Towards Real-time GNSS Troposphere Delay Monitoring Service for Poland

Tomasz Hadas, Kaplon Jan, Bosy Jaroslaw

Institute of Geodesy and Geoinformatics
Wroclaw University of Environmental and Life Sciences

5th International Colloquium Scientific and Fundamental Aspects of the Galileo Programme
Session 3A: E3 Atmospheric Research

27-29 October 2015, Braunschweig, Germany
1. Introduction:
   • Real-time PPP
   • GNSS for NWP

2. Near-real time ZTD service
   • Processing strategy
   • Quality of results

3. Development of real-time ZTD service
   • GNSS-WARP software
   • Benchmark campaigns
   • Current status
IGS RTS - IGS Real Time Service

- real-time orbit and clock correction (SSR RTCM) + broadcast messages (RCTM)

- official products for GPS: 5cm for orbits, 0.3ns (8.5cm) for clocks
- unofficial for GLONASS: 13cm for orbits, 0.8ns (24.5cm) for clocks
- availability >90%, latency ~30 sec.

Hadaś T., Bosy J.: *IGS RTS precise orbits and clocks verification and quality degradation over time*, GPS Solutions, Vol. 19, 2015, pp. 93-105
Real-time PPP in static / kinematic mode

Time series of residuals for GPS only with IGS01 stream (top) and GPS+GLONASS with IGS03 stream (bottom) real-time positioning in static (left) and kinematic (right) mode for station WROC, DOY 114, 2014

<table>
<thead>
<tr>
<th></th>
<th>GPS only</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std.Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>North</td>
<td>0.005</td>
<td>0.002</td>
<td>0.025</td>
</tr>
<tr>
<td>East</td>
<td>0.007</td>
<td>0.006</td>
<td>0.012</td>
</tr>
<tr>
<td>Up</td>
<td>0.001</td>
<td>0.006</td>
<td>-0.033</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>GPS only</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std.Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>North</td>
<td>0.007</td>
<td>0.03</td>
<td>0.015</td>
</tr>
<tr>
<td>East</td>
<td>0.004</td>
<td>0.027</td>
<td>0.004</td>
</tr>
<tr>
<td>Up</td>
<td>0.057</td>
<td>0.12</td>
<td>-0.031</td>
</tr>
</tbody>
</table>
GNSS troposphere monitoring

PPP estimates: X, Y, Z, dtrec, troposphere zenith delays (ZTD) and gradients

Integrated Water Vapour (IWV):

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

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

\[ ZWD = ZTD - ZHD \]

\[ IWV = \frac{ZWD}{10^{-6}(k_2' + k_3/T_m)R_v} \]

- \( P_0 \) - surface air pressure [mbar]
- \( h \) - point height [m]
- \( \phi \) - point latitude [rad]
- \( k_2', k_3 \) - empirical coefficients
- \( T_m \) - 70.7 + 0.72T_0
- \( T_0 \) - surface air temperature
- \( R_v \) - 461.525 [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.
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>Hourly ZTD</th>
<th>Treshold</th>
<th>Target</th>
<th>Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>15 mm</td>
<td>10 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Timeliness</td>
<td>2 h</td>
<td>1.5 h</td>
<td>1 h</td>
</tr>
<tr>
<td>Spatial coverage</td>
<td>Europe</td>
<td>Europe + N. America</td>
<td>Global</td>
</tr>
<tr>
<td>Horizontal Sampling</td>
<td>200 km</td>
<td>100 km</td>
<td>30 km</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-hourly ZTD</th>
<th>Treshold</th>
<th>Target</th>
<th>Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>15 mm</td>
<td>10 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Timeliness</td>
<td>1 h</td>
<td>30 min</td>
<td>15 min</td>
</tr>
<tr>
<td>Spatial coverage</td>
<td>Europe</td>
<td>Europe to National</td>
<td>Regional to National</td>
</tr>
<tr>
<td>Horizontal Sampling</td>
<td>100 km</td>
<td>50 km</td>
<td>20 km</td>
</tr>
</tbody>
</table>
Commercial RTK networks in Poland

