New Constellations for Geodesy: The IGS Multi-GNSS Pilot Project (MGEX)

O. Montenbruck[1], R. Dach[2], P. Steigenberger[1]

[1]DLR, German Space Operations Center

[2]Astronomisches Institut, Universität Bern

IGS stands for …

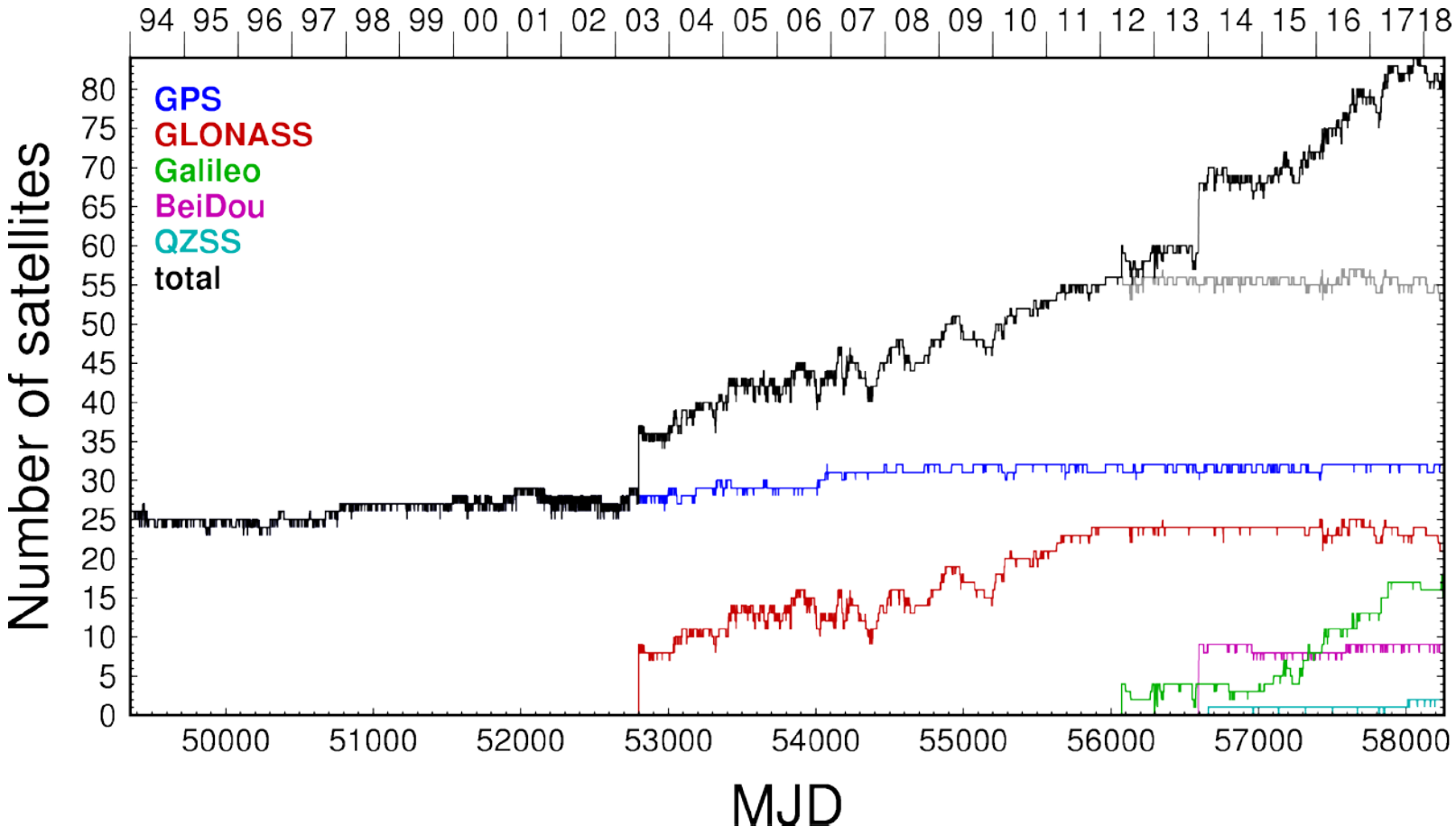
- International GPS Service for Geodesy and Geodynamics
  since January 1994
- International GPS Service
  since Mai 1998
- International GNSS Service
  since March 2005

  ... where GNSS reads in fact as GPS(+GLONASS)

Multi-GNSS Experiment (MGEX)

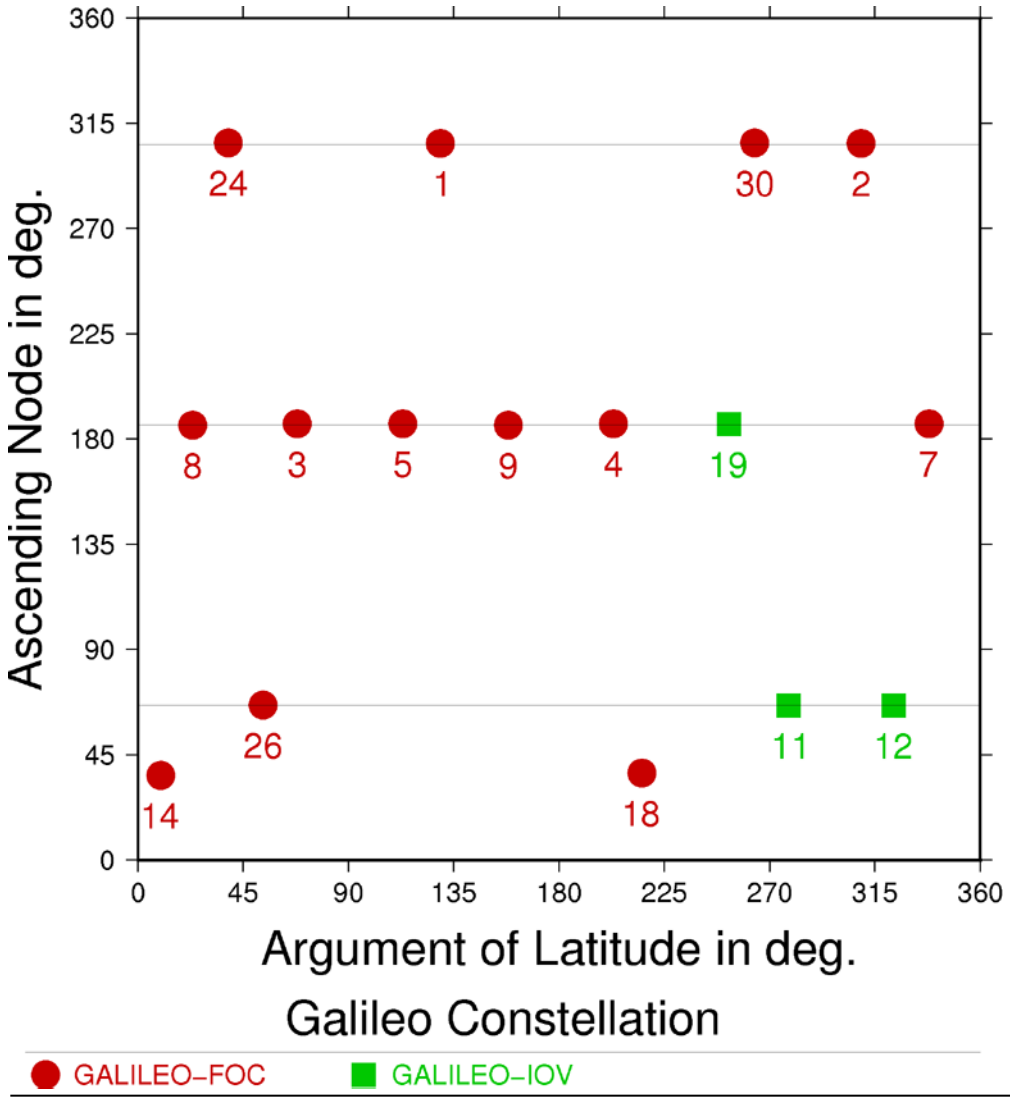
- MGEX call-for-participation released mid-2011
  - Steered by Multi-GNSS Working Group (MG WG)
  - Enable early familiarization with new signals and constellations
- Build up of global multi-GNSS network
  - 2012-2013: growth to ~90 stations world-wide, many real-time
  - Free an open access
  - 2016: unified IGS network with ~130 multi-GNSS stations
- Analyzing the multi-GNSS data
  - Generating real multi-GNSS products
- Continued as MGEX Pilot Project

