Multi-GNSS: Update, Latest Developments and Science Issues in Transition Document

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USA

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Multi-GNSS in 2017

GNSS Status

System	Blocks	Signals	Sats*)
GPS 	IIR IIR-M IIF	L1 C/A, L1/L2 P(Y) +L2C +L5	12 7+(1) 12
GLONASS 	M M+ K1	L1/L2 C/A+P L1/L2 C/A+P, L3 (CDMA) L1/L2 C/A+P, L3 (CDMA)	21+(2) 2 1+(1)
BeiDou 	GEO IGSO MEO 3rd generation	B1, B2, B3 B1, B2, B3 B1, B2, B3 B1, B3	5+(1) 6 3 (5)
Galileo 	IOV FOC	E1, E6, E5a/b/ab E1, E6, E5a/b/ab	3+(1) 8+(6)
QZSS 	IGSO	L1 C/A, L1C, SAIF L2C, E6 LEX, L5	1
IRNSS 	IGSO	L5, S	6+(1)

*) Status May 2017; brackets indicate satellites not declared healthy/operational

Status: May 2017

4 global systems (GPS, GLONASS, BeiDou-3, Galileo),

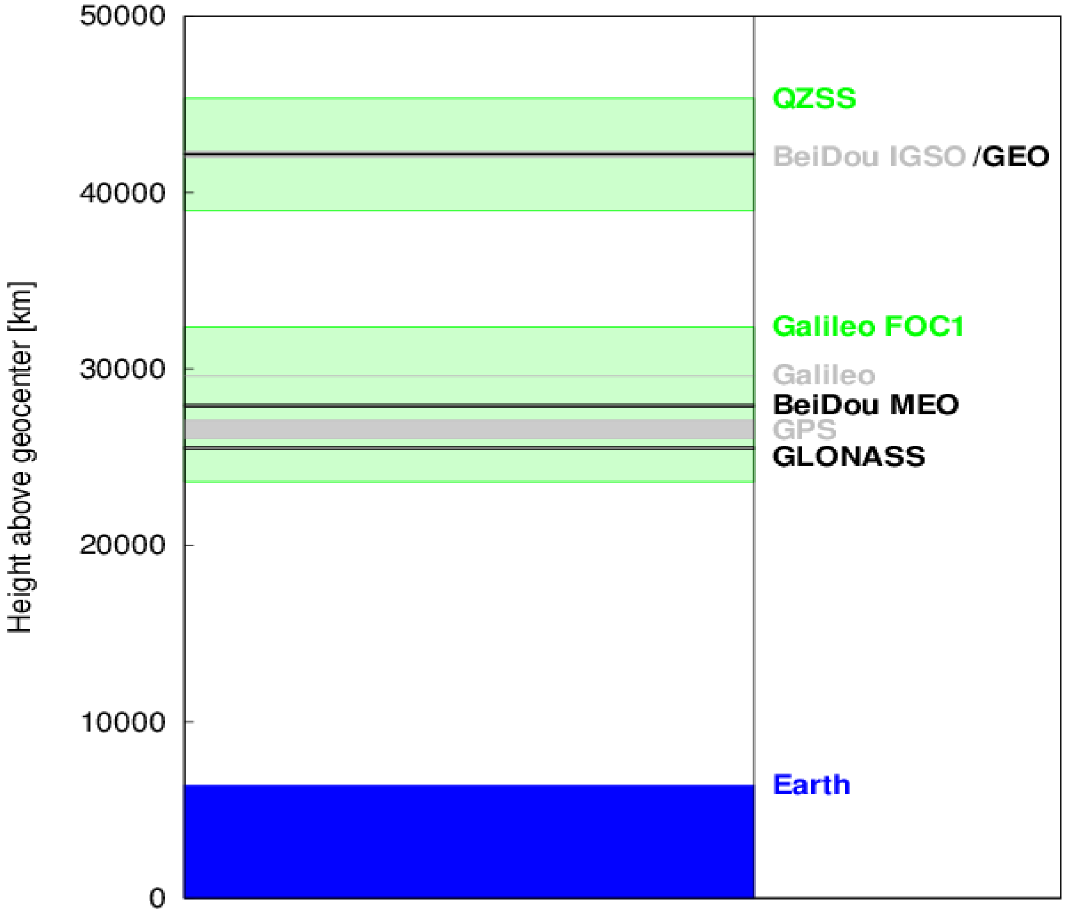
3 regional systems (QZSS, IRNSS, BeiDou-2)

GPS, GLONASS, BeiDou-2, IRNSS operational with 31, 24, 14, and 6 satellites, respectively

Galileo with 11(18) satellites, BeiDou-3 (5), QZSS, soon with 2 satellites, are "under construction"

From Steigenberger & Montenbruck (2017)

Multi-GNSS: the systems 2017

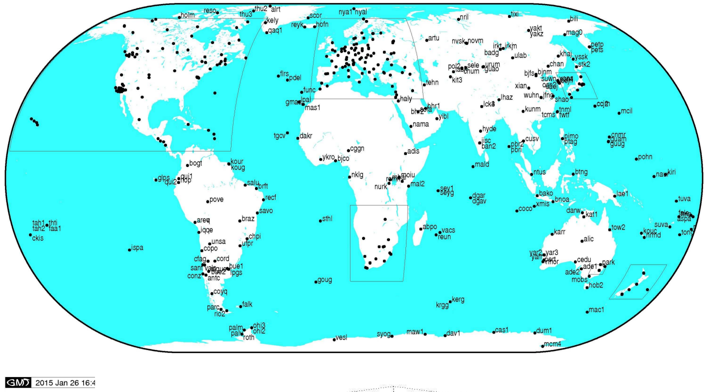


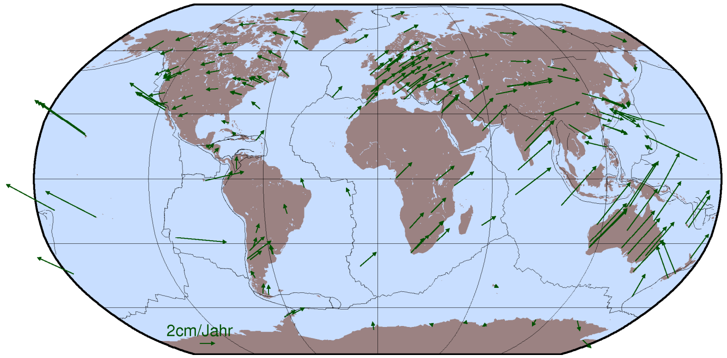
Close to 100 GNSS & RNSS satellites have different characteristics (semi-major axes *a*, eccentricities *e*, inclinations *i*) and different signals, tracking modes.

