Multi-GNSS Working Group Meeting

Oliver Montenbruck

MULTI-GNSS

Agenda

Time (UTC)	Speaker	Topic
13:00-13:05	O. Montenbruck	Introduction
13:05-13:15	All	1. Transfer of MGEX products to standard IGS product directory
13:15-14:10	Various	2. MGEX Product Combination
13:15-13:22	P. Steigenberger	2.1. Assessment of MGEX product consistency
13:22-13:30	G. Mansur	2.2. Multi-GNSS orbit combination at GFZ
13:30-13:37	S. Masoumi	2.3. Multi-GNSS product combination at GA and ACC
13:37-13:45	J. Geng	2.4. Multi-GNSS clock and bias combination in PPP-AR WG
13:45-13:52	G. Chen	2.5. iGMAS orbit and clock combination
13:52-14:10	All	2.6. Discussion of orbit/clock combination (requirements, way-forward)
14:10-14:15	P. Steigenberger	3. Satellite metadata file
14:15-14:20	O. Montenbruck	4. GPS L1/L5 product
14:20-14:30	O. Montenbruck, all	Formulation of WG recommendations

1. Transfer of MGEX Product Repository

Oliver Montenbruck

Transfer of MGEX Products Repository

- Pending Recommendation "*Move to long product file names for MGEX products (by 1 Jan 2019) and store the products in standard IGS directory tree*" from IGS 2018 Workshop
- Currently "products/mgex/<wwww>"; then "products/<wwww>";
- Cover ALL products from start of MGEX
- No conflict of names
  - MGEX ACs use long product file names (no short names since week 2038, end Jan 2019)
  - Old 8.3 names are unique (use of third letter "m" in AC name)
- Will be coordinated by Data Center Coordinator (Thanks to Jianghui Geng!)
- Target date 30 Sep. 2022, 2 months lead time for notification of users by IGS mail (TBC)

2. MGEX Product Combination

Motivation

- GNSS orbit/clock/bias combination addressed in previous research and s/w implementations
- Operational IGS system limited to GPS
- Prototype multi-GNSS orbit combination by IGS ACC (GA/MIT)
  - https://igs.org/acc/experimental-multi-gnss-combinations/
  - http://igsacc.s3.eu-central-1.amazonaws.com/index.html?prefix=products/mgex/final/
- Parallel activities GFZ (orbit), Wuhan University (clock & bias), iGMAS (orbit and clock)
- No comprehensive and “perfect” operational process within IGS
- Identify way forward toward consolidated IGS multi-GNSS product combination

Background Literature

- Beutler G, Kouba J, Springer TA (1995) Combining the orbits of the IGS analysis centers. Bull Geodesique 69:200–222
- Kobel C. S., Arnold D., Jäggi A. (2019). Combination of precise orbit solutions for Sentinel-3A using Variance Component Estimation. Advances in Geosciences 50:27-37. https://doi.org/10.5194/adgeo-50-27-2019
- Mansur G, Sakic P, Männel B, Schuh H. (2020) Multi-constellation GNSS orbit combination based on MGEX products. Advances in Geosciences 50:57-64. https://doi.org/10.5194/adgeo-50-57-2020
- Mansur G., Sakic P., Brack A., Männel B., Schuh H. (2020). Combination of GNSS orbits using variance component estimation. Preprint https://doi.org/10.31223/X5MK64
- Sakic P., Mansur G., Männel B. (2020) A prototype for a Multi-GNSS orbit combination; European GNSS Conference. https://doi.org/10.23919/ENC48637.2020.9317316
- Zhou W, Cai H, Chen G, Jiao W, He Q, Yang Y (2022). Multi-GNSS Combined Orbit and Clock Solutions at iGMAS. Sensors. 22(2):457. https://doi.org/10.3390/s22020457
- Banville S, Geng J, Loyer S, Schaer S, Springer T, Strasser S (2020). On the interoperability of IGS products for precise point positioning with ambiguity resolution. Journal of Geodesy 94:010. https://doi.org/10.1007/s00190-019-01335-w

2.1 Consistency of MGEX products

Peter Steigenberger, DLR/GSOC

MGEX Orbit and Clock Products

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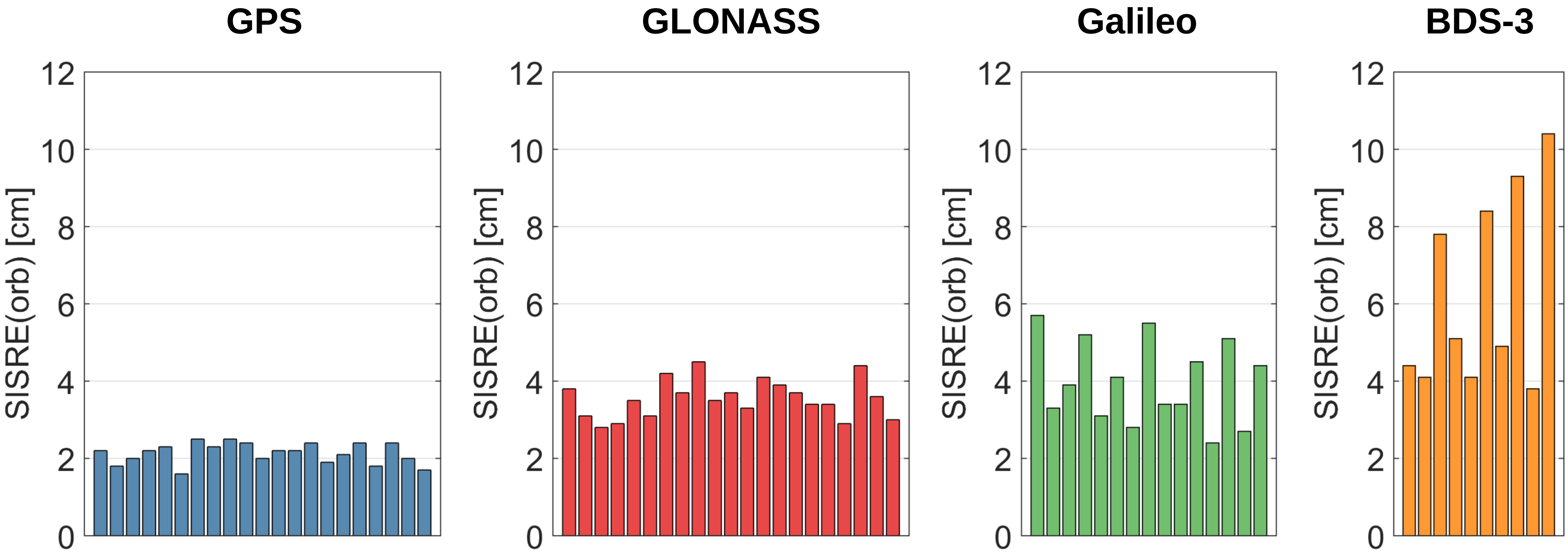
Analysis Center	GPS	GLO	GAL	BDS-3	BDS-2	QZSS	Clocks
CNES/CLS	X	X	X				30 s
CODE	X	X	X	X	X	X	30 s
GFZ	X	X	X	X	X	X	30 s
IAC	X	X	X	X	X	X	30 s
JAXA	X	X				X	30 s
SHAO	X	X	X	X	X		5 min
WUM	X	X	X	X	X	X	30 s

