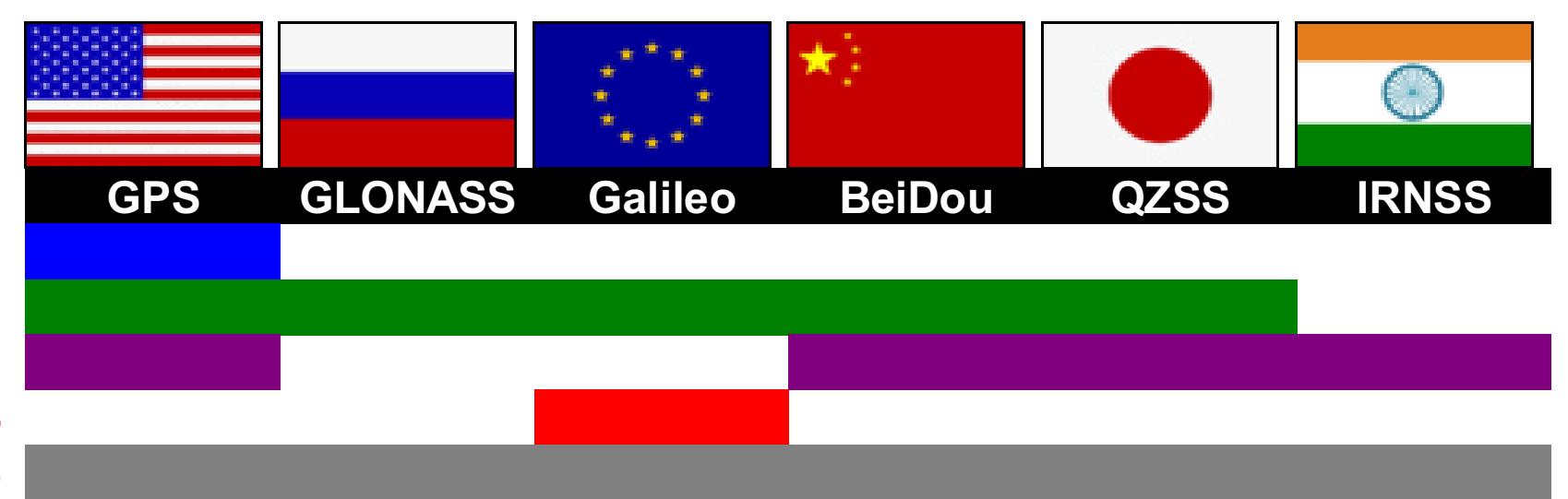


Introduction

The International GNSS Service (IGS, Dow et al. 2009) is well established as a scientific reference for GPS data processing since more than 20 years. The observations from a global tracking network are processed by a number of Analysis Centers (AC's, typically around ten nowadays) and combined to the official IGS products by the Analysis Center Coordinator (ACC) using an algorithm described by Beutler et al. (1995).

Some of the AC's have extended their activities to GLONASS, the Russian counterpart to GPS by a rigorously combined GPS and GLONASS solution. At the same time, the combination within the IGS takes place in two fully independent chains for GPS and GLONASS.

Extrapolating this current situation by the current development in the frame of IGS-MGEX (multi-GNSS experiment, Montenbruck et al. 2014) we will be faced in the future with inhomogeneous contributions by the different IGS AC's:



(hypothetical scenario on the selection of constellations by IGS AC's)

Emerging questions:

What is the optimal combination strategy in order to

- ✓ keep the internal consistency between the systems from the contributing solutions into the combined products?
- ✓ obtain the optimal quality for the combined orbits of all satellites considering that the quality of the orbits from the different constellations may vary.

With the modernization programs of the established Global Navigation Satellite Systems (GNSS) and the new systems under construction the manifold of frequencies and signals will significantly increase. This development is accomplished by an even more dramatic increase of signal tracking techniques indicated, e.g, in the RINEX3 format description:

System	Block, type	Frequency	Signal tracking (according to RINEX3)
GPS	IIA, IIR-A/B	L1, L2	C1C, C1S, C1L, C1X, C1P, C1W, C1Y, C1M C2C, C2D, C2P, C2W, C2Y, C2M
	IIR-M	+L5	+C2S, C2L, C2X +C5I, C5Q, CSX
GLONASS	M	L1, L2	C1C, C1P, C2C, C2P +C3I, C3Q, C3X
	K	+L3	
BeiDou	GEO, IGSO, MEO	B1, B2, B3	C2I, C2Q, X2X C7I, C7Q, C7X C6I, C6Q, C6X
	IOV, FOC	E1, E5a, E5b, E6	C1A, C1B, C1C, C1X, C1Z C5I, C5Q, C5X C7I, C7Q, C7X C8I, C8Q, C8X C6A, C6B, C6C, C6X, C6Z
	IGSO	L1, L2, L5, LEX	C1C, C1S, C1L, C1X, C1Z C2S, C2L, C2X C5I, C5Q, C5X C6S, C6L, C6X
IRNSS	IGSO	L5, S	C5A, C5B, C5C, C5X C9A, C9B, C9C, C9X

(overview of the available GNSS with their frequencies and signal tracking modes)

Emerging questions:

In particular for the clock combination:

- ✓ How to consider the potential biases if each AC shall be free to choose any of the frequencies, signals and available observation types.