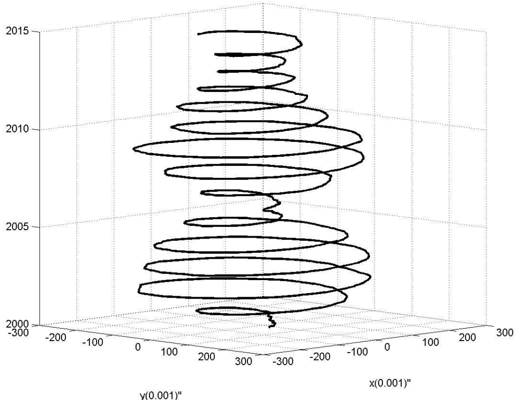
QZSS and Galileo FOC1 satellites have elliptic orbits ($e \approx 0.075$, $e \approx 0.16$, respectively)

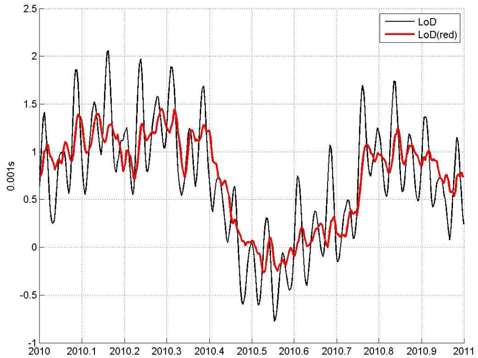
From Prange et al. (2015).

Transition: key points



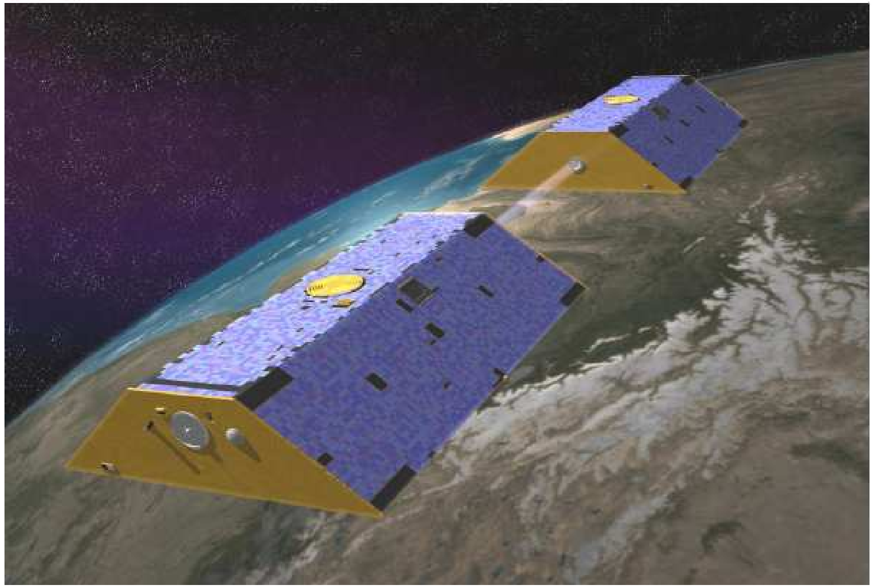


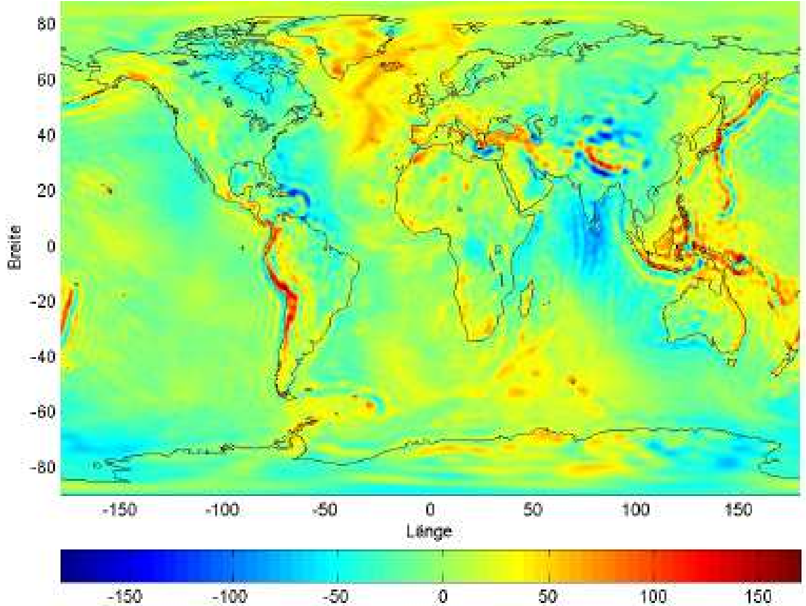




GNSS is fundamental for Earth and atmosphere sciences. From the permanent IGS tracking network (top, left) the ITRF positions/velocities (top, right), polar motion (bottom, left) and variations of Length of Day (bottom, right) are derived. Final IERS products include all space techniques!

Transition: key points





IGS products enable, e.g., precise orbit and gravity field determin- ation – the latter in combination with GRACE inter-satellite link.

Left: GRACE twin satellites, right: gravity anomalies from GRACE

Transition: Recommended Actions (I)

Recommended Actions

In order to ensure high-accuracy multi-GNSS applications the following action items are proposed from the point of view of science:

- The PNT advisory board recommends to minimize bureaucratic obstacles hindering the use of all GNSS signals and it endorses all measures to mitigate or to avoid interference.
- The PNT advisory board recommends that all future GPS satellites should be equipped with SLR reflectors for independent orbit validation.
- The PNT advisory board recommends free access to GPS satellite information needed for precise orbit determination and expresses its expectations towards other GNSS providers to act in the same sense.
- The PNT board endorses all monitoring and coordinating activities for scientific GNSS applications of the IGS and International Committee on GNSS (ICG), in particular in the area of multi-GNSS.