Number of GNSS satellites



as contained in the CODE legacy and MGEX solution

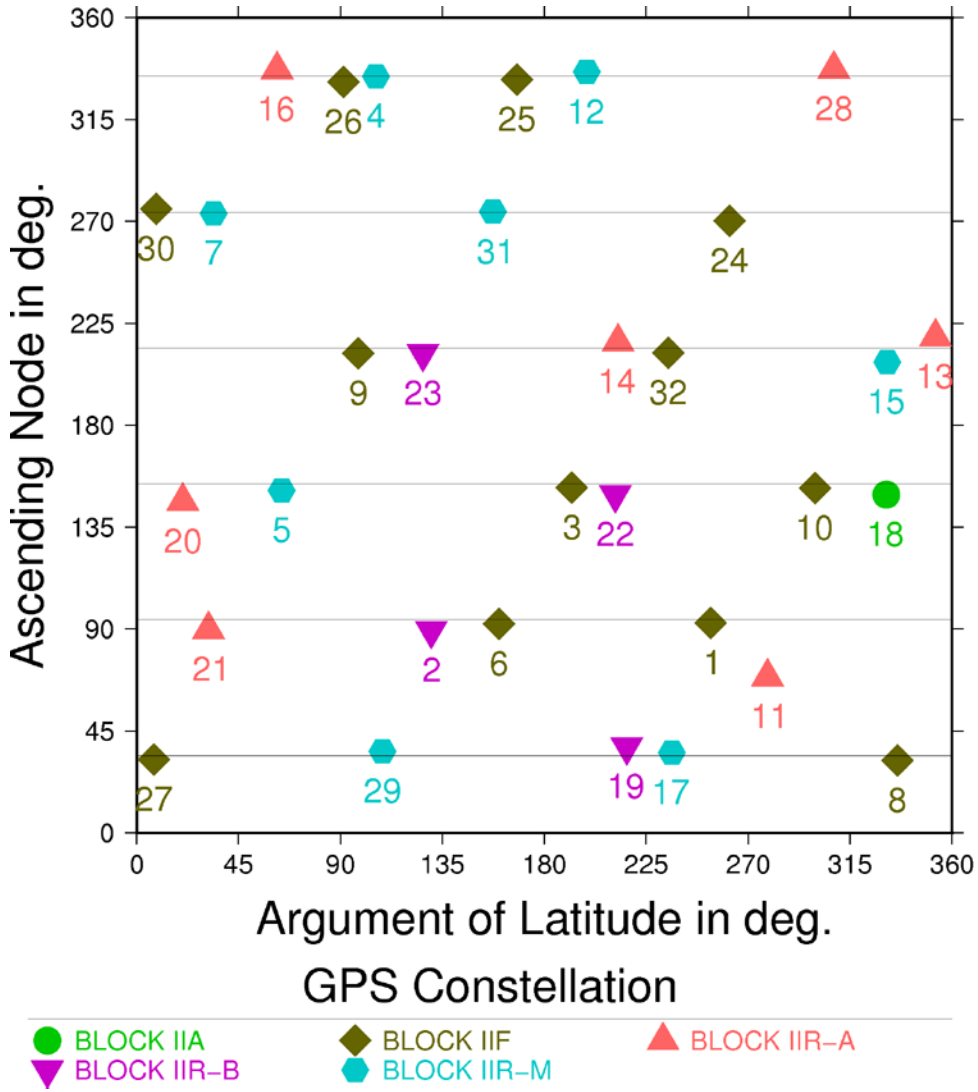
Galileo constellation status



Status: 23. May 2018

as contained in the CODE MGEX solution

GPS constellation status



Status: 23. May 2018

as contained in the CODE MGEX solution

Constellation Status

System	Blocks	Signals	Sats*)
GPS	IIA IIR IIR-M IIF	L1 C/A, L1/L2 P(Y) L1 C/A, L1/L2 P(Y) +L2C +L5	1 11 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)	22 1 1+(1)
Galileo	IOV FOC	E1, E6, E5a/b/ab E1, E6, E5a/b/ab	3+(1) 11+(7)
BeiDou	BDS-2 (GEO/IGSO/MEO) BDS-3S BDS-3	B1-2, B2, B3 B1-2, B1, B2ab, B3 B1-2, B1, B2ab, B3	6 / 6 / 3 (5) (8)
QZSS	Block I (IGSO) Block II (GEO/IGSO)	L1 C/A, L1C, SAIF, L2C, E61, L5 L1 C/A, L1C, SAIF, L2C, E62, L5, L5S	1 1 / 2
IRNSS	IGSO	L5, S	6+(2)

*) Status Apr 2018; brackets indicate satellites not declared healthy/operational

