Interoperability of the GNSS's for positioning and timing applications

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EUREF Symposium, Leipzig 2015

Systematic monitoring of 14 (22 since Jan 1, 2015) multiGNSS European sites

- Web page: map of multiGNSS permanent sites in Europe, with different receiver types; updated weekly
- For each site, link to downladable plots and data sheets (.csv) with the following information
  - Time offset to GPS
  - Coordinate residuals from multiGNSS processing
  - Post Fit residuals, with different symbols for different GNSS's
  - TZD estimates
- Software: own Matlab development

View files

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About this Web Page

Background

To investigate the interoperability of the various GNSS constellations we compute epochwise the positions of European permanent GNSS receivers by analyzing data simultaneously from different GNSS constellations.

Method

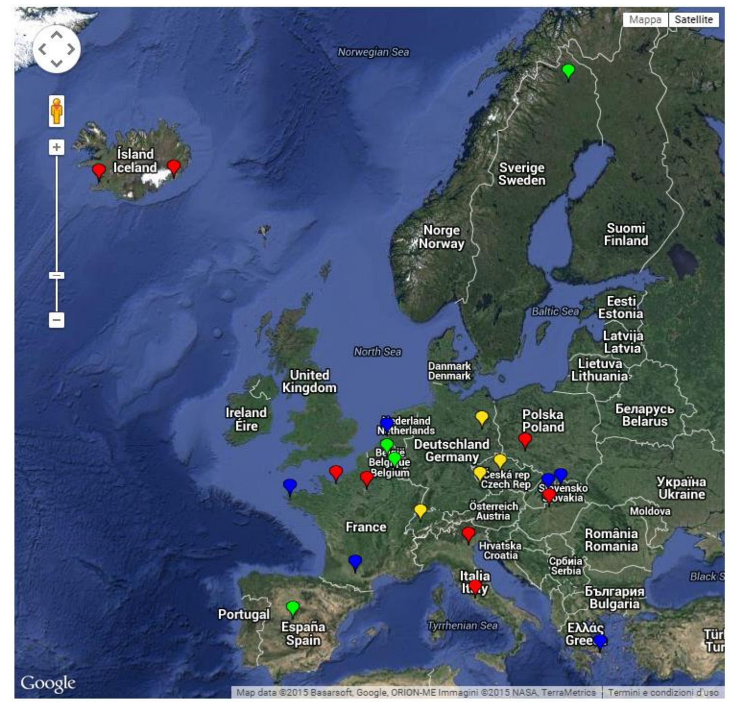
Use RINEX 3.02 data freely available within the MGEX data base. Process pseudoranges in ionofree combination, and broadcast ephemeris. Use as apriori coordinates official ITRF2008/IGb08 values.

Solve for 3 coordinates, 1 clock offset for each GNSS constellation, 1 Tropospheric Zenith Delay (ZTD) at each computation epoch.

The computation is made daily for a sample of European GNSS sites, and different receiver types. This Web site is updated on a weekly basis, beginning Jan. 1, 2014.

Goal

Our goal is to provide data, in tabular and plot format (**see Keyword File Type**), enabling one to assess (**see Keyword Parameter**):



STATION	RECEIVER		FIRMWARE	ANTENNA		SATELLITE SYSTEM
BBYS	TRIMBLE	NETR9	4.85/4.71	TRM59800.00	NONE	GPS+GLO+GAL+BDS+SBAS
BRST	TRIMBLE	NETR9	4.85	TRM57971.00	NONE	GPS+GLO+GAL+BDS+SBAS
BRUX	SEPTENTRIO	POLARX4TR	2.5.2	JAVRINGANT_DM	NONE	GPS+GLO+GAL+BDS
CAEN	LEICA	GR25	3.11	TRM57971.00	NONE	GPS+GLO+GAL+BDS+SBAS
CEBR	SEPTENTRIO	POLARX4	2.5.2-esa3	SEPCHOKE_MC	NONE	GPS+GLO+GAL+BDS+SBAS
DLF1	TRIMBLE	NETR9	4.81	LEIAR25.R3	LEIT	GPS+GLO+GAL+BDS+SBAS
DYNG	TRIMBLE	NETR9	4.85	TRM59800.00	NONE	GPS+GLO+GAL+BDS+SBAS
GANP	TRIMBLE	NETR9	4.93/4.93	TRM55971.00	NONE	GPS+GLO+GAL+BDS+QZSS+SBAS
GOP7	JAVAD	TRE_G3TH DELTA	3.5.1	LEIAR25.R4	LEIT	GPS+GLO+GAL+QZSS+SBAS
HOFN	LEICA	GR25	3.11.1639/6.403	LEIAR25.R4	LEIT	GPS+GLO+GAL+SBAS
KIRU	SEPTENTRIO	POLARX4	2.5.2-esa3	SEPCHOKE_MC	SPKE	GPS+GLO+GAL+BDS+QZSS+SBAS
M0SE	LEICA	GR25	3.20.B1759/6.403	LEIAR25.R4	LEIT	GPS+GLO+GAL+SBAS
MLVL	LEICA	GR25	3.11	TRM57971.00	NONE	GPS+GLO+GAL+BDS+SBAS
PADO	LEICA	GR10	3.10.1633/6.403	LEIAR25.R4	NONE	GPS+GLO+GAL+BDS
PEN2	LEICA	GRX1200+GNSS	8.51/6.110	LEIAR25.R4	LEIT	GPS+GLO+GAL+SBAS
POTS	JAVAD	TRE_G3TH DELTA	3.4.7	JAV_RINGANT_G3T	NONE	GPS+GLO+GAL
REDU	SEPTENTRIO	POLARX4	2.5.2-esa3	SEPCHOKE_MC	NONE	GPS+GLO+GAL+BDS+SBAS
REYK	LEICA	GR25	3.11.1639/6.403	LEIAR25.R4	LEIT	GPS+GLO+GAL+BDS+SBAS
TLSE	TRIMBLE	NETR9	4.85	TRM59800.00	NONE	GPS+GLO+GAL+BDS+SBAS
WROC	LEICA	GR25	3.11.1639/6.403	LEIAR25.R4	LEIT	GPS+GLO+GAL+BDS+QZSS+SBAS
WTZZ	JAVAD	TRE_G3TH DELTA	3.6.1 DEC,30,2014	LEIAR25.R3	LEIT	GPS+GLO+GAL+BDS+SBAS
ZIMJ	JAVAD	TRE_G3TH DELTA	3.4.9 Apr,18,2013	JAVRINGANT_DM	NONE	GPS+GLO+GAL+SBAS

GNSS used

- 31 satellites GPS
- 28 satellites GLONASS
- 13 satellites Beidou (1 2 3 4 5 6 7 8 9 10 11 12 14)
- 3 satellites Galileo (11 12 19) out of 8 (11 12 14 18 19 20 xx xx)
- 1 satellite QZSS