Recommendations from the science part of the transition document

Multi-GNSS: Latest developments

Galileo IOV Satellite Metadata

Table of Contents

Left: Publication of satellite meta data for Galileo IOV satellites in Dec. 2016

Right: Successful launch of QZS-2 on June 1, 2017 (publication of metadata imminent)

Moreover: first dual-frequency observation on BDS-3

Multi-GNSS: Latest developments

IGS White Paper on Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products

O. Montenbruck on behalf of the IGS Multi-GNSS Working Group

Abstract

The International GNSS Service (IGS) provides precise orbit and clock solutions for GNSS satellites that support a wide range of science and engineering applications with numerous benefits for society at large. All IGS data and products are made freely available to the scientific community and the general public. To best fulfill its mission, the IGS depends on information from the GNSS providers concerning the characteristics of individual types of satellites as well as their operations. This white paper describes the parameters needed to ensure the highest possible performance of IGS products for all constellations and motivates the need for provision of satellite and operations information by the GNSS providers. All information requested by the IGS is considered to be sufficiently abstract such as to neither interfere with the GNSS providers' safety and security interests nor with intellectual property rights.

Montenbruck et al (2017c) IGS White Paper on Metadata asking system providers for information concerning *mass, center of mass, antenna & reflector data, solar panels, radiated power, satellite attitude, and maneouvres*

→ *White paper should be endorsed by PNT!*

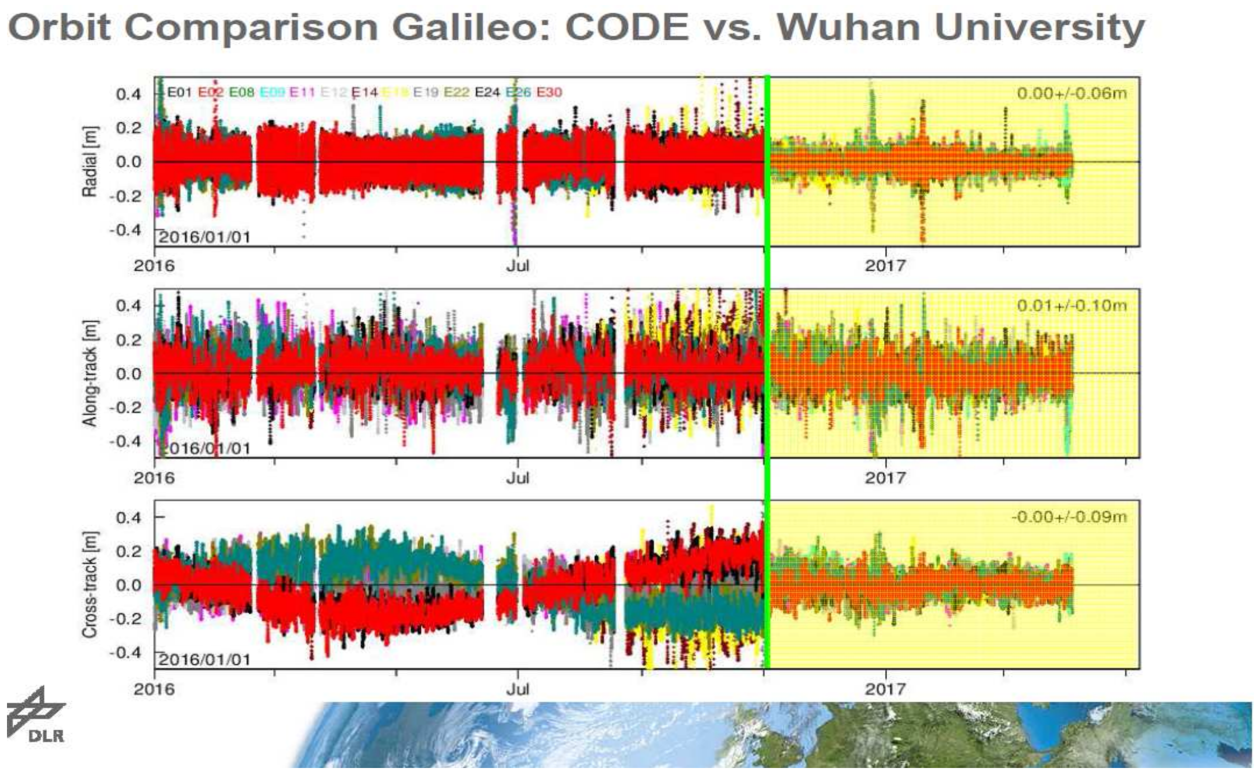
Transition: Recommended Actions (II)

Item	Type	Used for	Desired properties	Relevance	Availability of provider information
Mass	S/C	Modeling of non-gravitational forces (radiation pressure, Earth radiation pressure, antenna thrust)	Accuracy 0.1-1.0% (1-10kg)	High	GAL
			Variation over time	Low	GAL
Center-of-mass (in s/c frame)	S/C	Modeling of antenna and laser reflector coordinates relative to the reference point of all orbit products	0.1-1.0 cm in all axes	High	GLO,GAL,QZS
	OPS		Variation over time	Low	GAL
Laser reflector position in (s/c frame)	S/C	Modeling of satellite laser ranging observations	0.1-1.0 cm	High	GLO,BDS,GAL,QZS
GNSS antenna phase center location (in s/c frame)	S/C	Modeling of the effective point of signal emission	1 cm; to be supplied for each individual antenna and signal frequency	High	(GPS),(GLO),(GAL),QZS
			Direction dependent phase center variations (1 mm)	Medium	(GPS), (GAL)
Panel model	S/C	Modeling of solar and Earth radiation pressure	Dimension of solar panels (1-10%) Dimensions of satellite body (six surfaces, 1-10%) Optical properties (absorption, specular and diffuse reflection; 1-5%) Distance of panels from body (for BeiDou and QZSS)	High	(GAL)
			CAD model (coarse; for complex structures with relevant shading)	Low/ Medium	-
Radiated antenna power	S/C	Modelling of antenna thrust	Accuracy 20W	Low	(QZS)
	OPS		Variation over time	Low	-
Attitude	S/C	Modelling of antenna offset, phase wind-up and radiation pressure	Nominal attitude law outside eclipses (1-2 deg)	High	GPS,GLO,BDS, GAL,QZS,IRNSS
	S/C, OPS		Attitude during noon and midnight turns in the eclipse season (not applicable for BeiDou, QZSS)	High	(GPS),(GLO),(GAL)
	OPS		Epochs of mode transition (yaw steering vs normal mode; for BeiDou and QZSS)	High	-
Orbit maneuvers	OPS	Modeling of orbit discontinuities	Time (5s) and Delta-V (0.1-1cm/s)	High (BDS) Medium (others)	-

In view of the now available IGS White Paper on GNSS metadata, we recommend that

- **the board takes note of the IGS White Paper**
- **the board endorses/encourages its application for GPS**

MGEX: Orbit Validation



Documentation of an orbit model change by Wuhan AC towards end of 2016. Much improved consistency in 2017 (from Steigenberger & Montenbruck (2017)). Example illustrates consequences of incorrect/missing GNSS-metadata.

