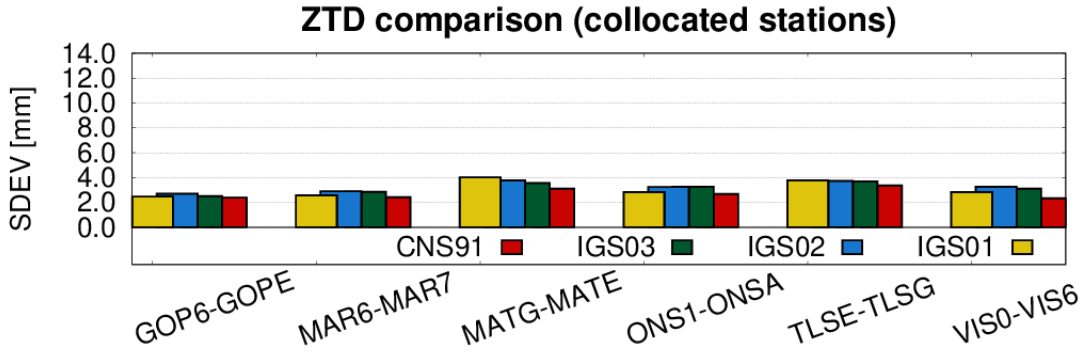
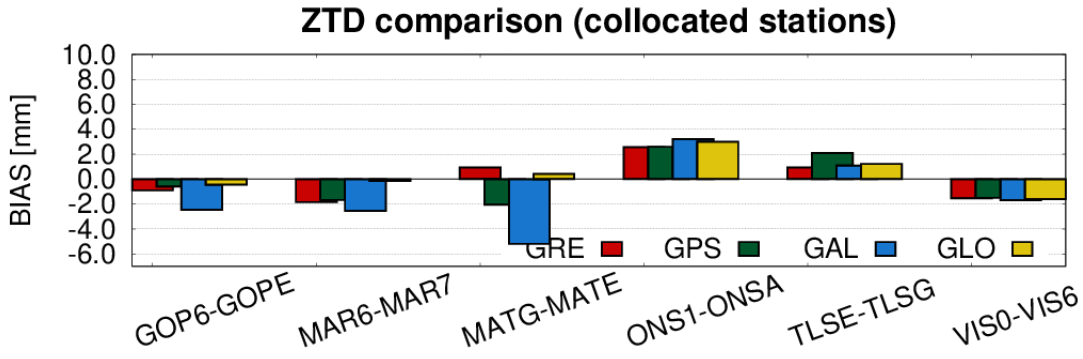
Constellation benchmark (collocation stations)