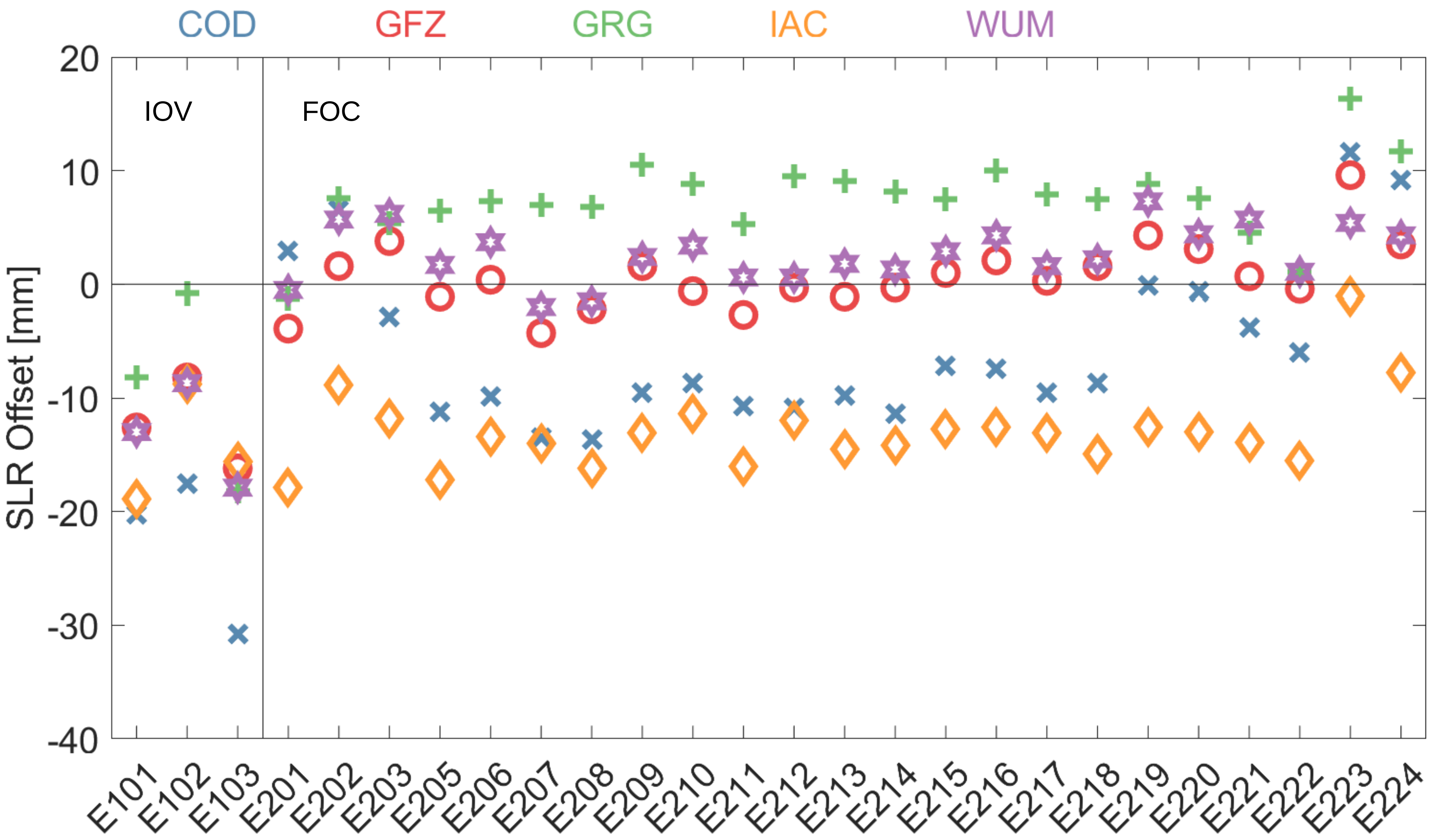
MGEX Orbit Consistency



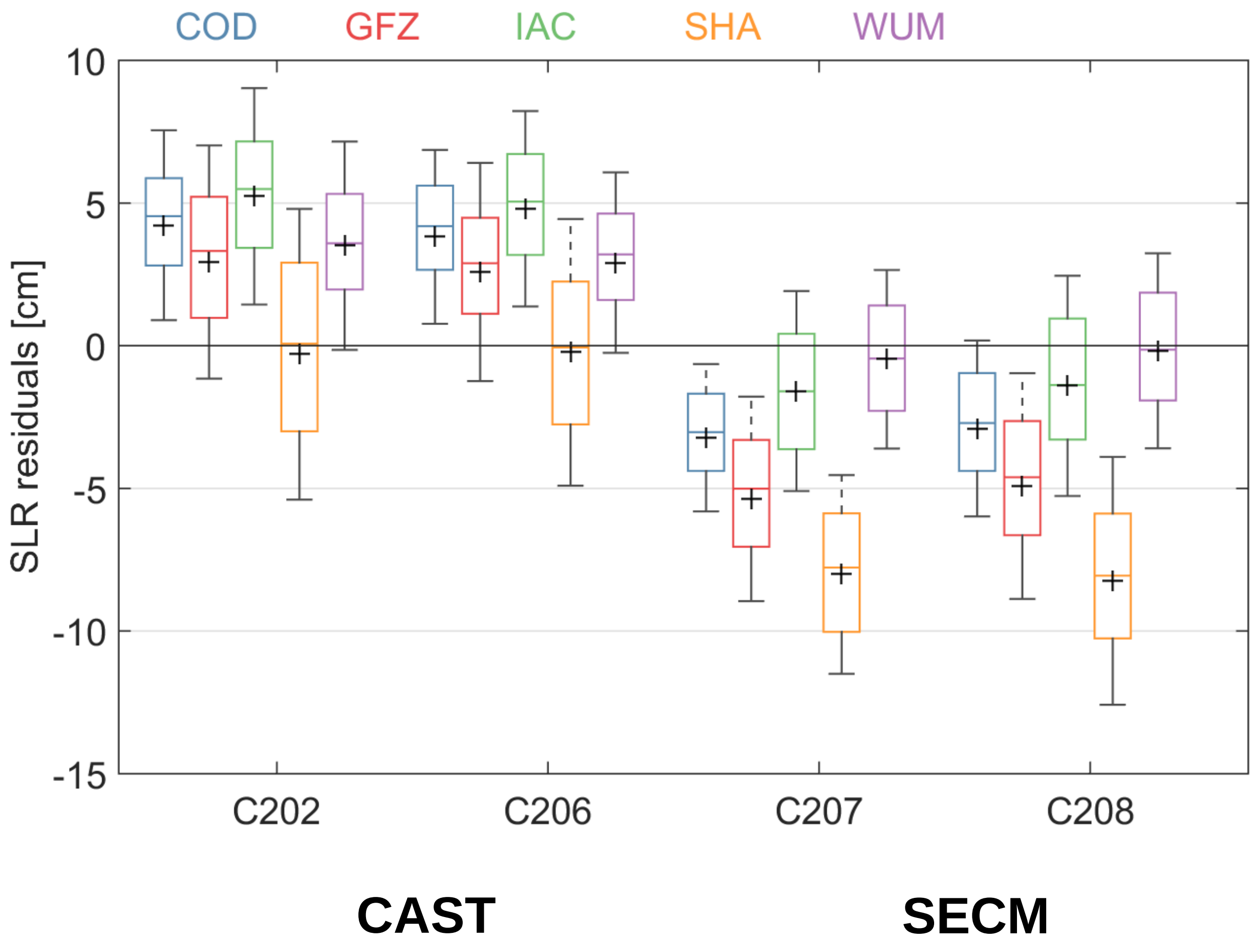
$$\mathrm{SISRE}_{\mathrm{orb}} = \sqrt{w_1^2 R^2 + w_2^2 \left(A^2 + C^2\right)}$$

May 2022, only MEO satellites for BDS-3

Galileo Satellite Laser Ranging Residuals



BDS-3 Satellite Laser Ranging Residuals



AC	Albedo/IR	Antenna Thrust		
		MEO CAST	MEO SECM	IGSO
COD	No	310 W	280 W	--
GFZ	No	310 W	280 W	100 W
IAC	Yes	200 W	200 W	200 W
SHA	No	--	--	--
WUM	Yes	310 W	280 W	100 W

AC modeling options not as homogeneous as for GPS

Orbit Scale; Translation and Rotation Stability

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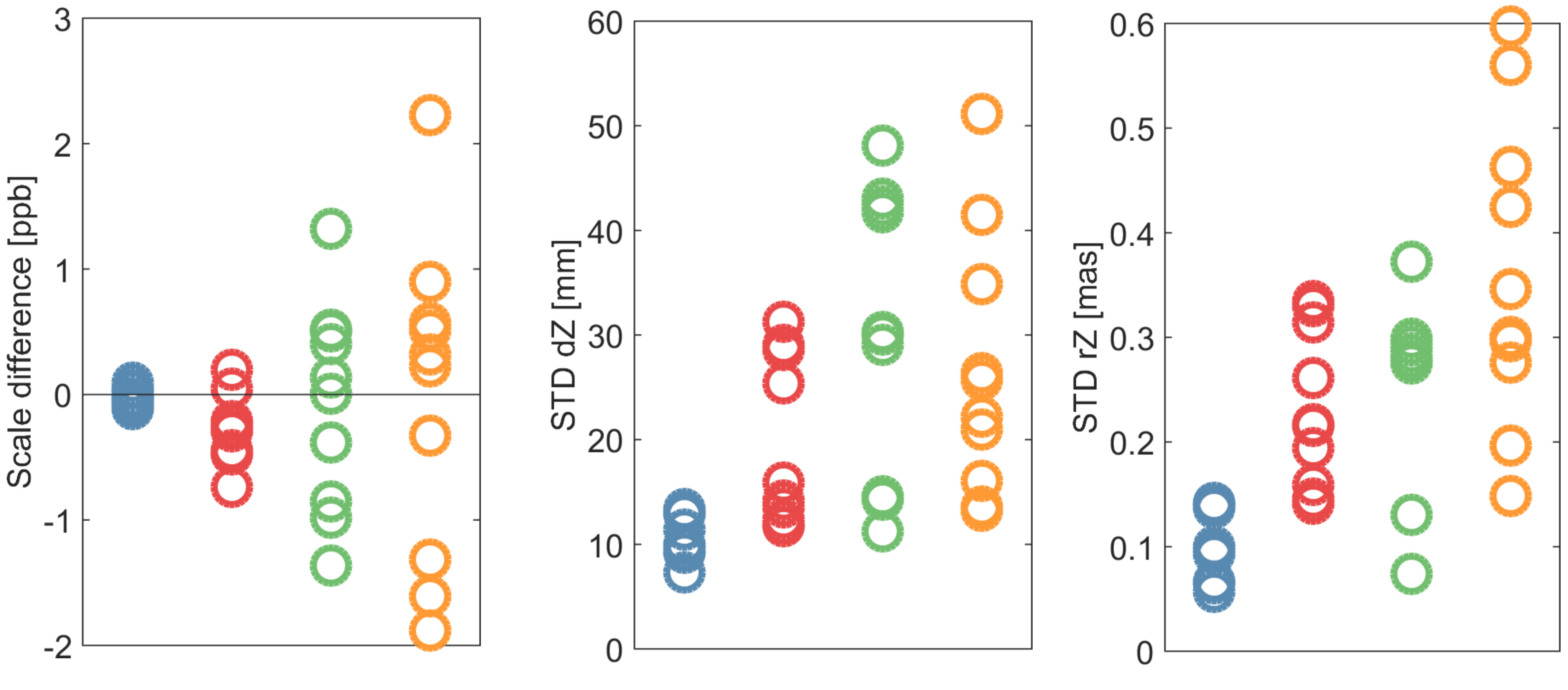
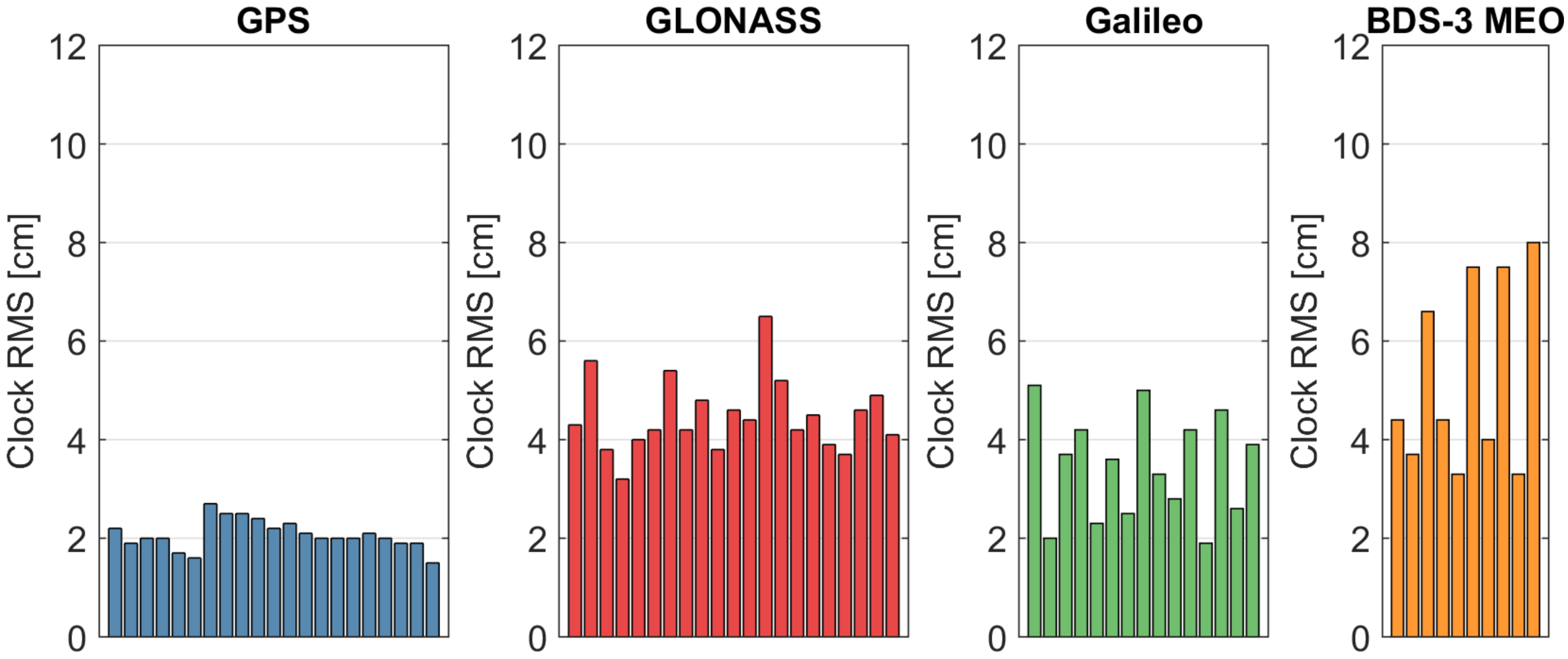


March 2021-February 2022, only MEO satellites for BDS-3, only ACs processing all 4 constellations

GPS GLO GAL BDS-3

MGEX Clock Consistency



RMS of inter-AC clock differences after removing a constellation mean bias per epoch and a daily satellite-specific bias for May 2022, only MEO satellites considered for BDS-3

Open Issues

- All IGS ACs are encouraged to process at least all global constellations (GPS, GLO, GAL, BDS-3)
- Analysis summaries not available for all MGEX ACs
- More diverse processing options for BDS-3 than for GPS resulting in degraded consistency
- Do we need detailed recommendations for GAL and BDS modeling as for GPS/GLO repro3?
- BDS-3 SRP modeling deficiencies
    - Incomplete metadata
        - Optical properties
        - Geometry (SAR-antenna, T-shape)
- Extended coverage of SLR tracking of the BDS-3 constellation is strongly encouraged
- How to handle reference frame consistency within and across individual MGEX products?