Knowledge-based vs. Empirical Models

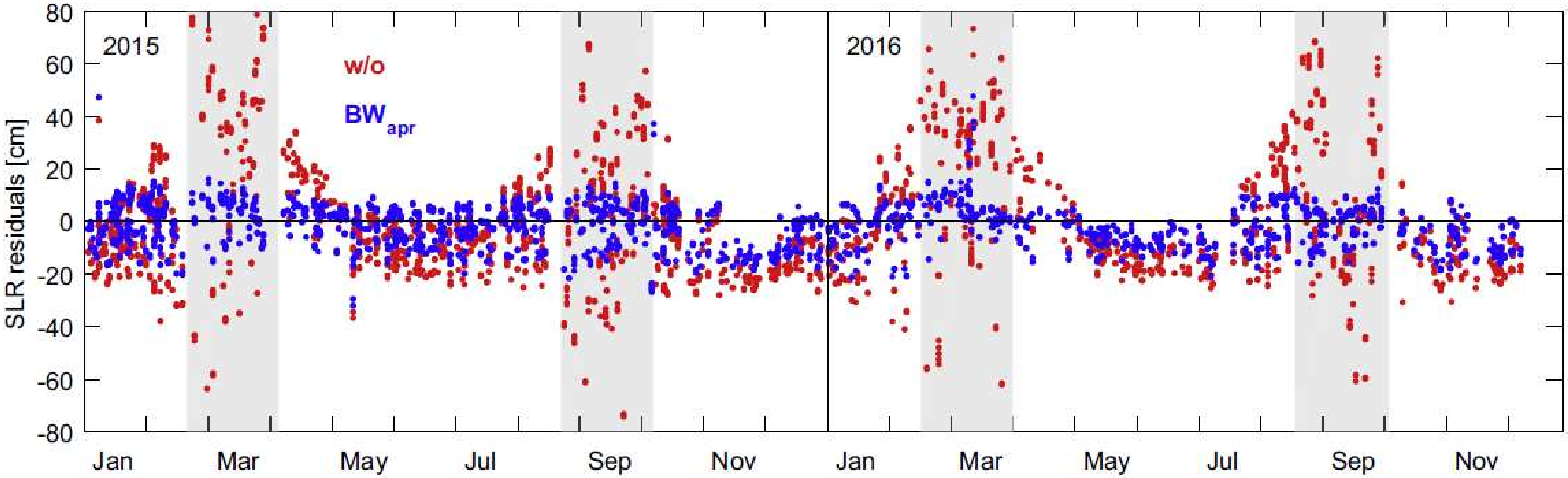


Fig. 8. Satellite laser ranging residuals (gray: without a priori model; blue/red: with a priori box-wing model in YS/ON mode). The gray shaded areas indicate time periods with ON mode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

A priori box-wing model for QZS-1, based on metadata combined with empirical model ECOM (blue), without a priori model (red). From Montenbruck et al. (2017b). Bottom-line: the better the a priori knowledge, the better the results.

References

Prange, L., E. Orliac, R. Dach, D. Arnold, G. Beutler, S. Schaer, A. Jäggi (2015) CODE's multi-GNSS orbit and clock solution*. 5th International Galileo Science Colloquium, Braunschweig, Germany, 27.-29. October, 2015*

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O. Montenbruck et al. (2017a) The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, Prospects and Challenges**,** *Adv. Space Res. 59, pp. 1671-1697*

O. Montenbruck, P. Steigenberger, F. Darugna (2017b) Semi-analytical solar radiation pressure modeling for QZS-1 orbit-normal and yaw-steering attitude, *Adv. Space Res. 59, pp. 2088-2100*

P. Steigenberger and O. Montenbruck (2017): MGEX – the Multi-GNSS Pilot Project of the IGS. Presenation at *Chinese Satellite Navigation Conference (CSNC 2017), May 2017 in Shanghai, China*

G. Beutler, A. Dimmen, M. Higgins, R. Neilan: PNTAB (2017) ***i****nformation Package for transition briefings: science part*