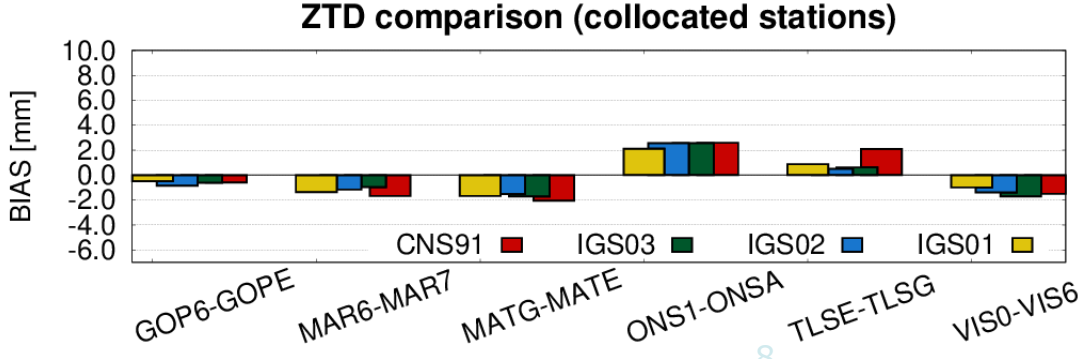




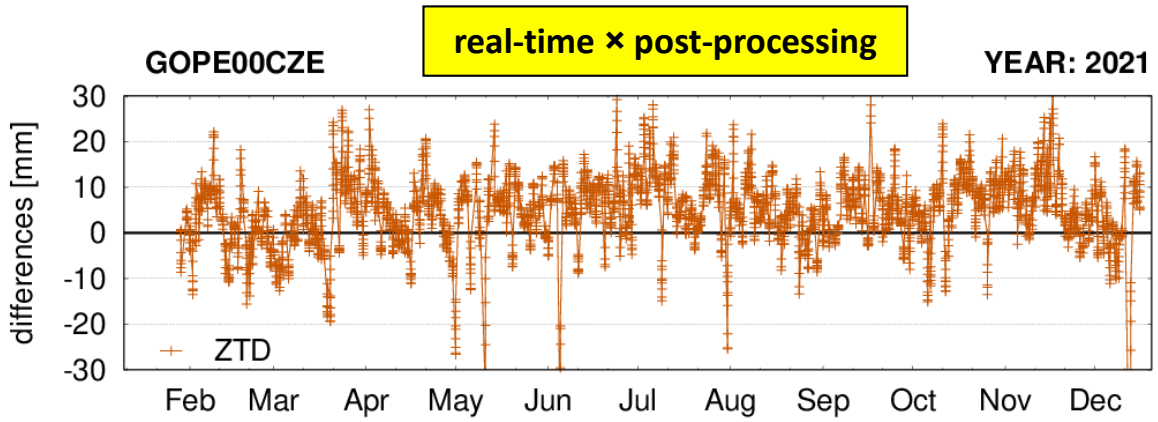


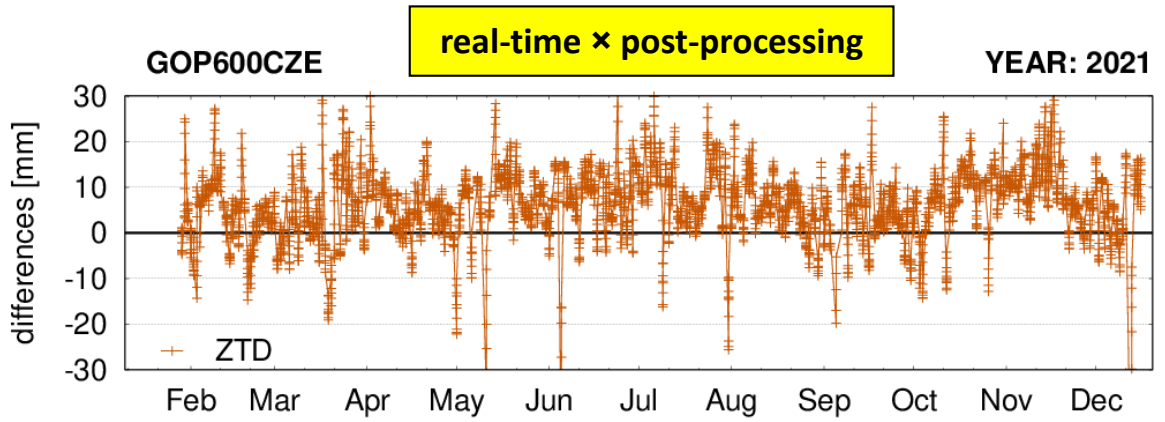


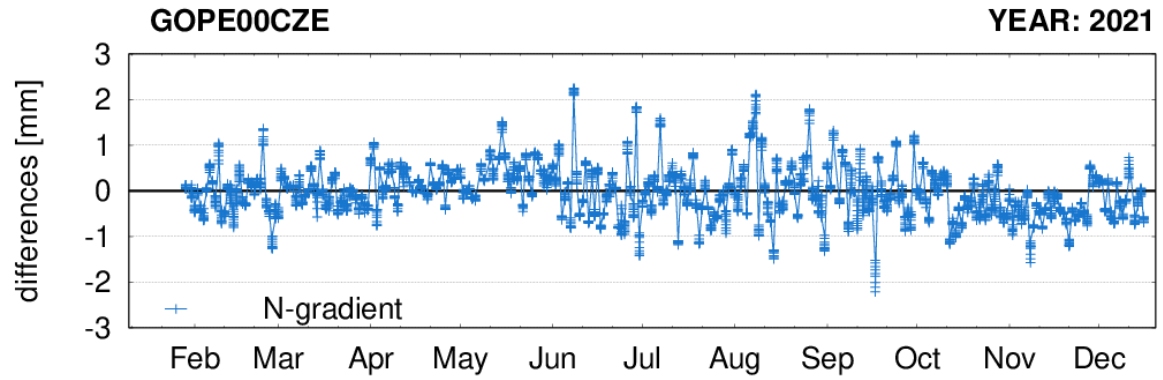


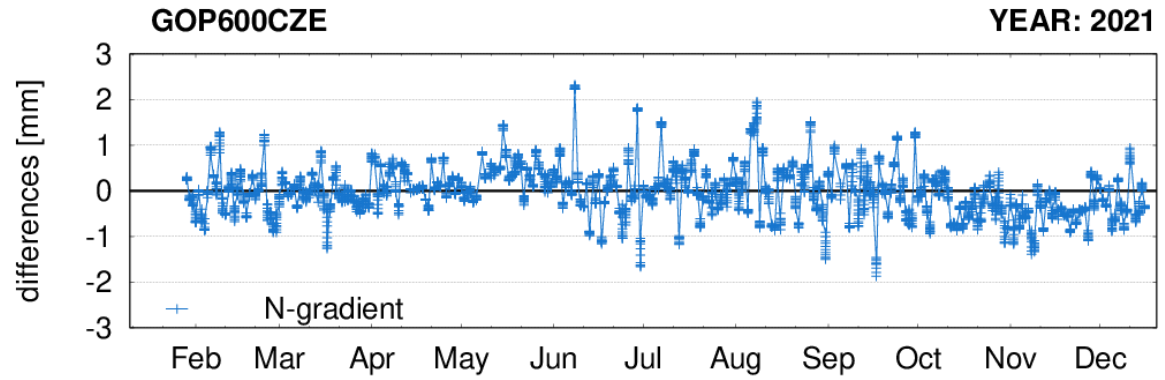


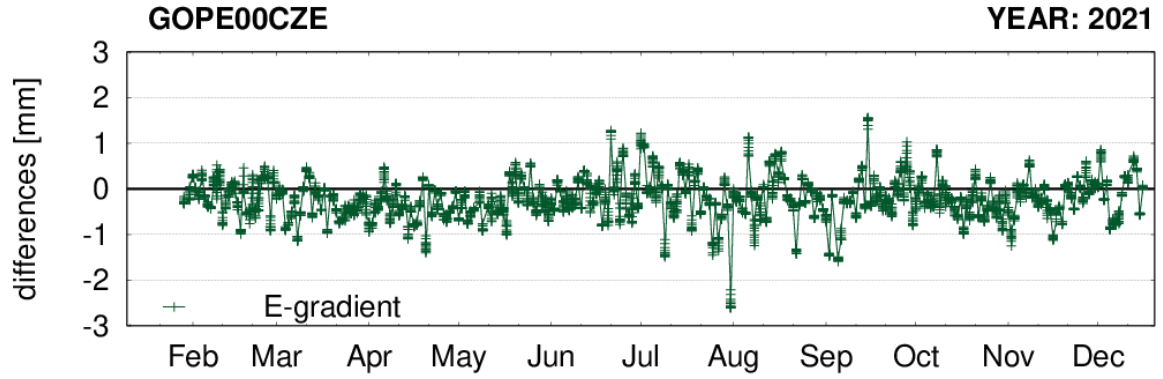
real-time – post-processing (@ collocation stations)