Combination of precise GNSS orbit and clocks in a multi-constellation, multi-frequency environment

CODE and ESA IGS orbit products comparison

As a first step we compared the IGS final solutions from CODE and ESA, which are both generated to provide fully consistent GPS and GLONASS orbit products. This setup allows to get a first answer to the question to which extent the noisier orbit from GLONASS degrades the better GPS orbit in a combined combination scheme.

For this purpose we consider three different schemes to compare the two orbit products:

- (1) extracting **only the GPS satellites**,
- (2) considering **only the GLONASS satellites**,
- (3) taking **all GPS and GLONASS satellites** into account.

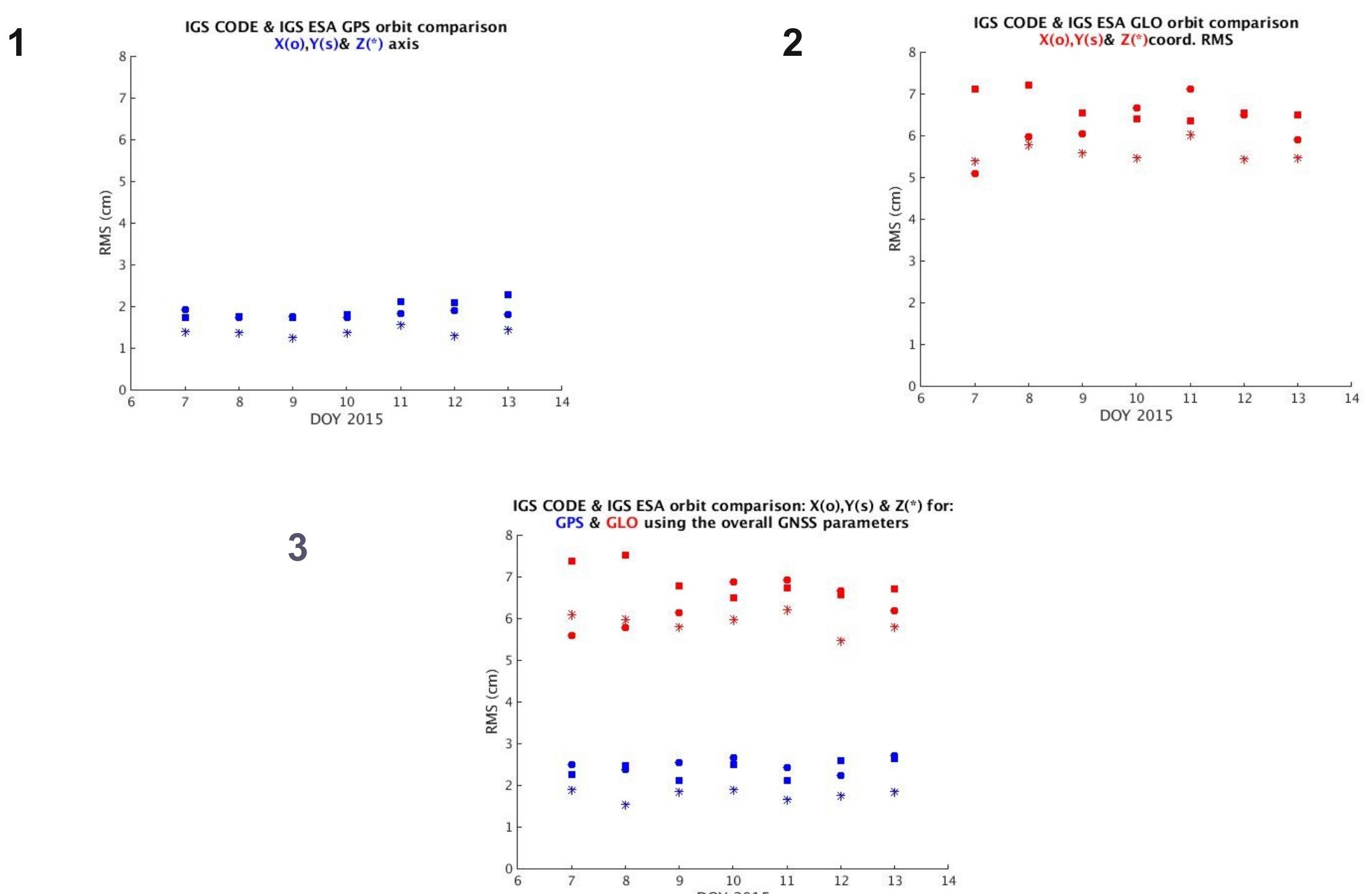
The comparison includes the 7-Helmert transformation parameters (scale, 3 rotation and 3 translation parameters) between the two set of orbits, one being CODE solution and the other one ESA solution. The table below shows the mean values and standard deviations of Helmert transformation parameters estimated from the orbit comparisons of one week.

