Quality assessment of real-time GNSS Precise Point Positioning using IGS-RTS products

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Presentation plan

1. Introduction:
   - Precise Point Positioning
   - IGS Real-Time Service
2. GNSS-WARP software
   - Adjustment model and features
   - Validation campaign
3. Real-Time PPP
   - GPS or GPS+GLONASSS?
   - PPP-RTK approach

PPP – Mathematical model

Zumberge J.F., i in. (1997). Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks. J.Geophys. Res., 102(B3), 5005-5017:

$$I_p = \frac{1}{f_1^2 - f_1^2}\left(f_1^2 P_1 - f_2^2 P_2\right) = \rho + c(\delta t_r - \delta t^s) + \delta T_r^s + \epsilon_p$$

$$I_\Phi = \left[\frac{1}{f_1^2 - f_1^2}\left(f_1^2 P_1 - f_2^2 P_2\right)\right]\lambda_{L3} = \rho + c(\delta t_r - \delta t^s) + \delta T_r^s + N\lambda_{L3} + \epsilon_\Phi$$

where:

- I_p – ionosphere-free combination of pseudorange measurements
- I_Φ – ionosphere-free combination of carrier-phase measurements in metric units
- ρ – geometric distance between satellite and receiver antenna phase centers
- c – the speed of light
- $\delta t^s, \delta t_r$ – the clock errors of satellite and receiver
- δT_r^s – troposphere delay,
- N – ionosphere-free carrier-phase ambiguity parameter
- λ_{L3} – ionosphere-free carrier-phase wavelength
- $\epsilon_p, \epsilon_\Phi$ – measurement noises of ionosphere-free pseudoranges and carrier-phase

Unknowns: receiver coordinates (X, Y, Z) involved into ρ, and: δt_r, δT_r^s, N

PPP – advantages and limitations

Advantages:

- single-receiver precise positioning,
- fast, simple and straightforward (no differencing) calculations
- world-wide positioning,
- independent positioning technique, a validation of RTK

Limitations:

- accuracy and availability of precise products
- accuracy – because of float ambiguities,
- long convergence time,
- all systematic effects (site and station) must be included
- global reference frame

IGS Real-Time Service (IGS)

In April 2014, International GNSS Service (IGS) launched Real-time Service (RTS) with official GPS and unofficial GLONASS products

IGS INTERNATIONAL GNSS SERVICE

Target accuracy:

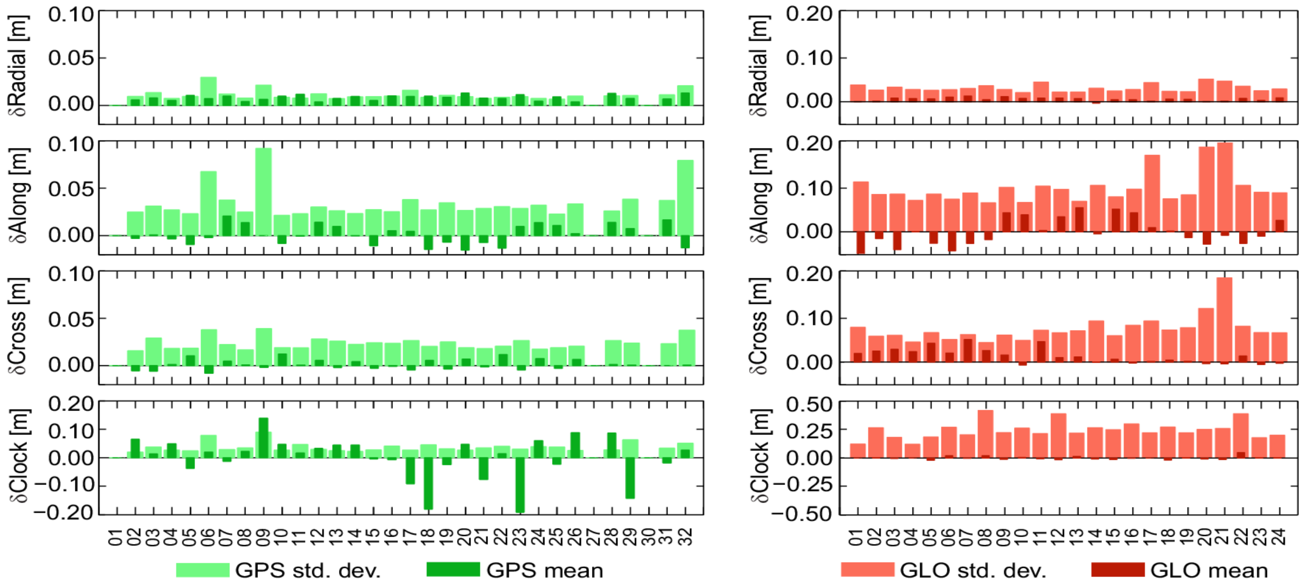
- satellite orbits: at the level of ultra-rapid products(0.10m)
- clock corrections: 0.3ns (0.09m)
- maximum latency: 10 seconds