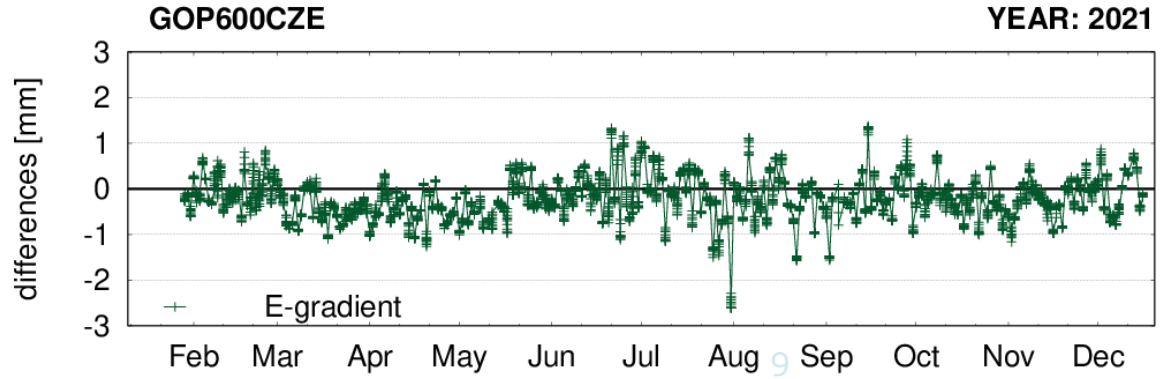






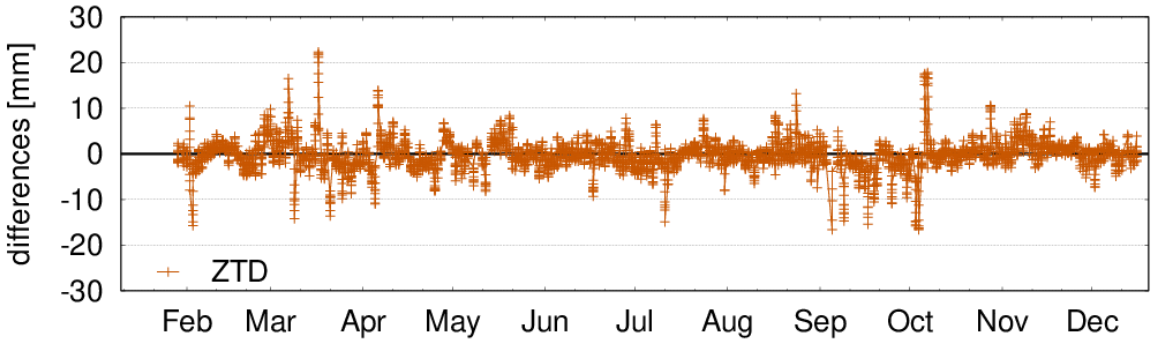


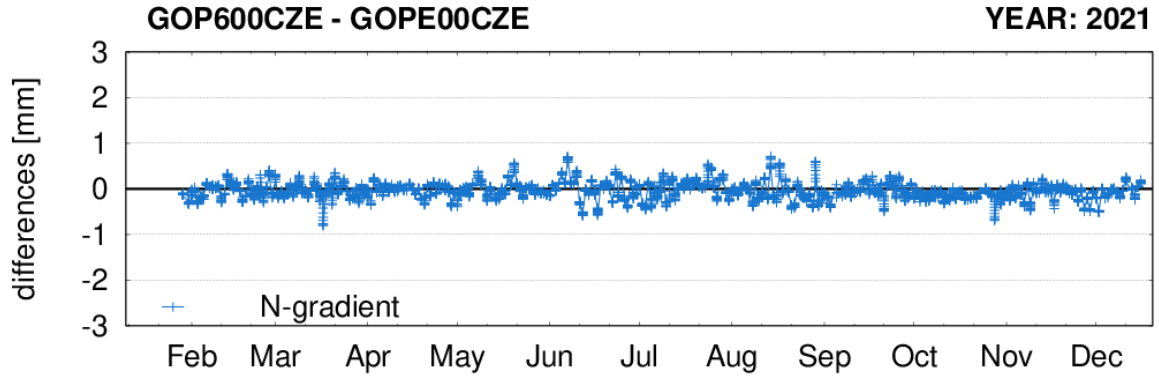


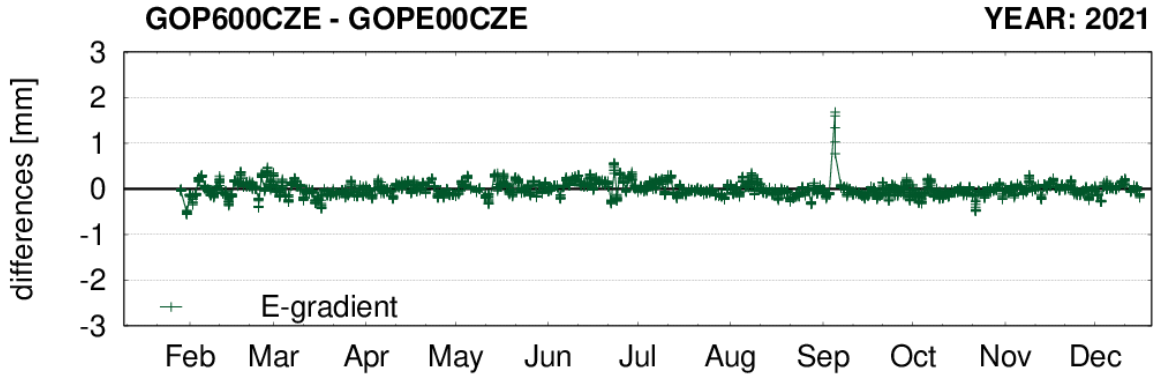


real-time | post-processing (use collocation stations)