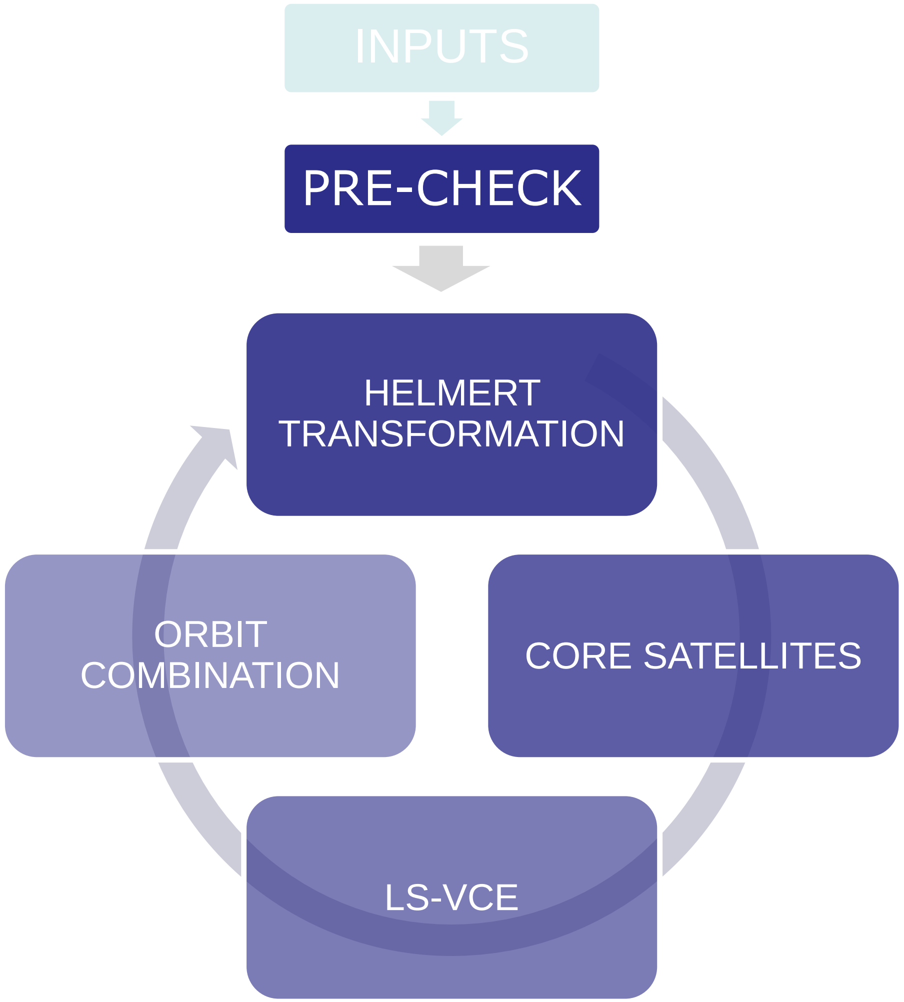
2.2 Multi-GNSS Orbit Combination at GFZ

Gustavo Mansur[1,2] · Pierre Sakic[1,3] · Andreas Brack[1] · Benjamin Maennel[1] · Harald Schuh[1,2]

1 - Deutsches GeoForschungsZentrum GFZ, Potsdam, Germany
2 - Technische Universität Berlin, Berlin, Germany
3 - Institut de Physique du Globe de Paris - Université Paris Cité, Volcanological and seismological observatories, Paris, France

IGS Workshop 2022 - MGWG Meeting - 2022/06/28

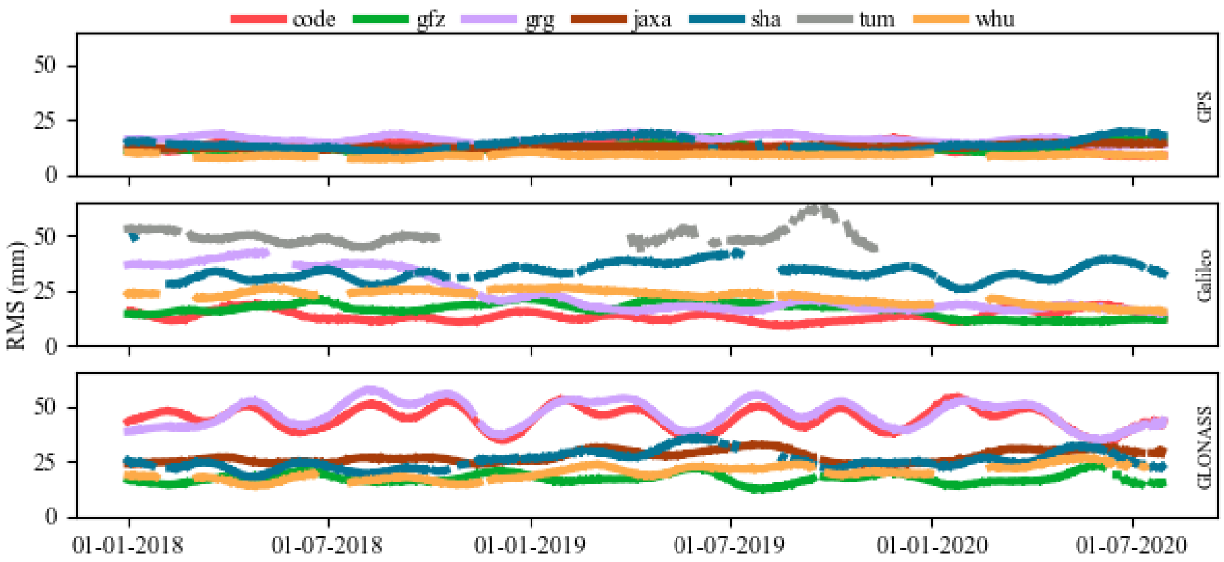
Orbit Combination - Methodology

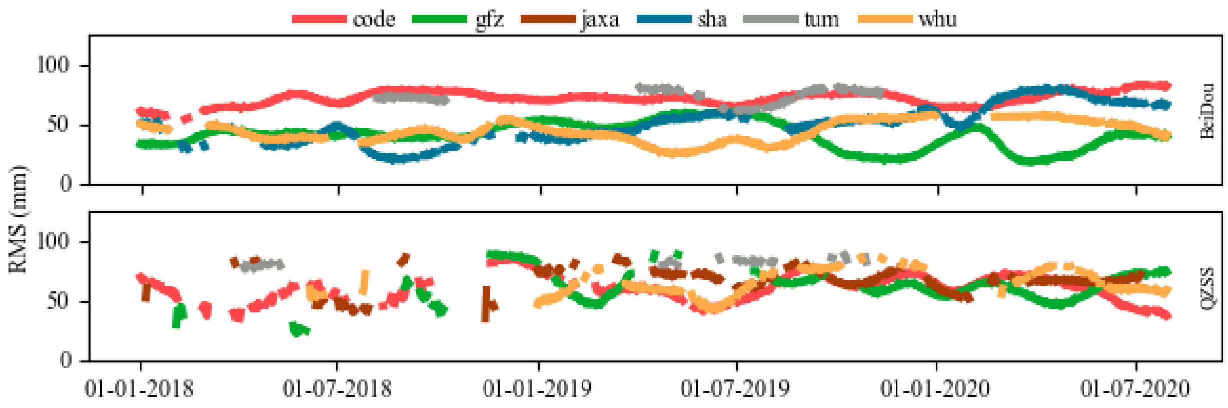


1) Rough exclusion of satellites; A mean orbit is computed;
2) Helmert Transformation between mean orbit and ACs' solution;
3) The set of core satellites ensures that the satellites for computing the variance components are the same for all ACs;
4) Estimation of the variance components, using only the core satellites;
5) The inverse variances are normalized and then applied as weights to the ACs' orbits.