Constants to be used for the broadcast orbit and clock model

	μ [m^3/s^2]	$\omega_\oplus$ [rad/s]	Source
GPS	$3.986005 \cdot 10^{14}$	$7.2921151467 \cdot 10^{-5}$	ICD-GPS-200 Rev.c http://www.navcen.uscg.gov/pubs/gps/icd200/icd200cw1234.pdf
Glonass	$3.986004418 \cdot 10^{14}$	$7.292115 \cdot 10^{-5}$	Glonass ICD v.5.1 facility.unavco.org/data/docs/**ICD_GLONASS**_5.1_(2008)_en.pdf
Galileo	$3.986004418 \cdot 10^{14}$	$7.2921151467 \cdot 10^{-5}$	Galileo OS SIS ICD 1.1 http://ec.europa.eu/enterprise/policies/satnav/galileo/open-service/
BeiDou	$3.986004418 \cdot 10^{14}$	$7.2921150 \cdot 10^{-5}$	http://en.beidou.gov.cn/
QZSS	$3.986005 \cdot 10^{14}$	$7.2921151467 \cdot 10^{-5}$	Interface Specifications for QZSS http://qz-vision.jaxa.jp/USE/is-qzss/DOCS/IS-QZSS_15_E.pdf
IERS standard	$3.986004418 \cdot 10^{14}$	$7.2921150 \cdot 10^{-5}$	IERS Technical Note No.36 http://tai.bipm.org/iers/conv2010/conv2010.html

The two broadcast models

	Model	Update rate	Validity
GPS	Keplerian with secular and periodic perturbations; GPS time (no leap seconds; fixed offset to UTC)	2 hr	2 hr
Galileo		(10 min – 3 hr)(*)	
BeiDou		1 hr	
QZSS		15 min	
Glonass	Runge Kutta (4.order) numerical integration of 9D state vector; Potential up to J_2; Glonass: UTC(SU) time scale (leap seconds required for interoperability) SBAS: probably UTC	30 min	15 min
SBAS		(2 min –30 min)	
(*) different clock offsets (40 ns in this case) and offset rate (10^-14 s/s) depending on frequency and service (Free vs. Integrity)			

Two clock models are available in the navigation messages of GALILEO:

•F/NAV (free accessible navigation)

•I/NAV (integrity navigation)

The SV clock parameters depend on the origin of the message (F-NAV vs. I-NAV) and define the satellite clock for the dual-frequency iono-free combination:

- •F/NAV: E5a-E1 (1176.45 - 1575.42 MHz)
- •I/NAV: E5b-E1 (1207.40 – 1575.42 MHz)

Decoding the 2. word, 6.line (Rinex 3.x + ICD):

HS=3 *'signal component currently in test'*

DVS=0 *'Navigation Data Valid (tbc)'*

```
E11 2013 03 30 02 50 00 4.727053456008e-04 8.196820999729e-11-5.204170427930e-18
     1.130000000000e+02 1.143750000000e+01 3.869089734546e-09-2.259200878362e+00
     4.637986421585e-07 2.963528968394e-04 3.503635525703e-06 5.440594156265e+03
     5.286000000000e+05-2.048909664154e-08-1.161089147383e+00 5.587935447693e-09
     9.570887936756e-01 2.623125000000e+02-1.080462976088e+00-5.986677940595e-09
     1.310768884500e-10 5.130000000000e+02 1.733000000000e+03
    -1.000000000000e+00 3.900000000000e+02-5.355104804039e-09-6.519258022308e-09
     5.292850000000e+05
E11 2013 03 30 02 50 00 4.727416671813e-04 8.198242085200e-11-5.204170427930e-18
     1.130000000000e+02 1.143750000000e+01 3.869089734546e-09-2.259200878362e+00
     4.637986421585e-07 2.963528968394e-04 3.503635525703e-06 5.440594156265e+03
     5.286000000000e+05-2.048909664154e-08-1.161089147383e+00 5.587935447693e-09
     9.570887936756e-01 2.623125000000e+02-1.080462976088e+00-5.986677940595e-09
     1.310768884500e-10 2.580000000000e+02 1.733000000000e+03
    -1.000000000000e+00 4.800000000000e+01-5.355104804039e-09 0.000000000000e+00
     5.293300000000e+05
```

Bit0=1 →I-NAV E1-B

Bit1=1 →F-NAV E5a-I

Software implementation

- C program for unpacking Rinex Obs and Nav files (3.02)
- Matlab routines
  - I/O
  - Broadcast orbit model
    - Analytic for GPS Galileo BeiDou QZSS, with adaptation for BeiDou low inclination orbits (C05), according to ICD
    - Runge Kutta 4. order (Earth potential truncated to J_2) for Glonass, SBAS (EGNOS, GAGAN-GSAT)
  - Measurement model : 3 coordinates, 1 rcvr+GNSS clock bias, 1 TZD solved for every epoch
  - All GNSS data are processed in one block simultaneously at each epoch (interoperability!)
  - Partials, AZ El angles, TZD, clock bias and post fit residuals saved to file for possible reprocessing/smoothing

Intersystem time bias

<u>Theoretically:</u>

- once the satellite clock error has been included into the pseudorange model, all the GNSS's should be synchronized among each other within few ns
- Consequently, one has to solve for coordinates and receiver clock error (4 unknowns)

<u>In practice it turns out that:</u>

- each GNSS, after the polynomial correction of satellite clock drift, has its own bias
- One has to solve for the sum of receiver clock error **<u>and a GNSS specific clock bias</u>**

$$
H = \begin{bmatrix}
-\frac{x_{1G}-x_0}{\rho_{1G}} & -\frac{y_{1G}-y_0}{\rho_{1G}} & -\frac{z_{1G}-z_0}{\rho_{1G}} & 1 & 0 & 0 & 0 & 0 & \frac{1}{\sin El_{1G}} \\
-\frac{x_{2G}-x_0}{\rho_{2G}} & -\frac{y_{2G}-y_0}{\rho_{2G}} & -\frac{z_{2G}-z_0}{\rho_{2G}} & 1 & 0 & 0 & 0 & 0 & \frac{1}{\sin El_{2G}} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \\
-\frac{x_{nG}-x_0}{\rho_{nG}} & -\frac{y_{nG}-y_0}{\rho_{nG}} & -\frac{z_{nG}-z_0}{\rho_{nG}} & 1 & 0 & 0 & 0 & 0 & \frac{1}{\sin El_{nG}} \\
-\frac{x_{1R}-x_0}{\rho_{1R}} & -\frac{y_{1R}-y_0}{\rho_{1R}} & -\frac{z_{1R}-z_0}{\rho_{1R}} & 0 & 1 & 0 & 0 & 0 & \frac{1}{\sin El_{1R}} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \\
-\frac{x_{nR}-x_0}{\rho_{nR}} & -\frac{y_{nR}-y_0}{\rho_{nR}} & -\frac{z_{nR}-z_0}{\rho_{nR}} & 0 & 1 & 0 & 0 & 0 & \frac{1}{\sin El_{nR}} \\
-\frac{x_{1E}-x_0}{\rho_{1E}} & -\frac{y_{1E}-y_0}{\rho_{1E}} & -\frac{z_{1E}-z_0}{\rho_{1E}} & 0 & 0 & 1 & 0 & 0 & \frac{1}{\sin El_{1E}} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \\
-\frac{x_{nR}-x_0}{\rho_{nR}} & -\frac{y_{nR}-y_0}{\rho_{nR}} & -\frac{z_{nE}-z_0}{\rho_{nE}} & 0 & 0 & 1 & 0 & 0 & \frac{1}{\sin El_{nE}} \\
-\frac{x_{1C}-x_0}{\rho_{1C}} & -\frac{y_{1C}-y_0}{\rho_{1C}} & -\frac{z_{1C}-z_0}{\rho_{1C}} & 0 & 0 & 0 & 1 & 0 & \frac{1}{\sin El_{1C}} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \\
-\frac{x_{nC}-x_0}{\rho_{nC}} & -\frac{y_{nC}-y_0}{\rho_{nC}} & -\frac{z_{nC}-z_0}{\rho_{nC}} & 0 & 0 & 0 & 1 & 0 & \frac{1}{\sin El_{nC}} \\
-\frac{x_{1J}-x_0}{\rho_{1J}} & -\frac{y_{1J}-y_0}{\rho_{1J}} & -\frac{z_{1J}-z_0}{\rho_{1J}} & 0 & 0 & 0 & 0 & 1 & \frac{1}{\sin El_{1J}} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \\
-\frac{x_{nJ}-x_0}{\rho_{nJ}} & -\frac{y_{nJ}-y_0}{\rho_{nJ}} & -\frac{z_{nJ}-z_0}{\rho_{nJ}} & 0 & 0 & 0 & 0 & 1 & \frac{1}{\sin El_{nJ}}
\end{bmatrix}
$$

