INDIVIDUAL VS. TYPE CALIBRATION OF MULTIGNSS RECEIVERS

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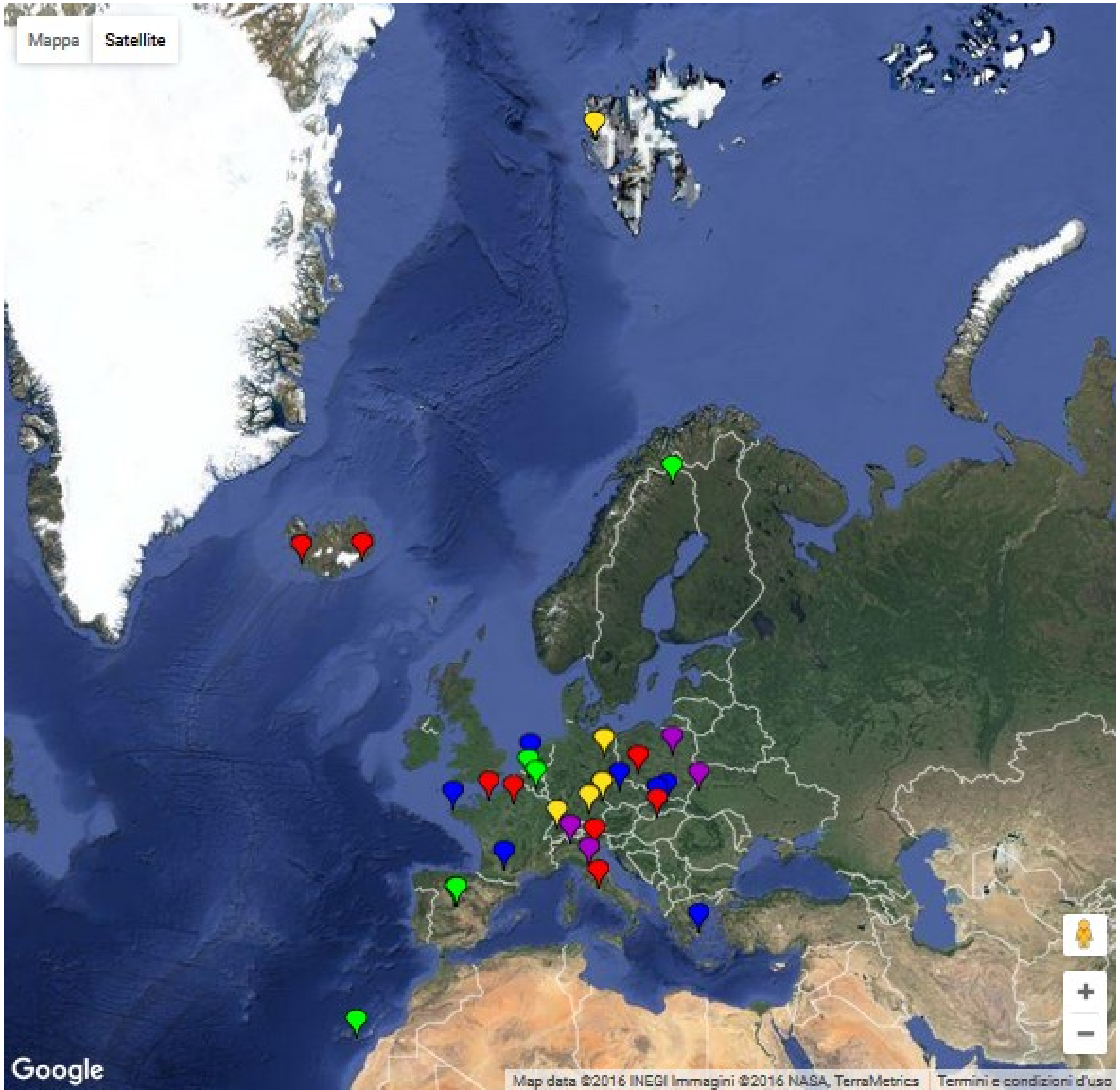
Outlook

- Monitor 31 European GNSS sites with 5 different receivers (Javad, Leica, Septentrio, Topcon, Trimble)
- Questions to be addressed:
  - Offset among the time scales of different GNSS constellations? (Note: 3 m ⇔ 10 ns: we observe biases of tens to hundreds of ns)
  - Do different receivers measure different offsets?
- Use own MATLAB software
- Focus on Glonass, Galileo, Beidou, QZSS taking GPS as reference
- Use Broadcast ephemeris, and SP3 from GFZ and CODE
- Use RINEX 3.x data, except Topcon Stations, for which the provided RINEX 2.x are converted to RINEX 3.x with gfzrnx of GFZ (http://semisys.gfz-potsdam.de/semisys/scripts/download/)

Stations Map

- Javad
- Leica
- Septentrio
- Trimble
- Topcon



Input Data

- Static receivers -> sample at 15 min, synchronous with SP3 epochs; at each epoch solve for coords, clock, TZD
- Pseudoranges/carrier phases combined in iono free mode

	Carrier/Frequency [MHz]		Coding in RINEX 3.03		
GPS	L1 (1575.42)	L2 (1227.60)	C1C	C2W	
Galileo*	E1 (1575.42)	E5b (1207.14)	C1	C7I/C7Q/C7X	I/NAV
	E1 (1575.42)	E5a (1176.45)	C1	C5I/C5Q/C5X	F/NAV
BeiDou	B1 (1561.098)	B2 (1207.14)	C1I	C7I	

According to Rinex version 3.03, tables 4, 6, 9.

(*) For Galileo we use E1-E5b (I/NAV)

	E08	E09	E11	E12	E14(2)	E18(2)	E19	E20(1)	E22	E24	E26	E30
obs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
brdm	✓	✓	✓	✓			✓		✓	✓	✓	✓
sp3	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓

(1) Unavailable

(2) Incorrect orbit

Pseudo-range model for a combined multiGNSS positioning

$$p(t) = \sqrt{[X(t') + \omega_e \cdot Y(t-t') - x]^2 + [Y(t') - \omega_e \cdot X(t-t') - y]^2 + [Z(t') - z]^2} +$$
$$+c \cdot dt(t') + c \cdot (TSC_X + dT_{Rec}) + \frac{TZD}{\sin(El)} + DCB^i$$

- t = time of reception; t' = time of trasmission; ω_e = earth rotation rate
- TSC_X = Time System Correction of the X GNSS System (G = GPS; R = Glonass; E = Galileo; C = BeiDou) relative to an average time scale
- dT_{Rec} = Receiver Clock Error
- $dt(t')$ = Satellite Clock Error + leap seconds (LS: full leap seconds for Glonass; 14 seconds for BeiDou) .
  - Broadcast ephemeris:
  - Sp3 ephemeris: input data $dt(t') = a_0 + a_1 \cdot (t' - T_{oc}) + a_2 \cdot (t' - T_{oc})^2 - \frac{2\sqrt{\mu a}}{c^2} e \cdot \sin E(t') + LS$
- TZD = Tropospheric Zenith Delay
- DCB = Differential Code Bias