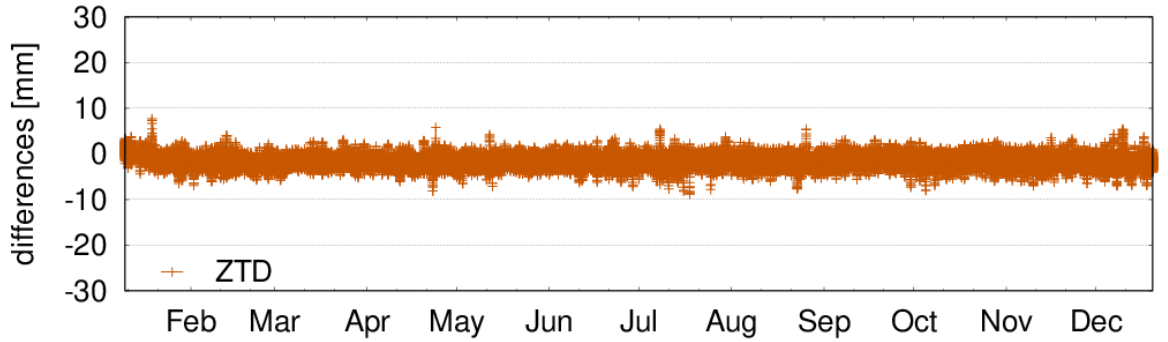
real-time

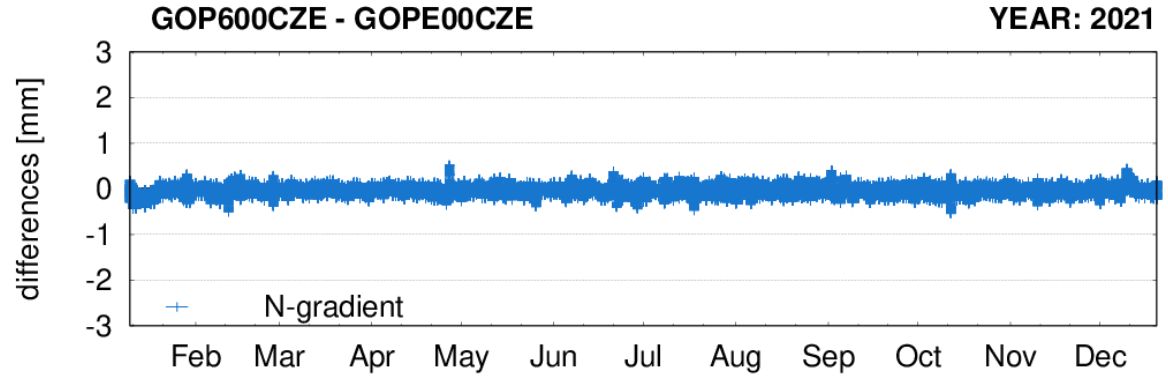


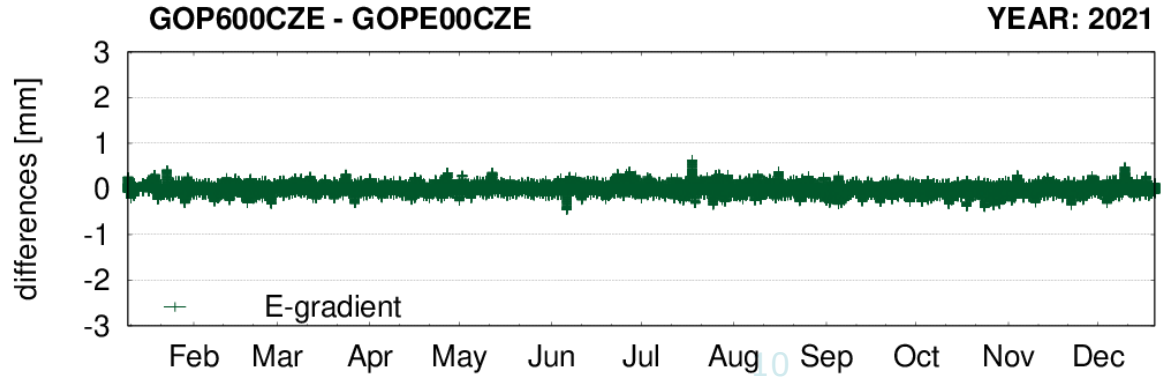




post-processing







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PPP observation model

Ionosphere-free LC:

- higher IF LC observation noise
  - weighting of LC observation only
- less parameters to be estimated
  - eliminate 1st order ionosphere
- dual-frequency only
  - no need for code biases if L1+L2 used

Undifference/uncombined:

- original observation noise
  - weighting of original signals
- more observations/more parameters
  - simultaneously derived ionosphere (product)
  - inter-frequency clock biases (for L5)
- dual & multi-frequency
  - optimal use of modern GPS (e.g. L5)
  - flexible use of multi-frequency observations
  - interesting support for low-cost receivers
- single-frequency
  - if precise input ionosphere available