GPS

GLONASS

GALILEO

BeiDou

QZSS

$$x = [H^T H]^{-1} H^T y$$

$$
x = \begin{bmatrix}
\Delta x \\
\Delta y \\
\Delta z \\
rcvrbias + TimeSystemCorr\_GPS \\
rcvrbias + TimeSystemCorr\_GLO \\
rcvrbias + TimeSystemCorr\_GAL \\
rcvrbias + TimeSystemCorr\_BeiDou \\
rcvrbias + TimeSystemCorr\_QZSS \\
TZD
\end{bmatrix}
$$

Intersystem time bias

Define TIME SYSTEM CORR relative to GPS

No need to solve for coordinates: assume ITRF2008 values

Strategy: 1. iteration: coordinates constrained, solve for tropo and clock

2. iteration: back substitute clock and tropo with constraints, adjust coords

$$x = [H^T H + C]^{-1} H^T y$$

$$C = \begin{bmatrix} \sigma & 0 & 0 & 0 & \dots & 0 \\ 0 & \sigma & 0 & 0 & \dots & 0 \\ 0 & 0 & \sigma & 0 & \dots & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & \dots & 0 \end{bmatrix}$$

$$x = \begin{bmatrix} \boxed{\begin{matrix} \Delta x \\ \Delta y \\ \Delta z \end{matrix}} \\ rcvrbias + TimeSystemCorr\_GPS \\ rcvrbias + TimeSystemCorr\_GLO \\ rcvrbias + TimeSystemCorr\_GAL \\ rcvrbias + TimeSystemCorr\_BeiDou \\ rcvrbias + TimeSystemCorr\_QZSS \\ TZD \end{bmatrix}$$

Constrained to near zero

Solved for parameters

$$GLGP = \cancel{rcvrbias} + TimeSystemCorr\_GLO - \left(\cancel{rcvrbias} + TimeSystemCorr\_GPS\right)$$

$$GPGA = \cancel{rcvrbias} + TimeSystemCorr\_GPS - \left(\cancel{rcvrbias} + TimeSystemCorr\_GAL\right)$$

.....

GAUT 1.8626451492e-09-8.881784197e-16 82800 1757 1757 0 TIME SYSTEM CORR

GLGP -3.7252902985e-07 0.000000000e+00 86400 1757 1757 0 TIME SYSTEM CORR

GLUT -1.8673017621e-07 0.000000000e+00 86400 1757 1757 0 TIME SYSTEM CORR

GPGA 8.7020453066e-09 1.776356839e-15 172800 1757 1757 0 TIME SYSTEM CORR

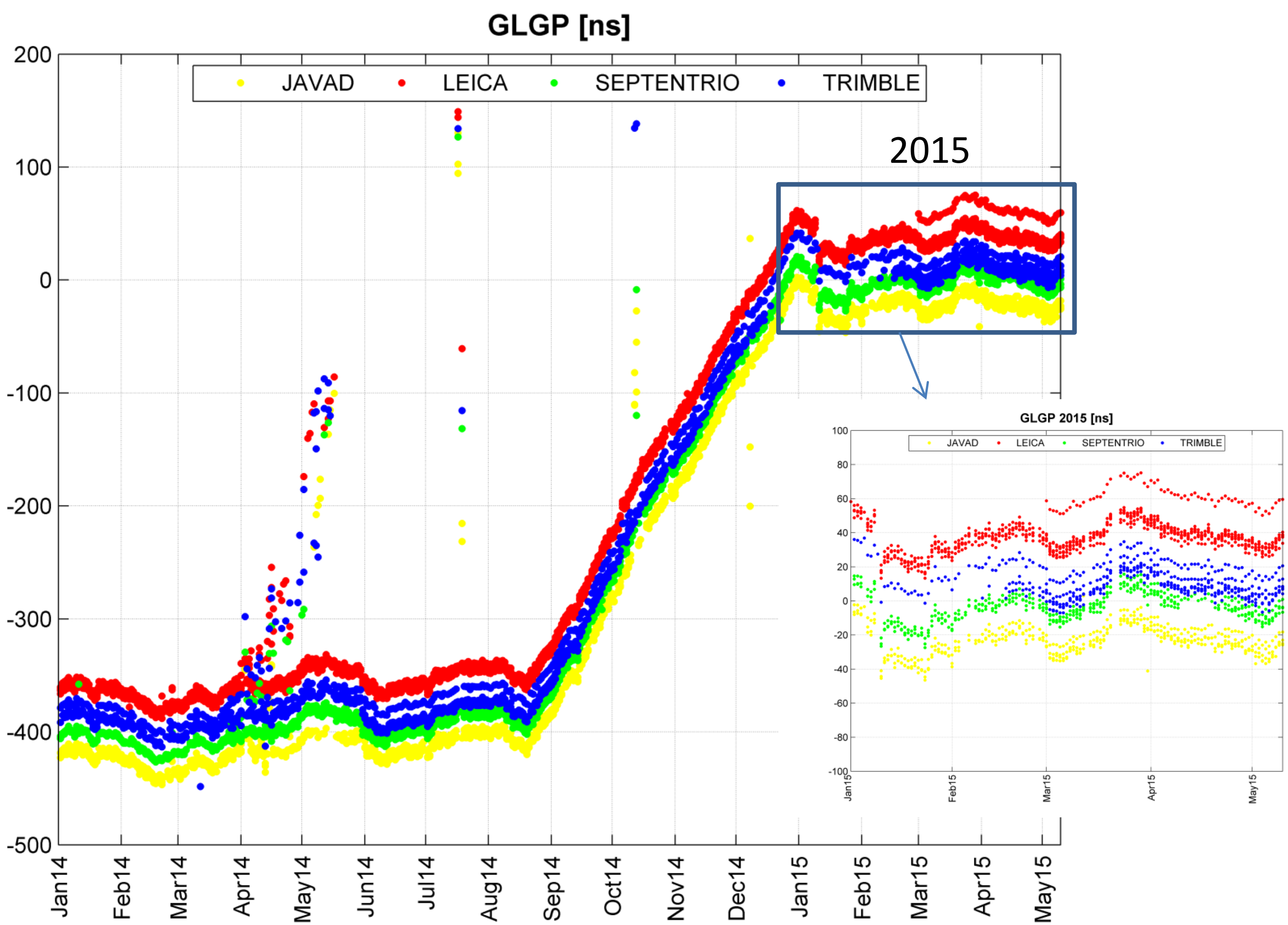
GPUT -9.3132257462e-10-7.993605777e-15 319488 1757 1757 0 TIME SYSTEM CORR