$$GLGP = c \cdot (TSC_R + dT_{Rec}) - c \cdot (TSC_G + dT_{Rec})$$

$$GPGA = c \cdot (TSC_G + dT_{Rec}) - c \cdot (TSC_E + dT_{Rec})$$

$$BDGP = c \cdot (TSC_C + dT_{Rec}) - c \cdot (TSC_G + dT_{Rec})$$

PPP analyses

WE USE SMOOTHED CODE + SP3 EPHEMERIS

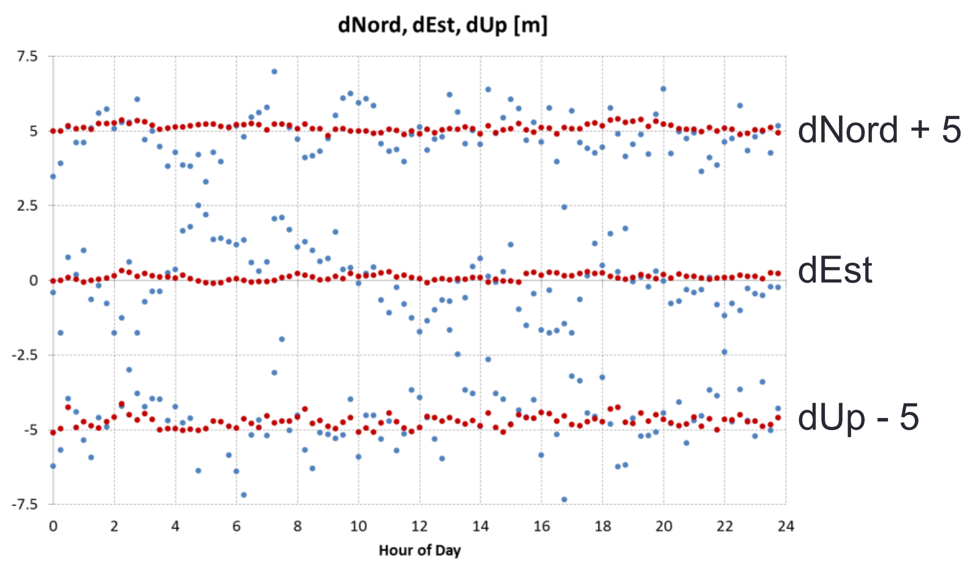
Procedure of smoothing:

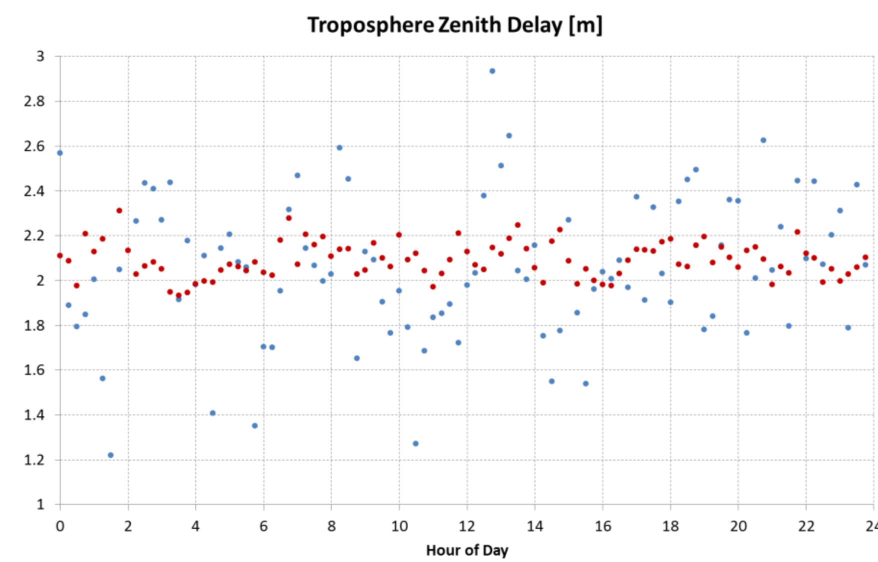
- Detection of passes ($\delta t > 180$ s)
- Calculation of L_1, L_2 ($L = \lambda \cdot \Phi$)
- Calculation of geometry-free Linear Combination: $L_4 = L_1 - L_2$
- Detection of arcs/cycle slips ($\delta L_4 > \Delta_{L4}$; $\Delta_{L4} = f(\lambda_1, \lambda_2)$)
- Calculation of ΔL_1, ΔL_2 $\left(\Delta L = \frac{\sum_{i=1}^{n}(L_i - P_i)}{n}\right)$

We need a second iteration in order to obtain, for each satellite, a zero-mean of post-fit residuals.

- Detection of passes ($\delta t > 180$ s)
- Calculation of L_3, μ_{PF} $\left(L_3 = \frac{f_1^2 \cdot L_1 - f_2^2 \cdot L_2}{f_1^2 - f_2^2}\right)$
- Reset of L_3 ($L_3 = L_3 - \mu_{PF}$)