Constellation News

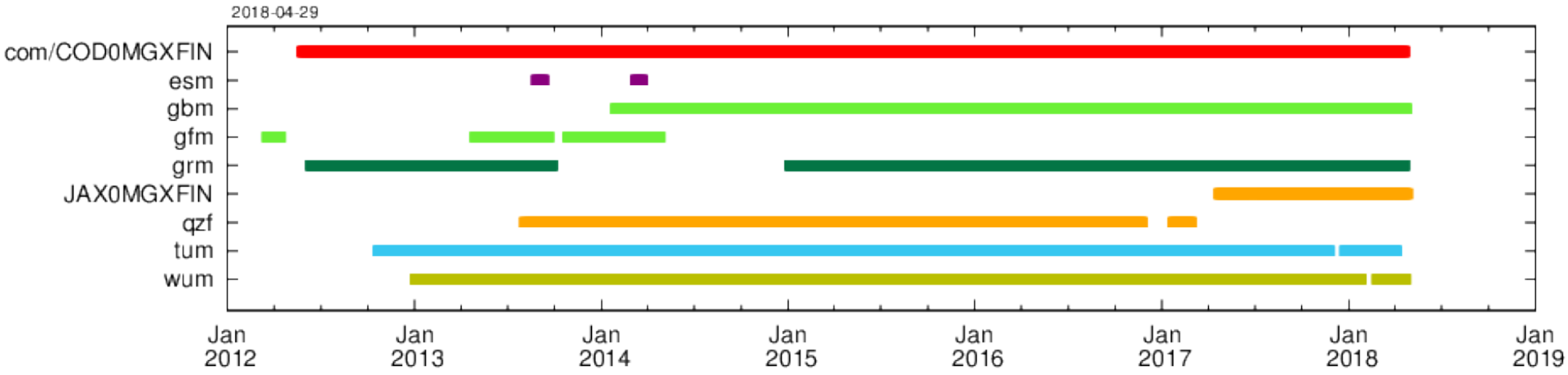
- New ICDs (to be incorporated into the RINEX standard)
  - BDS-3 open service signal ICD
  - BDS-2/3 B3I ICD released; signal now part of open service
  - GLONASS CDMA signals
- Satellites
  - QZSS provides 4-satellite service
  - 15 BDS-2 and 13 BDS-3S/3 satellites in orbit
  - 22 Galileo satellites in orbit (14 healthy/operational)
- Satellite metadata
  - QZSS satellite metadata and operational information released
  - Galileo IOV and FOC satellite metadata released

MGEX Status

- Multi-GNSS stations fully integrated into IGS network
  - 230 multi-GNSS stations
  - RINEX 3 files with long names in standard repository
  - Few stations with new capabilities (IRNSS L5, Galileo E6)
  - Various stations tracking BDS-3S/3 (legacy B1-2 and B3I signals)
- Products
  - Six multi-GNSS analysis centers
  - Three 5 constellation products (GPS, GLO, GAL, BDS, QZS)
  - Partial use of long product file names (CODE, JAXA)
  - New satellite metadata incorporated
  - QZS and BDS-3S/3 added to DCB products

Orbit and Clock Products

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



New Product File Naming Convention

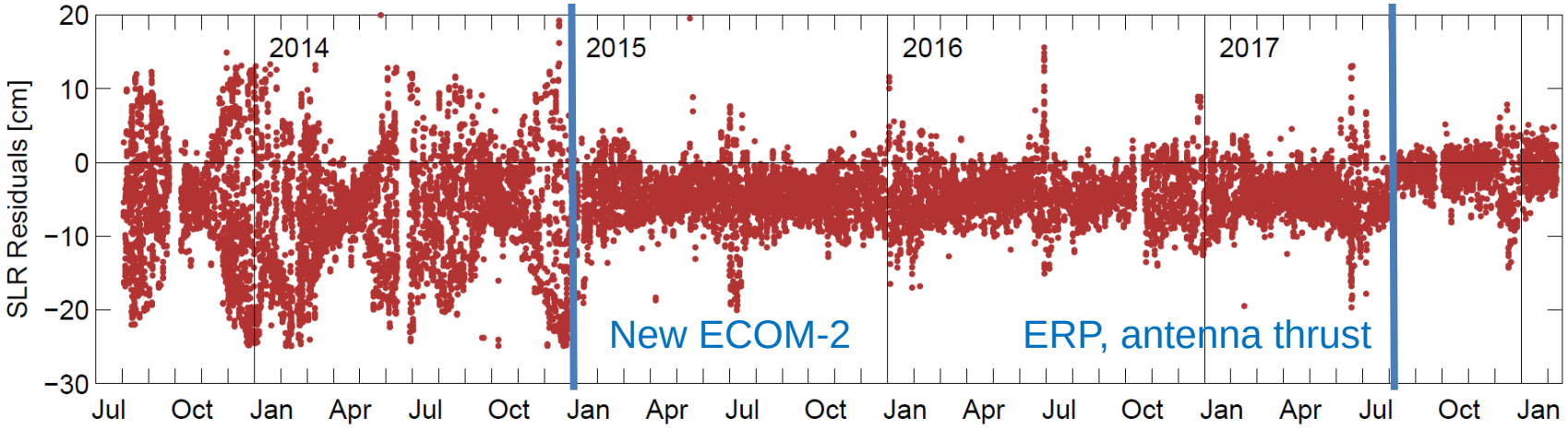
AAAVPPPTTT_YYYYDDDHHMM_LEN_SMP_CNT.FMT[.?*]
GFZ0MGXRAP_20160010000_01D_05M_ORB.SP3.gz

01-03	AAA	3-char AC name (e.g. GFZ)
04	V	1-char version/solution identifier (nominally 0)
05-07	PPP	3-char campaign/project specification (e.g.: "MGX")
08-10	TTT	3-char product type specification (here: RAP for "rapid", and FIN for "final")
11		1-char separator (underline)
12-15	YYYY	4-digit year of start epoch
16-18	DDD	3-digit day-of-year of start epoch
10-20	HH	2-digit hour of start epoch (her: 00)
21-22	MM	2-digit minute of start epoch (here: 00)
23		1-char separator (underline)
24-26	LEN	2-digits+1-char intended (nominal) product period (e.g. 01D for 1-day)
27		1-char separator (underline)
28-30	SMP	2-digits+1-char sampling interval (e.g 15M for 15-min; 000 if not-applicable)
31		1-char separator (underline)
32-34	CNT	3-char content type (e.g.: „ORB")
35	.	1-char separator
36-38	FMT	3-char format extension (e.g.: "SP3")