ASG-EUPOS:
- 102 in Poland + 23 foreign
  - 125 GPS / 73 GLO / 39 GAL
  - permanent service since 2009
  - GPS RTN (+GLO at some areas)

Leica SmartNet:
- now: 135 stations in Poland
  - GPS, GLO, GAL, BDS, QZSS
  - operational + developments
  - GNSS RTN

TPI Net PRO:
- 136 in Poland
  - GPS, GLO, GAL
  - operational
  - GNSS RTN

Trimble VRS Net:
- now: 56 in Poland
  - GPS, GLO, GAL, 1 BDS
  - under development?
  - GNSS RTN

4 commercial RTK/RTN networks (2 still under developments) with > 370 stations
WUELS cooperates with ASG-EUPOS and Leica SmartNet:
- hourly RINEX files from both network, including foreign stations
- 1Hz data streams from ~100 Leica SmartNet stations
- hopefully soon 1Hz data streams from ASG-EUPOS and +30 from Leica SmartNet
## NRT DD processing details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Processing type</strong></td>
<td>Post-processing (Double-differenced) with IGU orbits and clocks</td>
</tr>
<tr>
<td><strong>Satellite system considered</strong></td>
<td>GPS only</td>
</tr>
<tr>
<td><strong>Observation window</strong></td>
<td>6 hours</td>
</tr>
<tr>
<td><strong>Observation cut-off angle</strong></td>
<td>5°</td>
</tr>
<tr>
<td><strong>Baseline forming strategy</strong></td>
<td>OBS-MAX</td>
</tr>
<tr>
<td><strong>Ambiguity resolution strategy</strong></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><strong>Ionosphere handling</strong></td>
<td>Baseline length dependent:</td>
</tr>
<tr>
<td></td>
<td>a) &lt; 20km: Global model (CODE) for L1/L2;</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><strong>Troposphere handling</strong></td>
<td><strong>Phase observables screening stage:</strong></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><strong>Final solution stage:</strong></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; gradient model: CHENHER <em>Chen and Herring</em> (1997), gradient spacing: 6h)</td>
</tr>
<tr>
<td></td>
<td><strong>Product output:</strong></td>
</tr>
<tr>
<td></td>
<td>Relative constraining over 1 hour (3mm for ZTD and 0.5 mm for gradients).</td>
</tr>
<tr>
<td><strong>Method of referencing epoch solutions</strong></td>
<td>Minimum constraining on all reference station positions.</td>
</tr>
</tbody>
</table>
Introduction
Near-real time ZTD service
Development of real-time ZTD service

GNSS NRT ZTD network

Total: 310 stations
Mean dist.: 40 km
Plan prezentacji

Near-real time ZTD service
Development of real-time ZTD service

Introduction

"VICNET" network

Total: 156 stations
Mean dist.: ~70 km

CEDU
SYDN
MOBS
HOB2
PARK

27-29 October 2015, Braunschweig, Germany
Quality assessment of „WUEL“ NRT service (1)

Comparison of ZTD estimates with CODE Rapid ZTDs on common IGS stations for the last three weeks of September 2015
Quality assessment of „WUEL” NRT service (2)
GNSS-WARP
Wroclaw Algorithms for Real-time Positioning

- original, self-developed, state-of-the-art PPP software
- purpose: RT-PPP & PPP-RTK algorithms development
- 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: 147 stations every 60 seconds)

Strategy:
- GPS PPP, static positioning, VMF, IGS03, IERS 2010 models
Introduction

Near-real time ZTD service

Development of real-time ZTD service

GNSS-WARP software

Benchmark campaigns

Current status

GNSS-WARP software (2)