PPP (phase+sp3$_{GFZ}$) vs SPP (pseudorange+broadcast) results, epochwise

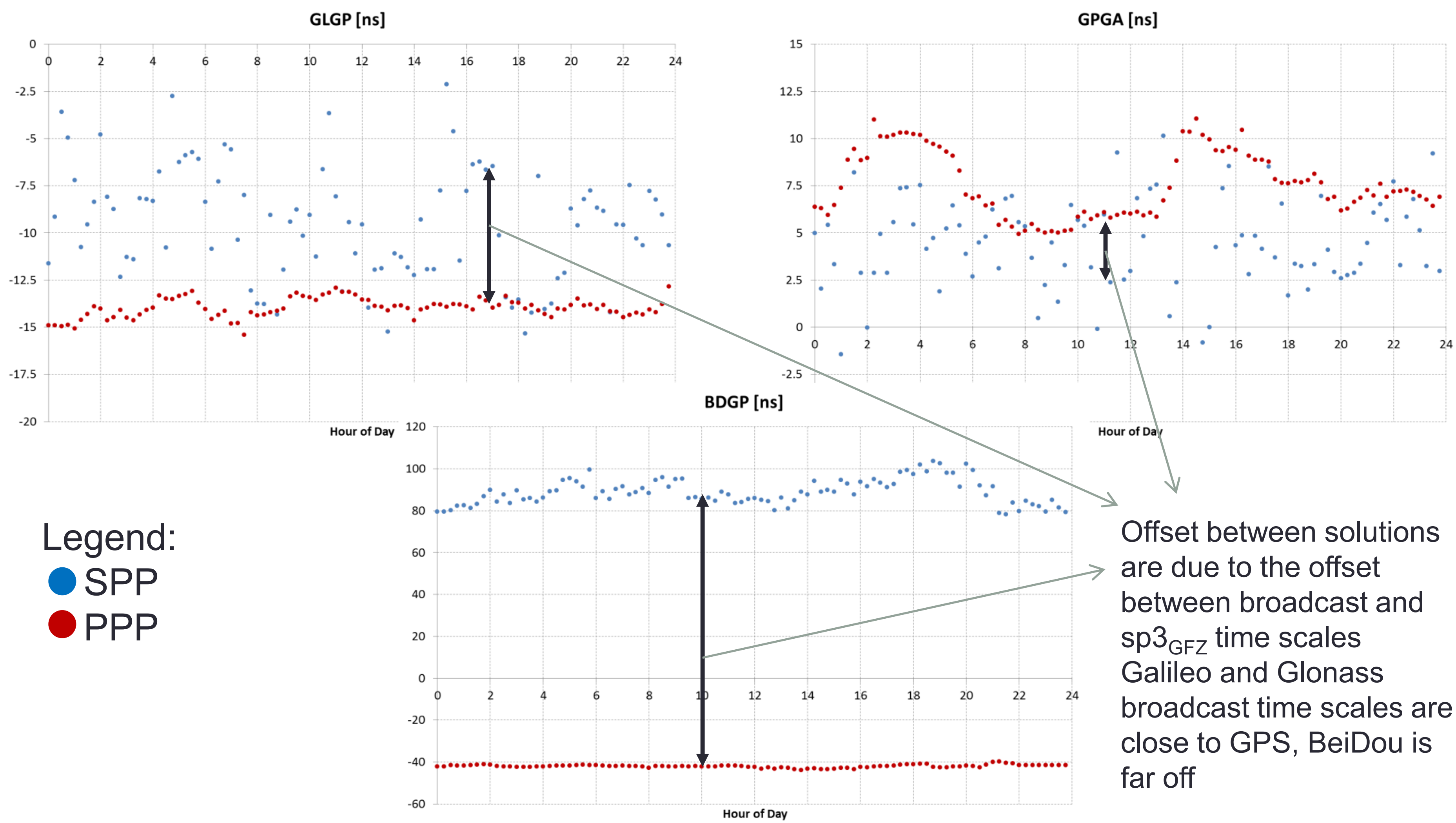




Legend:
- SPP
- PPP

	TZD [m]	dNord [m]	dEst [m]	dUp [m]
mean SPP	2.07	-0.10	0.03	0.25
mean PPP	2.09	0.11	0.10	0.27
RMS SPP	0.33	0.82	1.04	1.27
RMS PPP	0.08	0.13	0.10	0.21

PPP (phase+sp3$_{GFZ}$) vs SPP (pseudorange+broadcast) results



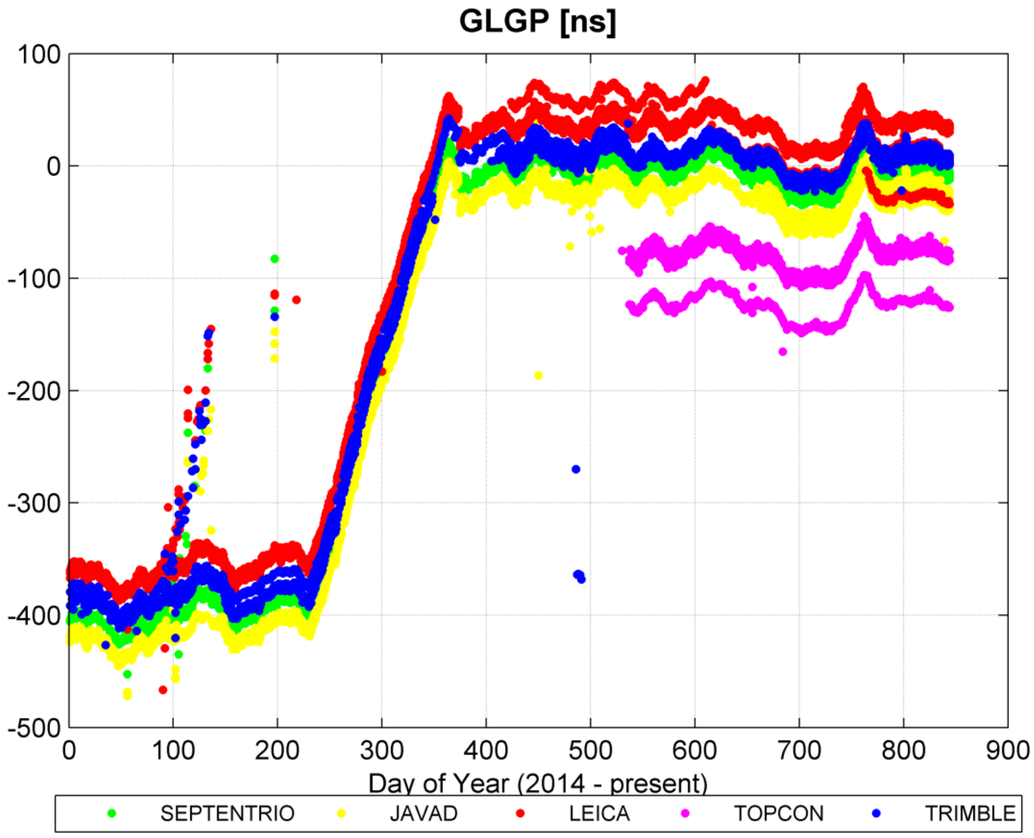
Legend:

- SPP
- PPP

Offset between solutions are due to the offset between broadcast and sp3$_{GFZ}$ time scales Galileo and Glonass broadcast time scales are close to GPS, BeiDou is far off

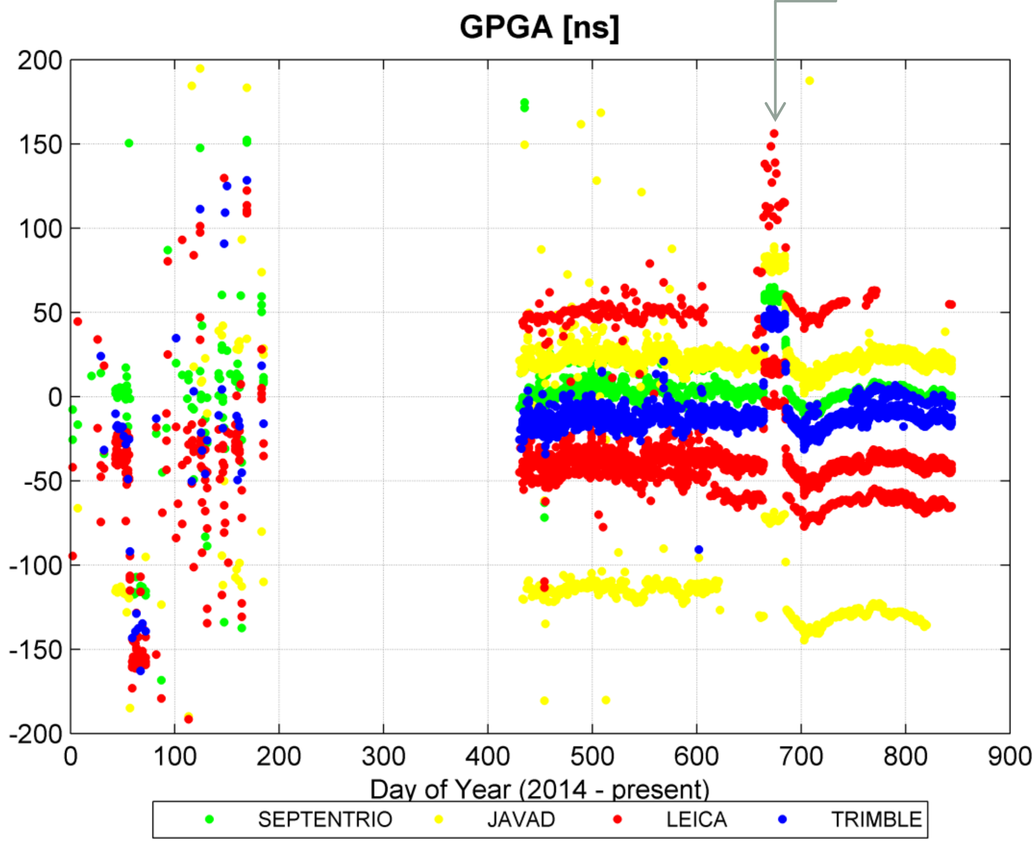
GLGP: Glonass to GPS Time Offset

- Large offset until summer 2014
- Offset steered to nearly zero
- However different receivers show different offsets
- Different sites with same type of receiver can have slightly biased offsets