QZUT -1.0710209608e-08-3.019806627e-14 403200 1757 1757 0 TIME SYSTEM CORR

Verify information in the header of the RINEX 3.x NAV header

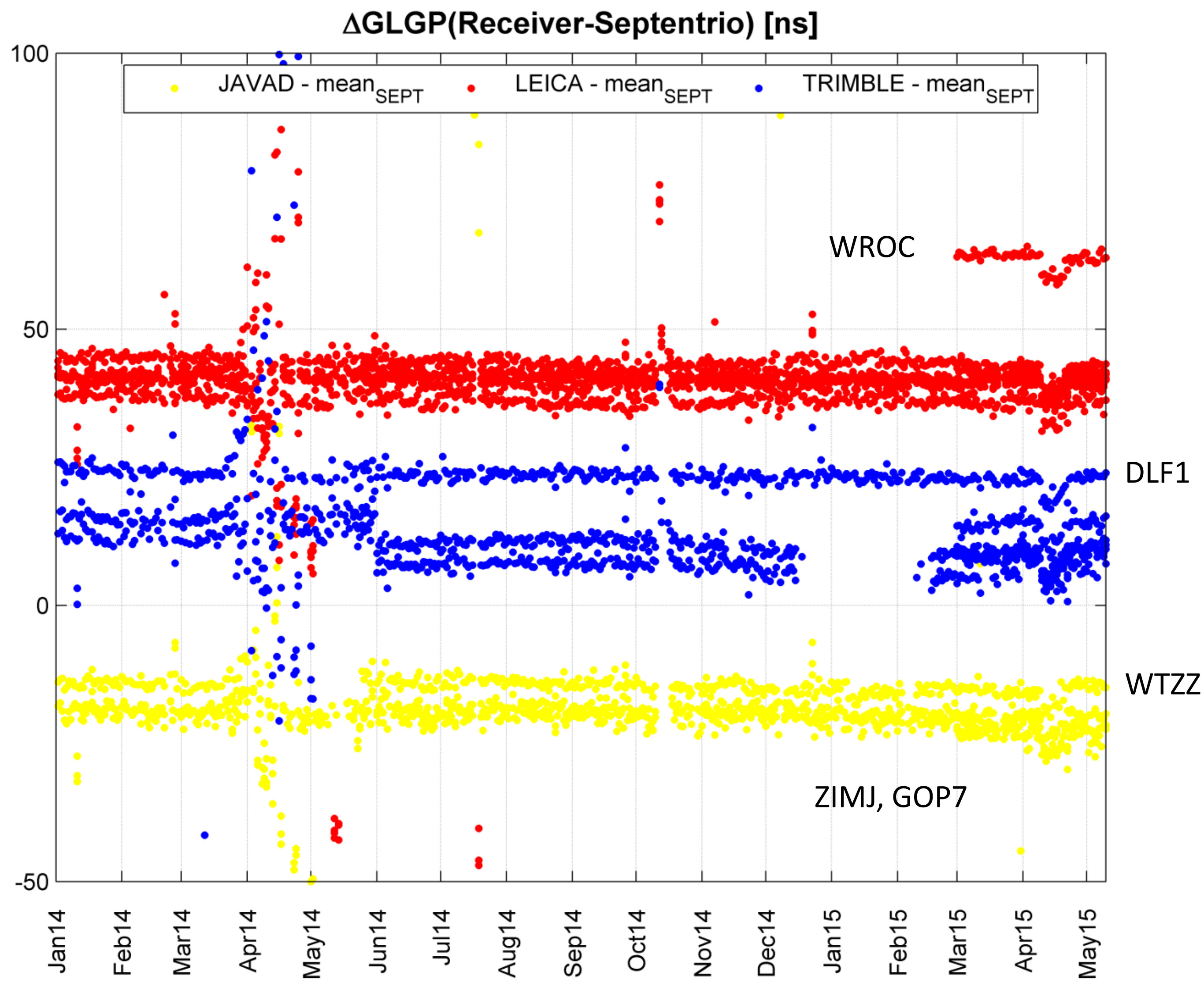
GLONASS to GPS Time Offset

Time tag offset between Glonass and GPS data

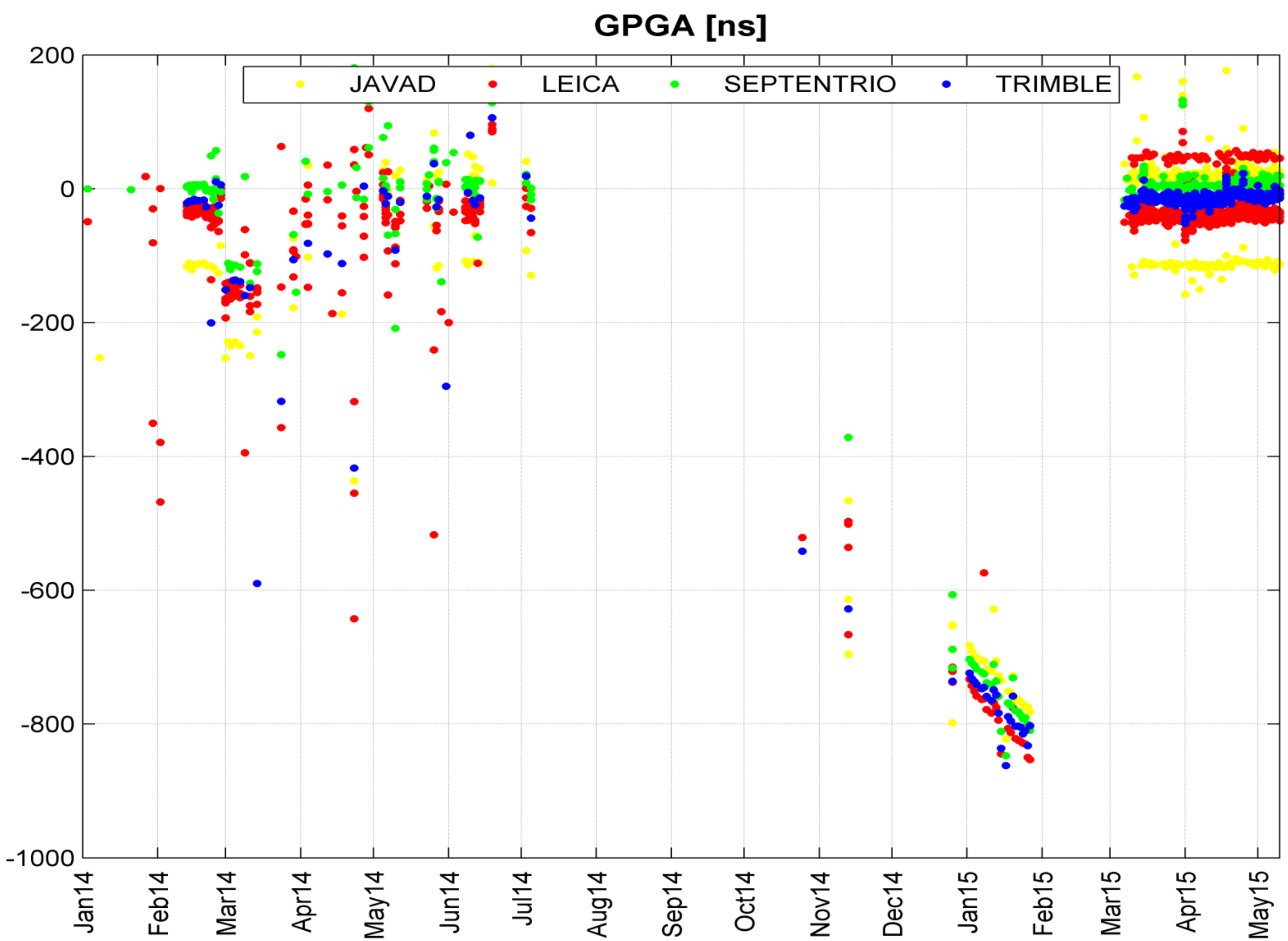


Glonass to GPS Time Offset, relative to Septentrio (average of BRUX CEBR KIRU REDU)

- Receiver dependent biases are clearly visible
- Combination firmware/antenna/radome possible causes
- Calibration is definitely needed