Stream Name	Description	Ref Point	RTCM Messages	Provider / Solution ID	Bandwidth kbits	Software
IGS01	Orbit/Clock Correction, Single-Epoch Combination	APC	1059 (5),1060 (5)	258 / 1	1.8/sec	ESA/ESOC
IGC01	Orbit/Clock Correction, Single-Epoch Combination	CoM	1059 (5),1060 (5)	258 / 9	1.8/sec	ESA/ESOC
IGS02	Orbit/Clock Correction, Kalman Filter Combination	APC	1057 (60), 1058 (10), 1059 (10)	258 / 2	0.6/sec	BKG
IGS03	Orbit/Clock Correction, Kalman Filter Combination	APC	1057(60), 1058(10), 1059(10), 1063(60), 1064(10), 1065(10)	258 / 3	0.8/sec	BKG

APC: Antenna Phase Center CoM: Center of Mass, (not compliant with current RTCM-SSR standard). The figures in brackets next to each RTCM message ID denote the message sample interval in seconds.

Stream Name	Description	RTCM Messages	Supported GNSS	Bandwidth kbits	Software
RTCM3EPH	Broadcast Ephemeris	1019(5), 1020(5), 1045(5)	GPS, GLONASS, Galileo	6.0/sec	BKG/BNC
RTCM3EPH01	Broadcast Ephemeris	1019(5)	GPS	4.0/sec	DLR/RETICLE

Verification of IGS RTS



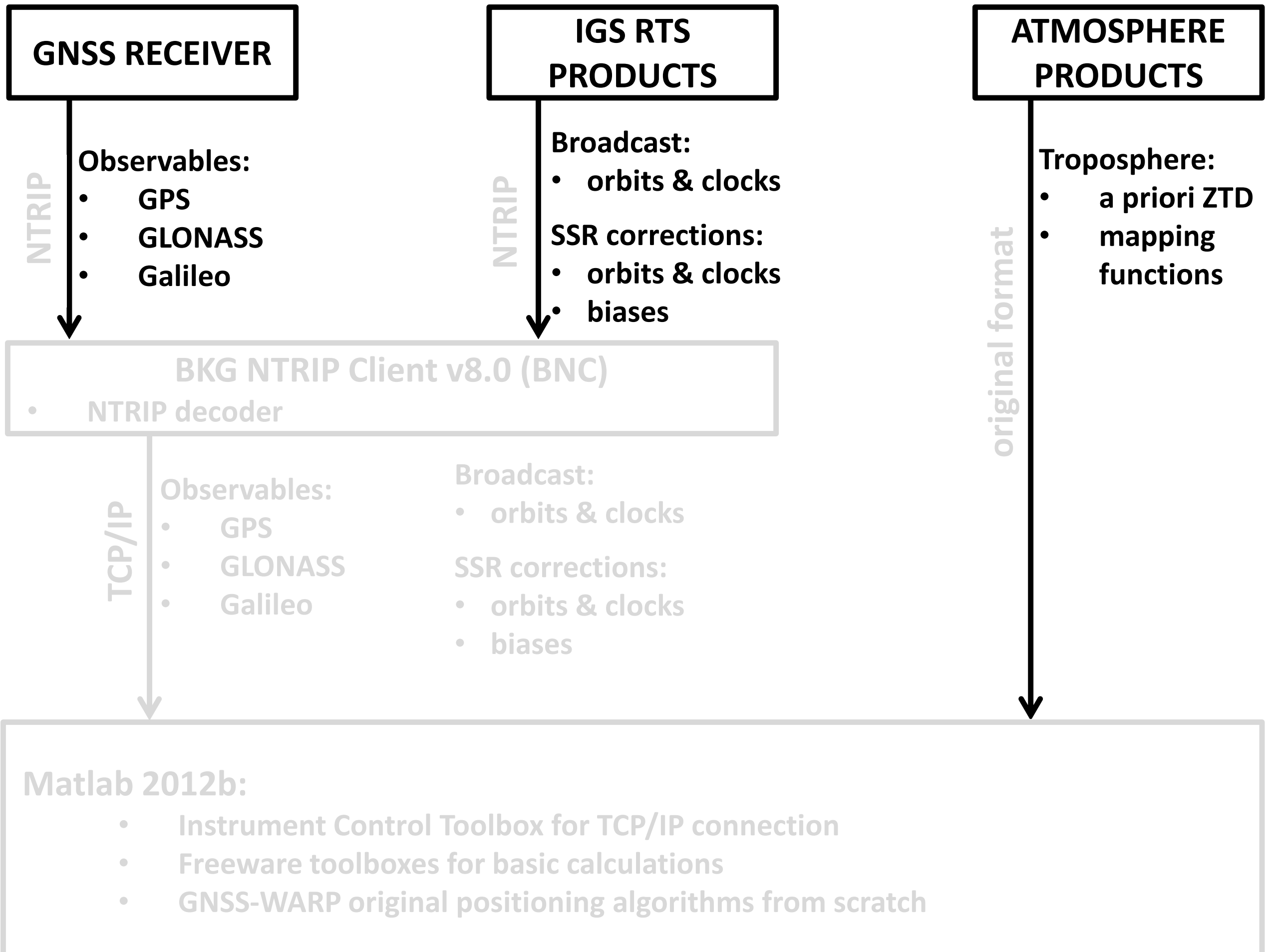
3D RMS of orbit and clocks w/r to ESOC final