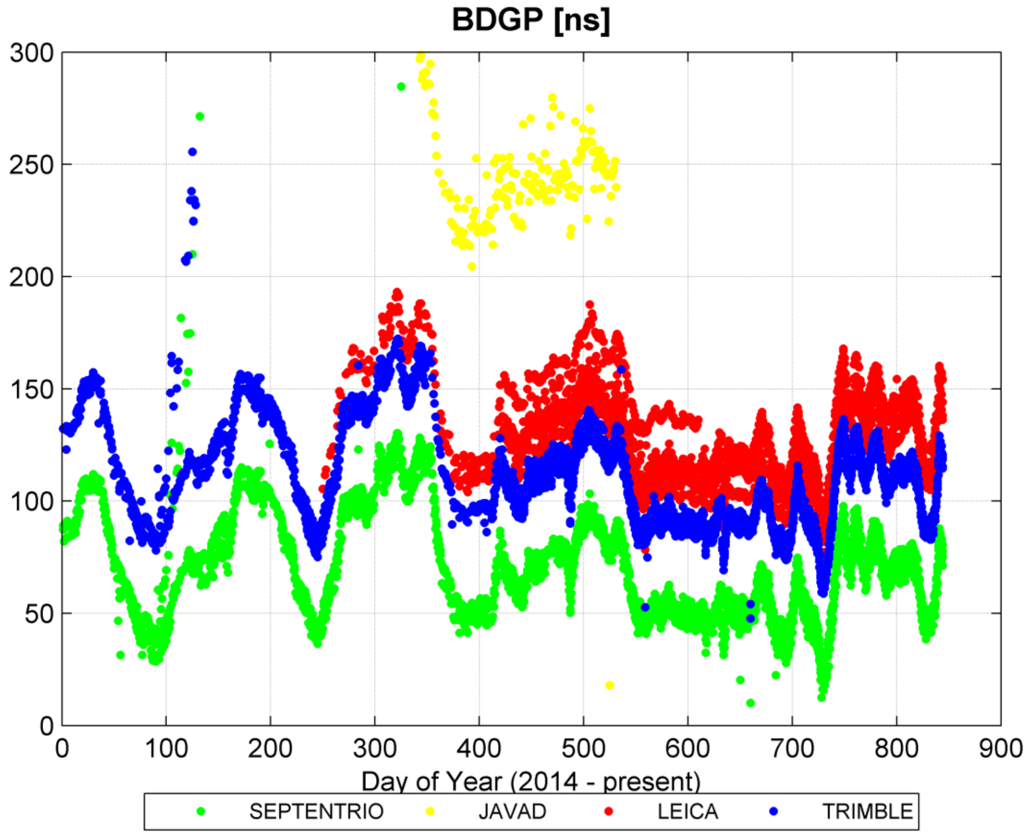
GPGA: Galileo to GPS Time Offset

- Very good performance in 2015
- **Offset ~50 ns between 26/10 and 16/11 2015**
- Receiver dependent biases are clearly visible



BDGP; BeiDou to GPS Time Offset

- Contrary to GPGA and GLGP, BDGP seems to vary in time periodically with a large mean value (80-100 ns)
- Receiver dependent biases and site dependent biases are visible



Receiver dependent biases: type vs. individual calibration

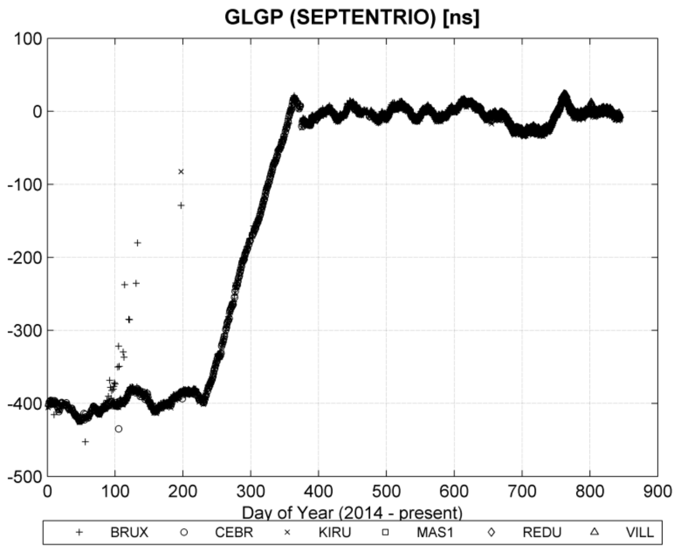
- We will now examine how different types of receivers introduce time biases for the various GNSS

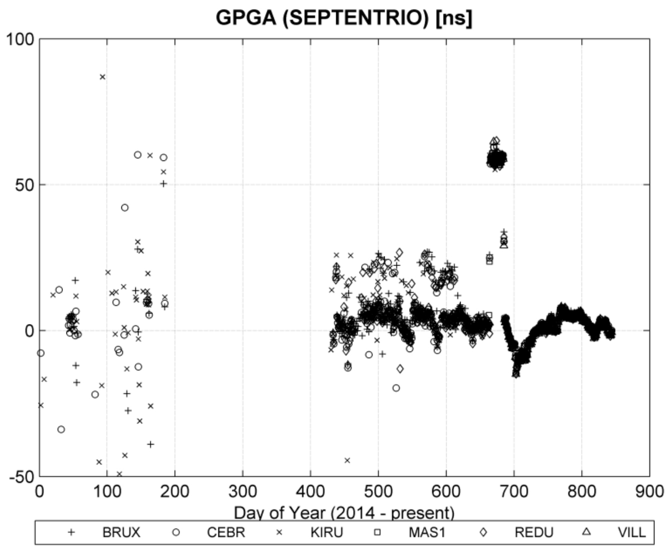
- We will also see that the same receiver brand at different sites can have different bias (Firmware dependence? Antenna dependence? Receiver architecture dependence?)

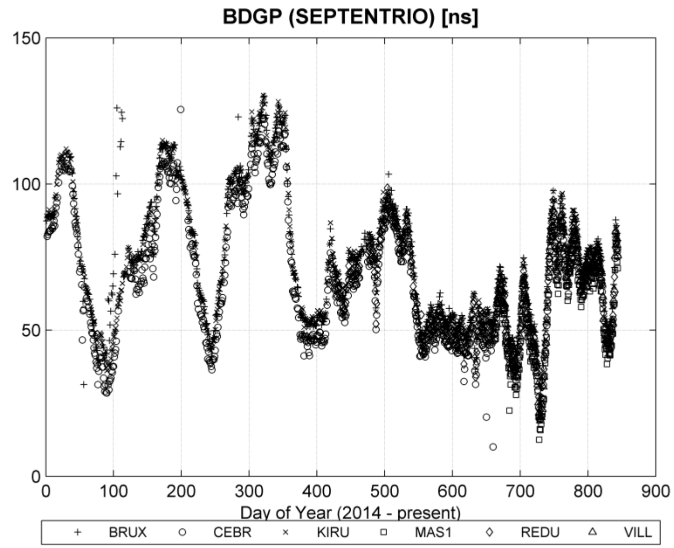
- We will conclude by proposing a preliminary table of calibration coefficients for the time offsets relative to GPS, for each receiver relative to Septentrio (=mean of 6 receivers BRUX CEBR KIRU MAS1 REDU VILL)
- Disclaimer: no endorsement is implied. For example, Trimble performed equally well