- IGS-RTS products
  - products.igs-ip.net

- EPN stations data
  - www.euref-ip.net

- external data
  - IGS/EPN data centers

- GNSS/WARP software (2)

- RT-ZTD estimator

- Ntrip

- BNC 2.11

- GNSS-WARP v2.1

- 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

- monitoring & evaluation

- resampling
  - 5 min., 3 methods

- archiving
  - .zip logs, remove

- basic statistics
  - % of results, ZTD range

- COST 716 format conversion

- COST Tropo benchmark

- monitoring

- reporting
  - e-mail every 1 hour

- admin
Benchmark 1 – simulated real time

- RTS IGS03 stored (BNC) in SP3 and CLK files, RINEX files for 10 stations, one week
- station by station postprocessing (0.1Hz) with GNSS-WARP v2
- comparison with final-ZTD estimates from EPN (1 hour sampling)
- purpose: optimize methodology, evaluate possible quality

An optimal solutions among all stations were obtained for 2mm/h to 5mm/hour random walk. The results were slightly biased: -4 mm to +7 mm (note: DD vs PPP solution) and the standard deviations varies from 7 mm to 12 mm.
Benchmark 2 – real-time demonstrator (1)

- 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 **WROC**
13-14.06.2015
availability: 86%
mean formal error: 1.1mm
mean bias: +1.5mm
StdDev of residuals: 15.7mm
Benchmark 2 – real-time demonstrator (1)

- **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
Bugs & errors

1) Real-time service problems:
   - IGS03/RTCMEPH stream failure (e.g. mismatching IOD’s)
   - stream recovery failure in BNC (solved: use Ntrip 1, not Ntrip 2)
   - long gaps in streams availability (re-initialization of the solution)

2) Processing errors:
   - some rapid ZTD changes not present in RT estimation
   - unexpected ZTD peaks in RT
   - systematic biases between RT and NRT (DD vs. PPP)
Towards COST Tropo benchmark (1) – general performance

Real-time ZTD:
33 stations @ 5 sec. sampling:
- COST RT TROPO benchmark stations (some have problems!)
- Polish EPN stations

Week 1863 performance:
- 68% mZTD is below 0.0036 m
- 95% mZTD is below 0.0148 m
- 99% mZTD is below 0.0241 m
- data availability: 88.6%
Towards COST Tropo benchmark (2) – ZTD formal errors at stations
Towards RT-ZTD monitoring service in Poland (1) – GNSS network

Recent problems:
- bad / missing antenna type (monitor.ant) – station is incorrect / not processed
- BNC 2.11 failure / errors - no data until restarted
- no access to ASG-EPOS streams (all stations) and SmartNet streams (south east)
Towards RT-ZTD monitoring service in Poland (2) – comparison with NRT ZTD
Towards RT-ZTD monitoring service in Poland (2) – comparison with NRT ZTD

mZTD threshold: 0.01m; 83% of data
**Summary**

**NRT ZTD service** (fully operational)
- XXX EPN + XXX ASG-EUPOS + XXX Leica SmartNet

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

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

<table>
<thead>
<tr>
<th>Sub-hourly ZTD</th>
<th>Treshold</th>
<th>Target</th>
<th>Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>15 mm</td>
<td>10 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Timeliness</td>
<td>1 h</td>
<td>30 min</td>
<td>15 min</td>
</tr>
<tr>
<td>Spatial coverage</td>
<td>Europe</td>
<td>Europe to National</td>
<td>Regional to National</td>
</tr>
<tr>
<td>Horizontal Sampling</td>
<td>100 km</td>
<td>50 km</td>
<td>20 km</td>
</tr>
</tbody>
</table>
Thank You!

tomasz.hadas@up.wroc.pl

Institute of Geodesy and Geoinformatics
Wroclaw University of Environmental and Life Sciences

5th International Colloquium
Scientific and Fundamental Aspects of the Galileo Programme
Session 3A: E3 Atmospheric Research

27-29 October 2015, Braunschweig, Germany