Troposphere products for GNSS precise positioning and meteorology

Jaroslaw Bosy, Witold Rohm, Jan Kaplon, Tomasz Hadas, Karina Wilgan, Pawel Hordyniec, Krzysztof Sosnica, Kamil Kazmierski, Jan Sierny
Presentation plan

1. Introduction
2. Near Real Time products
3. Real Time products
4. Conclusion
Motivation for GNSS positioning

- SPP: ~25m
- DGPS: ~1m
- PPP: ~1dm
- RTK/GNSS: ~1cm
GNSS and METEO comunity integration
GNSS Troposphere delay

Apriori model of delay into the direction of satellite

Estimated parameter of delay into zenith direction (dZTD)

Gradients in North (n) and East (e) direction

STD is a sum of all estimated parameters
GNSS Troposphere delay

\[ \delta T(z) = m_d(z) \cdot \delta T_{d,0} + m_w(z) \cdot \delta T_{w,0} \]

Saastamoinen (Saastamoinen, 1973)

\[ \delta T = \frac{0.002277}{\cos z} \left[ P + \left( \frac{1255}{T_K} + 0.05 \right) e - \tan^2 z \right] \]

Hopfield (Hopfield, 1969)

\[ \delta T = \frac{10^{-6}}{5} \left[ \frac{N_{d,0}^{trop} h_d}{\sin \sqrt{\varepsilon^2 + 6.25}} + \frac{N_{w,0}^{trop} h_w}{\sin \sqrt{\varepsilon^2 + 2.25}} \right] \]
GNSS Troposphere delay
Table 4.7: Input parameters for zenith troposphere dry delay models

<table>
<thead>
<tr>
<th>Model</th>
<th>e</th>
<th>T</th>
<th>P</th>
<th>φ</th>
<th>h</th>
<th>β</th>
<th>κ</th>
<th>inne (other)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Hopfield, 1969, 1971, 1972)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Goad and Goodman, 1974)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Saastamoinen, 1973)</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Davis et al., 1985)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Baby et al., 1988)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>g, Re</td>
</tr>
<tr>
<td>(Elgered et al., 1991)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(MOPS, 1998)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>DOY, g</td>
</tr>
</tbody>
</table>
GNSS Troposphere delay – mapping functions

\[ m(z) = \frac{1}{\cos z + \frac{a}{\cos z + \frac{b}{\cos z + \frac{c}{\cos z + \ldots}}}} \]

<table>
<thead>
<tr>
<th>Table 4.11: Comparison of selected mapping functions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Funkcja (function)</strong></td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>(Baby et al., 1988)</td>
</tr>
<tr>
<td>(Black, 1978)</td>
</tr>
<tr>
<td>(Chao, 1972, 1974)</td>
</tr>
<tr>
<td>(Davis et al., 1985)</td>
</tr>
<tr>
<td>(Goad and Goodman, 1974)</td>
</tr>
<tr>
<td>(Herring, 1992)</td>
</tr>
<tr>
<td>(Hopfield, 1969)</td>
</tr>
<tr>
<td>(Ifadis, 1986)</td>
</tr>
<tr>
<td>(Marini and Murray, 1973)</td>
</tr>
<tr>
<td>(Niell, 1996)</td>
</tr>
<tr>
<td>(Saastamoinen, 1973)</td>
</tr>
<tr>
<td>(Yan and Ping, 1995)</td>
</tr>
<tr>
<td>(Guo and Langley, 2003)</td>
</tr>
<tr>
<td>(Foelsche and Kirchengast, 2001, 2002)</td>
</tr>
</tbody>
</table>
GNSS Troposphere delay for meteorology

\[ \text{ZTD} - \text{ZHD} = \text{ZWD} \]