Orbit Combination - Results

The figure shows the RMS between the combined orbit and the ACs' products

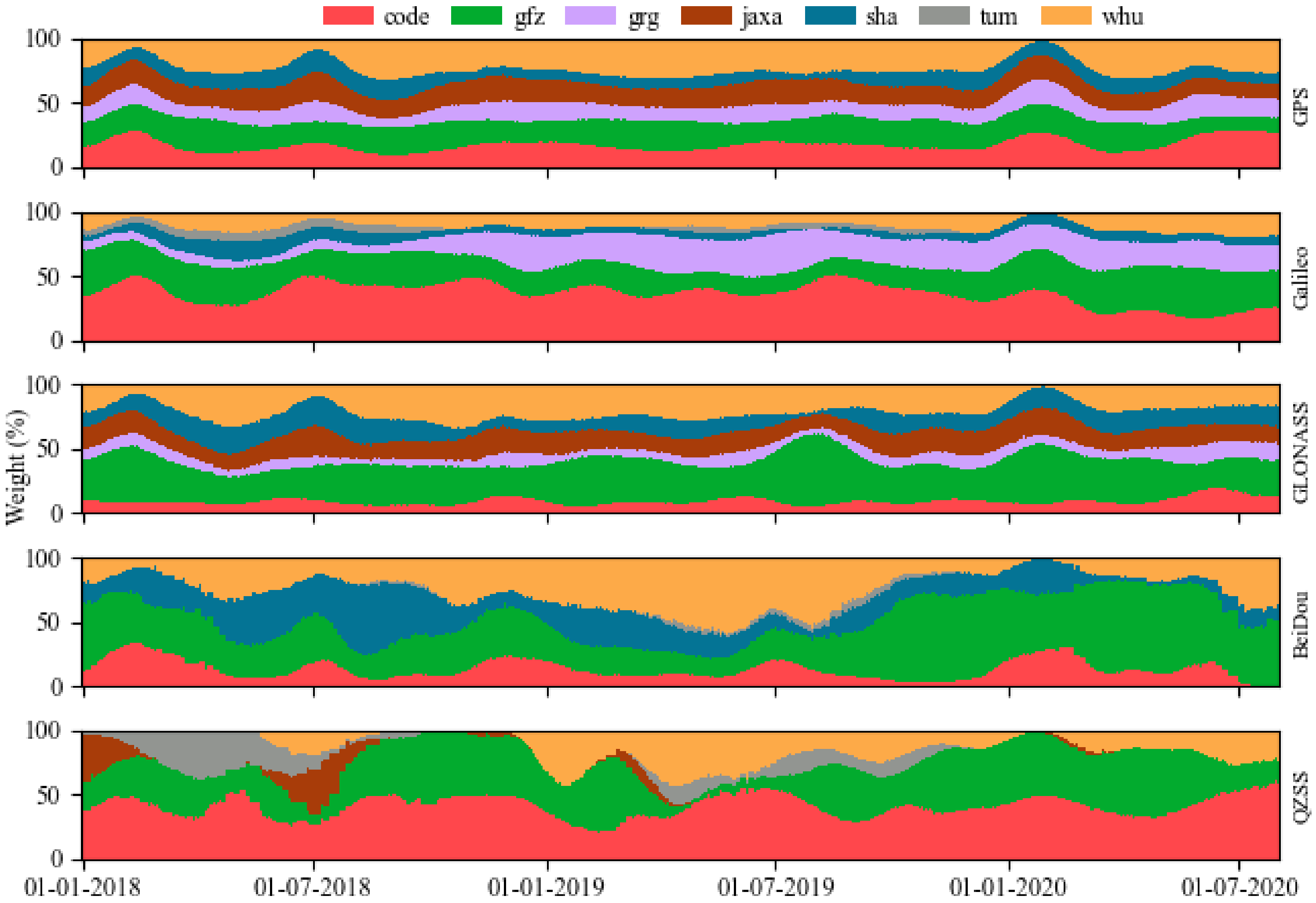




- As a validation of the method, we compared the RMS also for the final IGS regular routine, and our combined solution where the comparison is better than 4 mm.

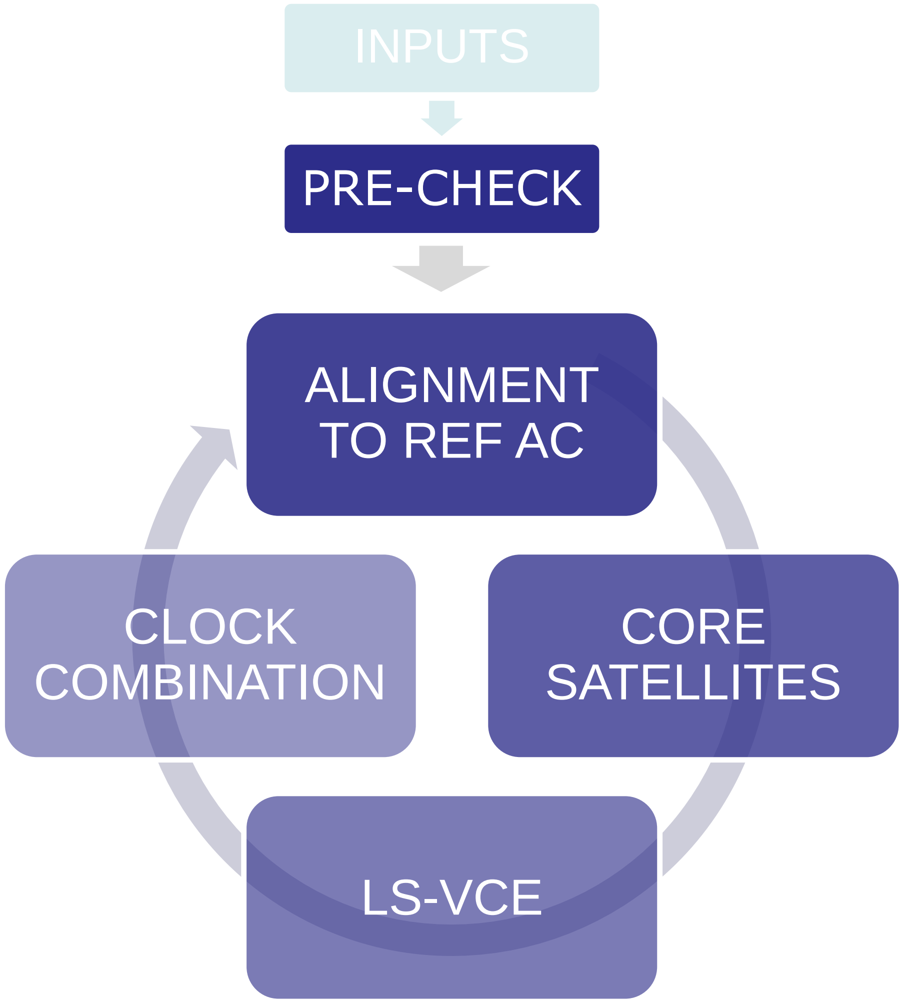
Orbit Combination - Results

The figure shows the weight per AC per constellation



- The AC plus constellation weighting scheme shows the different behavior of the ACs for each system over time, e.g. significant changes for Galileo constellation, when analyzing the weights for GRG, GFZ and CODE.

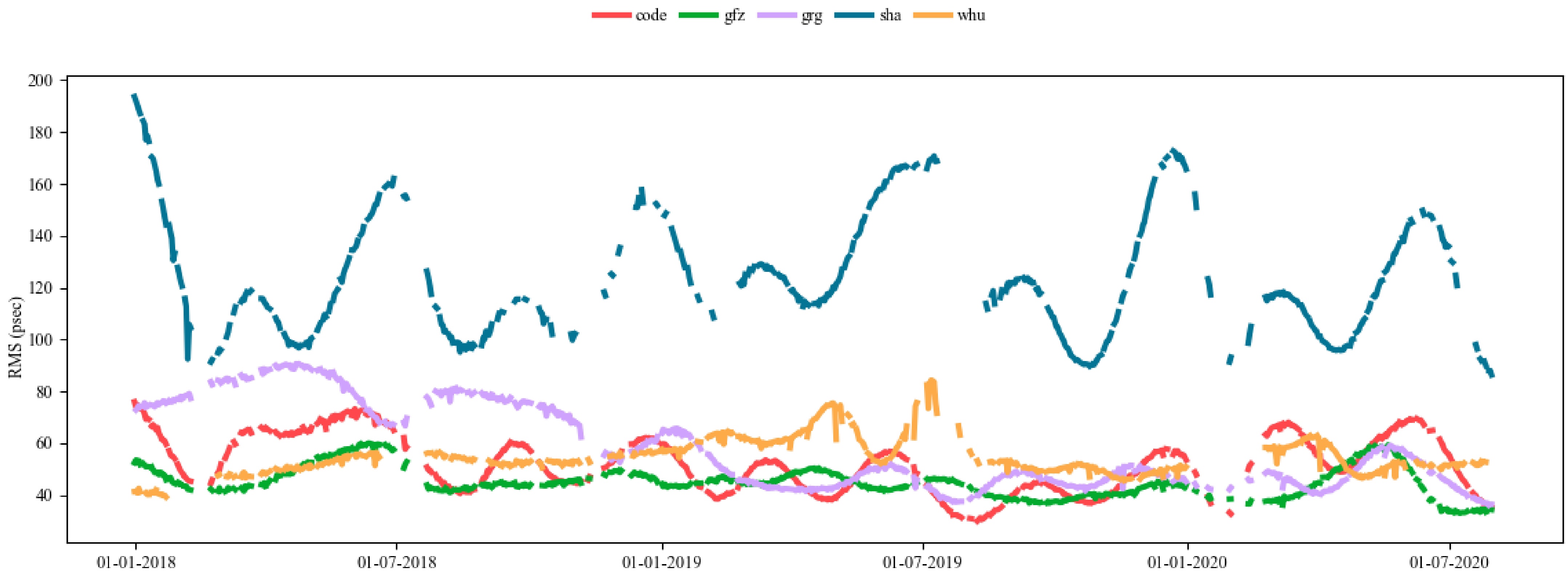
Clock Combination - Methodology



1) Rough exclusion of satellites; A reference AC is selected;
2) Alignment to the reference AC, using a drift and offset;
3) The set of core satellites ensures that the satellites for computing the variance components are the same for all ACs;
4) Estimation of the variance components, using only the core satellites;
5) The inverse variances are normalized and then applied as weights to the ACs' clocks.

Clock Combination - Results

The figure shows the RMS between the ACs and the combination for Galileo constellation



- As a validation of the clock combination we compared with the final IGS clock products, where the agreement is around 40 psec.

Remarks and Current Work

- The alignment for the MGEX products can only be conducted as a "relative process" since we have no specific SINEX for MGEX solutions
- From the combination results and analysis, we can state that in general the ACs solutions submitted to the MGEX project are getting more stable over the years
- Would be good if the ACs could provide the same set of files e.g.: Orbits, ERP, Clock, SINEX, and bias
- The LSVCE method is now extended to the clock products, yielding in the clock combination for MGEX, also tested with REPRO 3 data

