Real-time troposphere monitoring at GOP

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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, $\sigma_{ZTD} < 10$ mm ($IWV < 1.5$ kg/m$^2$)

... 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) ...

[https://egvap.dmi.dk](https://egvap.dmi.dk)
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)

Collocation stations:

ZTD from collocation stations @GOP:

a) https://www.gnutsoftware.com
GOP real-time GNSS tropospheric portal

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

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean [mm]</th>
<th>Std Dev [mm]</th>
<th>RMS [mm]</th>
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<tbody>
<tr>
<td>BRST</td>
<td>2.58</td>
<td>5.95</td>
<td>6.43</td>
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<td>NICO</td>
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<td>6.04</td>
<td>6.53</td>
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<td>8.53</td>
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<td>WTZR</td>
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<td>5.16</td>
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<td>4.28</td>
<td>5.08</td>
<td>6.82</td>
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<tr>
<td>GOPE</td>
<td>4.14</td>
<td>5.43</td>
<td>6.81</td>
</tr>
</tbody>
</table>
Constellation/product benchmark (July/August 2021)
Constellation benchmark (collocation stations)

ZTD comparison (collocated stations)

![Graph showing ZTD comparison for different constellations]

- RMSE [mm]
- SDEV [mm]
- BIAS [mm]
real-time – post-processing (@ collocation stations)

GOPE00CZE

real-time × post-processing

YEAR: 2021

differences [mm]

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

real-time × post-processing

YEAR: 2021

differences [mm]

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

GOPE00CZE

YEAR: 2021

differences [mm]

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

GOP600CZE

real-time × post-processing

YEAR: 2021

differences [mm]

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

GOP600CZE

YEAR: 2021

differences [mm]

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

real-time × post-processing

YEAR: 2021

GOPE00CZE

differences [mm]

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

real-time × post-processing

YEAR: 2021

differences [mm]

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

GOP600CZE

differences [mm]

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

real-time × post-processing

YEAR: 2021

differences [mm]

Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
real-time \mid post-processing \quad (use collocation stations)
PPP observation model

**Ionosphere-free LC:**
- higher IF LC observation noise
  - weighting of LC observation only
- less parameters to be estimated
  - eliminate 1\textsuperscript{st} 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
Collocation station: PPP with IF / UU observations

Ionosphere-free

GOP600CZE / GOPE00CZE time series - ZTD

2.38
2.36
2.34
2.32
2.30
2.28
2.26
2.24
2.22
2.20
ZTD [m]

Undifference/uncombined

GOP600CZE / GOPE00CZE time series - ZTD

2.38
2.36
2.34
2.32
2.30
2.28
2.26
2.24
2.22
2.20
ZTD [m]

Collocation station: PPP with IF / UU observations

Ionosphere-free

GOP600CZE / GOPE00CZE time series - ZTD difference

Undifference/uncombined

GOP600CZE / GOPE00CZE time series - ZTD difference
Collocation station: geodetic x low-cost receiver

Ionosphere-free

GOPB - low-cost receiver

**undifference/uncombined**

GOPB - low-cost receiver
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)
GNSS x ERA5 (numerical weather)

GOP600CZE - ZTD time series [GRC-ERA]

GOP600CZE - ZTD difference time series [GRC-ERA]
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 \(\text{so far limited with the accuracy of RT precise products}\)
  - 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, ..)