1. GPS:
   - orbits: 48 mm
   - clocks: 0.28 ns
2. GLONASS:
   - orbits: 132 mm
   - clocks : 0.82 ns

Availability

- 92% for both GNSS
- gaps for eclipsing GLO
- 28-30 sec of latency (95%) for combined products

GNSS-WARP architecture



Data processing (1)

1. Initialize filters:
   - receiver clock, ambiguities, full covariance matrix with initial variances
2. Synchronize broadcast orbits &clocks with SSR corrections
3. Code-based receiver clock synchronization + a priori receiver position
4. Ionosphere free combination for code and phase:

$$I_p = \frac{f_1^2 \cdot P_1 - f_2^2 \cdot P_2}{f_1^2 - f_2^2} \qquad I_\Phi = \frac{f_1^2 \cdot \Phi_1 - f_2^2 \cdot \Phi_2}{f_1^2 - f_2^2} \qquad \lambda_{L3} = \frac{f_1^2 \cdot \lambda_{L1} - f_2^2 \cdot \lambda_{L2}}{f_1^2 - f_2^2}$$

5. Troposphere handling (using current time and a priori position):
   - get a priori troposphere and mapping functions
   - calculate slants
6. Calculate:
   - receiver effects: antenna phase center (APC) offset and variation
   - satellites effects: phase wind-up, relativistic effect, APC offset
   - Site displacement effects (Sagnac effect, solid earth tides, ocean tide loading, atmosphere pressure loading)

…

Data processing (2)

…

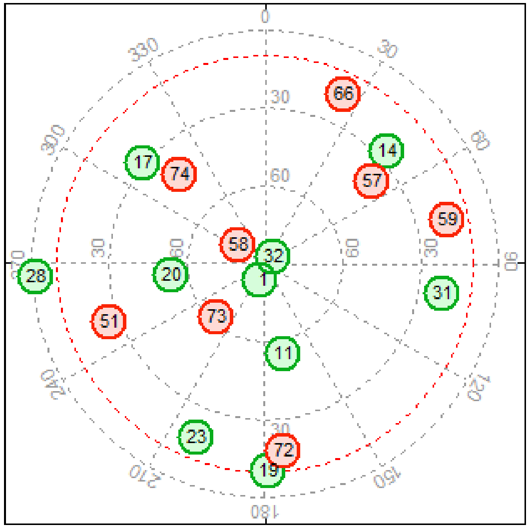
7. Last squares adjustment (LSA):
   - create design (***A***), misclosure (***L***) and weight (***P***)matrixes
   - build covariance matrix (select data from full covariance matrix)
   - estimate parameters