Septentrio timeoffsets

Septentrio stations compare well to each other: for each day the RMS is generally lower than 3 ns

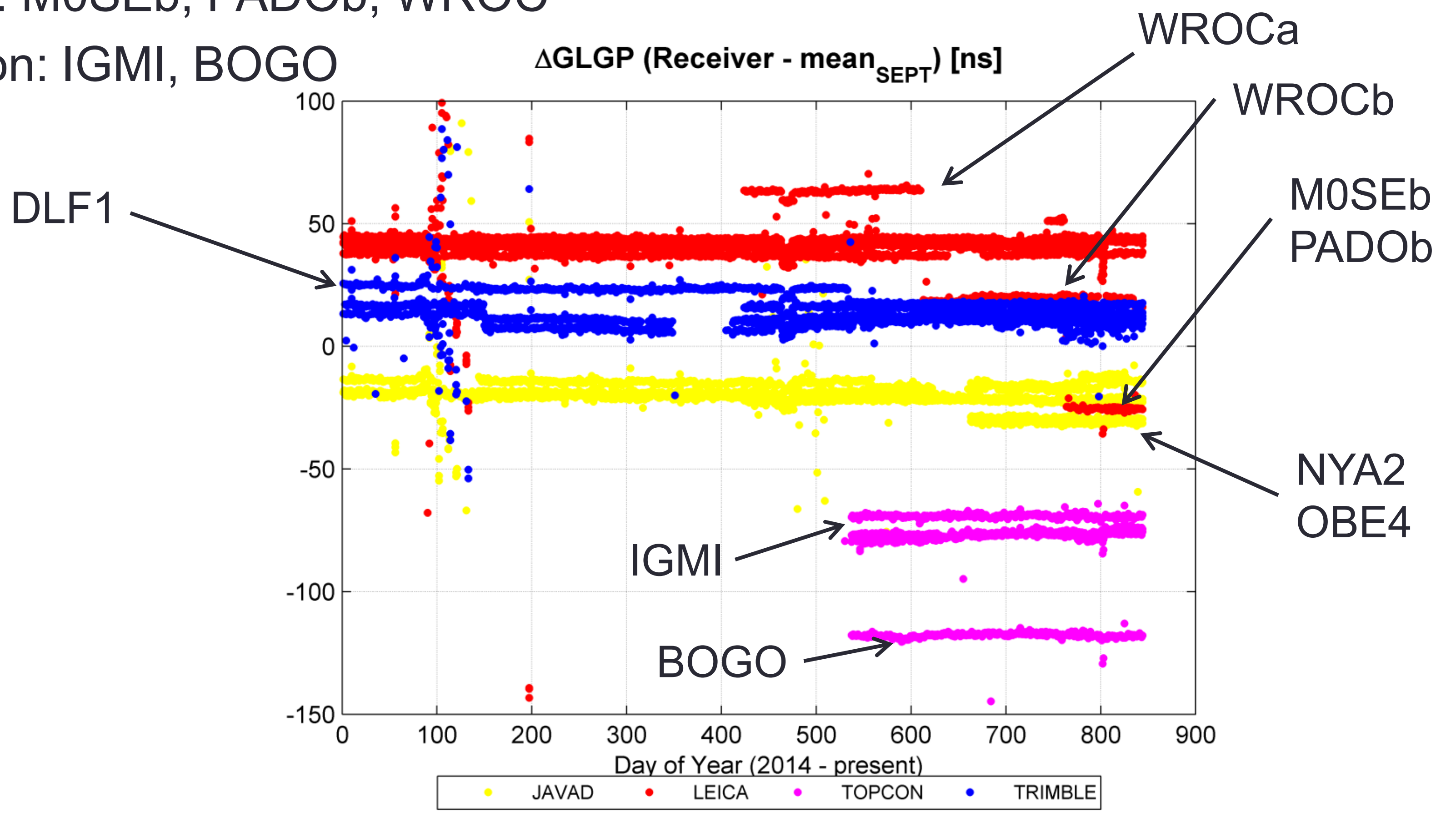






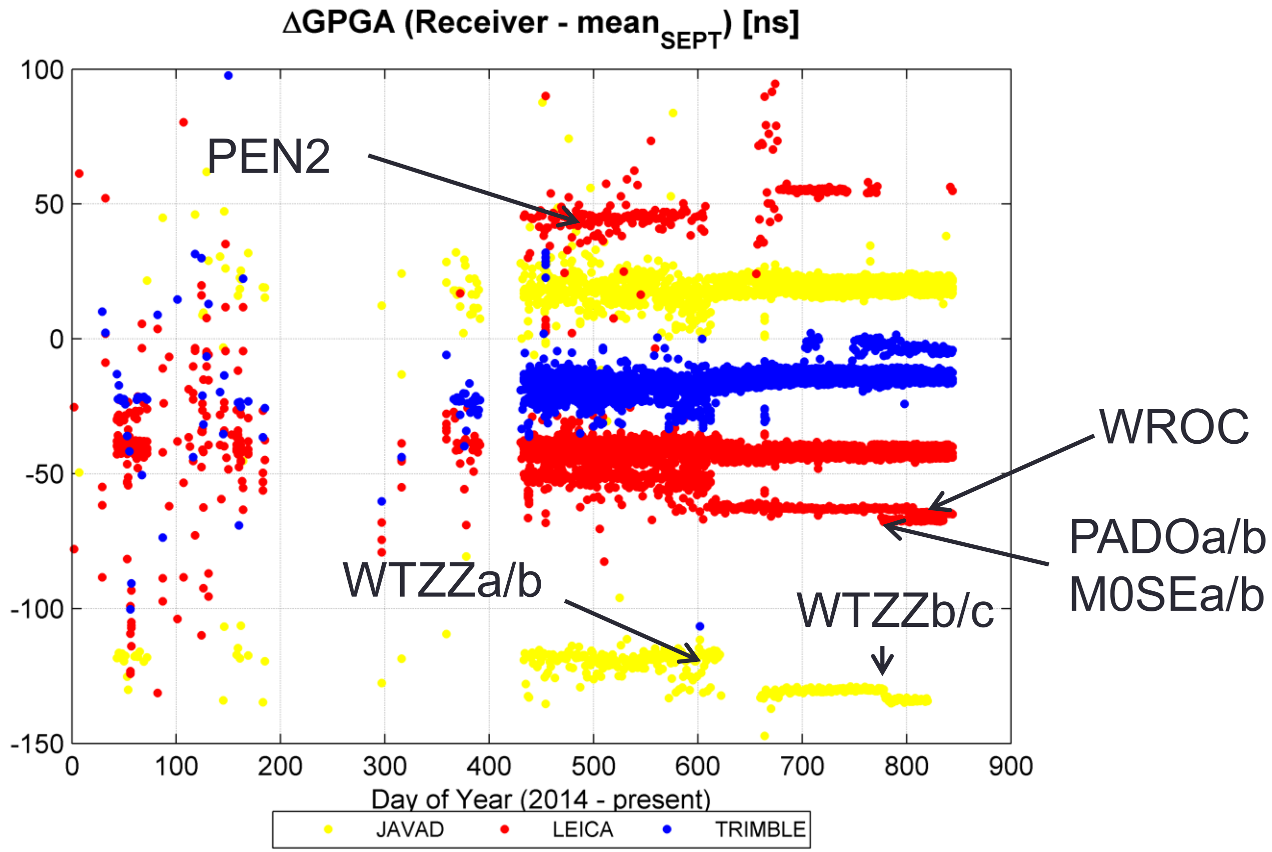
dGLGP (Receiver - Septentrio)