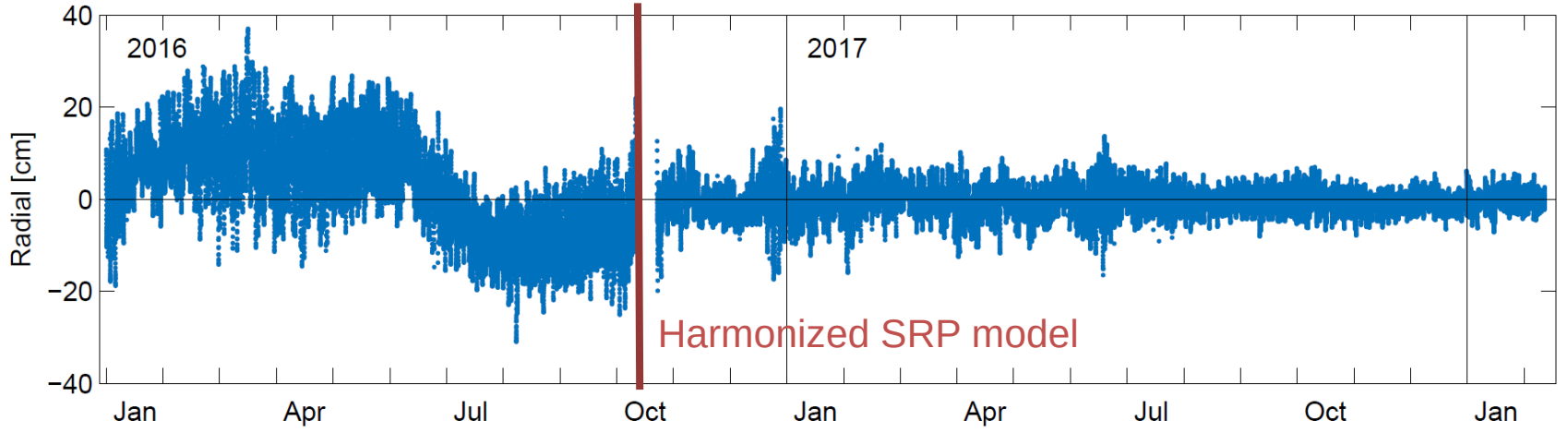
Derived from the long filenaming convention for RINEX
ZIM300CHE_20160010000_01D_30S_MO.crx.gz

Orbit Product Quality

SLR Residuals COM product for Galileo E102



Radial orbit difference COM-GBM product



Orbit Product Quality

IGS INTERNATIONAL GNSS SERVICE

GPS

	CODE	GFZ	GRGS
GFZ	25		
GRGS	26	32	
JAXA	26	26	31

GLONASS

	CODE	GFZ	GRGS
GFZ	69		
GRGS	60	63	
JAXA	75	41	65

Galileo

	CODE	GFZ	GRGS
GFZ	36		
GRGS	59	61	
TUM	79	79	91

QZSS

	CODE	GFZ	JAXA
GFZ	447		
JAXA	306	511	
TUM	1257	1273	1032

BeiDou, MEO

	CODE		
GFZ	65		

BeiDou, IGSO

	CODE		
GFZ	139		

(all values in mm)

Median of orbit differences between MGEX orbits from the MGEX analysis centers in January 2018