Scale	GPS-only		GLONASS-only		GPS+GLONASS	
	mean	std-dev.	mean	std-dev.	mean	std-dev.
Rotation x	0.23 ppb	0.05 ppb	0.35 ppb	0.10 ppb	0.28 ppb	0.07 ppb
Rotation y	0.04 mas	0.02 mas	0.04 mas	0.03 mas	0.04 mas	0.02 mas
Rotation z	0.01 mas	0.01 mas	0.06 mas	0.02 mas	0.03 mas	0.02 mas
Translation x	-0.2 mm	0.5 mm	-1.1 mm	1.6 mm	-0.1 mm	0.8 mm
Translation y	2.1 mm	0.7 mm	-1.1 mm	1.1 mm	0.7 mm	0.4 mm
Translation z	-7.1 mm	2.8 mm	21.7 mm	3.7 mm	5.5 mm	2.8 mm

(Transformation parameters when comparing the CODE and ESA contributions to the IGS final product during one week in January 2015 considering a subset or even all satellites; the values exceeding 3 times the standard deviation are indicated.)

The scale and the translations in the z direction are the two parameters where the two solutions show significant differences. The scale difference between the GPS-only and GLONASS-only comparison is about 0.1 ppb which corresponds to about 2.5 cm in the radial component at the height of the GPS and GLONASS satellites. In addition, the CODE and ESA GLO-only orbit products differ by about 3 cm in the z translation.

Both discrepancies are reflected in the differences between the transformation parameters obtained by the single-system and the GPS+GLONASS approach. This is reflected in a degradation of the residuals, which affects the RMS after applying the transformation parameters to the orbit comparisons. The corresponding plots for GPS-only (1), GLONASS-only (2) and GPS+ GLONASS (3, where the RMS for the GPS and GLONASS satellites are computed separately to make it comparable to the single system cases) are shown below.



As expected, the RMS of the orbit comparison increases by ~25% for the GPS and by ~9% for the GLONASS satellites, when applying the transformation parameters obtained from both GPS and GLONASS instead of separately derived ones.

With the current combination scheme both AC's would be «punished» by a reduction of their weight to the combined product when they are submitting multi-GNSS instead of single system contributions.

Ortiz Geist E.(1,2), Dach R.(1), Schönemann E.(2), Enderle W.(2), Jäggi A.(1)

(1) Astronomical Institute, University of Bern, Bern, Switzerland

(2) European Space Operations Centre, Darmstadt, Germany



Next steps

In the table of Helmert parameters from the orbit comparison the scale and the translation in the Z direction were significantly different between the GPS- and GLONASS-only satellites. Both components differences are typically related to differences in the processing schemes between AC's. It is noticeable that they also appear because CODE as well as ESA follow an approach of a rigorously combined processing of GPS and GLONASS observations. It seems to be essential at this point, to understand the differences in the processing schemes of the two IGS analysis centers and their impact on the GPS and GLONASS satellites to derive a new, multi-GNSS capable combination scheme for the orbit products.

For this matter, we compared and analyzed the two IGS standard processing schemes from CODE and ESA in the table below. In addition a common reference scheme was developed for both software packages BSW and NAPEOS in order to create an impact matrix to improve the understanding of different effects on the GPS and GLONASS orbits and to derive the necessary degrees of freedom for a new multi-GNSS capable orbit combination scheme.