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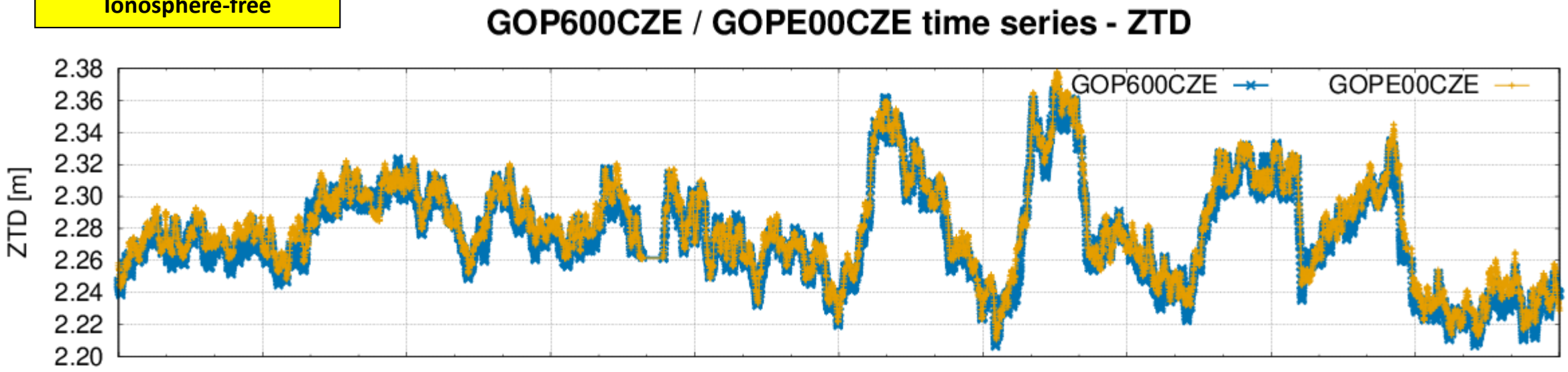
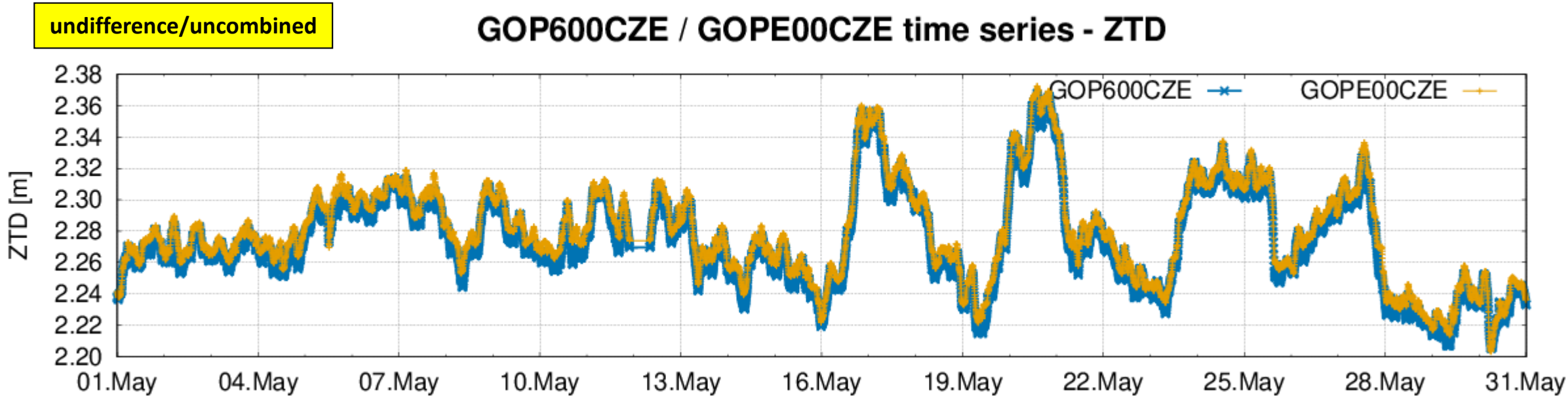
Collocation station: PPP with IF / UU observations