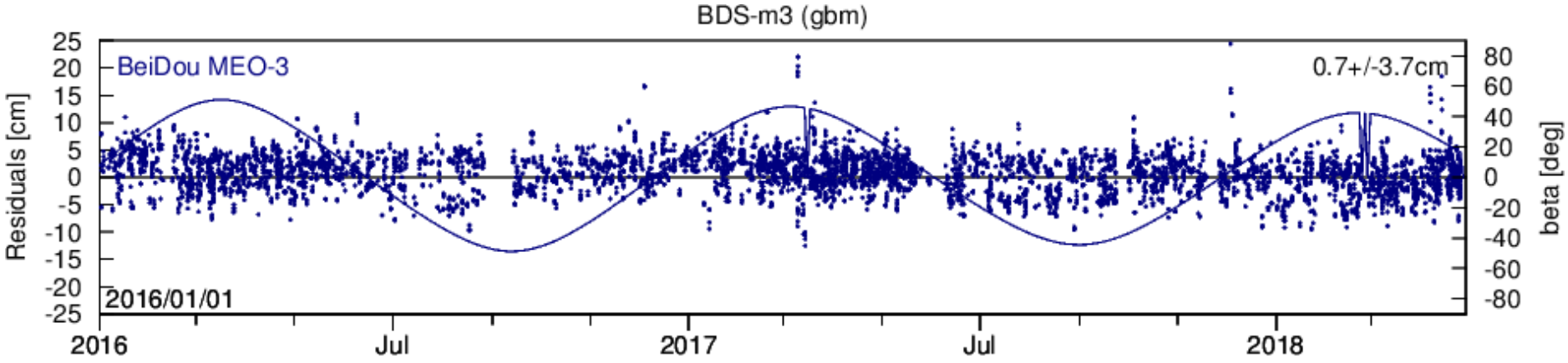
Orbit Product Quality

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

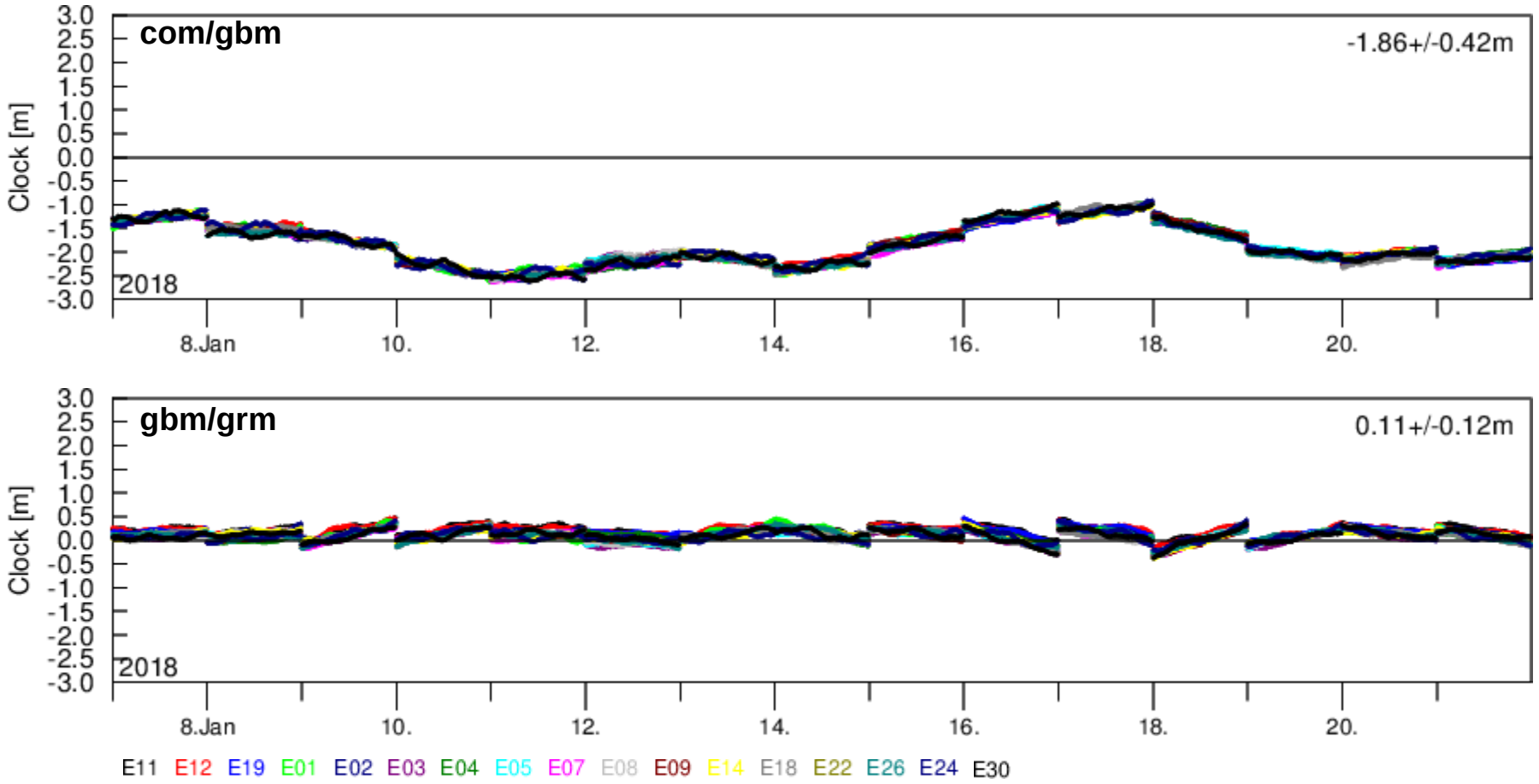
http://mgex.igs.org/analysis/



See also: GOVUS SLR visualization tool at http://multi-slrgnss.rhcloud.com/slr/

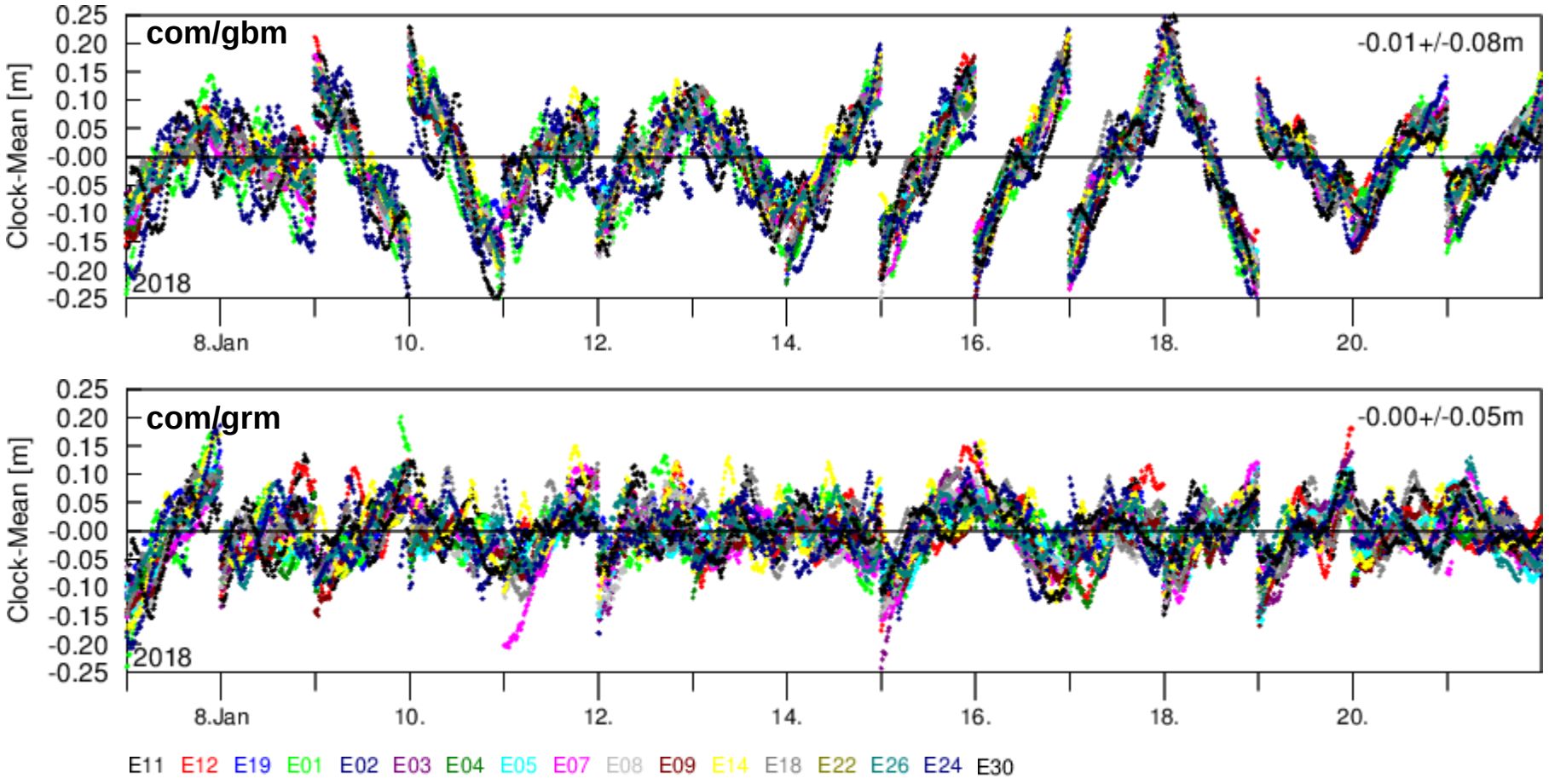
Clock Product Quality

Clock differences



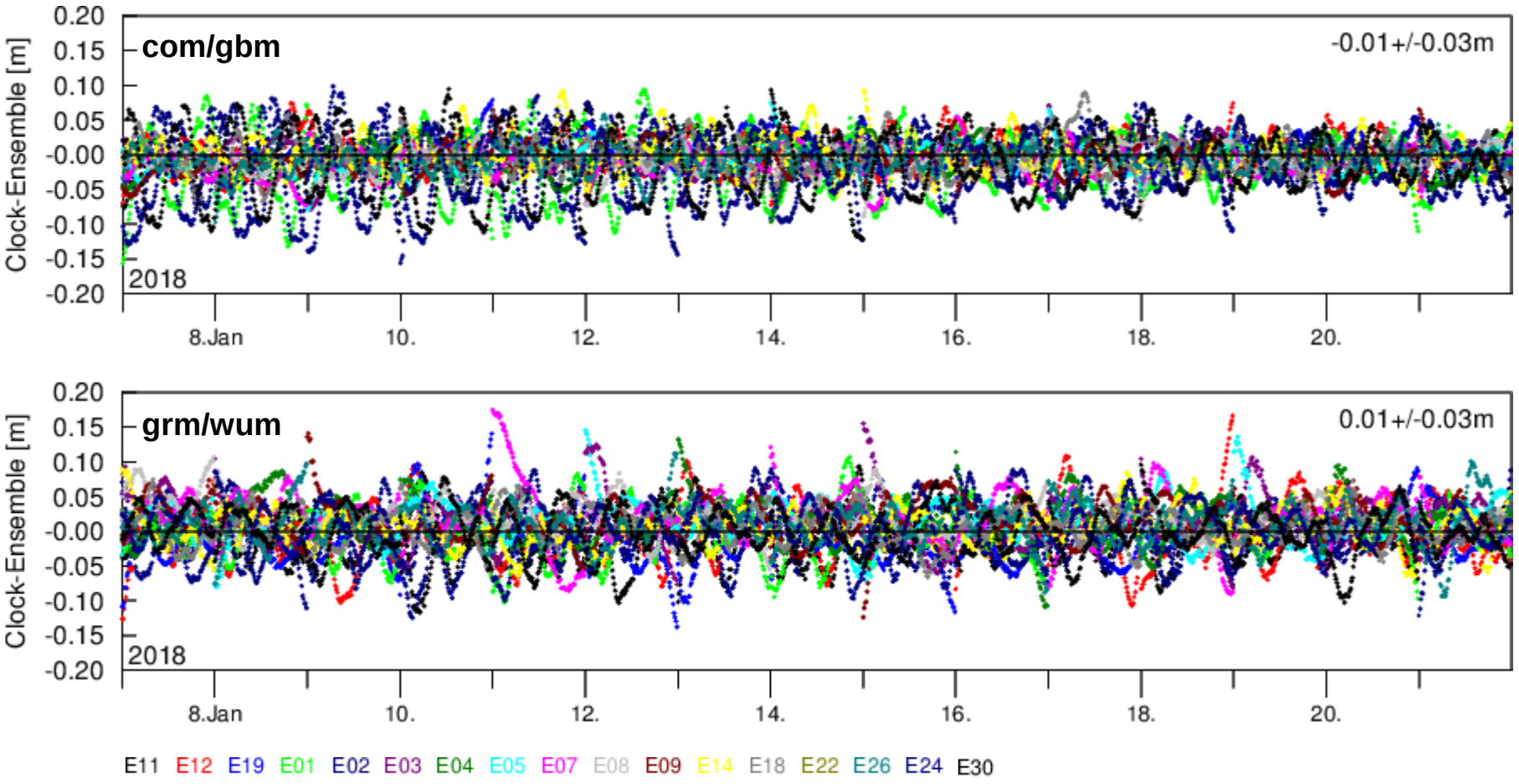
Clock Product Quality

Clock differences, daily bias adjusted



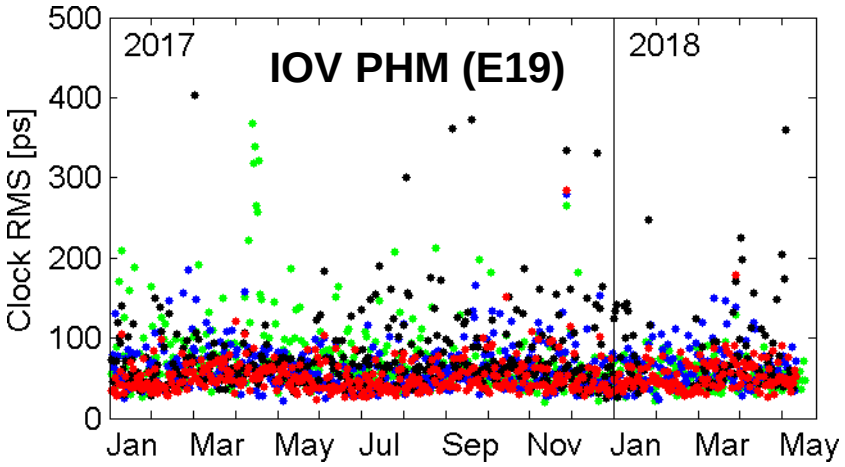
Clock Product Quality

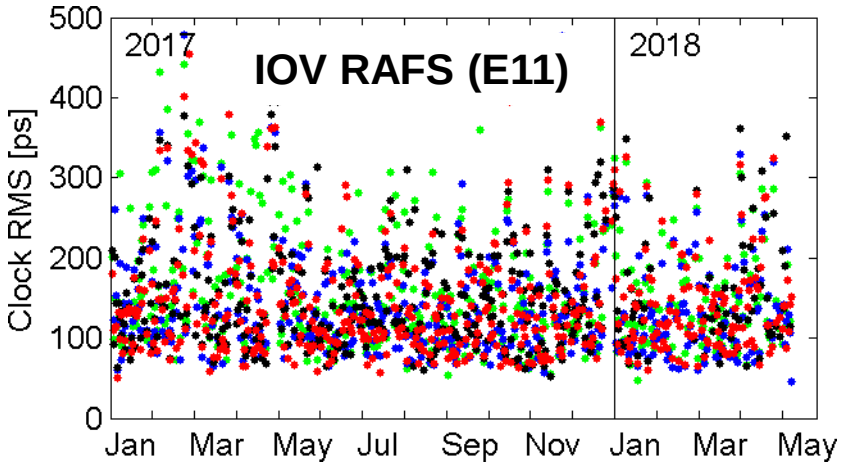
Clock differences, epoch clock adjusted

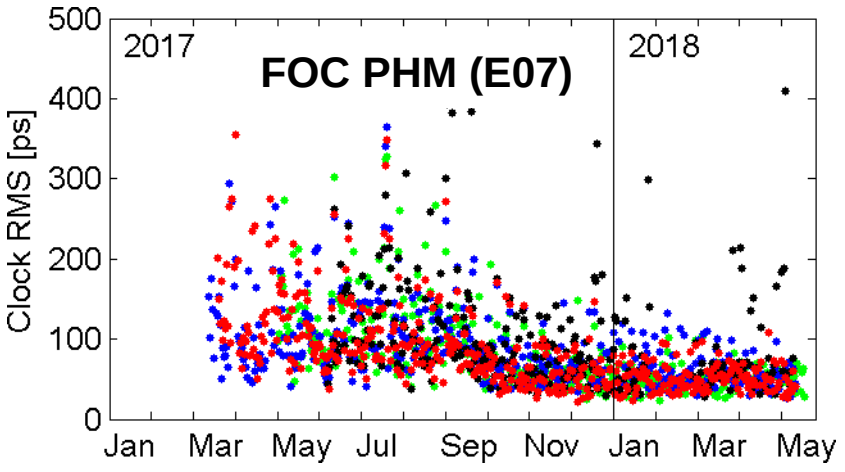


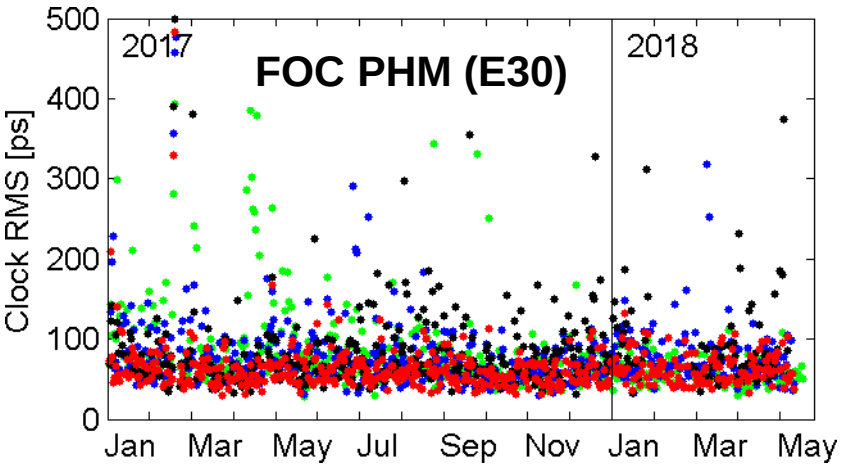
Clock Product Quality

RMS w.r.t. linear fit **com** **gbm** **grm** **wum**









MGEX Website

- Constellations status, Network, Data, Products
- New “Analysis” section http://mgex.igs.org/analysis/index.php
