Emerging GNSS based tropospheric products

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Presentation plan

1. Introduction and motivation
2. Near Real Time PPP GNSS service
3. Real Time PPP GNSS service
4. RO GNSS service
5. GNSS tomography service
6. GNSS and NWP data integration
7. Conclusion
GNSS NRT ZTD assimilation in NWP

Forecast **without** GPS

Forecast **with** GPS

(source Siebren de Haan KNMI)

Radar composite
GNSS and METEO comunity integration
Growing ground-based infrastructure – CORS

- E-GVAP (~2500 GNSS stations) dedicated processing for meteorology
- Interesting example of geodesy and meteorology collaboration
- Near real-time processing with quality control
- BUFR and COST format export for EUMETNET consortium members
- WUELS hosts GNSS processing centre for Poland

www.egvap.dmi.dk

http://www.suominet.ucar.edu/
New satellite mission e.g. COSMIC II

6 satellite on low inclination angle (2016), 6 satellite in high inclination orbits (2018), P NOAA + NSPO programme, 12,000 profiles per day

Źródło: www.cosmic.ucar.edu, credits: NSPO - Taiwan
New „WUEL” network (ASG-EUPOS + SmartNet)

Since Aug 26, 2015
12:00 UTC (BSW 5.2)
## NRT DD processing details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing type</td>
<td>Post-processing (Double-differenced)</td>
</tr>
<tr>
<td>Satellite system considered</td>
<td>GPS only</td>
</tr>
<tr>
<td>Observation window</td>
<td>6 hours</td>
</tr>
<tr>
<td>Observation cut-off angle</td>
<td>5°</td>
</tr>
<tr>
<td>Baseline forming strategy</td>
<td>OBS-MAX</td>
</tr>
<tr>
<td>Ambiguity resolution strategy</td>
<td>Baseline length dependent:</td>
</tr>
<tr>
<td></td>
<td>a) &lt; 20km: SIGMA on L1 and L2,</td>
</tr>
<tr>
<td></td>
<td>b) 20km to 180km: SIGMA L5/L3 (wide-lane/narrow-lane),</td>
</tr>
<tr>
<td></td>
<td>c) &gt; 180km: QIF (quasi iono-free)</td>
</tr>
<tr>
<td>Ionosphere handling</td>
<td>Baseline length dependent:</td>
</tr>
<tr>
<td></td>
<td>a) &lt; 20km: Global model (CODE) for L1L2;</td>
</tr>
<tr>
<td></td>
<td>b) 20km to 180km: Global model (CODE) for L5 and HOI L3;</td>
</tr>
<tr>
<td></td>
<td>c) 180km to 1000km: Global model (CODE) + stochastic ionosphere parameters estimation (QIF)</td>
</tr>
<tr>
<td>Troposphere handling</td>
<td>Phase observables screening stage:</td>
</tr>
<tr>
<td></td>
<td>a) A priori model DRY GMF,</td>
</tr>
<tr>
<td></td>
<td>b) Site specific parameters WET GMF (ZTD spacing: 2h; no constraining),</td>
</tr>
<tr>
<td></td>
<td>Final solution stage:</td>
</tr>
<tr>
<td></td>
<td>a) A priori model: DRY GMF,</td>
</tr>
<tr>
<td></td>
<td>b) Site specific parameters: WET GMF (ZTD spacing: 30min; no constraining;</td>
</tr>
<tr>
<td></td>
<td>gradient model: CHENHER <em>Chen and Herring (1997)</em>, gradient spacing: 6h)</td>
</tr>
<tr>
<td></td>
<td>Product output:</td>
</tr>
<tr>
<td></td>
<td>Relative constraining over 1 hour (3mm for ZTD and 0.5 mm for gradients).</td>
</tr>
<tr>
<td>Reference frame for epoch solution</td>
<td>IGS and ARGN IGb08 coordinates and velocities</td>
</tr>
<tr>
<td>Method of referencing epoch solutions</td>
<td>Minimum constraining on all reference station positions.</td>
</tr>
</tbody>
</table>
GNSS troposphere monitoring