O. Montenbruck, on behalf of IGS Multi-GNSS Working Group: (2017c)

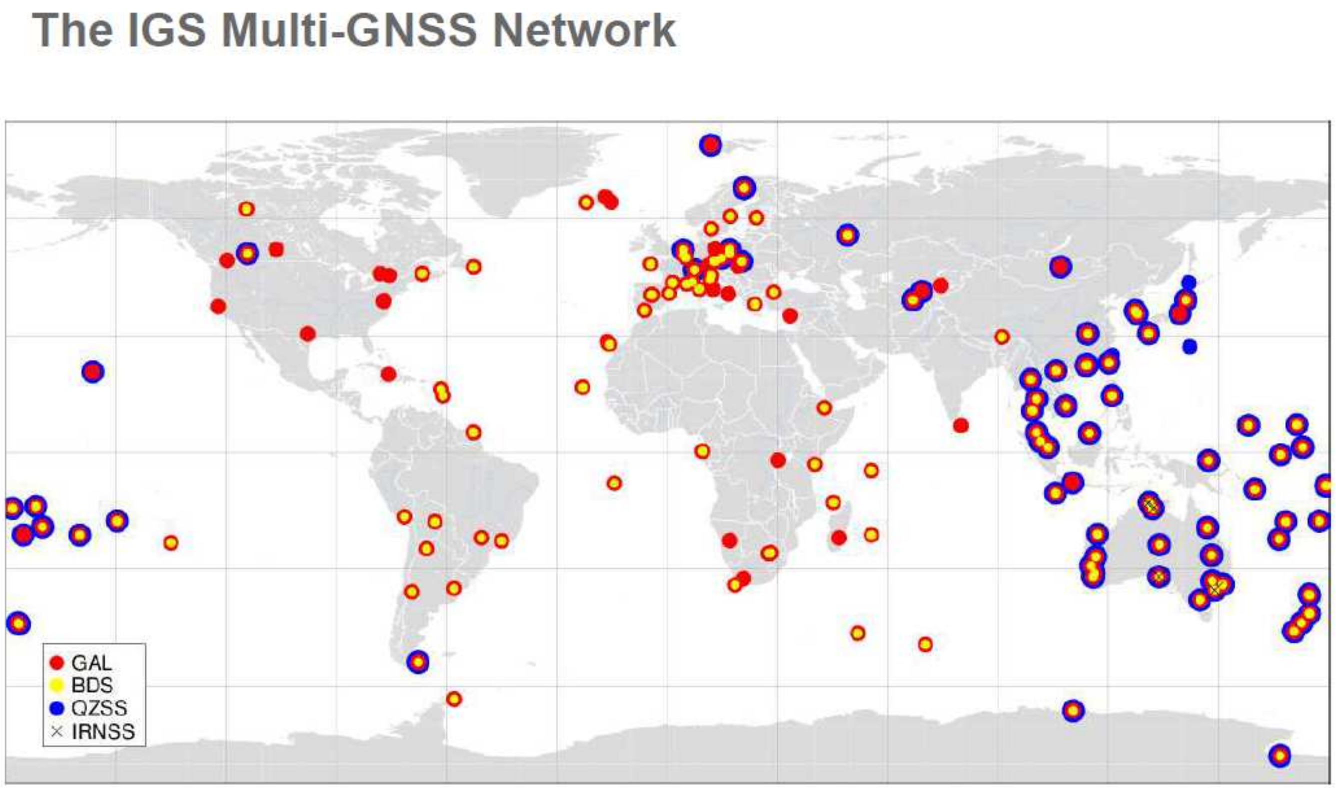
IGS White Paper on Satellite and Operations Information for Generation of precise GNSS orbits and clock products – to be posted under http://www.igs.org/

Additional Material

The following slides document

- **The work the MGEX experiment/pilot and**
- **the work of one of its analysis centers (CODE)**
- **A semi-empirical model for the QZS-1 satellite**

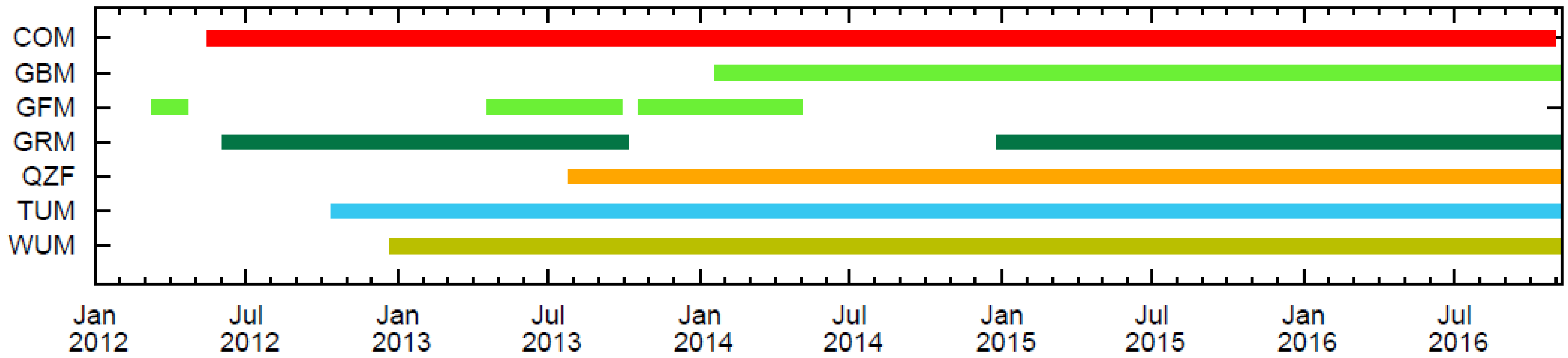
The MGEX ground-tracking network



Currently, about 190 Multi-GNSS stations track a combination of Galileo, Beidou, QZSS, in addition to GPS and GLONASS (from Steigenberger & Montenbruck (2017)).

MGEX Analysis

Institution	Abbr.	Constellations	SP3	CLK	SNX	ERP	BSX
CNES/CLS	GRM	GPS+GLO+GAL	15 min	30 s	x	–	–
CODE	COM	GPS+GLO+GAL+BDS+QZS	15 min	5 min	–	x	x
GFZ	GBM	GPS+GLO+GAL+BDS+QZS	5 min	30 s	–	x	x
JAXA	QZF	GPS+QZS	5 min	–	–	–	–
TUM	TUM	GAL+QZS	5 min	–	–	–	–
Wuhan Univ.	WUM	GPS+GLO+GAL+BDS+QZS	15 min	5 min	–	x	–

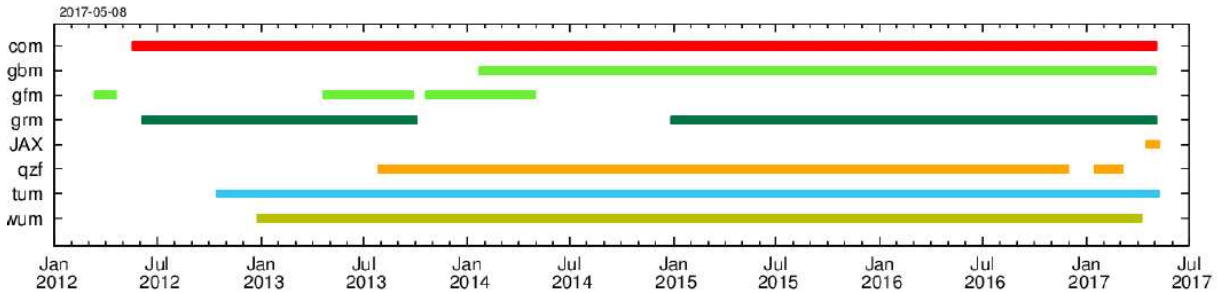


MGEX Analysis Centers (ACs) and products (orbits, clocks, coordinates of ground tracking network, Earth rotation parameters, intersystem biases); from Montenbuck et al (2017a)

MGEX Analysis

Orbit and Clock Products

Agency	ID	GNSS	Sampl (O/C)	Notes
CNES/CLS	grm	GRE	15 min/30 s	+ SNX for ~120 stations
CODE	com	GRECJ	15 min/5 min	+ BSX
GFZ	gbm	GRECJ	5 min/30 s	+ ERP, + BSX
JAXA	JAX	GRJ	5 min/30 s	+ SNX for ~140 stations
TUM	tum	EJ	5 min/(5 min)	SP3-only, no CLK
WU	wum	GRECJ	15 min/5 min	+ ERP



DLR

From Steigenberger & Montenbruck (2017)

MGEX Analysis

Table 9: RMS values derived from orbit comparisons for the time period 1 January – 30 June 2016. All values are given in cm.