  - Orbit/clock product availability bar chart
  - Signal transmission bar chart (all GNSS and SBAS)
  - Clock time series (BDS, GAL)
  - SLR residuals (BDS, GAL, GLO, QZS)
  - Orbit product comparisons (BDS, GAL, GLO, GPS, QZS)
- New “Metadata” section http://mgex.igs.org/IGS_MGEX_Metadata.php
  - SINEX metadata description and draft metadata file

Galileo Precise Point Positioning

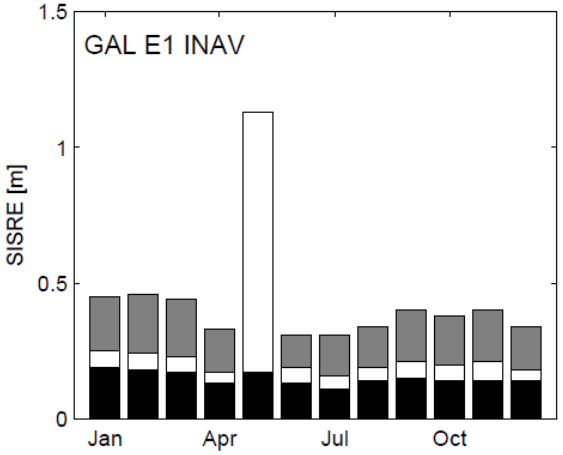
- Clock products refer to E1/E5a ionosphere-free combination
- Absolute calibrations of transmit phase center and variations for each frequency (igs14_xxxx.atx)
- GPS L1, L2 phase center offsets & variations substituted for E1, E5a/b/ab PCOs/PVs of receiver antennas
- ~17 supported satellites (dual-frequency; satellites in eccentric orbit fully usable)
- with ~22 h continuous 4^{++}-satellite coverage per station