PPP estimates: X, Y, Z, dt_{rec}, troposphere zenith delays (ZTD) and gradients

Integrated Water Vapour (IWV):

\[
ZHD = [0.0022768 \text{ m/mbar}] \cdot \frac{P_0}{f(\phi, h)}
\]

\[
f(\phi, h) = 1 - 0.00266 \cos(2\phi) - 0.00000028h \approx 1
\]

\[
ZWD = ZTD - ZHD
\]

\[
IWV = \frac{ZWD}{10^{-6}(k'_2 + k_3/T_m)R_v}
\]

\[
P_0 \quad - \text{surface air pressure [mbar]}
\]

\[
h \quad - \text{point height [m]}
\]

\[
\phi \quad - \text{point latitude [rad]}
\]

\[
k'_2, k_3 \quad - \text{empirical coefficients}
\]

\[
T_m \quad - 70.7 + 0.72T_0
\]

\[
T_0 \quad - \text{surface air temperature}
\]

\[
R_v \quad - 461.525 \text{ [J/(kg·K)]}
\]

Example of the Integrated Water Vapour (IWV) 2D distribution over the area of Poland calculated for November 7, 2012, shown as a time series with 4 hours interval.
COST-716 Format

<table>
<thead>
<tr>
<th>ZTD</th>
<th>mZTD</th>
<th>ZWD</th>
<th>IWV</th>
<th>P</th>
<th>T</th>
<th>RH</th>
<th>ZTD Gradients</th>
<th>Grad. Errors</th>
<th>TEC</th>
</tr>
</thead>
</table>
E-GVAP „WUEL“ - The WUELS contribution

http://egvap.dmi.dk

Oct 15th, 2012 to Apr 11 2015 (BSW 5.0)
NWM requirements for troposphere products

Running projects / actions:

- EIG EUMETNET, GNSS Water Vapour Programme (E-GVAP-II)
- Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)

<table>
<thead>
<tr>
<th></th>
<th>Hourly ZTD</th>
<th>Treshold</th>
<th>Target</th>
<th>Optimal</th>
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</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>15 mm</td>
<td>10 mm</td>
<td>5 mm</td>
<td></td>
</tr>
<tr>
<td>Timeliness</td>
<td>2 h</td>
<td>1.5 h</td>
<td>1 h</td>
<td></td>
</tr>
<tr>
<td>Spatial coverage</td>
<td>Europe</td>
<td>Europe + N. America</td>
<td>Global</td>
<td></td>
</tr>
<tr>
<td>Horizontal Sampling</td>
<td>200 km</td>
<td>100 km</td>
<td>30 km</td>
<td></td>
</tr>
</tbody>
</table>
**RT ZTD: GNSS-WARP software**

**GNSS-WARP**

**Wrocław Algorithms for Real-time Positioning**

- original, self-developed, state-of-the-art PPP software
- purpose: multi-GNSS RT-PPP & PPP-RTK algorithms development
- GNSS: GPS+GLO, GAL & BDS only with MGEX products, RT
- implemented in Matlab (2015a) + Instrument Control Toolbox
- BNC used as RTCM decoder of IGS RTS streams

RT-ZTD optimization (GNSS-WARP v2.1m):
- redeveloped and optimized for multi-station, continuous processing
- performance: >10 stations / 1 second @1CPU
  (currently: >200 stations every 60 seconds)

Strategy:
- PPP, static positioning, VMF, IGS03, IERS 2010 models
RT ZTD: GNSS-WARP - multi-GNSS status

<table>
<thead>
<tr>
<th></th>
<th>GPS</th>
<th>GLONASS</th>
<th>Galileo</th>
<th>BeiDou</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP3+CLK</td>
<td>operational</td>
<td>operational</td>
<td>operational</td>
<td>test phase</td>
</tr>
<tr>
<td>broadcast</td>
<td>operational</td>
<td>operational</td>
<td>operational</td>
<td>tracked</td>
</tr>
<tr>
<td>real-time</td>
<td>operational</td>
<td>IOD problems</td>
<td>test phase</td>
<td>not available</td>
</tr>
</tbody>
</table>
RT ZTD: GNSS-WARP software – real-time troposphere service

- IGS-RTS products (products.igs-ip.net)
- EPN stations data (www.euref-ip.net)
- External data (IGS/EPN data centers)

流入

IGS03, RTCM3EPH
Ntrip
P/L @ 2freq.