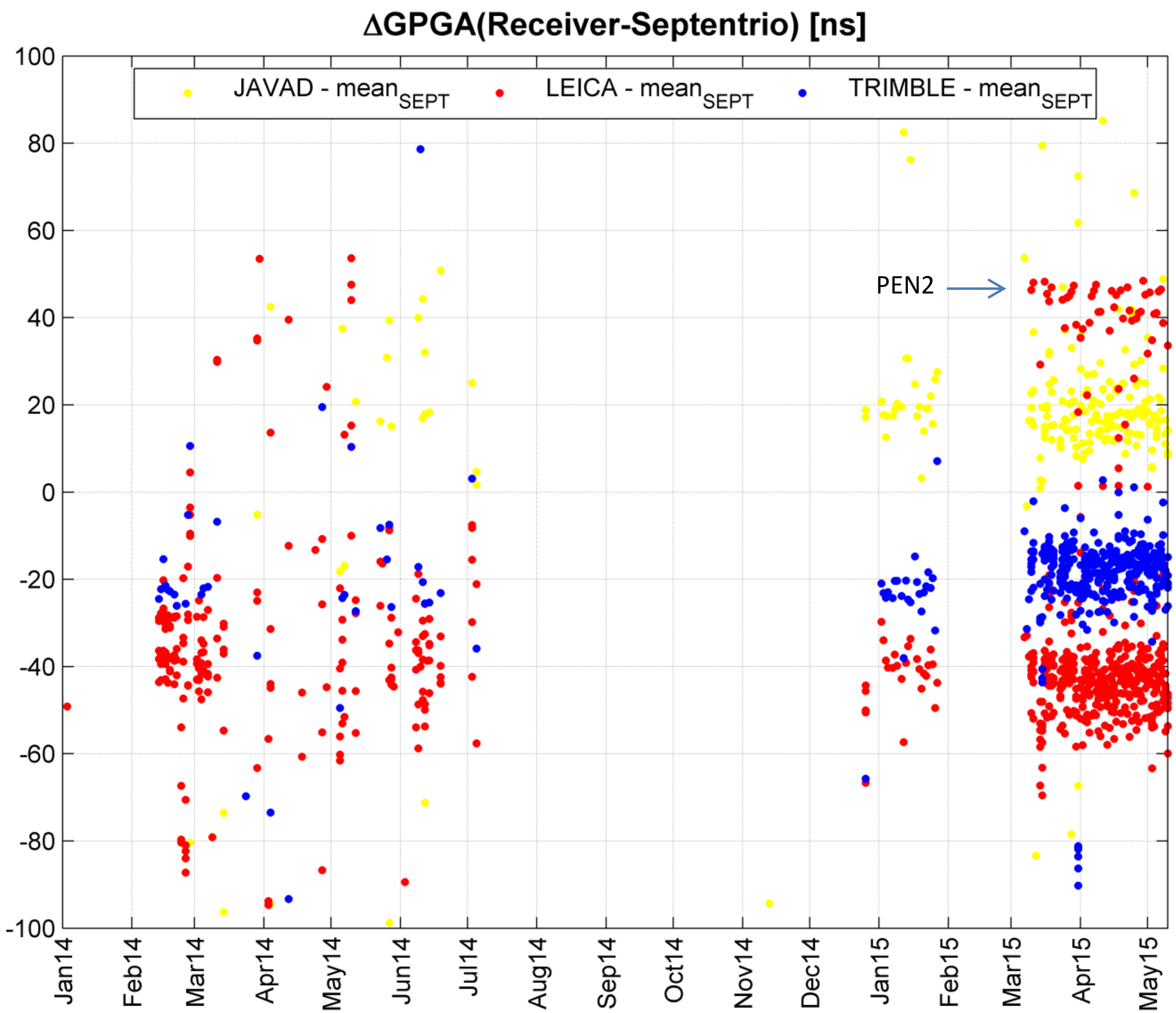


Galileo to GPS Time Offset

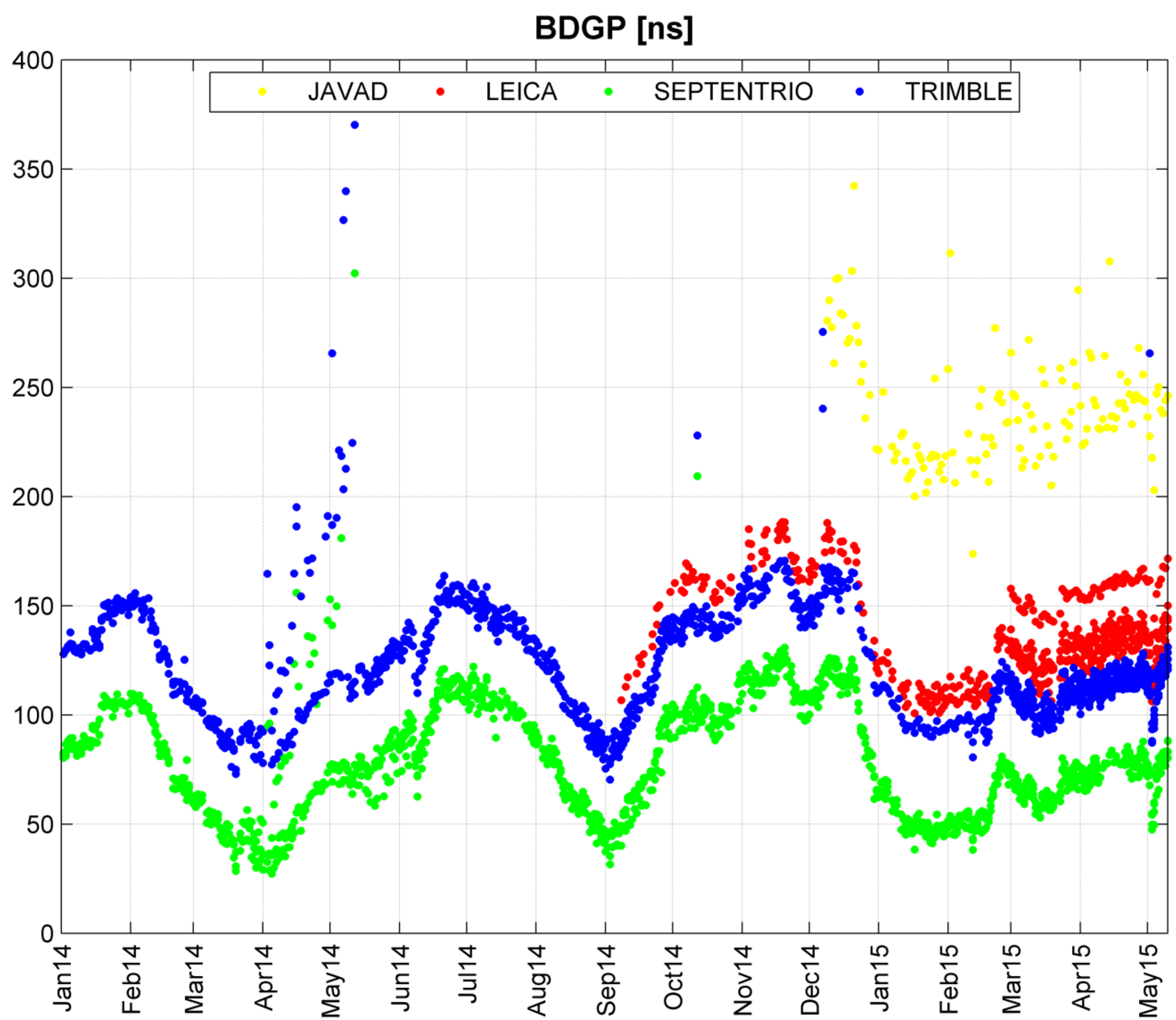


Galileo to GPS time offset, relative to Septentrio