- MGEX precise orbit and clock products of individual analysis centers are consistent at the 5 cm level (Q1/2018; modelled pseudorange difference)

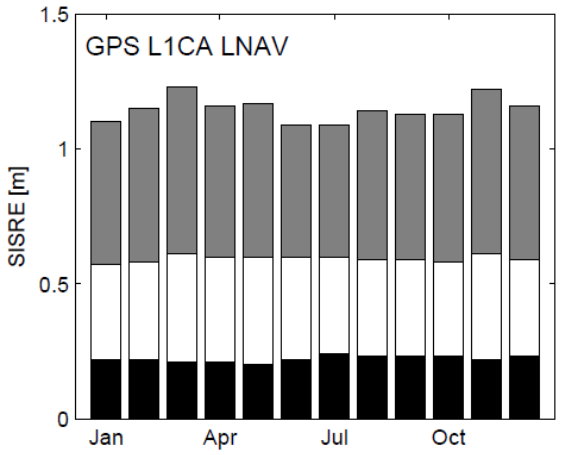
Signal-In-Space Performance

- New harmonized framework for IGS multi-GNSS signal-in-space range error (SISRE) analysis
  - Antenna offset handling,
  - Service-specific group delays
  - Global averaging
- SISRE analysis conducted for 4 constellations in 2017
  - SISRE(RMS) ~0.2 / 0.6 / 0.7-1.0 / 2 m for GAL/GPS/BDS/GLO
  - SISRE(95^{th}) ~ 2 x SISRE(RMS)
- IGS product quality causes various limitations!
- Satellite/user-specific clock biases in GLONASS

Montenbruck O., Steigenberger P., Hauschild A.; *Multi-GNSS Signal-in-Space Range Error Assessment – Methodology and Results*; Advances in Space Research (2018) DOI 10.1016/j.asr.2018.03.041

Signal-In-Space Performance (cntd.)

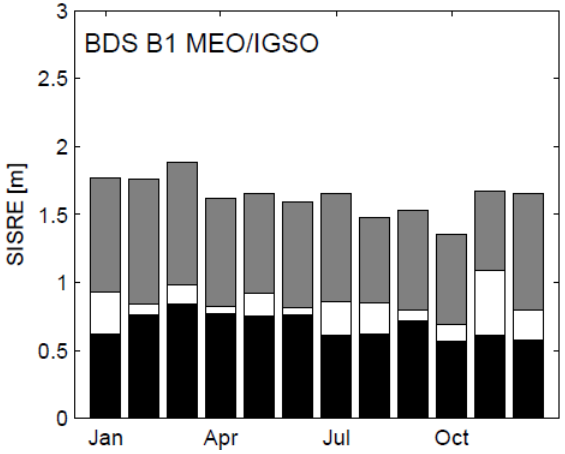


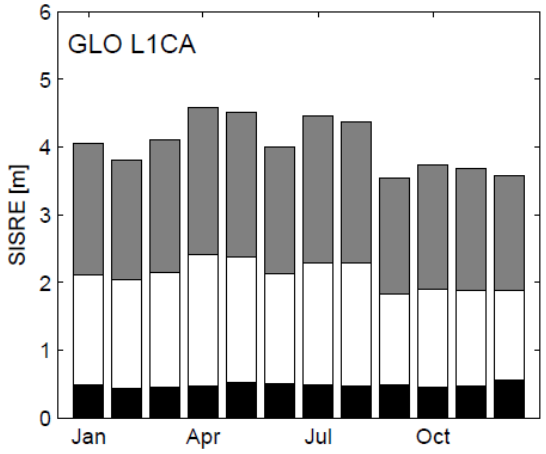


SISRE(95%)