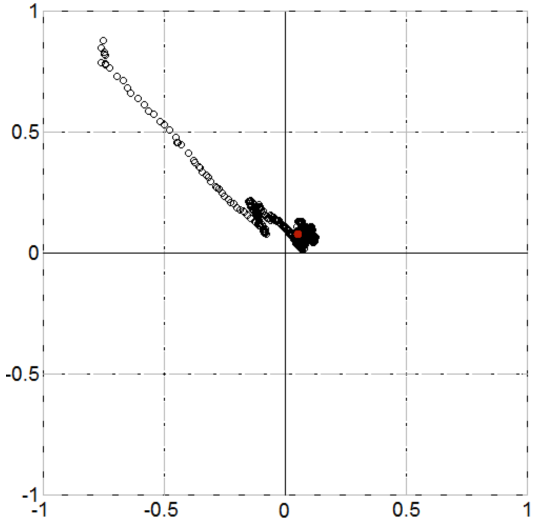
$$X = (A'PA + (Cx)^{-1})^{-1} A'PL$$

   - gloabal and local test (if failed: exclude outliers, reprocessing)
8. If solution is valid - update:
   - receiver position and type
   - Iono-free ambiguity and troposphere filter
   - full covariance matrix:
     - update from LSA covariance matrix
     - reset receiver clock – white noise
     - increase ZTD variance by drift
     - for kinematic positioning – reset coordinates (co)variances
9. Store and plot results

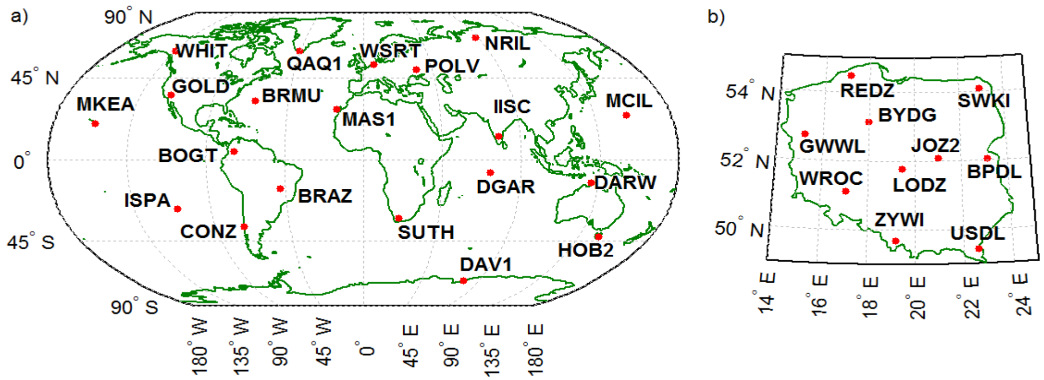
GNSS-WARP features

- Multi-GNSS ready (currently GPS and GLONASS)
- Multi-station processing (under optimization process, now: 3 stations / second on regular CPU)
- Data preprocessing and quality check
- Empirical and external models of troposphere delay and mapping functions (eg. GPT2, VMF)
- Last Squares Adjustment using code and phase measurements on *iono-free* combination with float ambiguities
- Static and kinematic mode, real-time and post processing
- Data import and export from / into files (standard and original formats)
- Dynamic visualization of results and parameters (also in real-time)