Models: Saastamoinen, Hopfield

\[ \text{SWD} \]

\[ \text{4DT} \]

\[ \text{WVD} \]

\[ m(z) = \frac{1 + \frac{a}{b}}{1 + \frac{1 + c}{a}} \]

\[ \frac{\cos(z)}{\cos(z) + \frac{b}{c}} \]

\[ \text{NMF: Neill Mapping Function} \]
\[ \text{IMF: Isobaric Mapping Function} \]
\[ \text{VMF: Vienna Mapping Function} \]
\[ \text{GMF: Global Mapping Function} \]
GNSS and METEO motivation

**NRT meteorological products**

- ZTD from NWP
- ZTD from GNSS GBAS network
- ZTD from ground meteorological stations

**GNSS positioning users**

- RT RTK users
- RT PPP users
- Post-processing users
EUREF Permanent Network troposphere products
IGS Global Network troposphere products

% = TRD 0.01 IGG 12:115:81494 ITR 12:115:68400 12:115:72000 P MIX

+FILE/REFERENCE
+INFO_TYPE INFO
DESCRIPTION Wroclaw University of Environmental and Life Sciences/IGG
OUTPUT NRT Hourly SINEX and Troposphere SINEX
CONTACT Jan Kaplon (jan.kaplon@igig.up.wroc.pl)
SOFTWARE Bernese GPS Software Version 5.0
HARDWARE 80 cores Intel(R) Xeon E7-4870 @ 2.4GHz, Debian 6.0.4
INPUT IGS/EPN/ASG-EUPOS GNSS tracking data

+TROP/DESCRIPTION
+______KEYWORD______ _VALUE(S)_
ELEVATION CUTOFF ANGLE 5
SAMPLING INTERVAL 30
SAMPLING TROP 3600
TROP MAPPING FUNCTION WET NIELL
SOLUTION_FIELDS_1 TROTUT STDDEV

+TROP/STA_COORDINATES
+SITE PT SOLN T __STA_X____ __STA_Y____ __STA_Z____ SYSTEM REMR
BAIA A 1 P 3945839.793 1720428.324 4691082.807 ITRF08 IGG
WROC A 1 P 3835751.214 1177250.080 4941605.366 ITRF08 IGG

+TROP/SOLUTION
+SITE ___EPOCH___ TROTUT STDDEV
BAIA 12:115:70200 2348.6 1.4
WROC 12:115:70200 2337.8 1.0

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<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 The EUMETNET EIG GNSS water vapour programme (http://egvap.dmi.dk)
E-GVAP The EUMETNET EIG GNSS water vapour programme (http://egvap.dmi.dk)
E-GVAP „WUEL“ - The WUELS contribution

Oct 15th, 2012 to Apr 11 2015 (BSW 5.0)

http://egvap.dmi.dk
COST Action ES1206 - **GNSS4SWEC** - Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate ([http://gnss4swec.knmi.nl](http://gnss4swec.knmi.nl))

**Action Chair:** Jonathan Jones (esr)
**Action co-chair:** Guergana Guerova (f)

**WG1 - Advanced GNSS Processing Techniques**
- Chair: Jan Dousa
- Co-chair: Galina Dick (f)

**WG2 - GNSS for Severe Weather Monitoring**
- Chair: Siebren de Haan (esr)
- Co-chair: Eric Pottiaux (esr)

**WG3 - GNSS for Climate Monitoring**
- Chair: Olivier Bock
- Co-chair: Rosa Pacione (f)
## NRT DD processing details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td><strong>Processing type</strong></td>
<td>Post-processing (Double-differenced)</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>
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<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 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</td>
</tr>
<tr>
<td></td>
<td>parameters estimation (QIF)</td>
</tr>
<tr>
<td><strong>Troposphere handling</strong></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><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</td>
</tr>
<tr>
<td></td>
<td>constraining; gradient model: CHENHER <em>Chen and Herring (1997)</em>,</td>
</tr>
<tr>
<td></td>
<td>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</td>
</tr>
<tr>
<td></td>
<td>gradients).</td>
</tr>
<tr>
<td><strong>Reference frame for epoch solution</strong></td>
<td>IGS and ARGN IGb08 coordinates and velocities</td>
</tr>
<tr>
<td><strong>Method of referencing epoch solutions</strong></td>
<td>Minimum constraining on all reference station positions.</td>
</tr>
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</table>
## NRT PPP processing details