- Javad: NYA2, OBE4
- Trimble: DLF1
- Leica: M0SEb, PADOb, WROC
- Topcon: IGMI, BOGO



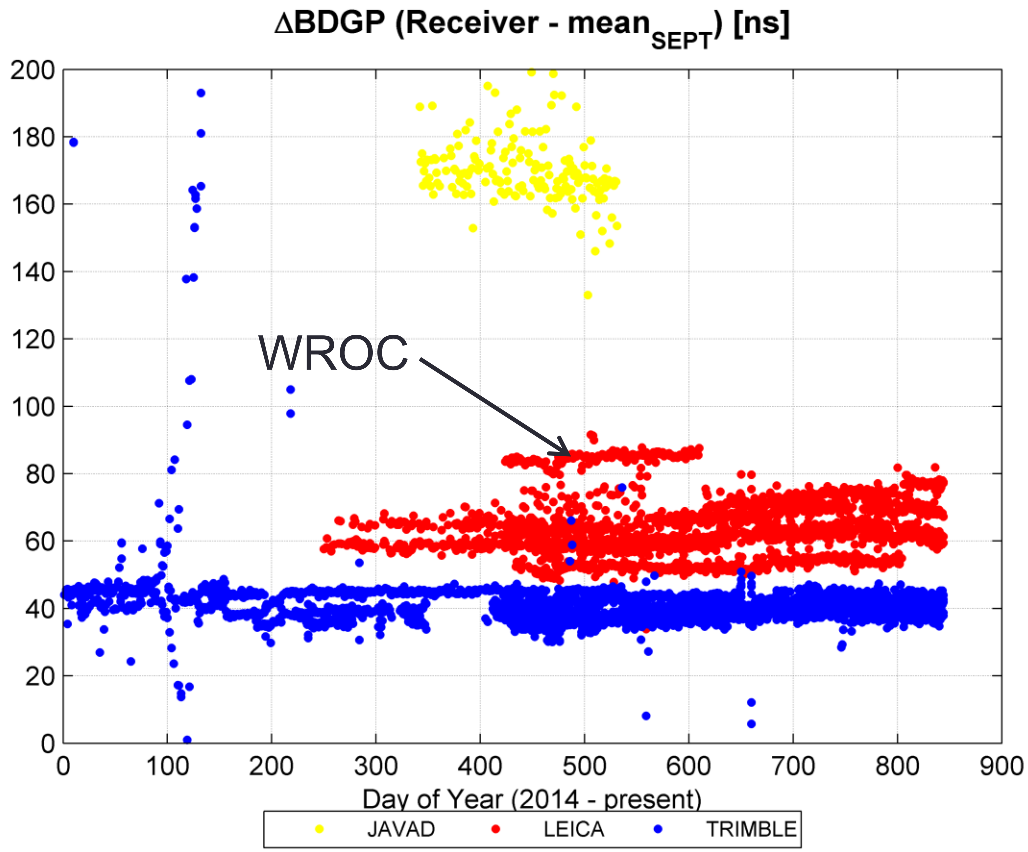
dGPGA (Receiver - Septentrio)

- Javad: WTZZ
- Leica: M0SEb, PADOb, PEN2, WROC



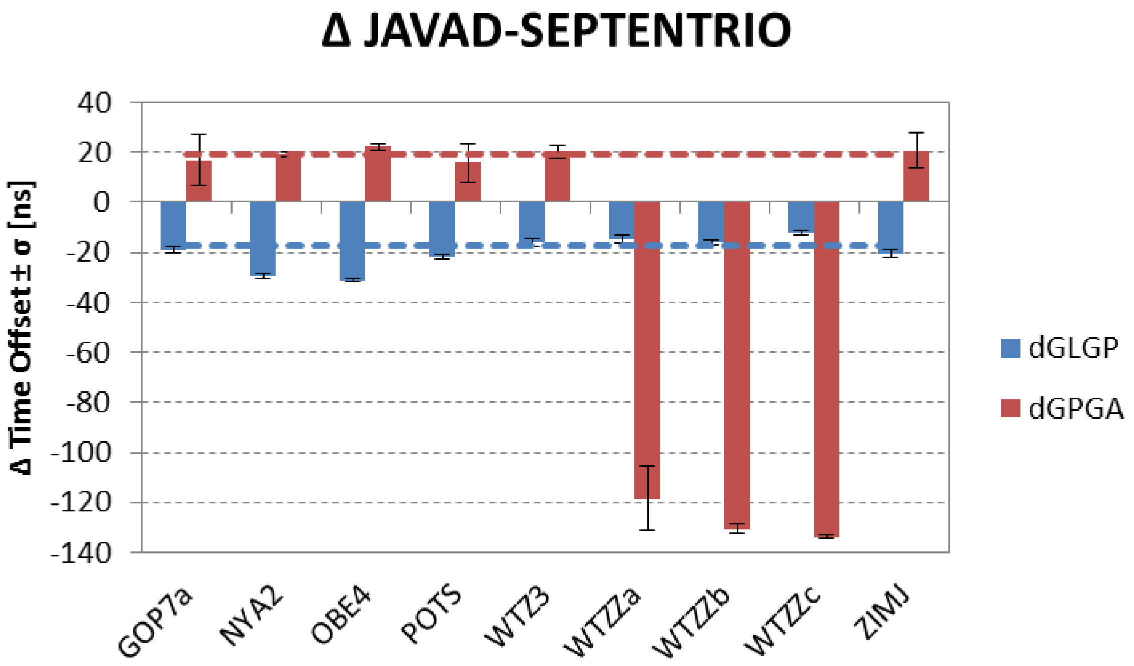
dBDGP (Receiver - Septentrio)

- Leica: WROC



Javad - Septentrio

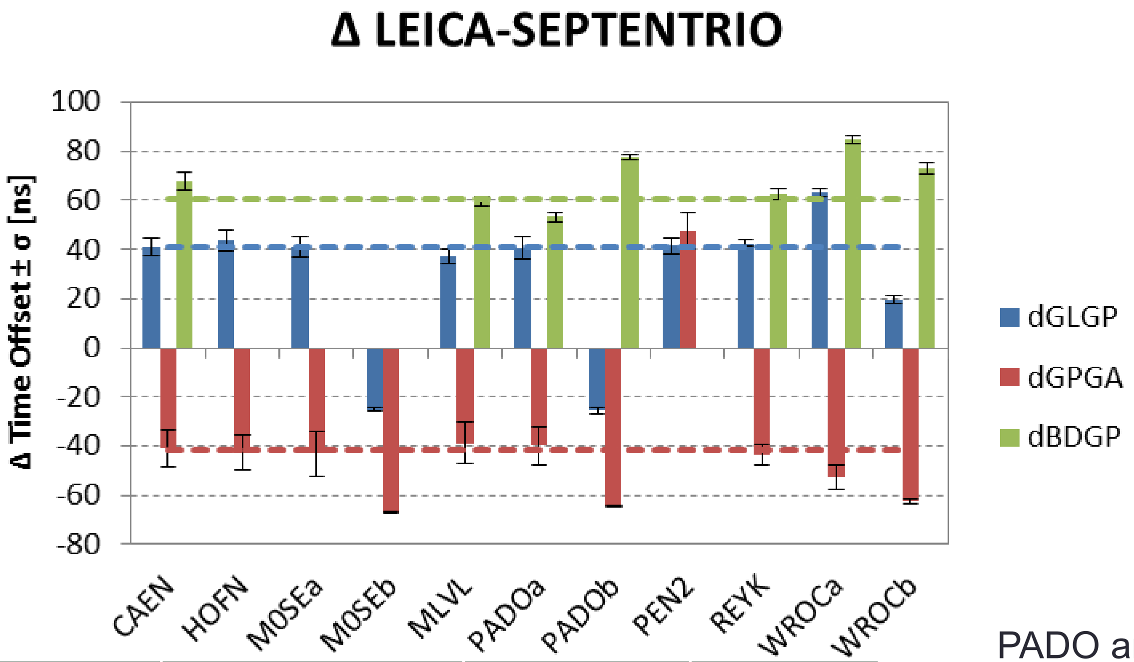
- WTZZ: GPGA (WTZZ behaviour is due to bad tracking of E5b frequency)
- NYA2, OBE4: GLGP