Ionosphere-free



undifference/uncombined



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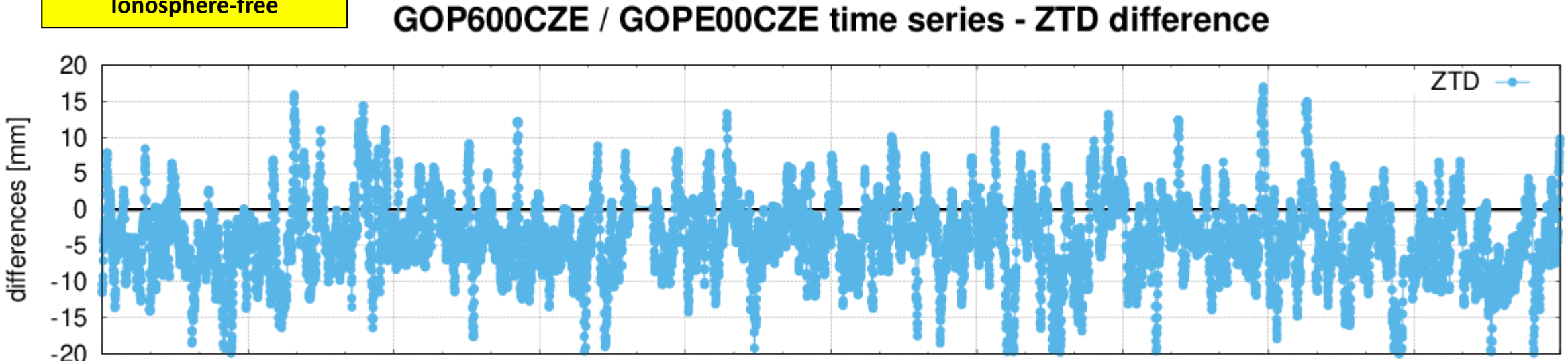
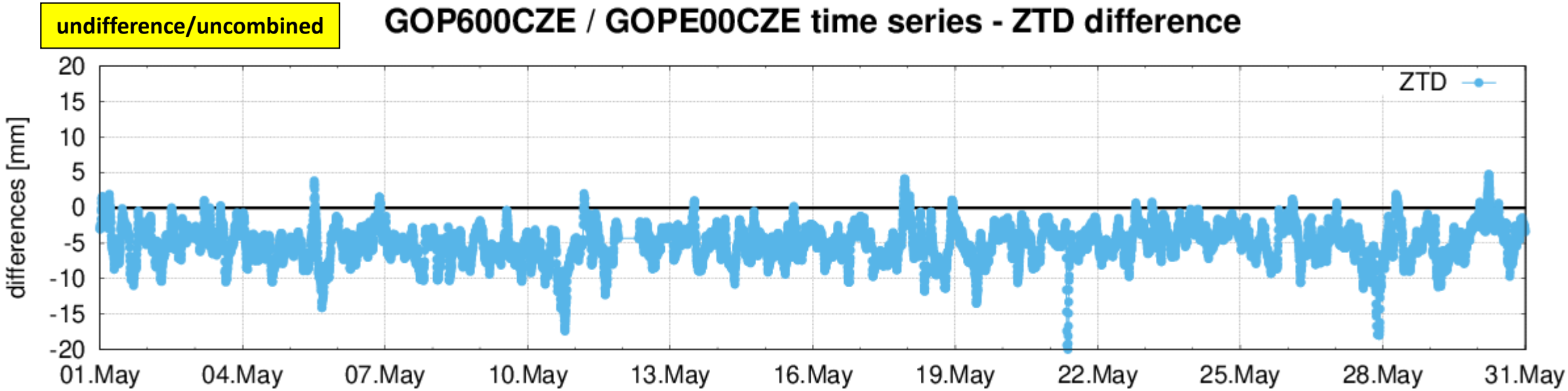
Collocation station: PPP with IF / UU observations

Ionosphere-free



undifference/uncombined



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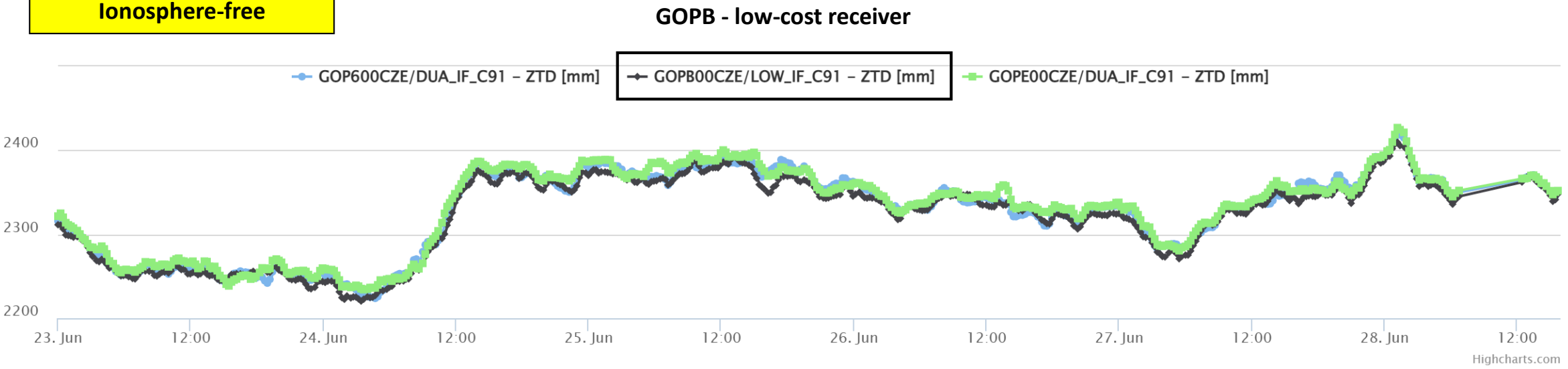
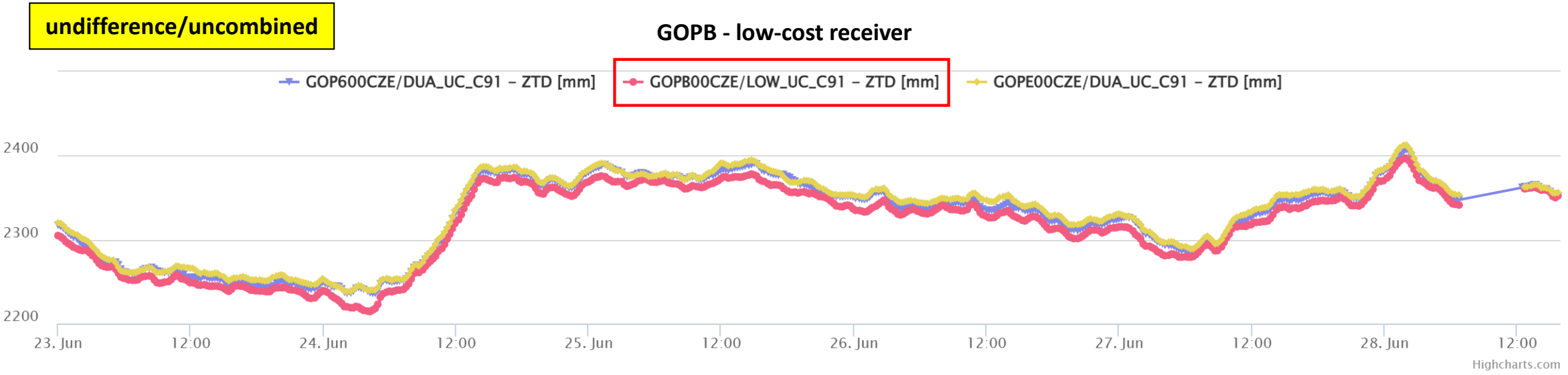
Collocation station: geodetic x low-cost receiver