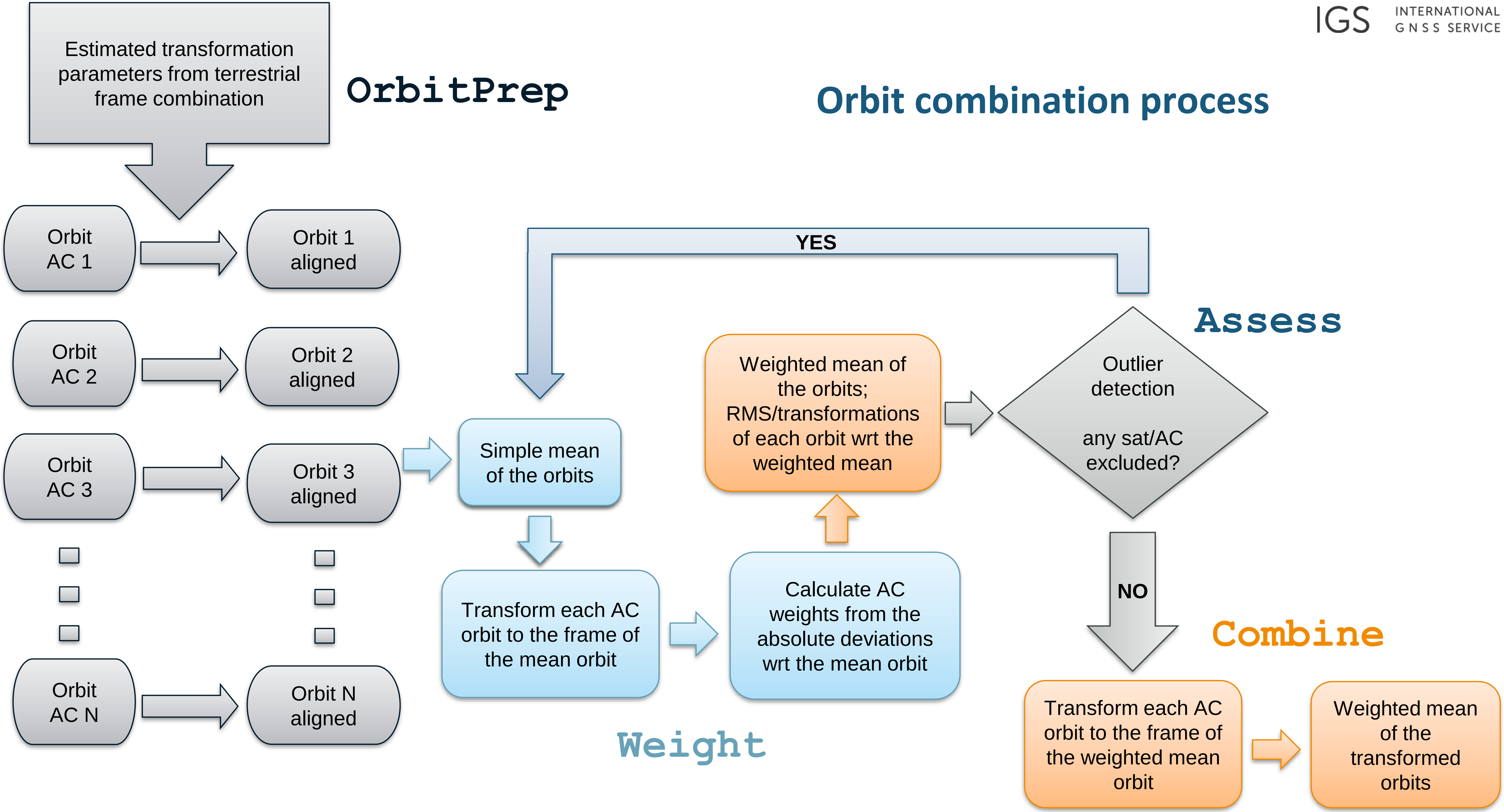
References

- Mansur G., Sakic P., Männel B., Schuh H. (2020) Multi-constellation GNSS orbit combination based on MGEX products. Advances in Geosciences 50:57-64. https://doi.org/10.5194/adgeo-50-57-2020
- Mansur G., Sakic P., Brack A., Männel B., Schuh H. (2020). Combination of GNSS orbits using variance component estimation. Preprint https://doi.org/10.31223/X5MK64
- Sakic P., Mansur G., Männel B. (2020) A prototype for a Multi-GNSS orbit combination; European GNSS Conference. https://doi.org/10.23919/ENC48637.2020.9317316
- Sakic, P., Mansur, G., Männel, B., Brack, A., & Schuh, H. (2021). An experimental combination of IGS repro3 campaign's orbit products using a variance component estimation strategy. Accepted in the International Association of Geodesy Symposia Proceedings. Preprint on EarthArxiv: https://doi.org/10.31223/x5k614

2.3 Multi-GNSS Orbit Combination at GA and ACC

Salim Masoumi, GeoScience Australia

Orbit combination process



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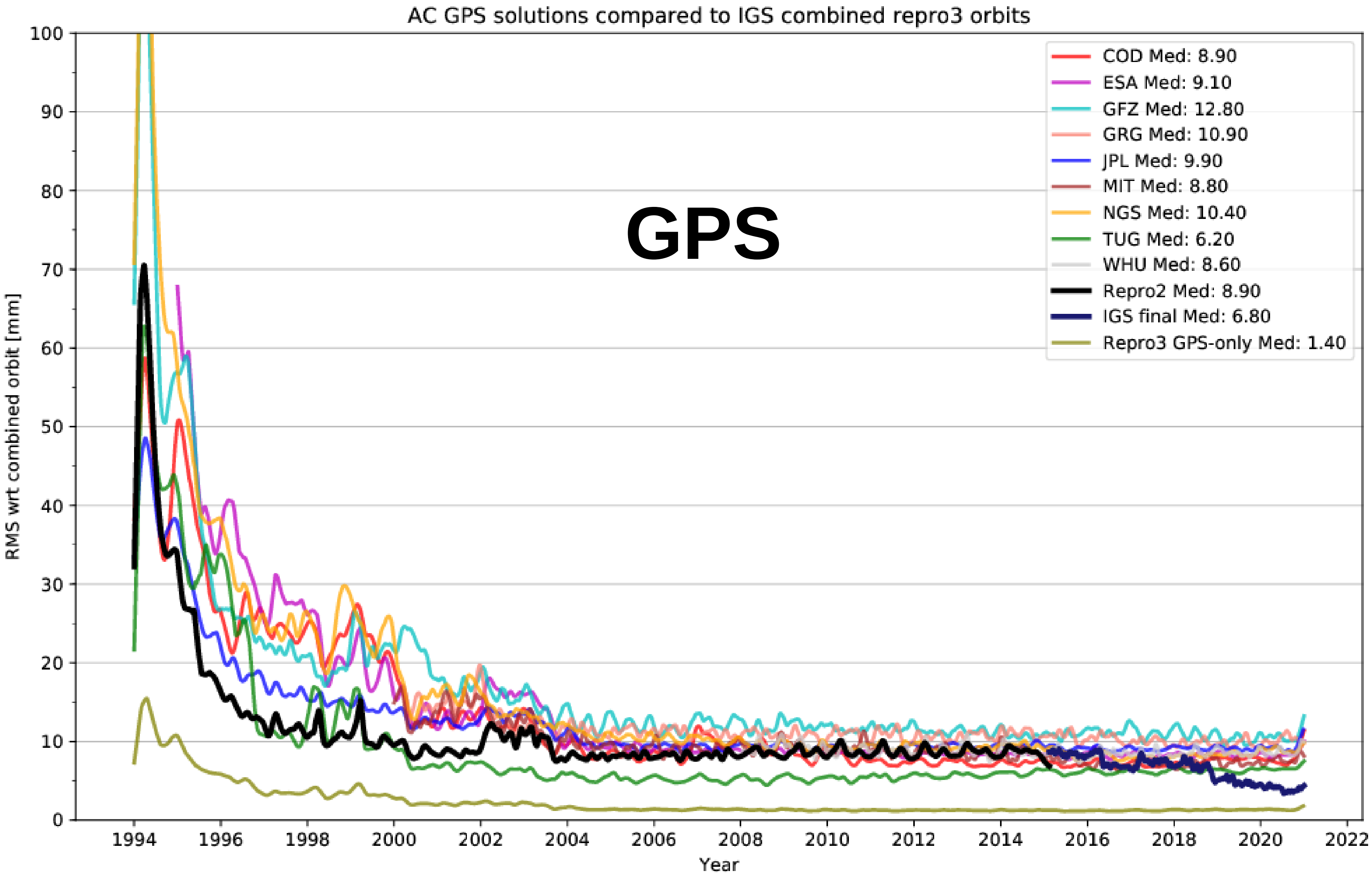
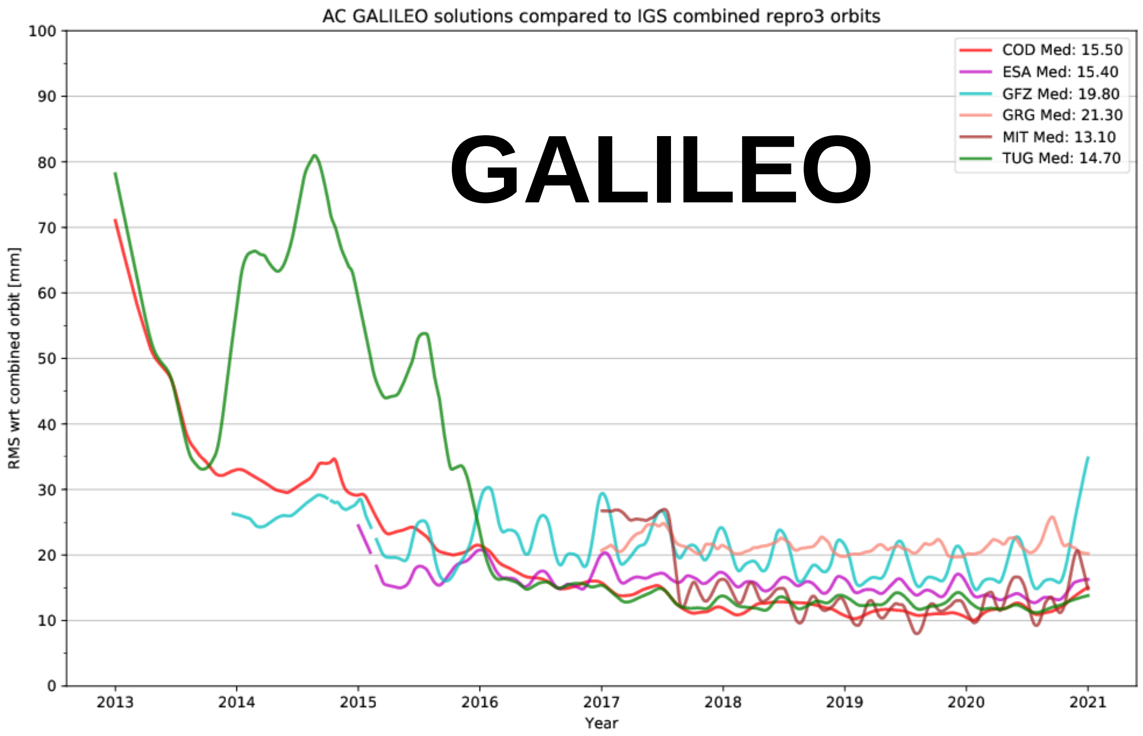
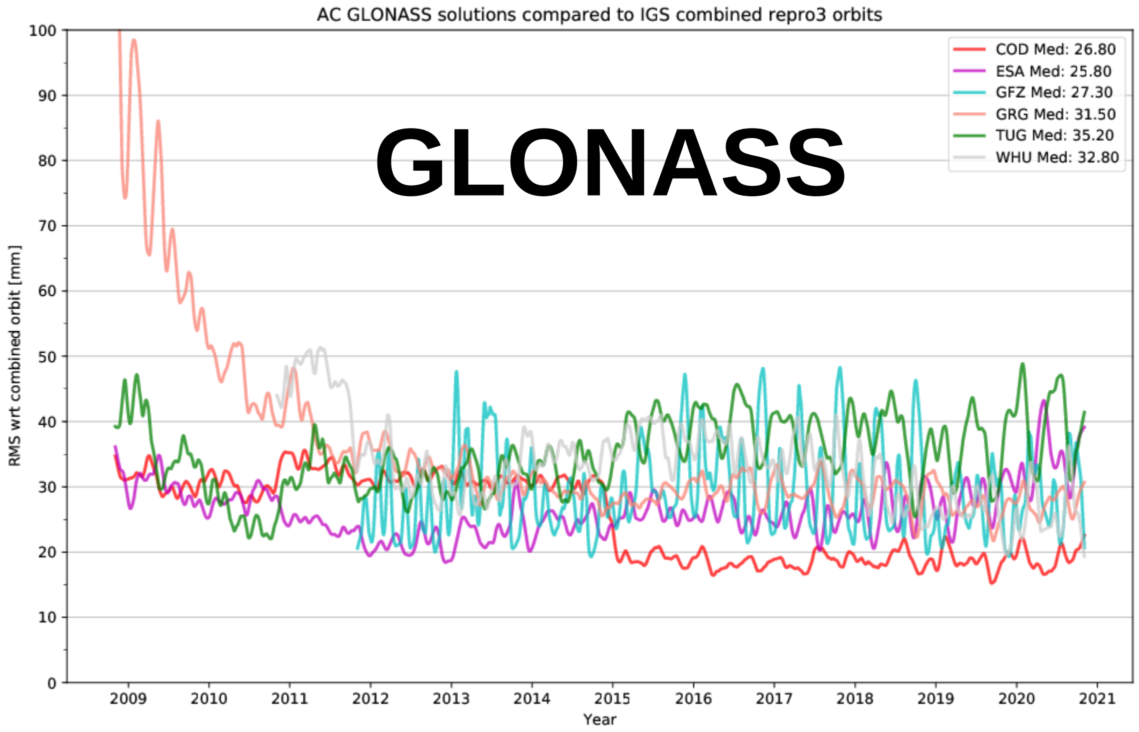