SISRE(RMS)

SISRE(orb)





DOI 10.1016/j.asr.2018.03.041

Galileo Eclipse Attitude

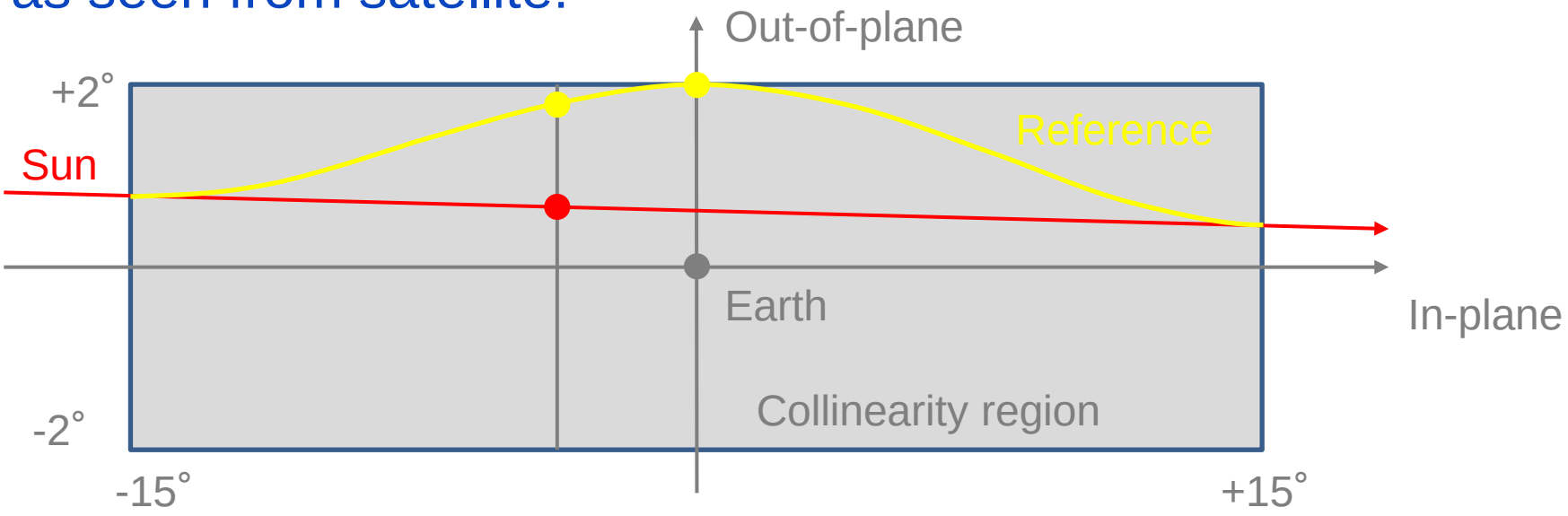
- Description of Galileo eclipse attitude provided along with satellite meta data in Dec. 2016 (IOV) and Oct. 2017 (FOC)
  https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata
- Different attitude laws in collinearity region for IOV and FOC satellites
- To be employed in precise orbit determination and precise point positioning

  (done by most of the MGEX ACs)

Reference Sun Vector (IOV)

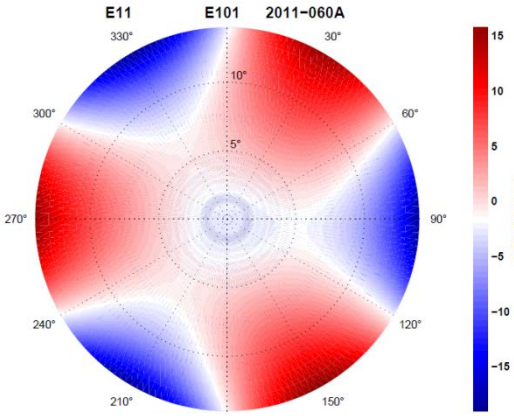
- Yaw-steering relative to a modified reference Sun vector
- Avoids excessive yaw-rates when Sun is close to orbital plane

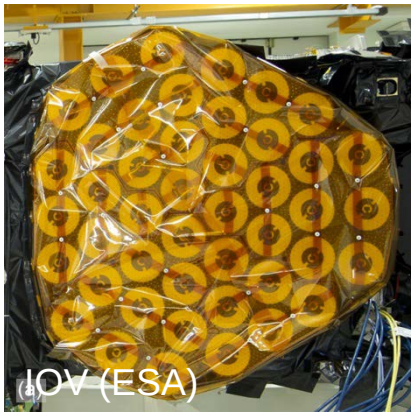
Apparent motion of Sun and Reference-Sun as seen from satellite:



Antenna Calibrations

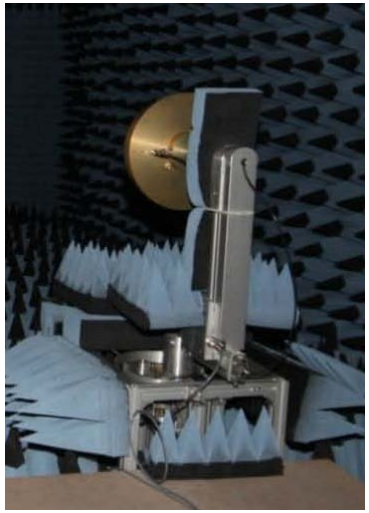
- Absolute calibrations of transmit antennas for IOV and FOC satellites
- Enables independent determination of ITRF scale!





- No robotic calibrations of receiver antennas for new frequencies
- Some chamber calibrations but inconsistencies for legacy signals

Becker et al. (2010)



Summary and Conclusions

- IGS/MGEX provides comprehensive observation data and products for multi-GNSS work
- Rapid build-up of Galileo and BeiDou as global constellations
- Galileo product performance reaches geodetic needs
  - Clear benefit of public satellite metadata (absolute transmit antenna calibration, radiation pressure modelling)
  - Still limited coverage (constellation not yet complete)
  - Lacking receiver antenna calibrations (contaminated orbit and clock products; no fully rigorous PPP)

Key Problems and “To Do”s

- Lack of screened broadcast ephemeris product for GNSS performance and integrity monitoring
- Lack of (robotic) receiver antenna phase center calibrations for new frequencies and signals
- No (concept and) software for combination of multi-GNSS orbit and clock products