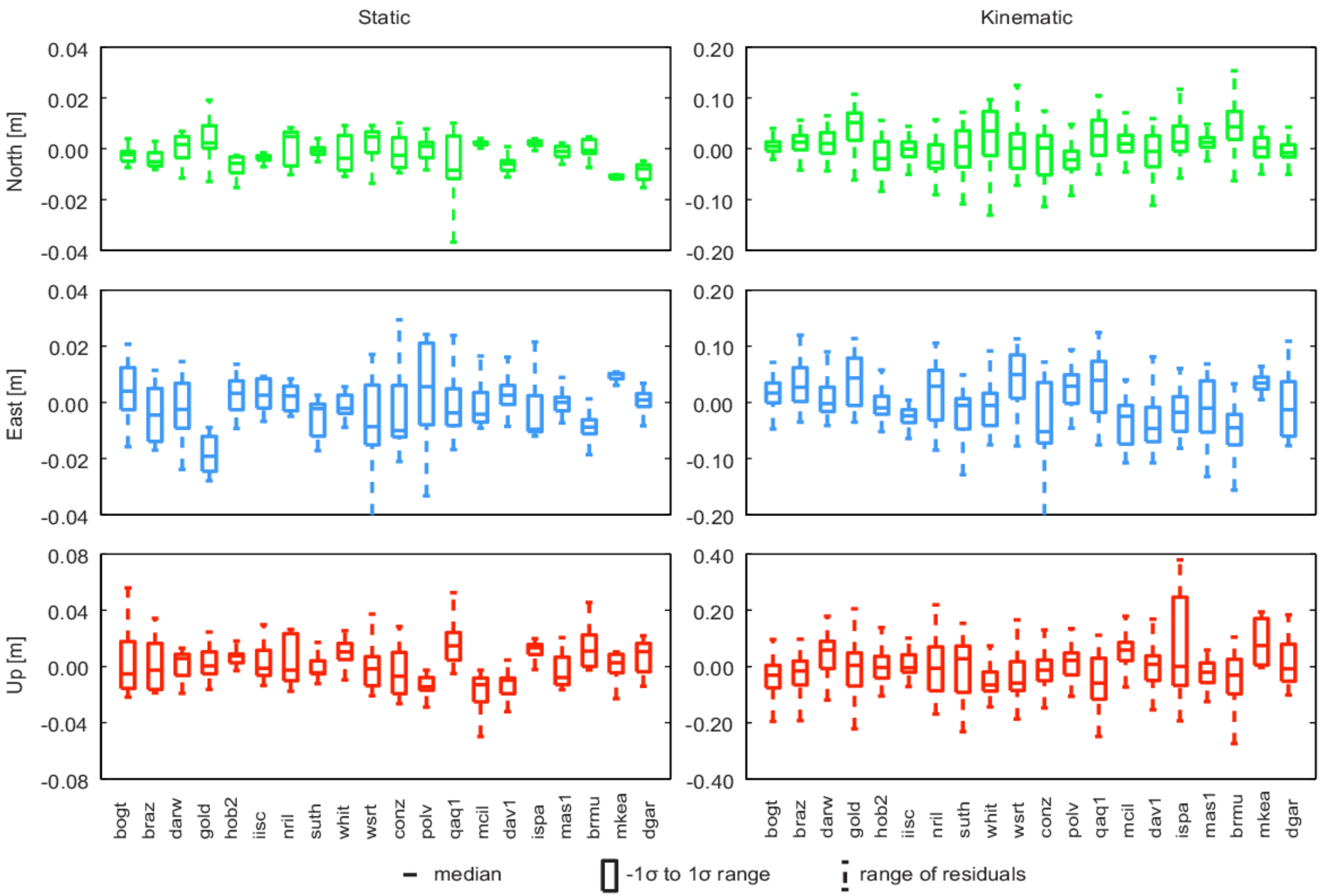
GNSS-WARP – validation (1)



Location of permanent stations used in the experiments: a) 20 selected IGS core stations b) 10 selected EPN stations in Poland

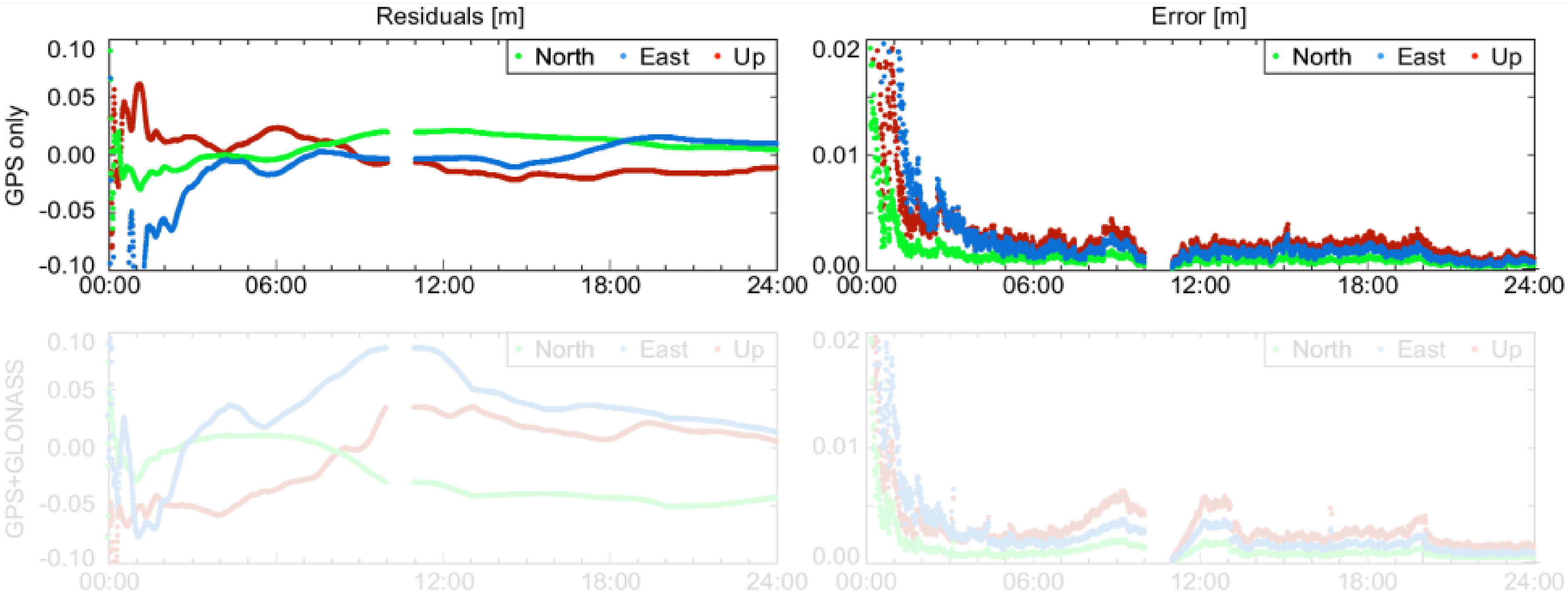
Time series of estimated parameters in GPS only static (left) and kinematic (right) mode for station WROC, DOY 053, 2014, 00:00 – 06:00