AC GALILEO solutions compared to IGS combined repro3 orbits
GALILEO
COD Med: 15.50
ESA Med: 15.40
GFZ Med: 19.80
GRG Med: 21.30
MIT Med: 13.10
TUG Med: 14.70
RMS wrt combined orbit [mm]
Year
100
90
80
70
60
50
40
30
20
10
0
2013
2014
2015
2016
2017
2018
2019
2020
2021


AC GLONASS solutions compared to IGS combined repro3 orbits
GLONASS
COD Med: 26.80
ESA Med: 25.80
GFZ Med: 27.30
GRG Med: 31.50
TUG Med: 35.20
WHU Med: 32.80
RMS wrt combined orbit [mm]
Year
100
90
80
70
60
50
40
30
20
10
0
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021

GPS

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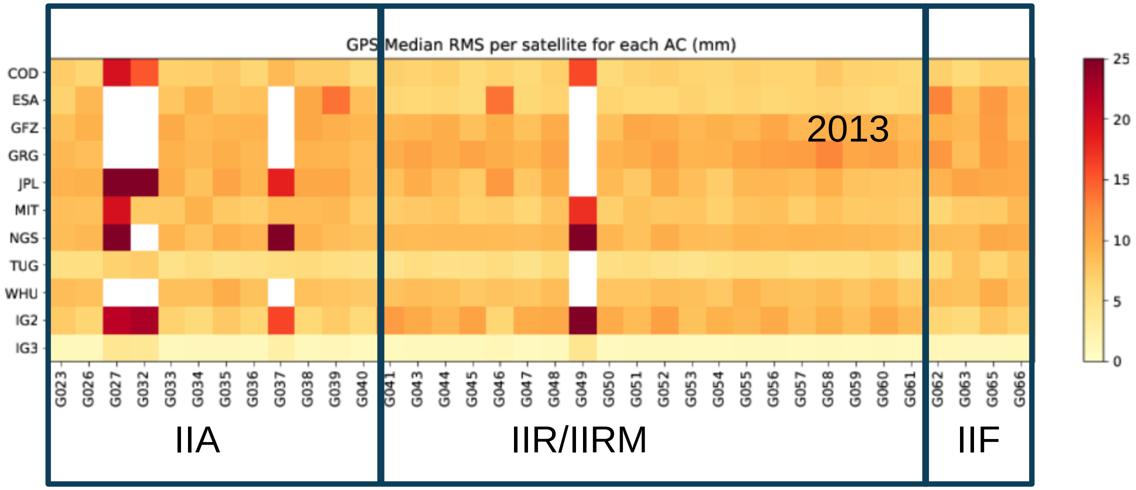
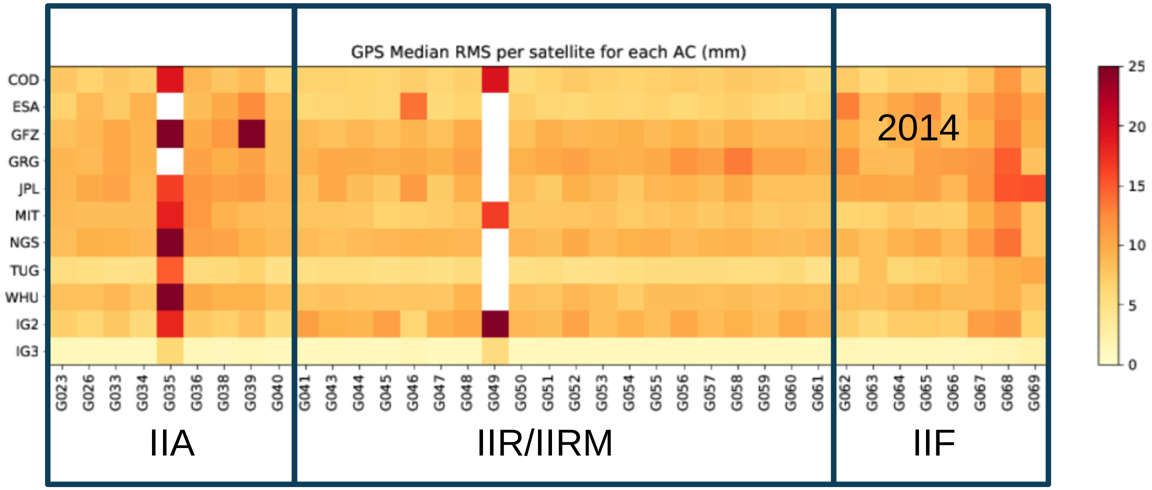
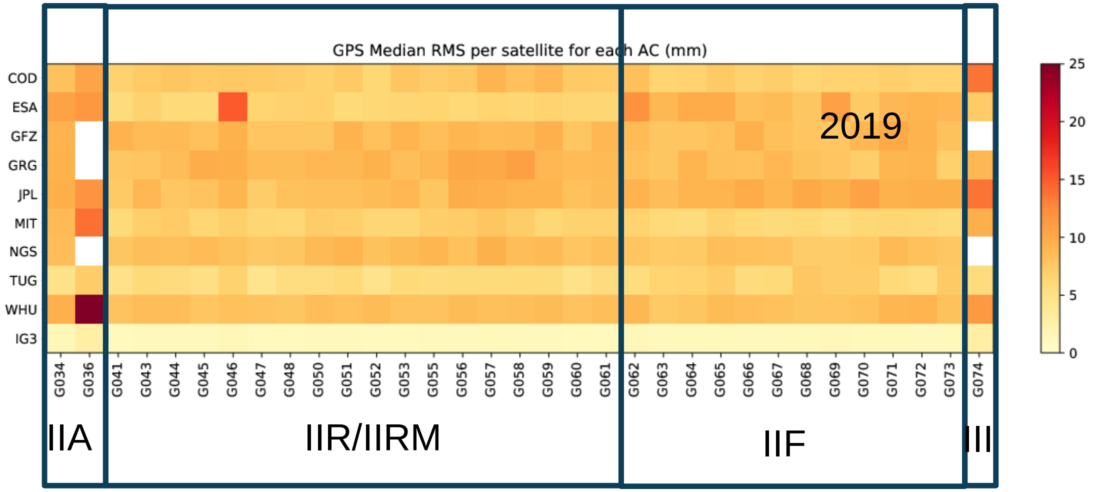
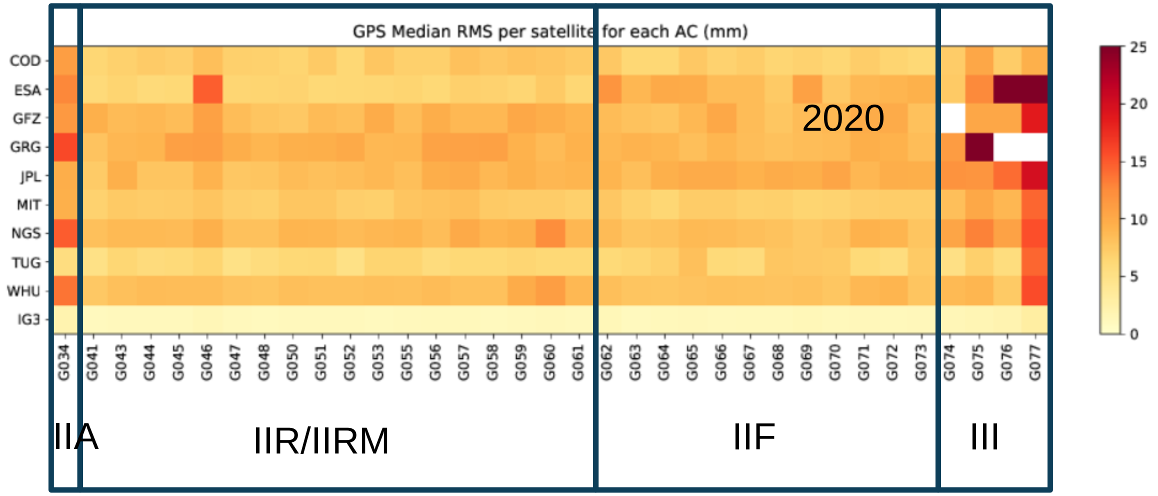
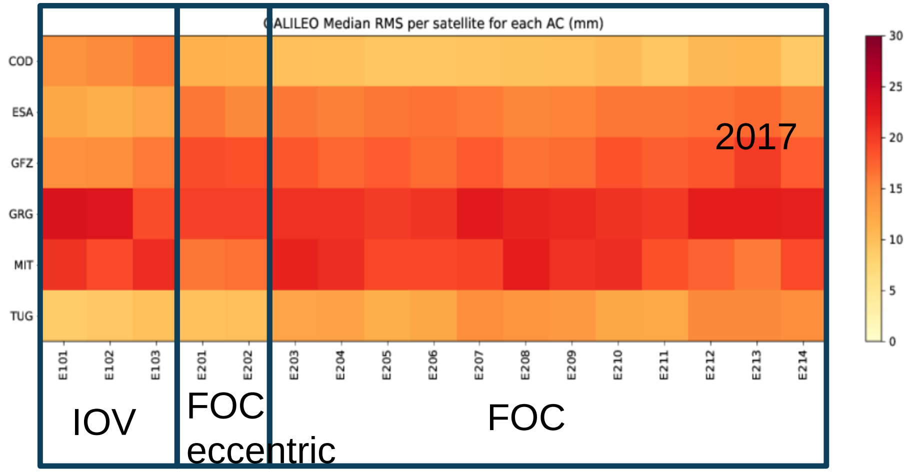