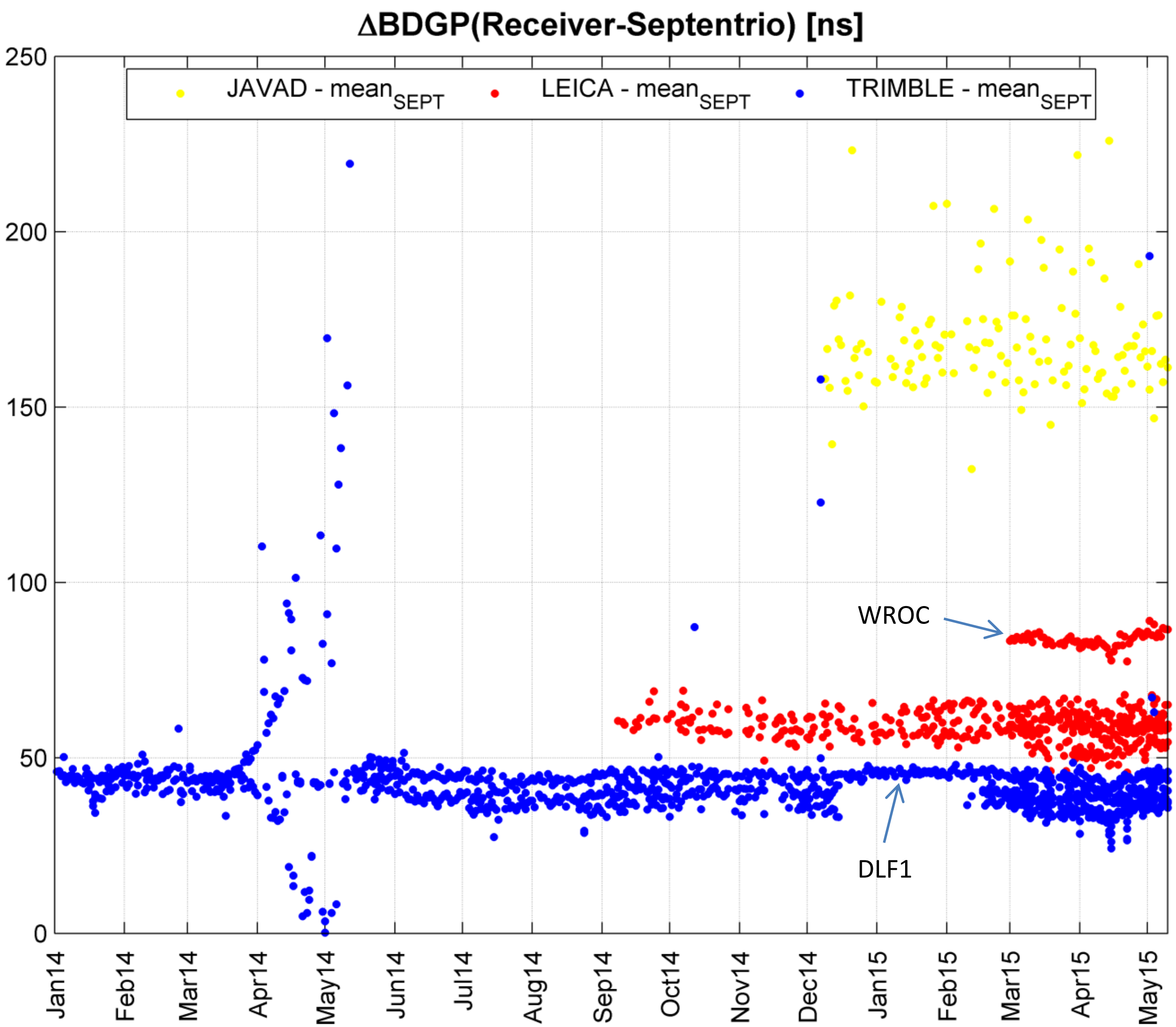
- Again receiver dependent biases are visible
- For certain receivers, one may have a different behavior from the mean of the others (e.g. PEN2)