GNSS-WARP – validation (2)



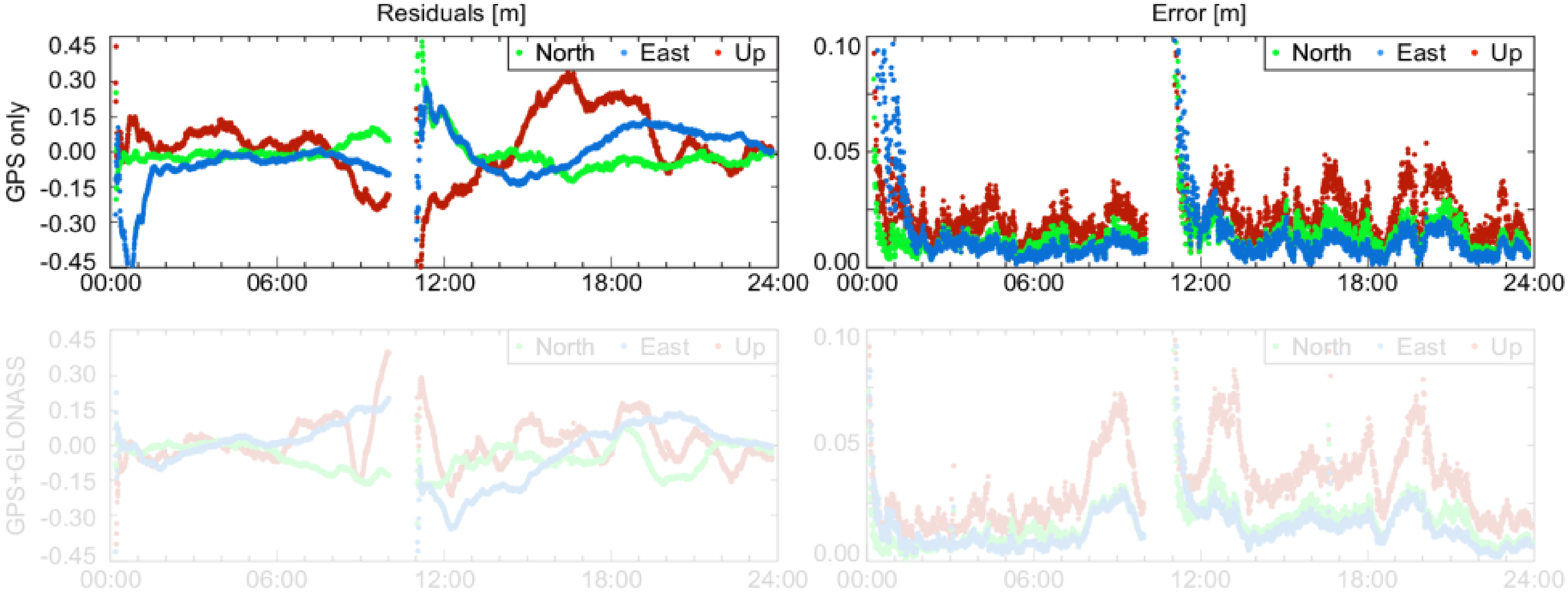
Statistics of coordinate residuals after 1 hour of convergence time, using final IGS products.