UPDATE	STATION	FROM	TO	DATE
Unknown	WTZZ	(a) 3.6.4B1-57-AB7E	(b) 3.6.4B1-57-AB7E	2015/09/13
Receiver Firmware	WTZZ	(b) 3.6.4B1-57-AB7E	(c) 3.6.4 JAN,12,2016	2016/02/16

Leica - Septentrio

- M0SEb: GLGP, GPGA
- PEN2: GPGA
- WROC, PADOb: GLGP+GPGA+BDGP

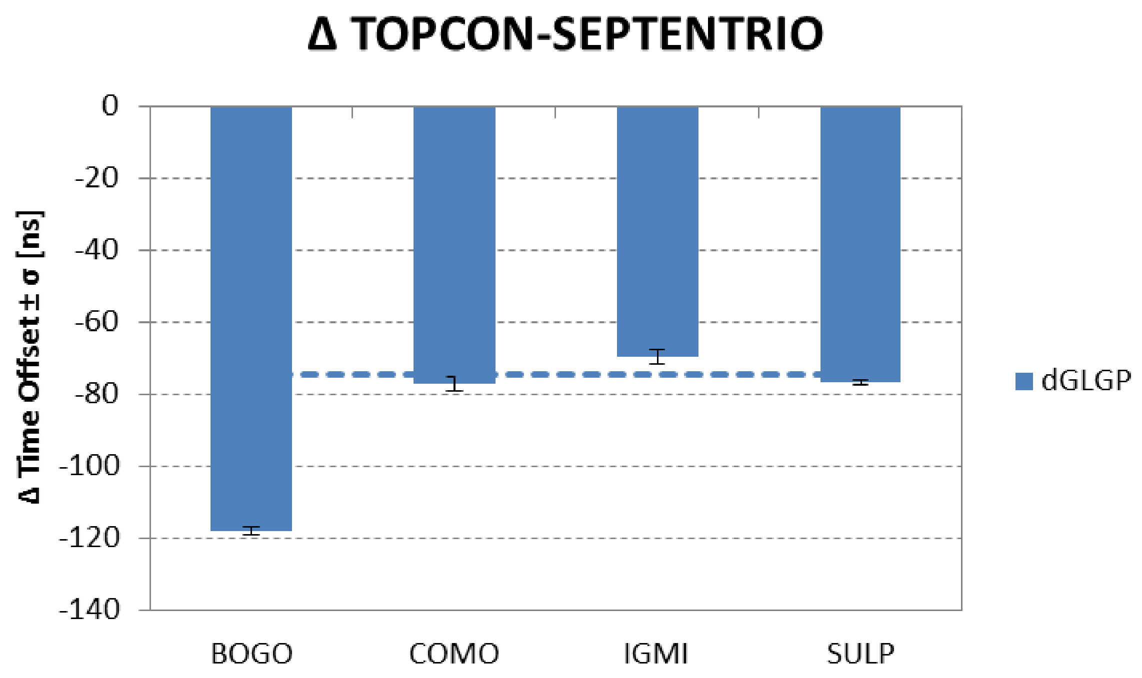


UPDATE	STATION	FROM	TO	DATE
Receiver Firmware	M0SE	(a) 3.20/6.403	(b) 3.22/6.521	2016/02/02
Receiver Firmware	PADO	(a) 3.10.1633/6.403	(b) 3.22/6.521	2016/03/15
Receiver Firmware	WROC	(a) 3.11.1639/6.403	(b) 3.21/6.403	2015/09/04

PADO and M0SE switched from different fw to the same fw and got the same GLGP and GPGA: Padob worsened its BDGP wrt PADOa