	CODE IGS final processing	BSW Reference scheme	ESA IGS final processing	Napeos Reference scheme
Measurement Models				
GNSS	GPS, GLO	GPS, GLO	GPS, GLO	GPS, GLO
Observable Type	Double difference	Double difference	Undifference	Undifference
Orbit/Clock data Rate	3 min	5 min	5 min; 30 sec	5 min
Elevation Cutoff	3 deg	5 deg	10 deg	5 deg
Terrestrial Reference Frame				
IGb08 for frame alignments?	submit NEQ	Common list station	submit NEQ	Common list station
Orbits consistency	IGb08	NNR on IGb08 core sites	NNR on IGb08	NNR on IGb08 core sites
Clocks consistency	IGb08	IGb08	NNR+NNT on IGb08	NNR on IGb08
Satellite Dynamics&Inertial Frame				
Subdaily EOP tide model	IERS 2010	IERS 2010	IERS 2010	IERS 2010
SRP Params (& constraints)	D,Y,X scales + X 1/rev; no constraints; Estimation of 5 parameters	No a priori Box-wing model; 5 parameters for SRP and NO stochastic pulses	Box-wing model for apriori modeling of the Solar Radiation Pressure Forces D,Y,B scales + B 1/rev; no constraints	No a priori Box-wing model; 5 parameters for SRP
GPS eclipse attitude	nominal	nominal	nominal	nominal
GLO SV Attitude for Eclipses	nominal	nominal	yaw rates applied (Dilsner, 2010)	nominal (no yaw rates)
Geopotential				
Static Gravity Field	EGM2008 (12x12)	EIGEN-GLO4C	EIGEN-GLO5C (12x12)	EIGEN-GLO05C
Low-degree time variations	IERS 2010	IERS 2010	None	None
Displacements at Stations				
Solid Earth, Ocean Pole & Loading	IERS 2010	IERS 2010	IERS 2010	IERS 2010
Atmospheric S1/S2	IERS 2010	IERS 2010	none	none
Atmospheric Pressure Loading	none	none	none	none
Tropospheric Delay				
Model	VMF1	GPT	GPT	GPT
a priori zenith delay	ECMWF-based ZDD	Saastamoinen model	Saastamoinen model	Saastamoinen model
Mapping function used for ZD?	VMF1_HT wet mapping function	GMF wet mapping function	GMF wet mapping function	GMF wet mapping function
Ionospheric Delay				
1st-order effect	eliminated L1/L2 linear comb.	eliminated L1/L2 linear comb.	eliminated L1/L2 linear comb.	eliminated L1/L2 linear comb.
Estimated Parameters				
Station coordinates	Adjusted with minimum constraints	Adjusted with minimum constraints	Adjusted relative to a priori values from IGS RF	Adjusted relative to a priori values from IGS RF (NNR)
Satellite & Receiver clocks	Elimination in DD processing	Estimated in CLOCKFINAL.BPE	30 sec rate	30 sec
Orbits	6 Keplerian elements + 5 solar radiation parameters (Constants in D-, Y- and X-direction; Periodic terms in X-direction); no a priori sigmas. Pseudo-stochastic orbit parameters (small velocity changes)	As for IGS processing (3 day arc solution) except: NO STOCH. PULSES	Deterministic positions and velocities; parameters from the Enhanced CODE orbit model (Springer 1999): D0, Y0, B0, Bcos(u) and Bsin(u) In addition we allow for small along-track accel. A0, Acos(u), Asin(u)	As for IGS processing except: NO ALONG-TRACK ACCELERATION
Troposphere zenith delay	Linear parameters every 2 hours	Linear parameters every 2 hours	Linear parameters every 1 hour	Linear parameters every 2 hours
Ambiguity fixing	Baseline-by-baseline mode - Melbourne-Wuebbena (< 6000 km) - Quasi-Ionosphere-Free (QIF) approach (< 2000 km) - Phase-based widelane(< 200 km) - Direct L1/L2 method	As for IGS processing except: NOT AMB FIX FOR GLO	Phase cycle ambiguities adjusted except when double-difference ambiguities can be resolved confidently; integer ambiguity resolution scheme from GFZ	As for IGS processing
Earth orientation parameters(EOP)	Daily x & y pole offsets, pole-rates, UT1, LOD	Daily x & y pole offsets, pole-rates, UT1, LOD	Daily x & y pole offsets, pole-rates, UT1, LOD	Daily x & y pole offsets, pole-rates, UT1, LOD
Intersystem biases	GPS <> GLONASS biases	(GPS <> GLO biases) per satellite	GPS <> GLONASS biases	(GPS <> GLO biases) per satellite

References

- Dach, R., Hugentobler, U., Fridez, P., Meindl, M., Eds. (2007). *Bernese GPS Software. Version 5.0, User Manual*. Astronomical Institute, University of Bern.
- Dow, J. M., Neelan, R. E., & Rizos, C. (2009). The International GNSS Service in a changing landscape of Global Navigation Satellite Systems. *Journal of Geodesy*, 83(3), 191–198. doi:10.1007/s00190-008-0300-3
- Beutler, G., Koubek, J., Springer T., (1995). Combining the orbits of the IGS analysis Centers. *Bulletin geodesique*, volume 69 number 4 pages: 200-222
- Springer T., (2009) NAPEOS mathematical models and algorithms. ESOC, Darmstadt, Germany.
- Montenbruck O., Steigenberger P., Khachikyan R., Weber G., Langley R., Mervart L.; (2014) Preparing the ground for Multi-Constellation (GNSS) Science. Inside GNSS, number 1, pages: 42-49, volume: 9

Contact address

Estefania.Ortiz@aiub.unibe.ch
Astronomical Institute, University of Bern
Sidlerstrasse 5
3012 Bern (Switzerland)