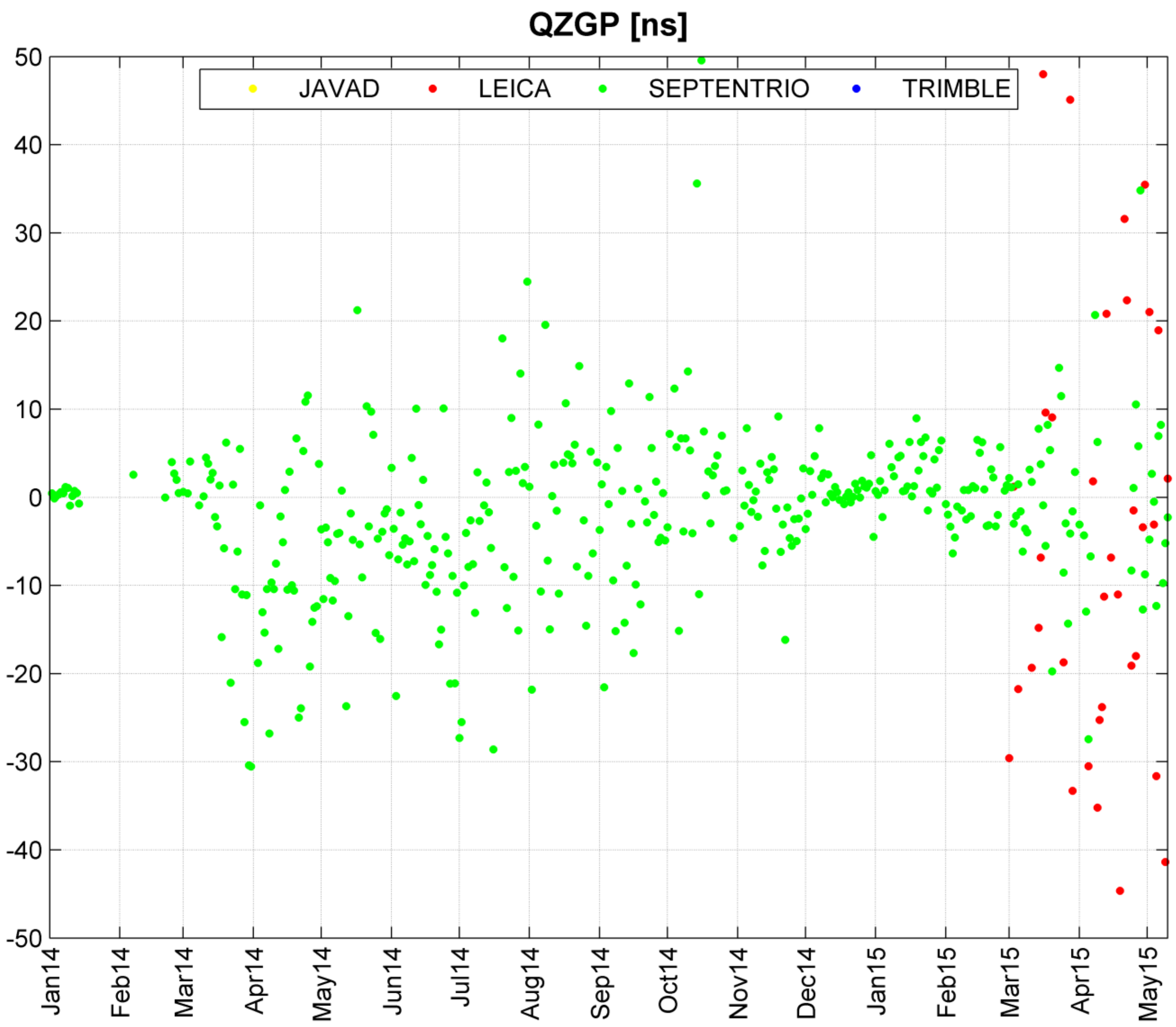
BeiDou to GPS Time Offset



BDGP Time Offset relative to Septentrio

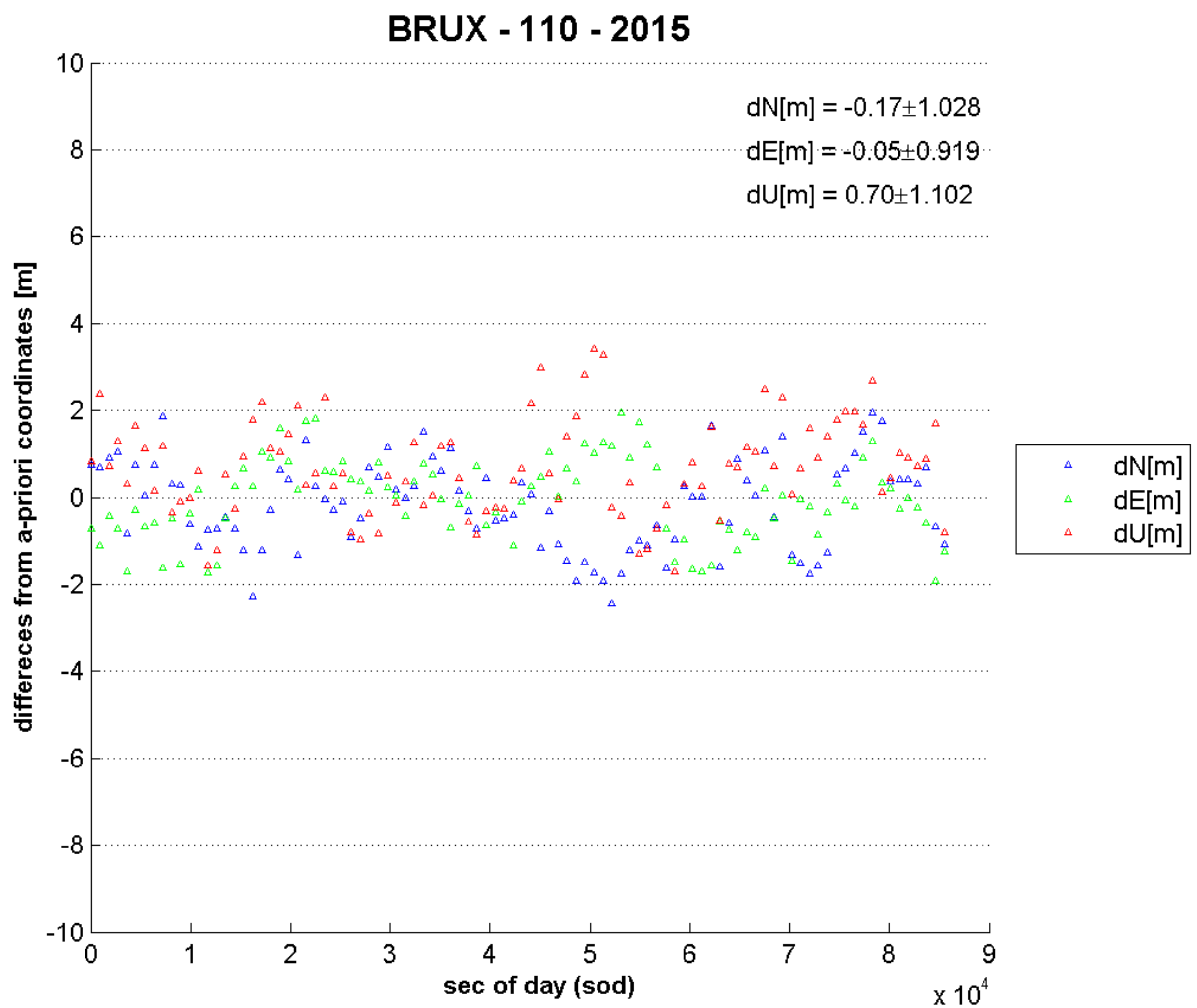


QZSS to GPS Time Offset (KIRU and WROC)