	GPS	GLONASS	Galileo		BeiDou			QZSS	
			IOV	FOC	MEO	IGSO	GEO	YS	ON
Radial	1 – 3	4 – 11	6 – 10	4 – 10	3 – 11	11 – 23	54	10 – 24	30 – 71
Along-Track	2 – 4	4 – 12	10 – 18	10 – 19	10 – 21	24 – 39	298	28 – 57	84 – 133
Cross-Track	2 – 3	3 – 9	9 – 20	6 – 14	6 – 10	17 – 23	410	16 – 39	59 – 156
3D	3 – 6	6 – 17	16 – 29	14 – 26	12 – 26	32 – 51	510	40 – 73	123 – 240

GNSS	Consistency (3D RMS)	SLR	Notes
Galileo	10-20 cm	10 cm	
BeiDou	20-40 cm few m	10 cm 50 cm	MEO/IGSO GEO
QZSS	40-80 cm	30 cm	

MGEX Analysis Website

- Signal Transmissions
- Product Availability
- Clock time series
- SLR Residuals
- Orbit Comparisons

http://mgex.igs.org/analysis/

Top: from Montenbruck et al (2017a), bottom: from Steigenberger & Montenbruck (2017)

MGEX, SLR Validation

Table 10: SLR residual offsets and standard deviations for the time period 1 January – 30 June 2016. All values are given in cm.

	GLONASS	Galileo IOV	Galileo FOC	BeiDou MEO	BeiDou IGSO	BeiDou GEO	QZSS
COM	0.5 ± 5.0	-4.3 ± 4.5	-3.5 ± 4.3	-3.4 ± 6.5	-2.8 ± 14.5		-2.0 ± 26.0
GBM	1.0 ± 5.5	-1.7 ± 8.0	-3.0 ± 8.2	-0.3 ± 3.5	-1.1 ± 6.5	-44.7 ± 42.0	15.4 ± 26.5
GRM	0.2 ± 5.2	-0.3 ± 4.5	-1.3 ± 4.7				
QZF							-13.8 ± 16.2
TUM		-6.1 ± 8.8	-4.6 ± 8.6				8.1 ± 28.9
WUM	1.0 ± 5.4	-2.0 ± 4.2	-6.2 ± 9.0	-2.5 ± 4.2	-3.4 ± 8.2	-37.7 ± 29.2	13.1 ± 25.8

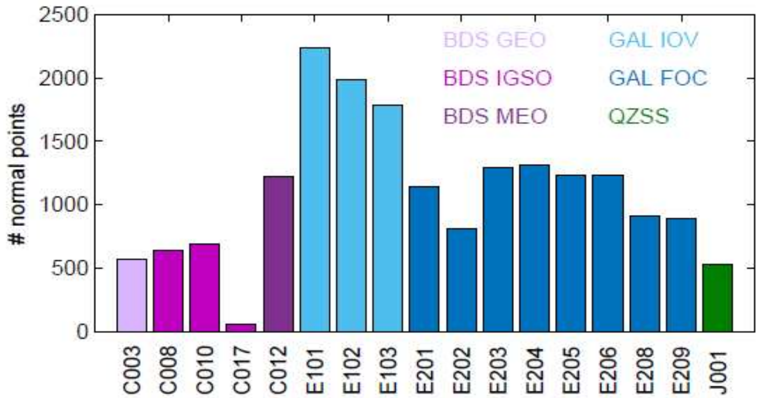


Figure 4: Number of SLR normal points of the new satellite navigation systems for the time period 1 January – 30 June 2016 as used for the analysis in Table 10. Satellites are identified by their space vehicle number (SVN).

SLR is the only independent validation technique for GNSS- and RNSS-derived orbits. All, except the GPS satellites, have SLR reflectors! Offsets indicate orbit model deficiencies!

From Montenbuck et al. (2017a)

MGEX@CODE

- CODE, Center for Orbit Determination in Europe, is one of at present ten Analysis Centers of the IGS. CODE is formed as a joint venture of
  - the Astronomical Institute of the University of Bern (AIUB),
  - the Swiss Federal Office of Topography (swisstopo),
  - the Institut für Kartographie und Geodäsie (BKG), and
  - the Institut für Astronomische und Physikalische Geodäsie of TU München (IAPG, TUM).

AIUB

Bundesamt für Kartographie und Geodäsie

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Technische Universität München

CODE Ultra–Rapid Solution

CODE Rapid Solution

CODE Final Solution

Reprocessing Solution (CODE and AIUB)

CODE MGEX Solution

Ultra-Rapid solutions are available four times/day with a latency of three hours, rapid solutions once per day with a latency of about half a day, final solution once per week with a latency < 1 week, MGEX solution once per week, with a latency < 1 week

MGEX@CODE

CODE participates as COM Analysis Center in the IGS MGEX (Multi-GNSS Experiment and Pilot Project).

COM regularly analyzes five systems, namely

- GPS (G), GLONASS (R), Galileo (E), Beidou (C), QZSS (J)

About 80 satellites and 140 permanent sites of the MGEX network contribute to the COM solutions.