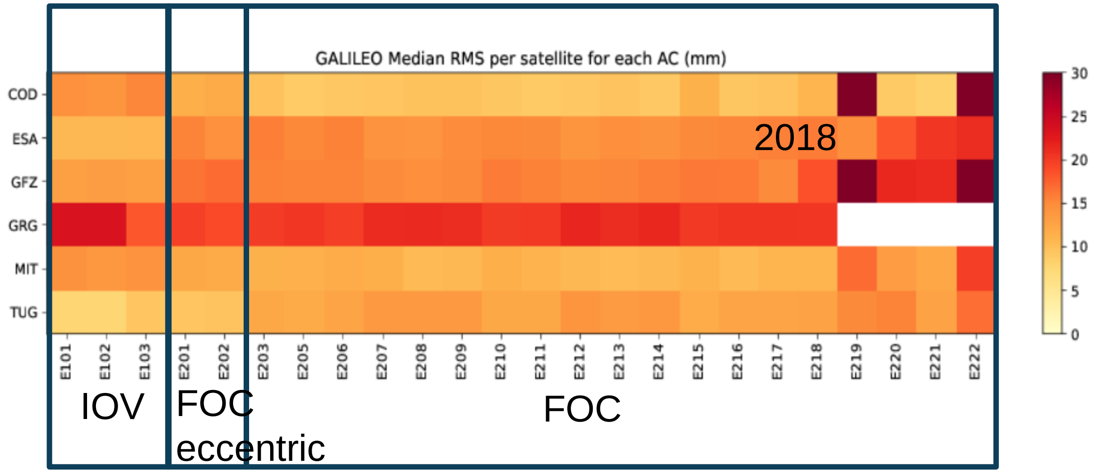


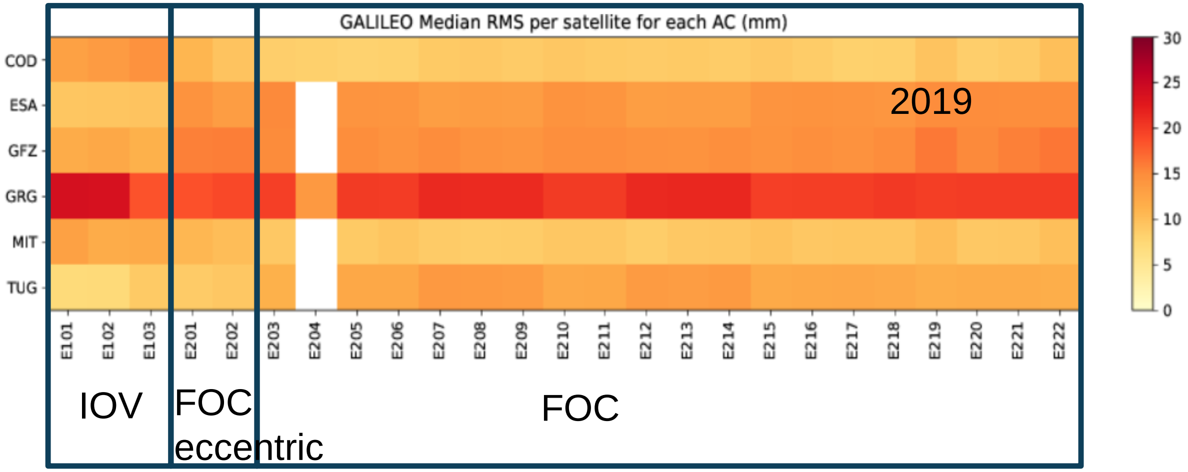


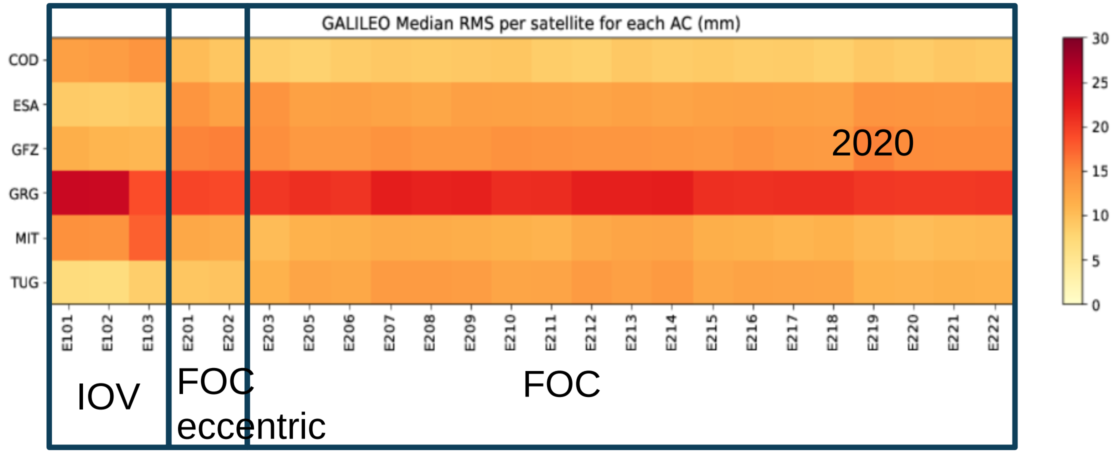


GALILEO

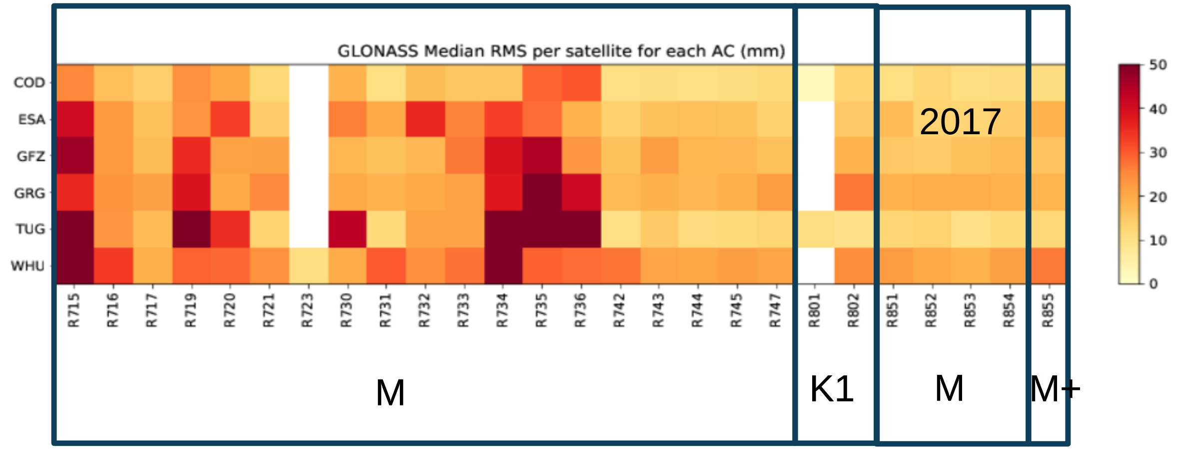

GALILEO Median RMS per satellite for each AC (mm)
COD
ESA
GFZ
GRG
MIT
TUG
E101 E102 E103 E201 E202 E203 E204 E205 E206 E207 E208 E209 E210 E211 E212 E213 E214
2017
IOV
FOC eccentric
FOC
0 5 10 15 20 25 30

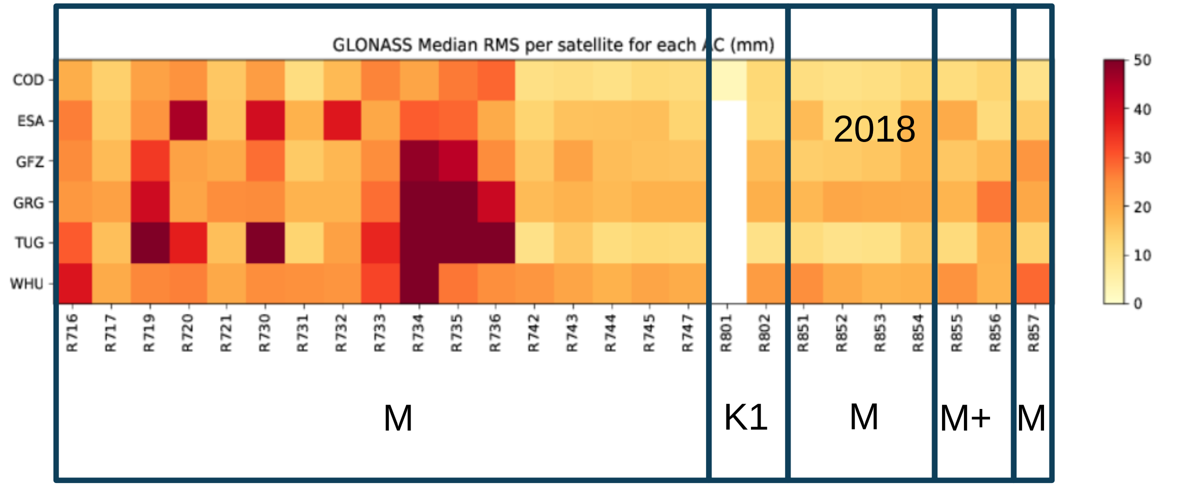

GALILEO Median RMS per satellite for each AC (mm)
COD
ESA
GFZ
GRG
MIT
TUG
E101 E102 E103 E201 E202 E203 E205 E206 E207 E208 E209 E210 E211 E212 E213 E214 E215 E216 E217 E218 E219 E220 E221 E222
2018
IOV
FOC eccentric
FOC
0 5 10 15 20 25 30

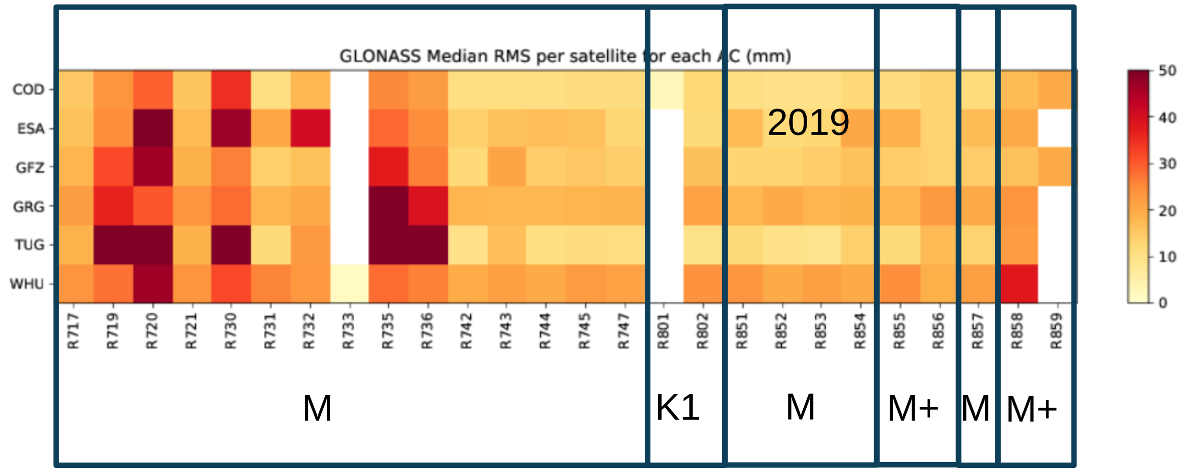

GALILEO Median RMS per satellite for each AC (mm)
COD
ESA
GFZ
GRG
MIT
TUG
E101 E102 E103 E201 E202 E203 E204 E205 E206 E207 E208 E209 E210 E211 E212 E213 E214 E215 E216 E217 E218 E219 E220 E221 E222
2019
IOV
FOC eccentric
FOC
0 5 10 15 20 25 30