Ionosphere-free



undifference/uncombined



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Troposphere validation

GNSS final:

Software: G-Nut/Tefnut Pro

Strategy: Precise Point Positioning

Orbits+clocks: CNES final product

Method: Kalman filter + smoother

Inputs: 30s observations (RINEXO)

Constellations: Galileo, GPS, GLONASS, multi-GNSS

Estimates: ZTD + GRD + SLT (5min) coordinates (24h)

ERA5 (NWM)

Software: G-Nut/Shu *(& DNS by F.Zus)*

Space resolution: 37 vertical pressure levels, 0.25deg × 0.25deg

Time resolution: 1-hour (original), any (interpolated)

Method: numerical integration

Inputs: ERA5 Grib files from ECMWF

Estimates: ZTD/ZHD/ZWD

(& gradients, slants, mapping factors)

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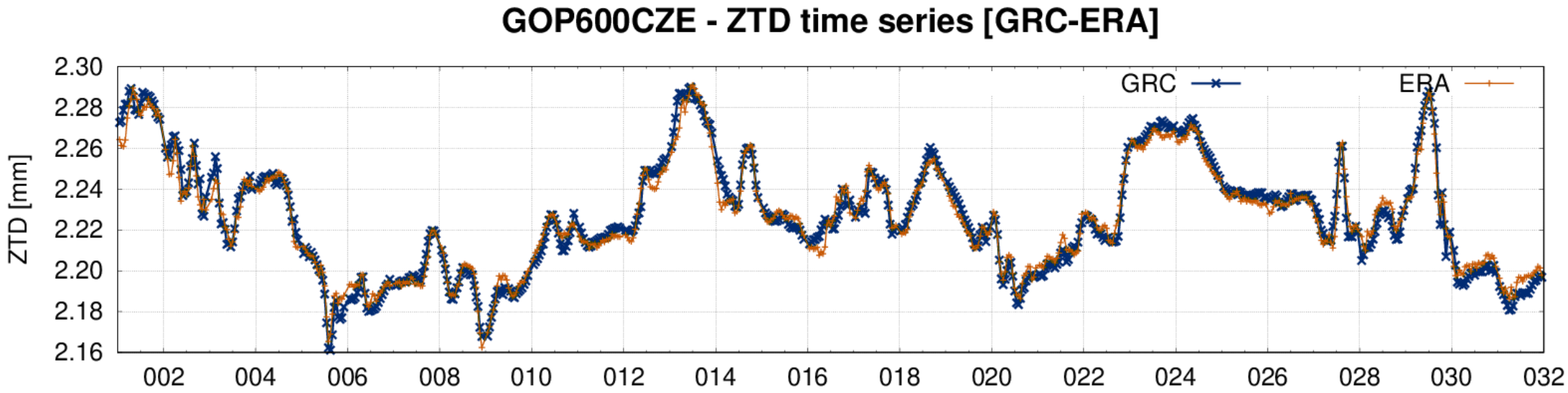
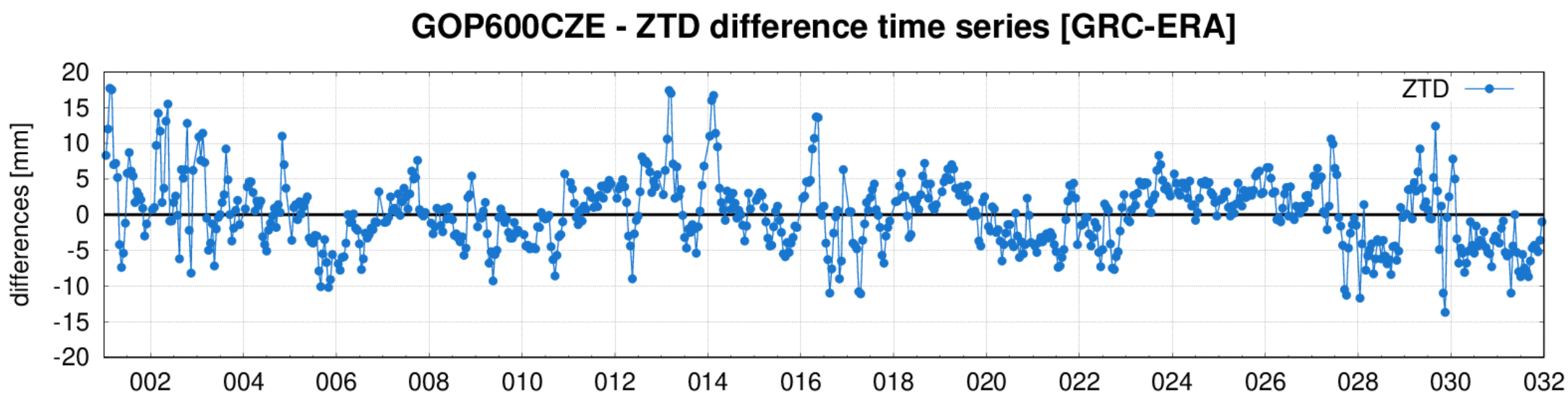
GNSS x ERA5 (numerical weather)