<table>
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<tr>
<th>Processing type</th>
<th>Post-processing (Zero-differenced)</th>
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</thead>
<tbody>
<tr>
<td>Satellite system considered</td>
<td>GPS only</td>
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<tr>
<td>Observation window</td>
<td>12 hours</td>
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<tr>
<td>Observation cut-off angle</td>
<td>5°</td>
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<td>Ambiguity resolution strategy</td>
<td>None</td>
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<tr>
<td>Ionosphere handling</td>
<td>Global model (CODE) for HOI L3;</td>
</tr>
<tr>
<td>Troposphere handling</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), <em>Effects of atmospheric azimuthal asymmetry on the analysis of space geodetic data</em>, <em>Journal of Geophysical Research</em>, 102(B9), pp. 20489-20502) gradient spacing: 1h)</td>
</tr>
<tr>
<td>Product output:</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>IGb08 coordinates of satellites</td>
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<tr>
<td>Method of referencing epoch solutions</td>
<td>Free solution</td>
</tr>
</tbody>
</table>
New „WUEL“ network (ASG-EUPOS + SmartNet)

Since Aug 26, 2015 12:00 UTC (BSW 5.2)
Quality assessment of new NRT service

Comparison of ZTD estimates with CODE Rapid ZTDs on common IGS stations for the last three weeks of September 2015
APPLICATION OF TROPOSPHERE MODEL FROM GNSS DATA INTO PPP

### Bernese GPS Software (postprocessing)

<table>
<thead>
<tr>
<th>Solution</th>
<th>Model a-priori</th>
<th>Model ZTD</th>
<th>ZTD Est.</th>
<th>Resolution</th>
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<tbody>
<tr>
<td>No model</td>
<td>without</td>
<td>without</td>
<td>no</td>
<td>n/a</td>
</tr>
<tr>
<td>Saastamoinenen</td>
<td>SA</td>
<td>Saastamoinenen</td>
<td>no</td>
<td>30 s.</td>
</tr>
<tr>
<td>Estimation</td>
<td>SA</td>
<td>Saastamoinenen</td>
<td>yes</td>
<td>30 s.</td>
</tr>
<tr>
<td>NRT-ZTD</td>
<td>without</td>
<td>NRT</td>
<td>no</td>
<td>1 h.</td>
</tr>
<tr>
<td>Meteo ZTD</td>
<td>meteo</td>
<td>Saastamoinenen</td>
<td>no</td>
<td>1 h.</td>
</tr>
</tbody>
</table>
APPLICATION OF TROPOSPHERE MODEL FROM GNSS DATA INTO PPP – comparison with IGS results
GNSS-WARP software

GNSS-WARP
Wroclaw 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
## GNSS-WARP status

<table>
<thead>
<tr>
<th></th>
<th>GPS</th>
<th>GLONASS</th>
<th>Galileo</th>
<th>BeiDou</th>
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<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>
GNSS-WARP software – real-time troposphere service

RT-RTD estimator
IGS-RTS products
products.igs-ip.net

IGS03,
RTCM3EPH
Ntrip

IGS03,
RTCM3EPH
P/L @ 2freq.

TCP/IP

BNC2.11

monitor.ant, monitor.coord,
VMF, igs08.atx
ASCII files (ftp)

1Hz data
ASCII file

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

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

monitoring & evaluation

resampling
5 min., 3 methods

COST716
frequent correction

COST Tropo
benchmark

COSTWARPv2.1

archiving
.zip logs, remove

basic statistics
% of results, ZTD range

reporting
e-mail every 1 hour

admin

EPN stations data
www.euref-ip.net

P/L @ 2freq.
Ntrip

external data
IGS/EPN data centers
APPLICATION OF TROPOSPHERE MODEL FROM GNSS DATA INTO RT PPP