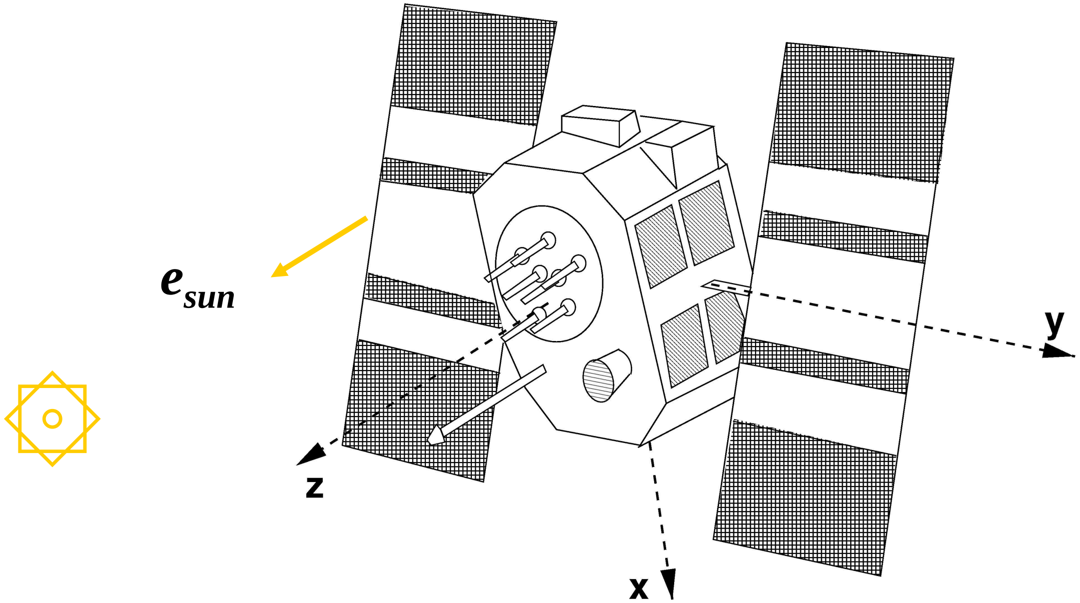
COM solutions include satellite orbits, satellite clock correction, ERPs, inter-system biases

In the long term CODE plans to incorporate all GNSS into its routine solutions.

In the framework of the COM solutions CODE contributes to implementing ``exotic'' satellite attitude/SRP models

Public access to MGEX monitoring results via FTP:
=> ftp://ftp.unibe.ch/aiub/CODE_MGEX/

MGEX@CODE



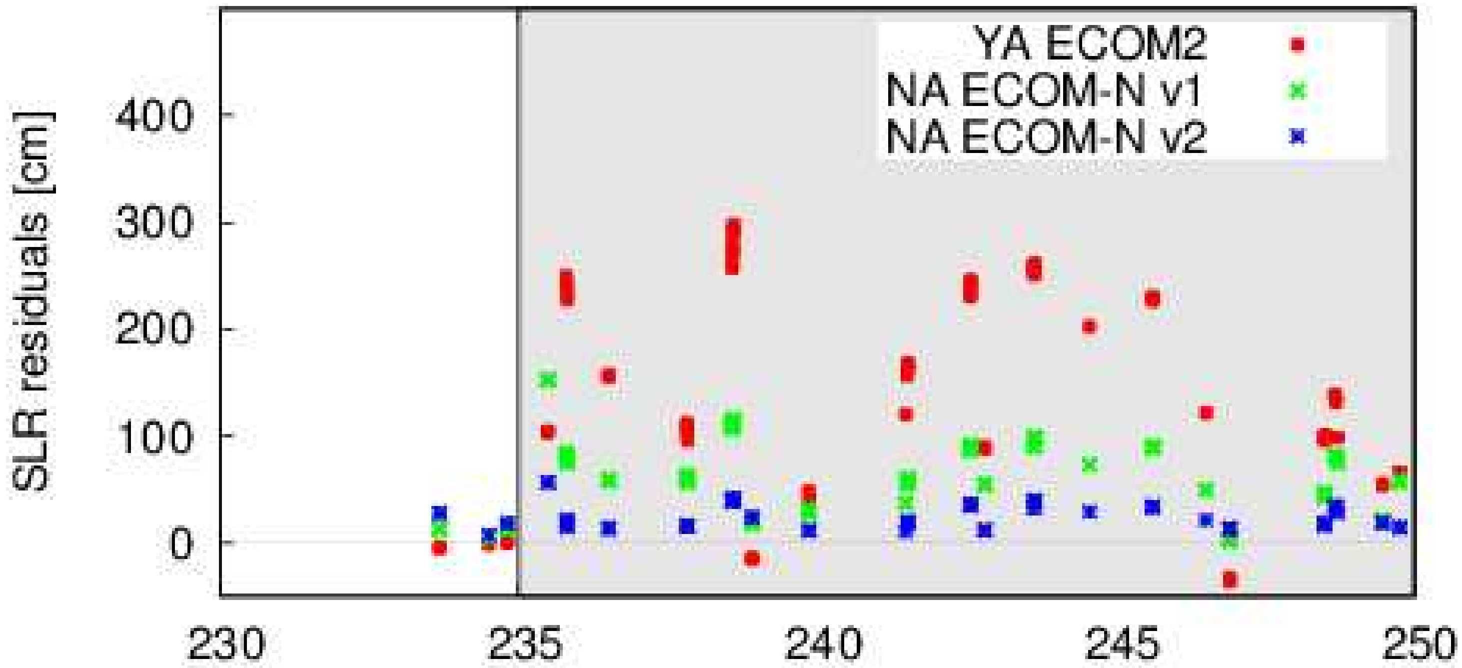
Satellite-fixed Cartesian coordinate system (x,y,z), unit vector e_{sun} pointing from satellite to Sun is perpendicular to solar panels under Yaw-steering, where z-axis points to Earth, y-axis is perpendicular to e_{sun}.

QZS-1 and most BeiDou satellites switch to orbit normal (ON) steering mode, when the Sun is close to the satellites' orbital planes.

CODE developed purely empirical models ECOM, ECOM2, ECOM-N for motion under orbit normal mode