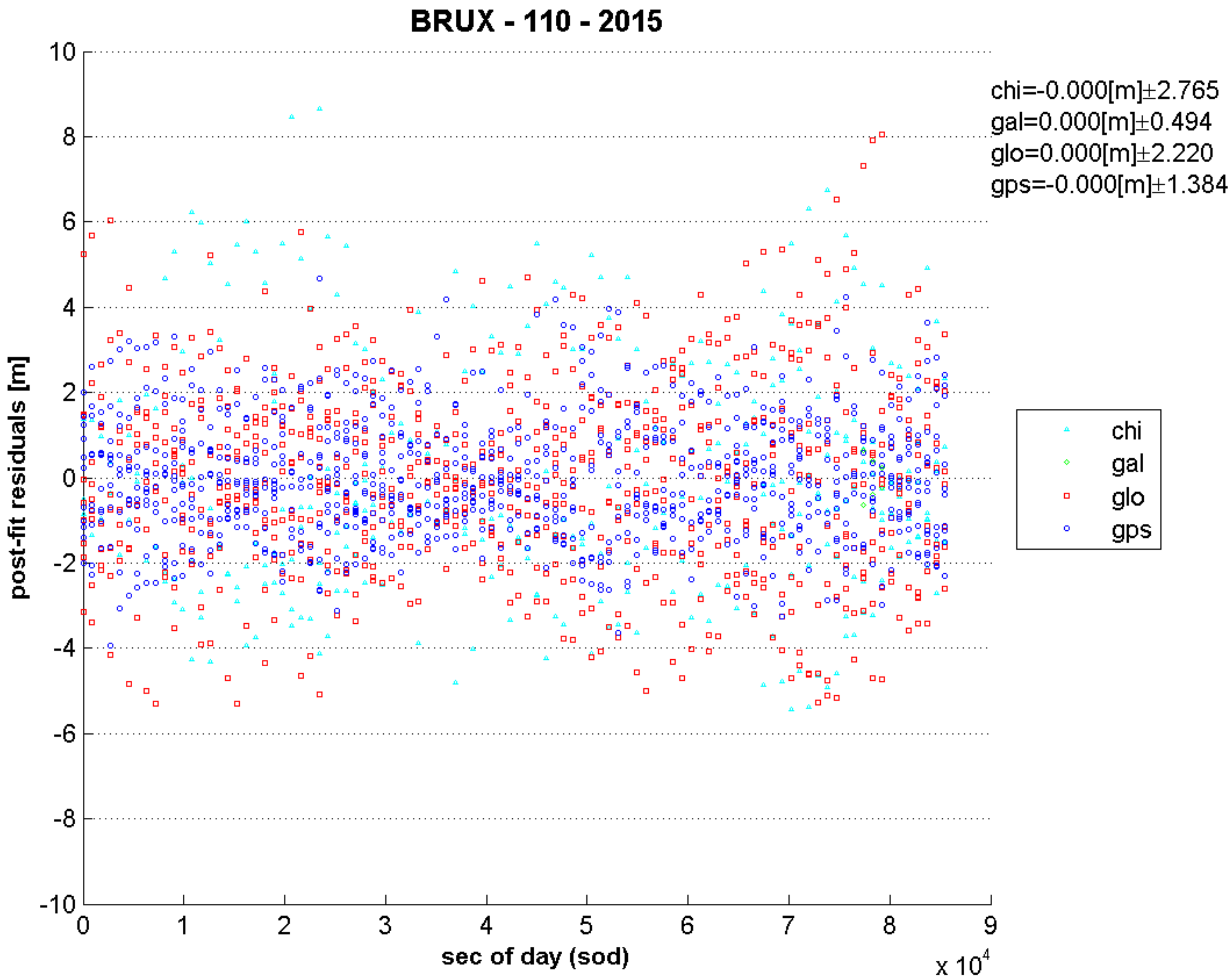
Epochwise discrepancy relative to IGb08 nominal coordinates

- Corrections to nominal coordinates are smaller than 1 standard deviation

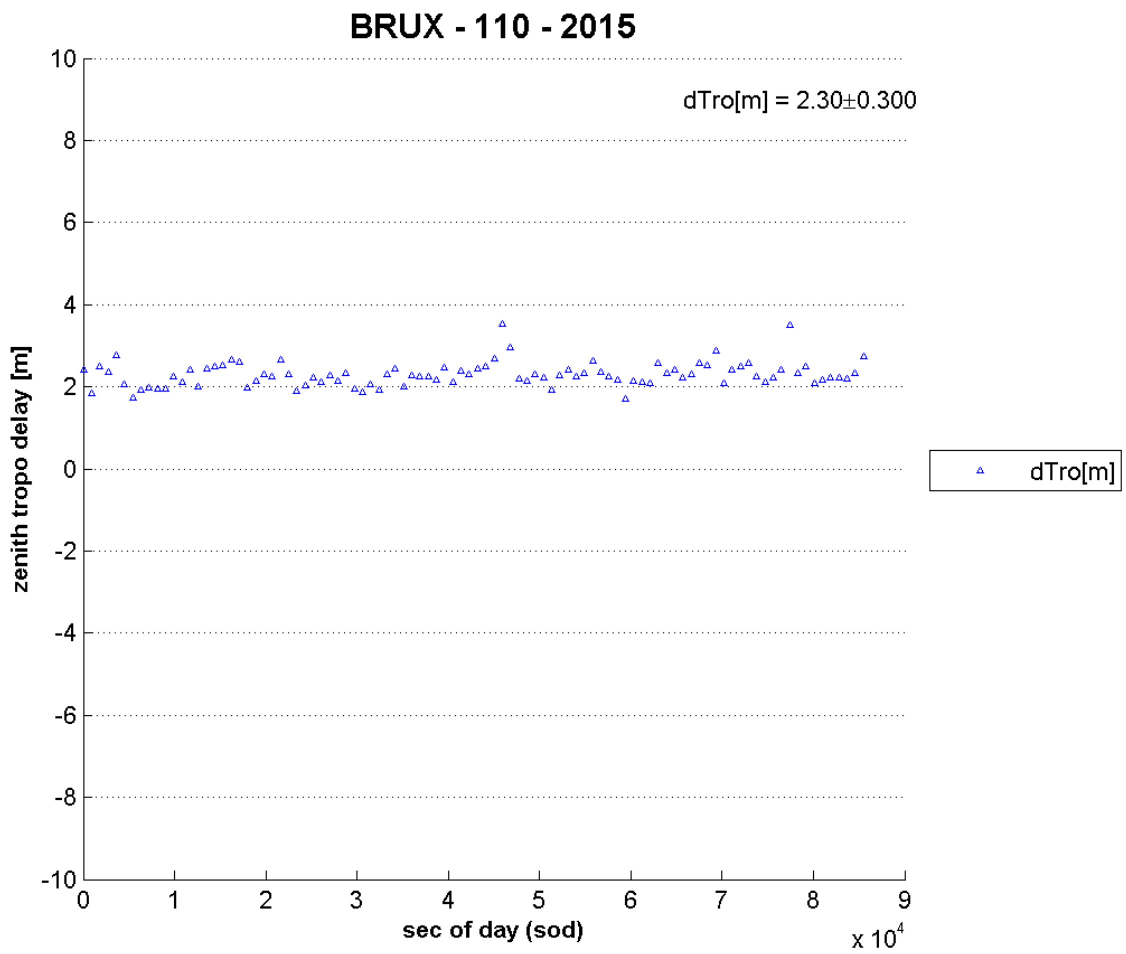


Positioning using ionofree pseudoranges, broadcast ephemeris

- Data from 4 GNSS simultaneously processed in one adjustment
- Solve for 3 coords and sum of rcvr clock bias, GNSS residual time bias, TZD at each epoch (8 parameters)
- Analyze post fit residuals separately for each GNSS, to asses interoperability



Tropospheric Zenith Delay estimated epochwise (ionofree pseudoranges, broadcast ephemeris)



Conclusions

- Statistics available for 22 european receivers of different type since 2014.0, routinely updated in Web site
- Glonass time has aligned to GPS time
- Galileo: improving
- BeiDou: periodic offsets to GPS time
- QZSS1: random offsets, improving
- Receiver dependent biases clearly visible