输出

IGN03, RTCM3EPH
P/L @ 2freq.
TCP/IP

GNSS-WARPv2.1
strategy:
- GPS PPP (L3) static positioning
- a priori XYZ: monitor.coord
- MF: VMF, a’priori ZTD: VMF
- ZTD random walk: 2mm/h
- models: igs08.atx, IERS2010

1Hz log files:
- station metadata
- station coordinates
- ZTD estimates
- processing warnings/errors
- code & phase residuals

1Hz data
ASCII file

监控与评估

- resampling (5 min., 3 methods)
- archiving (.zip logs, remove)
- basic statistics (% of results, ZTD range)
- COST 716 (frequent correction)
- COST Tropo benchmark
- reporting (e-mail every 1 hour)
- admin

Wrocław University of Environmental and Life Sciences
RT ZTD: COST benchmark 2 - real-time demonstrator (2)

- RTS IGS03 stream and 10 observation streams decoded with BNC, one week
- multi-station real-time processing with GNSS-WARP v2.1M
- comparison with NRT from MetOffice (ROBH, 15min sampling)
- purpose: optimize methodology, detect bugs & errors

Station WTZR
13-14.06.2015
availability: 97%
mean formal error: 1.1mm
mean bias: -1.0mm
StdDev of residuals: 15.5mm
Towards RT-ZTD monitoring service in Poland (3)

RT ZTD service (under development, improvements required)
- 14 IGS + 19 EPN + 110 Leica SmartNet

<table>
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<td>Regional to National</td>
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<td>100 km</td>
<td>50 km</td>
<td>20 km</td>
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Radio occultation

RO WUELS software (2)

\[ N = (n - 1) \times 10^6 = k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2} \]
Near-real time FORMOSAT-3/COSMIC atmospheric profiles

1. **Excess phase processing to dry atmospheric profiles**
   - Open Loop correction in the troposphere
   - Radioholographic methods to resolve signal multipath:
     - Full Spectrum Inversion (FSI) and Phase Matching (PM)
   - Inverse Abel transform to retrieve refractive index profile
   - Forward operator to bending angle
   - Validation with respect to CDAAC atmPrf and radiosonde profiles:
     - ± 100 km collocations
     - up to 4 units residuals for refractivity

Data from Taiwan Radio Occultation Process System (TROPS) will be included.
Impact of RO data assimilation

4-Day Ernesto Forecasts with WRF-ARW

The Actual Storm | Forecast with GPS | Forecast without GPS

54 hrs

78 hrs

102 hrs

źródło: The Impact of GPS Radio Occultation Data on the Analysis and Prediction of Tropical Cyclones Bill Kuo and Hui Liu UCAR COSMIC
TOMO2: 3D NRT GNSS tomography model for area of Poland
GNSS tomography STD assimilation / convection studies

Inversion of Radon transform

1D ZTD/STD  3D IWV/\(N_w\)

\[ x = \text{inv}(A) \cdot y \]

Zenith total delay -> refractivity

\[ N_w = \left( A^T \cdot P \cdot A \right)^{-1} \cdot A^T \cdot P \cdot \text{SWD} \]

\[ y_m = H x_m \]

Observations operator

Refractivity from NWP

Working Group 2, Task TOMO – GNSS tomography data assimilation
GNSS tomography 03.08.2014 – intensive rainfall

Torrential rain associated with strong movements of the ascending air within the large convection cells

Tomography retrieved water vapour densities on 3 consecutive levels, convection cores should match with the increase of water vapour in bottom part (pool) and with sudden decreases of WV in cloud section (rain).

Geo satellite cloud image
APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP - Data

- 277 Polish stations
- near-real time
- ZTD with 1 h resolution
- product of Bernese software v5.2
- post-processing
- double-differenced

- WRF – Weather Research and Forecasting
- 219x237 horizontal nodes
- 4x4 km² grid
- 47 vertical levels
- 24-hour forecasts at 0:00 UTC
- p, T, e with 1 h resolution
APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP – Collocation - ZTD results

Fig.1. Comparison of COMEDIE models w.r.t. reference GNSS data
1. The NRT ZDT service is operational and stable in DD for 1h timeliness and will be developed to PPP and 15 min. timeliness.

2. The RT PPP is the alternative technique in GNSS meteorology and will be developed in future.

3. The RO service give us in future more profiles for calibration of 4D GNSS models of troposphere

4. The GNSS tomography is the next step of assimilation of 4D GNSS data in NWP models.

5. The integration of GNSS outputs and NWP models data is very important for support of RT positing services and meteorology.
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Chair of Meteo section
Chair of IAG WG 4.3.6
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**Prof. Jarosław Bosy**
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Vice-Chair of IAG Sub-Commission 4.3:
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Multi-GNSS
IAG Commission 4 Positioning and Applications Symposium
Wroclaw Poland, September 4-7, 2016

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Registration: July 31, 2016

http://www.igig.up.wroc.pl/iag2016/
Emerging, GNSS based tropospheric products

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Thank You!
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