Real-time PPP in static mode



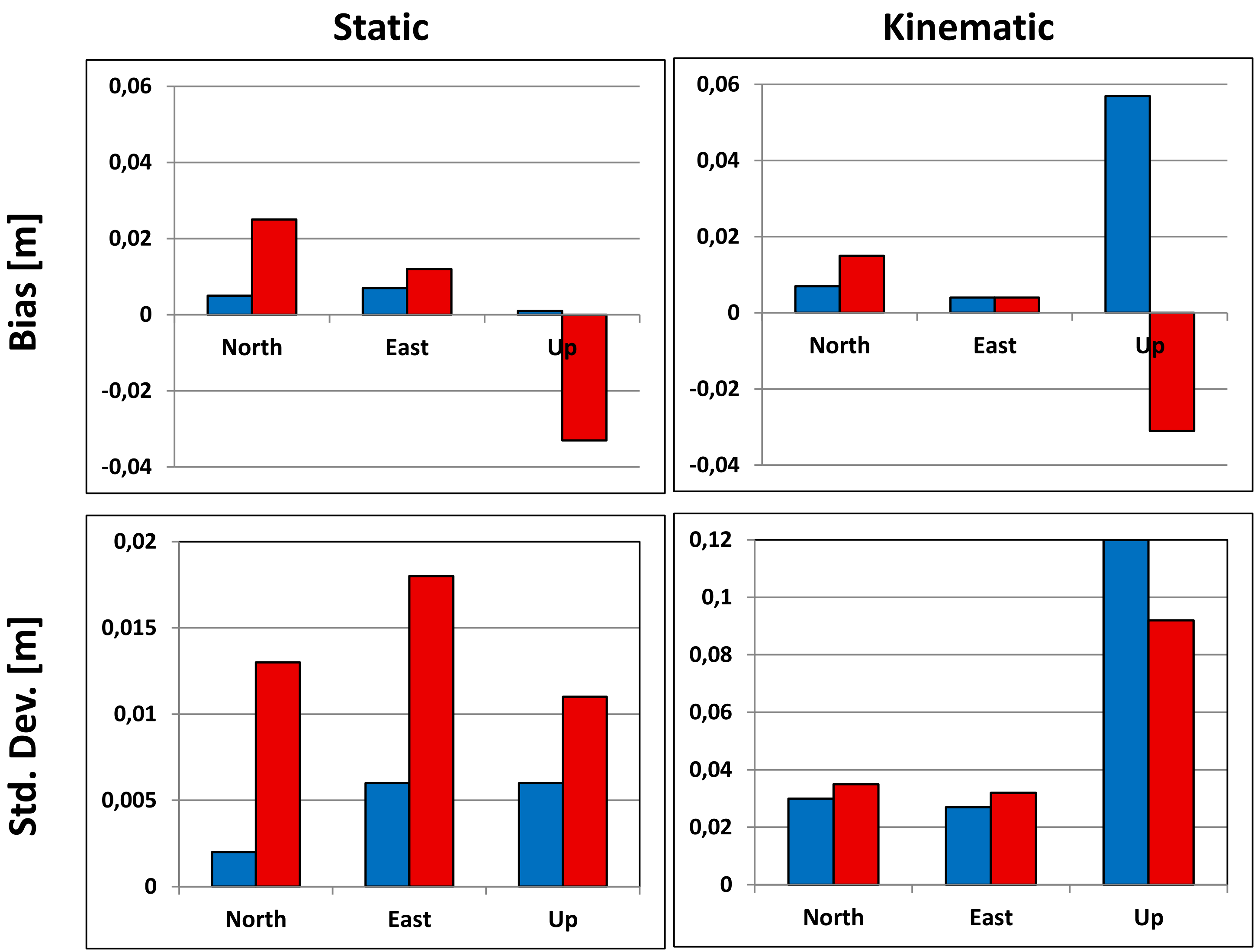
Time series of residuals and estimated errors for GPS only with IGS01 stream (top) and GPS+GLONASS with IGS03 stream (bottom) real-time positioning in static mode for station WROC, DOY 114, 2014

Real-time PPP in kinematic mode



Time series of residuals and estimated errors for GPS only with IGS02 stream (top) and GPS+GLONASS with IGS03 stream (bottom) real-time positioning in kinematic mode for station WROC, DOY 114, 2014

Real-time PPP accuracy and precision (summary)



PPP-RTK with troposphere constraining

Common approach:

- ZHD from external model as fixed value
- ZWD estimated as random walk process

Original approach:

- *a priori* ZTD=ZHD+ZWD from external model (in first epoch)
- ZWD estimated as random walk process
- additional equation in functional mode (ZTD constraining)

$$\delta ZTD = ZTD^{NRT} - ZTD'$$

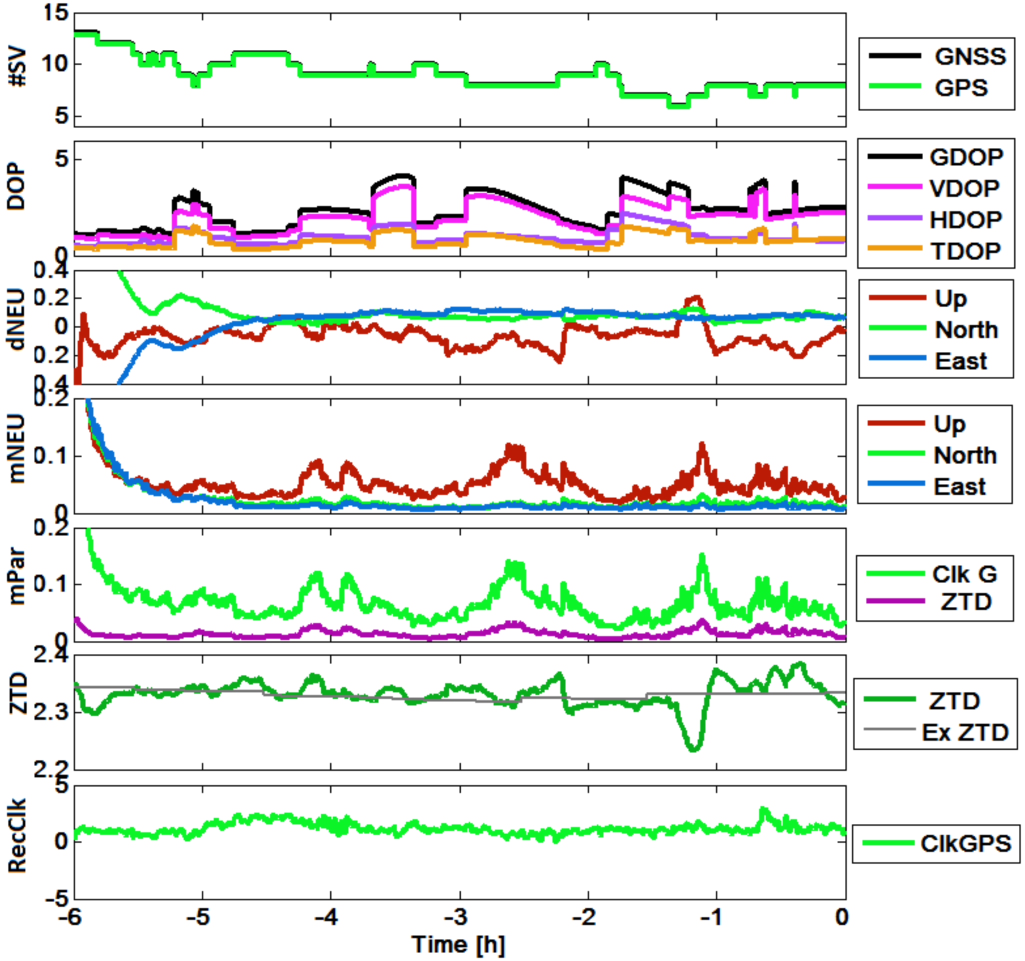
ZTD^{NRT} - the zenith troposphere delay from near-real time regional model
ZTD' - the a priori zenith troposphere delay value (from previous epoch)
δZTD - the correction to the a priori zenith troposphere delay value

Validation:

- 7 session of 24 hour data
- 10 EPN stations located in Poland
- IGS03 stream, 0.1Hz processing
- dynamic atmospheric conditions

Precise Point Positioning + NRT ZTD (1)

Common approach



Original strategy

Station WROC, 5° elevation cut-off angle, VMF, kinematic mode

Summary

1. An original **GNSS-WARP** software for real-time PPP was developed and verified

2. Real-time **static** PPP:
   - 1 cm accuracy for 24 h sessions, residuals below 2 cm after 3 h
   - addition of GLONASS degrades the accuracy

3. Real-time **kinematic** PPP:
   - accuracy of 3 cm in Horizontal and 5 cm in Vertical
   - residuals >20 cm for <5% of data
   - addition of GLONASS improves the convergence time (from 1 h to 15 min.), while accuracy and precision is better or maintained

4. Real-time PPP with **troposphere constraining:**
   - requires a reliable external troposphere delay with low latency
   - improves the Vertical accuracy and precision up to 40% in severe weather conditions

Thank You!

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