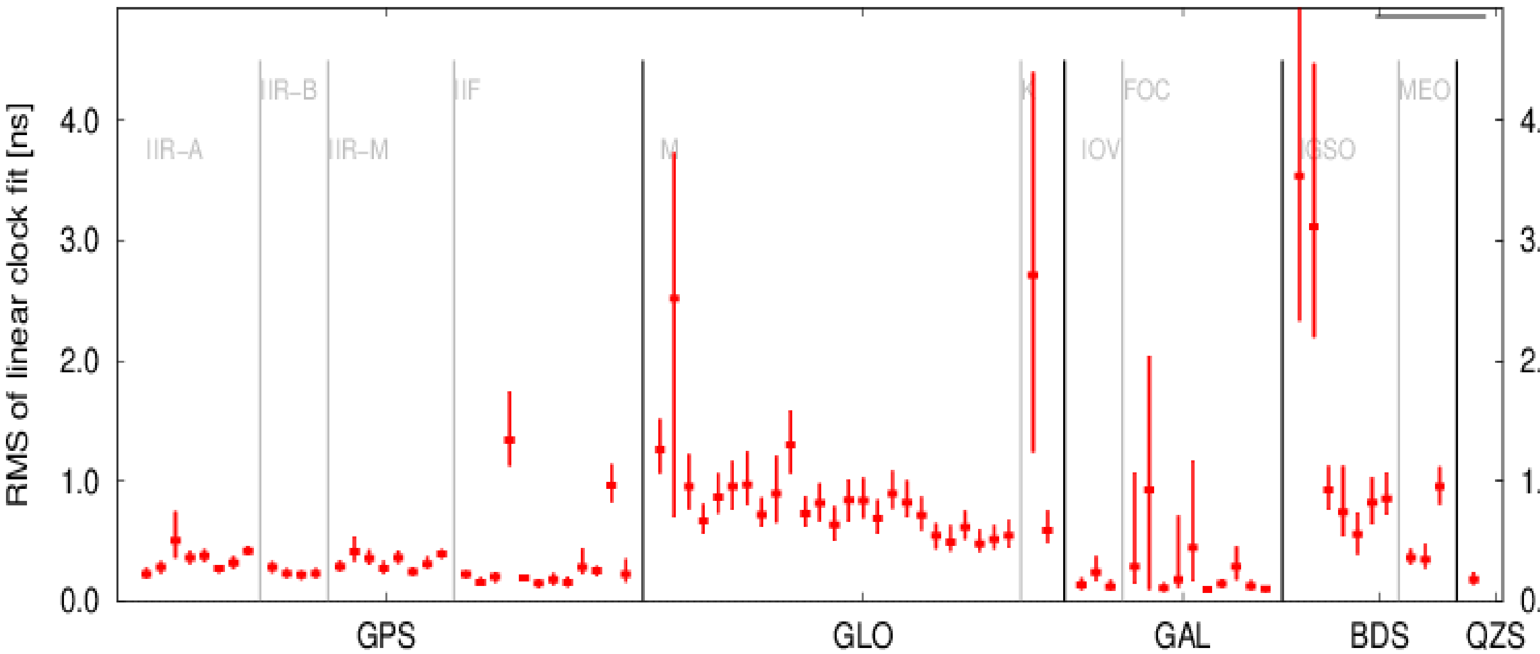
MGEX@CODE

SLR residuals of QZS-1 with SRP models (1 day solutions)



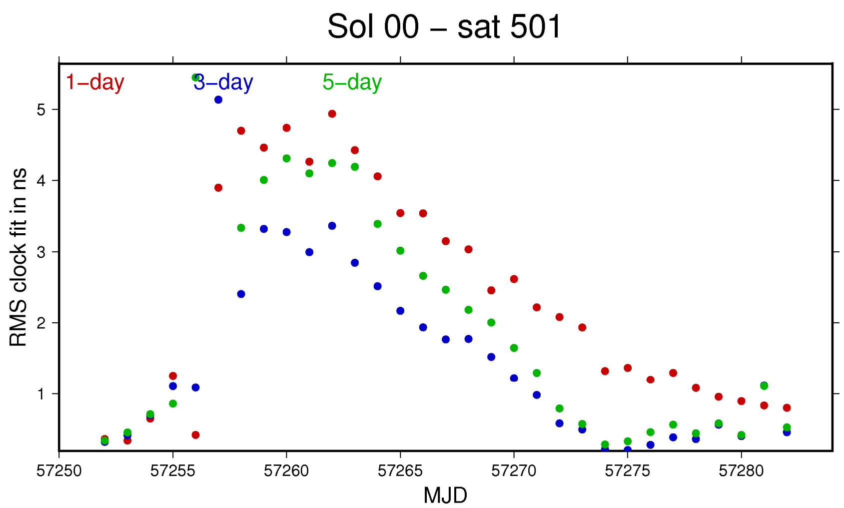
Yaw-Steering SRP (red) is not sufficient for ON mode
Experimental ECOM-N... models (green, blue) better represent SRP
Additional Challenge: switching epochs between YS and ON are unknown

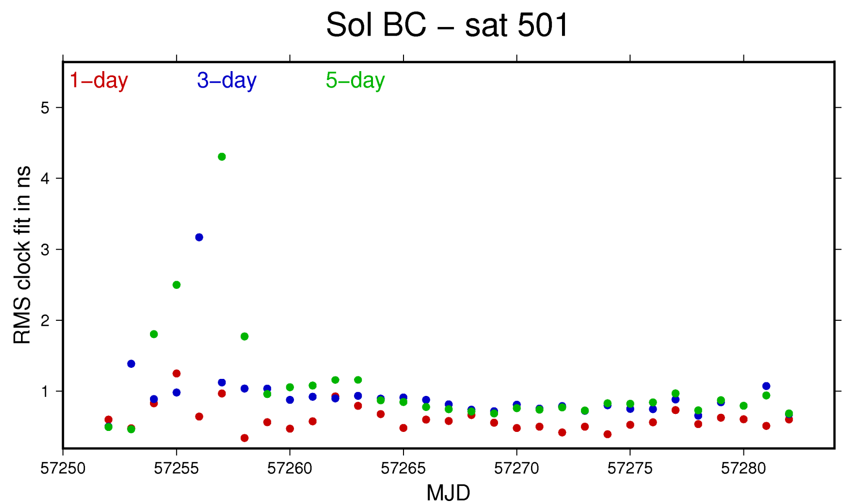
MGEX@CODE



Satellite orbits may also be validated by satellite clock corrections for those satellites which have high-accuracy oscillators. Figure shows the median of the daily RMS of clock estimates w.r.t. linear clock models for different satellite types. Large values indicate modeling problems and/or actual clock quality problems (Prange et al. (2017))

MGEX@CODE





QZS-1 moving under ON-Mode from MJD=57256 onwards, Sun in orbital plane for MJD=57275, 1-, 3-, and 5-day solutions.

Left: ECOM-2, Right: modified ECOM-N. Median of clock-RMS is < 1 ns (~30cm) for all solutions.

The solutions are remarkable in so far, as no a priori models were neede/used; only definition of ON- and YS-modes required.

Multi-GNSS: Latest developments

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Advances in Space Research 59 (2017) 2088–2100

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Semi-analytical solar radiation pressure modeling for QZS-1 orbit-normal and yaw-steering attitude

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SRP-model for QZS-1, based on sparse available information. Strong motivation to have *as accurate as possible* satellite metadata available.