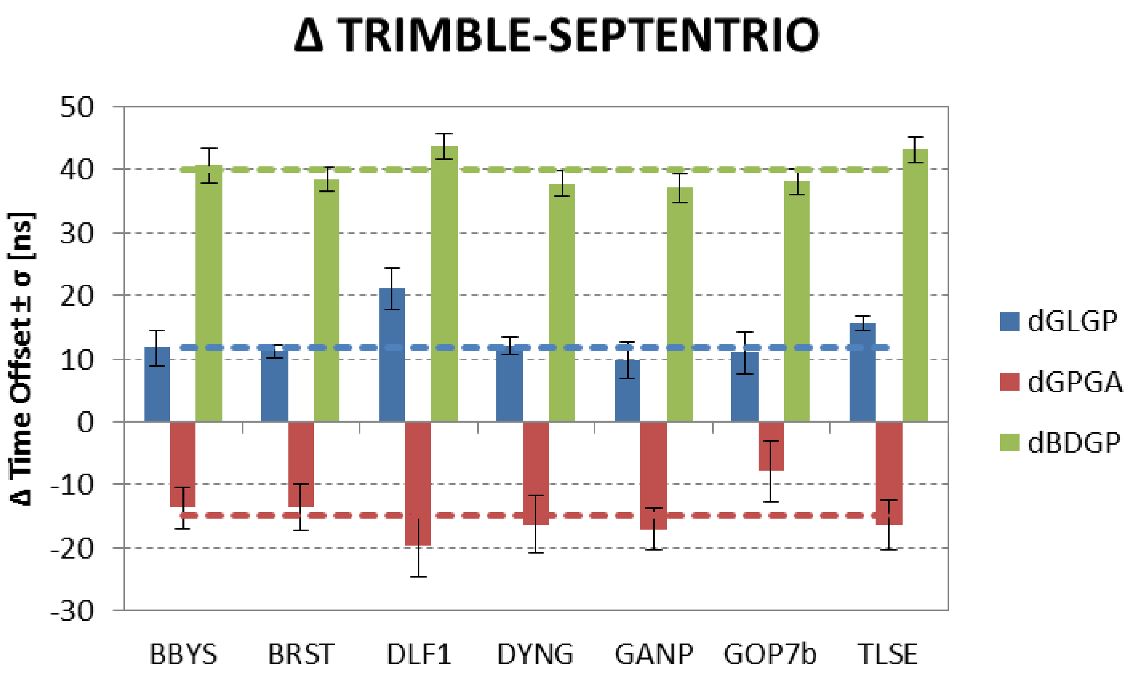
Topcon - Septentrio

- BOGO: GLGP



Trimble - Septentrio

- DLF1: GLGP
- GOP7b: GPGA



UPDATE	STATION	FROM	TO	DATE
Receiver	GOP7	(a) JAVAD TRE_G3TH DELTA	(b) TRIMBLE NETR9	2015/08/21

Summary table

STATION	RECEIVER			ANTENNA		CALIBRATION [ns]		
ID	RECEIVER	TYPE	FIRMWARE	TYPE	RADOME	dGLGP	dGPGA	dBDGP
GOP7a	JAVAD	TRE_G3TH DELTA	3.5.1	LEIAR25.R4	LEIT	-19 ± 1.3	16.9 ± 10.3	
NYA2	JAVAD	TRE_G3TH DELTA	3.5.10	JAV_RINGANT_G3T	NONE	-29.4 ± 0.9	19 ± 1	
OBE4	JAVAD	TRE_G3TH DELTA	3.5.10	JAV_RINGANT_G3T	NONE	-31.1 ± 0.6	22.4 ± 1.3	
POTS	JAVAD	TRE_G3TH DELTA	3.4.7	JAV_RINGANT_G3T	NONE	-22 ± 0.9	15.7 ± 8	
WTZ3	JAVAD	TRE_G3TH DELTA	3.6.1b1-68-7da1	LEIAR25.R3	LEIT	-16.2 ± 1.6	20.4 ± 2.6	
WTZZa	JAVAD	TRE_G3TH DELTA	3.6.4B1-57-AB7E	LEIAR25.R3	LEIT	-14.7 ± 1.7	-118.3 ± 13	
WTZZb	JAVAD	TRE_G3TH DELTA	3.6.4B1-57-AB7E	LEIAR25.R3	LEIT	-16.1 ± 0.8	-130.6 ± 1.8	
WTZZc	JAVAD	TRE_G3TH DELTA	3.6.4 JAN,12,2016	LEIAR25.R3	LEIT	-12.2 ± 1	-133.7 ± 0.8	
ZIMJ	JAVAD	TRE_G3TH DELTA	3.4.9 Apr,18,2013	JAVRINGANT_DM	NONE	-20.5 ± 1.9	20.8 ± 7.2	
CAEN	LEICA	GR25	3.11	TRM57971.00	NONE	41.2 ± 3.4	-41.1 ± 7.5	68 ± 3.5
HOFN	LEICA	GR25	3.11.1639/6.403	LEIAR25.R4	LEIT	43.5 ± 4.3	-42.7 ± 7.4	
M0SEa	LEICA	GR25	3.20/6.403	LEIAR25.R4	LEIT	41.1 ± 4.1	-43.2 ± 9.2	
M0SEb	LEICA	GR25	3.22/6.521	LEIAR25.R4	LEIT	-25.1 ± 0.7	-67.3 ± 0.3	
MLVL	LEICA	GR25	3.11	TRM57971.00	NONE	37.2 ± 2.9	-38.9 ± 8.4	59.6 ± 2.1
PADOa	LEICA	GR10	3.10.1633/6.403	LEIAR25.R4	NONE	40.7 ± 4.4	-40 ± 7.6	53.2 ± 2.2
PADOb	LEICA	GR10	3.22/6.521	LEIAR25.R4	NONE	-25.6 ± 1.1	-64.5 ± 0.2	77.4 ± 1.1
PEN2	LEICA	GRX1200+GNSS	8.51/6.110	LEIAR25.R4	LEIT	41.5 ± 3.1	47.6 ± 7.7	
REYK	LEICA	GR25	3.11.1639/6.403	LEIAR25.R4	LEIT	42.6 ± 1.2	-43.5 ± 4.1	62.3 ± 2.3
WROCa	LEICA	GR25	3.11.1639/6.403	LEIAR25.R4	LEIT	63.2 ± 1.4	-52.6 ± 5	84.7 ± 1.6
WROCb	LEICA	GR25	3.21/6.403	LEIAR25.R4	LEIT	19.6 ± 1.5	-62.7 ± 0.9	73 ± 2.2
BRUX	SEPTENTRIO	POLARX4TR	2.5.2	JAVRINGANT_DM	NONE	2.8 ± 3.3	1 ± 3.7	3.4 ± 4.1
CEBR	SEPTENTRIO	POLARX4	2.5.2-esa3	SEPCHOKE_MC	NONE	-0.5 ± 3.3	-0.6 ± 5.2	-4.2 ± 3.1
KIRU	SEPTENTRIO	POLARX4	2.5.2-esa3	SEPCHOKE_MC	SPKE	-3 ± 2.5	0.1 ± 5	2.4 ± 4.6
MAS1	SEPTENTRIO	POLARX4	2.9.0	LEIAR25.R4	NONE	-1.3 ± 0.4	0 ± 0.7	-5.8 ± 1.6
REDU	SEPTENTRIO	POLARX4	2.5.2-esa3	SEPCHOKE_MC	NONE	0.2 ± 0.5	-0.3 ± 3.5	-0.4 ± 1.4
VILL	SEPTENTRIO	POLARX4	2.9.0	SEPCHOKE_MC	NONE	2.6 ± 0.3	-0.4 ± 1.1	-1.5 ± 0.9
BOGO	TOPCON	EUROCARD	2.6.1 Jan,10,2008	ASH700936C_M	SNOW	-117.8 ± 1.2		
COMO	TOPCON	E_GGD	3.4 Dec,12,2009 p2	TPSCR3_GGD	CONE	-77.1 ± 1.9		
IGMI	TOPCON	ODYSSEY_E	3.3 JUL,10,2008 P4	TPSCR.G3	TPSH	-69.4 ± 2		
SULP	TOPCON	NET-G3A	4.1 May,31,2013	TPSCR.G5	TPSH	-76.6 ± 0.7		
BBYS	TRIMBLE	NETR9	4.85/4.71	TRM59800.00	NONE	11.7 ± 2.7	-13.6 ± 3.3	40.7 ± 2.8
BRST	TRIMBLE	NETR9	4.85	TRM57971.00	NONE	11.2 ± 1.1	-13.6 ± 3.7	38.5 ± 1.9
DLF1	TRIMBLE	NETR9	5.01	LEIAR25.R3	LEIT	21.1 ± 3.3	-19.6 ± 5	43.7 ± 2
DYNG	TRIMBLE	NETR9	5.01	TRM59800.00	NONE	12.2 ± 1.4	-16.3 ± 4.6	37.8 ± 2.1
GANP	TRIMBLE	NETR9	4.93/4.93	TRM55971.00	NONE	9.9 ± 2.9	-17 ± 3.3	37.1 ± 2.3
GOP7b	TRIMBLE	NETR9	5.01	LEIAR25.R4	LEIT	11 ± 3.3	-7.8 ± 4.9	38.1 ± 2.1
TLSE	TRIMBLE	NETR9	5.01	TRM59800.00	NONE	15.7 ± 1.1	-16.3 ± 4	43.2 ± 2

Updated to 2016-05-05

Conclusions

- Positioning and timing cannot be decoupled in multiGNSS positioning/navigation: 3 m ⇔ 10 ns is a reasonable level of sync one can require
- We have shown that the broadcast time sync polynomial contains considerable biases in the time scales, particularly for BeiDou, forcing to include a specific time bias in the navigation solution
- We present a first analysis of calibration constants which are specific of receivers at the various sites.
- We keep monitoring GNSS specific time biases and receiver specific time biases, in an attempt to precisely identify all those calibration constants which are necessary to know for a full interoperability of the various GNSSs with a variety of receivers.
- We also monitor the releases of SP3 data (by CODE, GFZ…), in the attempt to identify that release which best defines a continuous common time scale.