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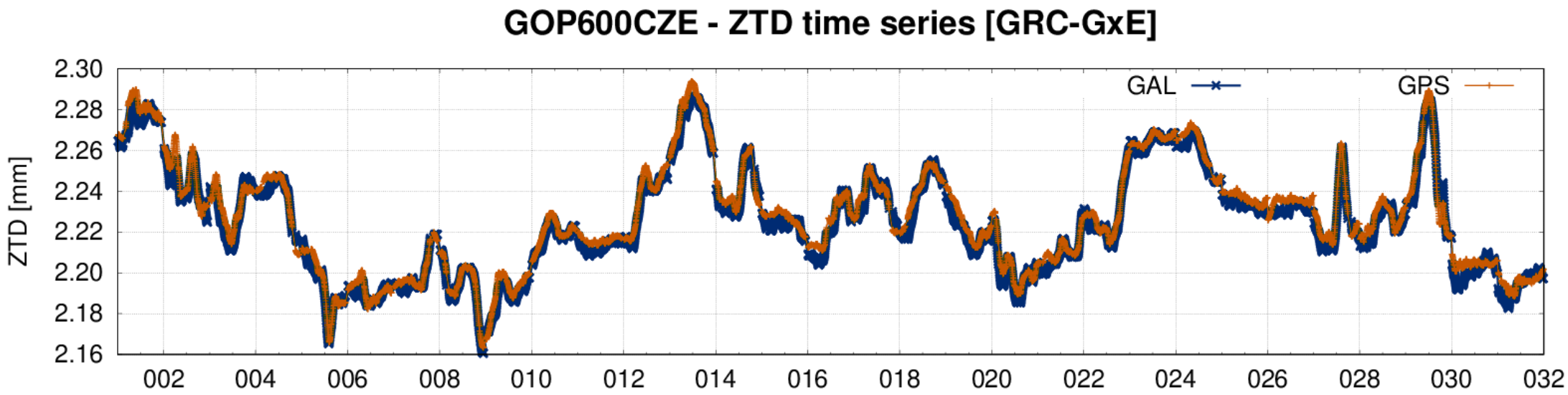
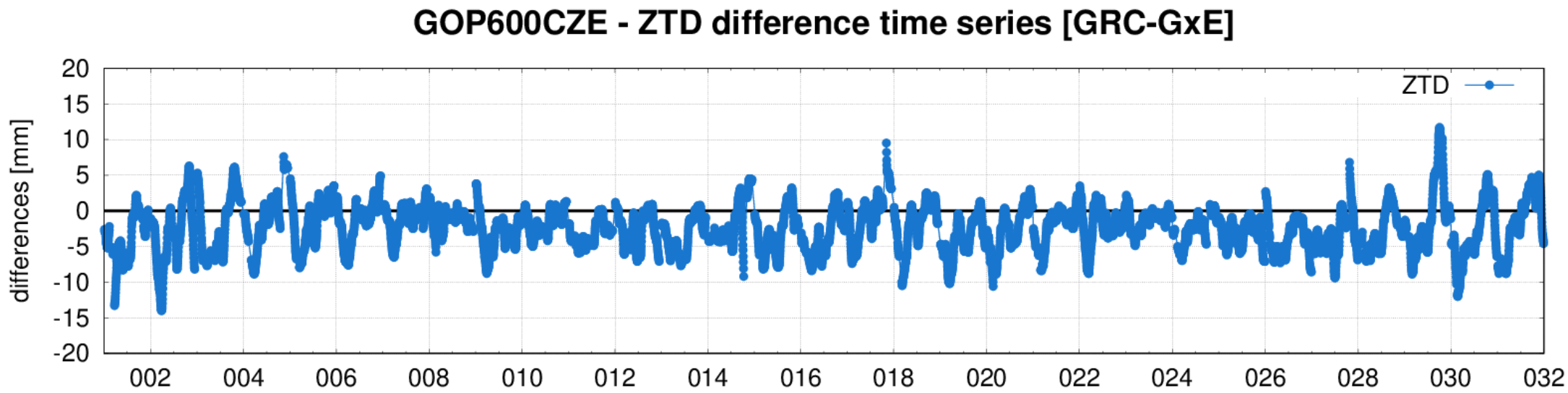
GAL x GPS troposphere





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Summary

Real-time PPP tropospheric production since 2013 & 2015 (GNSS4SWEC)

- ✓ RT operational solution covering Europe and global scopes (>250 sites since Dec 2020)
  - ✓ two different PPP processing modes: uncombine+undifferenced
- ✓ ZTD + horizontal gradients + slant delays (consistent at a unique time-resolution)
  - ✓ all parameters in the SINEX_TRO v2 format
- ✓ Production at 5-min temporal resolution & 1-min latency
  - ✓ quality approaching 'traditional' NRT solution ← **so far limited with the accuracy of RT precise products**
  - ✓ still possible simultaneously delivering NRT solution (hourly files + short-term backward smoothing)
- ✓ ready to support:
  - ✓ **multi-frequency & multi-constellation** (uncombine/undifference)
  - ✓ **troposphere anisotropy** (horizontal gradients + slant delays)
  - ✓ **support severe weather indicators**
  - ✓ **inter-comparisons & NWM validations**
  - ✓ **low-cost receivers**
  - ✓ **central & autonomous** (low cost receiver + raspberry-pi)
  - ✓ **kinematic** platforms (ships, buys, ..)

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