Solution with ZTD estimation

Solution with NRT ZTD input
APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP - Methodology

\[ N_{tot} = k_1 \frac{p - e}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2} \]

1. NWP parameters \((p, T, e)\)
2. Calculation of total refractivity at NWP grid node location
3. Total refractivity \((N_{tot})\)
4. Least-squares collocation of ZTD and \(N_{tot}\)
5. Interpolation to reference station location
6. Validation with reference GNSS station
7. Application into PPP software
APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP - Data

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

- NWP WRF
  - 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

\begin{align*}
\text{m}_{\text{WRF}} &= 34.11 \text{ mm} \\
\sigma_{\text{WRF}} &= 24.72 \text{ mm} \\
\text{m}_{\text{WRF:GNSS}} &= 0.19 \text{ mm} \\
\sigma_{\text{WRF:GNSS}} &= 8.39 \text{ mm}
\end{align*}
APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP – tropospheric constrainting (1)

Fig. 3. Results of real-time kinematic PPP with ZTD constrained to COMEDIE model, station WROC, DoY 337-343, 2015
APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP – troposphere constraining (2)

Fig. 6. Comparison of unconstrained and COMEDIE-constrained solutions (top - absolute differences in coordinates, bottom - general statistics for solutions w.r.t. static weekly PPP solution)
APPLICATION OF TROPOSPHERE MODEL FROM NWP AND GNSS DATA INTO RT PPP – troposphere constraining (3)

Fig.7. Coordinate residuals w.r.t. static weekly PPP solution from unconstrained (red) and COMEDIE-constrained (green) solutions, imposed re-initialization every 2 hour, 2-hour period overlaid, station WROC, DoY 337-343, 2015
CONCLUSIONS

1. NRT ZTD future developments:
   • to reduce the latency to 5 minutes (from 20 minutes)
   • to increase the processing interval to 15 minutes (from 1 hour)
   • to support Multi-GNSS data (currently GPS and GLONASS solution)
   • improvements in PPP solution
   • development of optimal ZTD and gradient constraining strategy to obtain consistency with NWP models
   • NRT estimation of Slant Tropospheric Delays

2. Real-Time future developments:
   • continuous processing (without re-initializations)
   • full GNSS constellation
   • ambiguity fixing
   • estimation of Slant Tropospheric Delays
   • Mapping functions development
GNSS&Meteo WUELS working group

Prof. Jarosław Bosy
Chair of WG
Vice-Chair of IAG Sub-Commission 4.3:
Atmosphere Remote Sensing

Dr. Tomasz Hadas
GNSS-WARP software
Chair of IAG WG 4.3.4
Ionosphere and Troposphere Impact on GNSS Positioning

Dr. Krzysztof Sosnica
Chair of IAG JSG0.21:
Fusion of multi-technique satellite geodetic data

Kamil Kaźmierski
PhD student
Multi-GNSS

Jan Sierny
PhD student and IT support
GNSS and meteo data base

Karina Wilgan
PhD student
GNSS and meteo integration

Pawel Hordyniec
PhD student
ROWUELS software

Dr. Witold Rohm
Chair of Meteo section
Chair of IAG WG 4.3.6
Troposphere Tomography

Dr. Jan Kaplon
GNSS and Meteo
NRT services
Abstract submission: **June 15, 2016**
Notification of acceptance: July 1, 2016
Registration: July 31, 2016

http://www.igig.up.wroc.pl/iag2016/
Multi-GNSS real-time troposphere delay estimation

Presenting author:
Professor Jaroslaw Bosy
Institute of Geodesy and Geoinformatics
Wroclaw University of Environmental and Life Sciences

Coresponding authors:
• meteo: witold.rohm@up.wroc.pl
• real-time: tomasz.hadas@up.wroc.pl
• near real-time: jan.kaplon@up.wroc.pl
• multi-GNSS: kamil.kazmierski@up.wroc.pl

Thank You!

jaroslaw.bosy@up.wroc.pl

www.up.wroc.pl