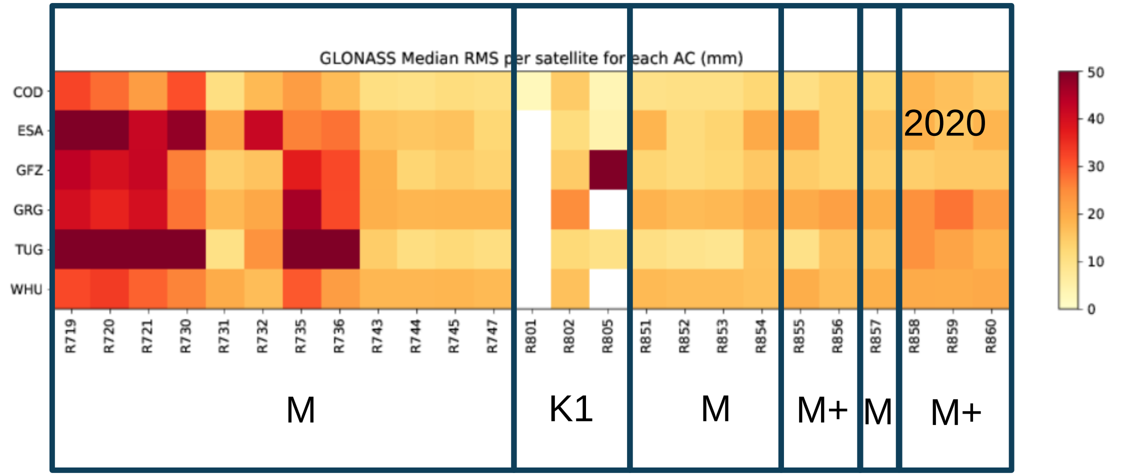

GALILEO Median RMS per satellite for each AC (mm)
COD
ESA
GFZ
GRG
MIT
TUG
E101 E102 E103 E201 E202 E203 E205 E206 E207 E208 E209 E210 E211 E212 E213 E214 E215 E216 E217 E218 E219 E220 E221 E222
2020
IOV
FOC eccentric
FOC
0 5 10 15 20 25 30

GLONASS


GLONASS Median RMS per satellite for each AC (mm)
2017
COD
ESA
GFZ
GRG
TUG
WHU
R715 R716 R717 R719 R720 R721 R723 R730 R731 R732 R733 R734 R735 R736 R742 R743 R744 R745 R747 R801 R802 R851 R852 R853 R854 R855
M
K1
M
M+
0 10 20 30 40 50


GLONASS Median RMS per satellite for each AC (mm)
2018
COD
ESA
GFZ
GRG
TUG
WHU
R716 R717 R719 R720 R721 R730 R731 R732 R733 R734 R735 R736 R742 R743 R744 R745 R747 R801 R802 R851 R852 R853 R854 R855 R856 R857
M
K1
M
M+
M
0 10 20 30 40 50


GLONASS Median RMS per satellite for each AC (mm)
2019
COD
ESA
GFZ
GRG
TUG
WHU
R717 R719 R720 R721 R730 R731 R732 R733 R735 R736 R742 R743 R744 R745 R747 R801 R802 R851 R852 R853 R854 R855 R856 R857 R858 R859
M
K1
M
M+
M
M+
0 10 20 30 40 50


GLONASS Median RMS per satellite for each AC (mm)
2020
COD
ESA
GFZ
GRG
TUG
WHU
R719 R720 R721 R730 R731 R732 R735 R736 R743 R744 R745 R747 R801 R802 R805 R851 R852 R853 R854 R855 R856 R857 R858 R859 R860
M
K1
M
M+
M
M+
0 10 20 30 40 50

Preliminary assessments – PPP tests at NRCan

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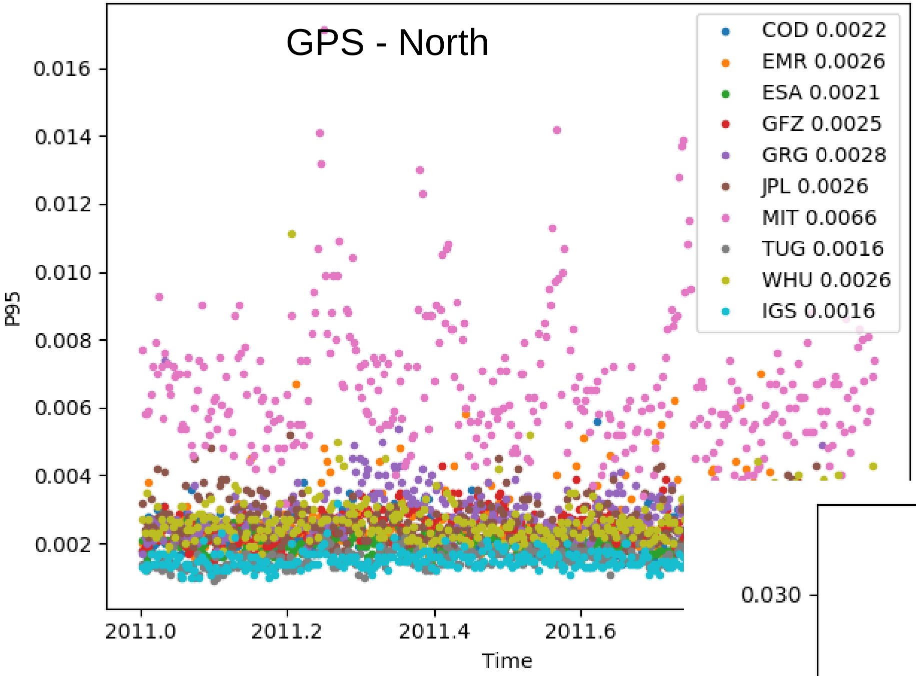
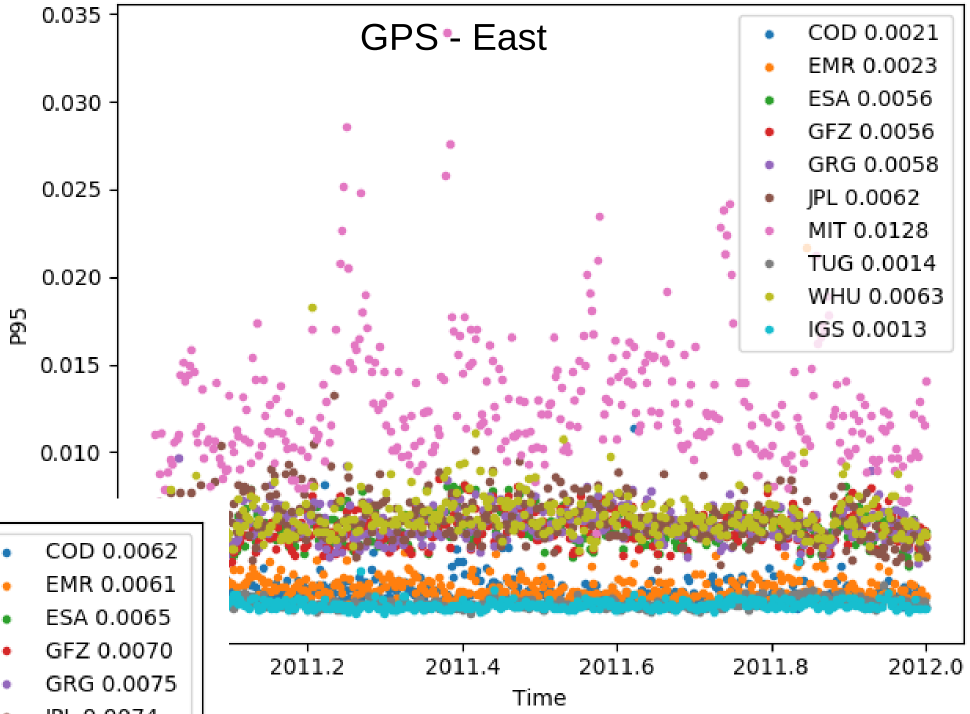
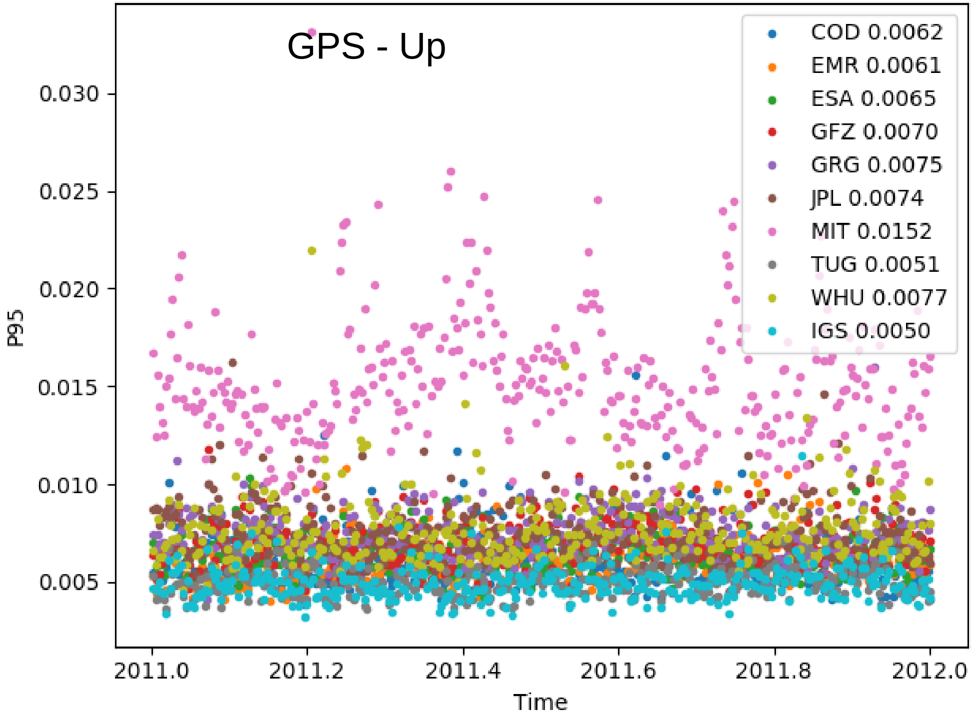


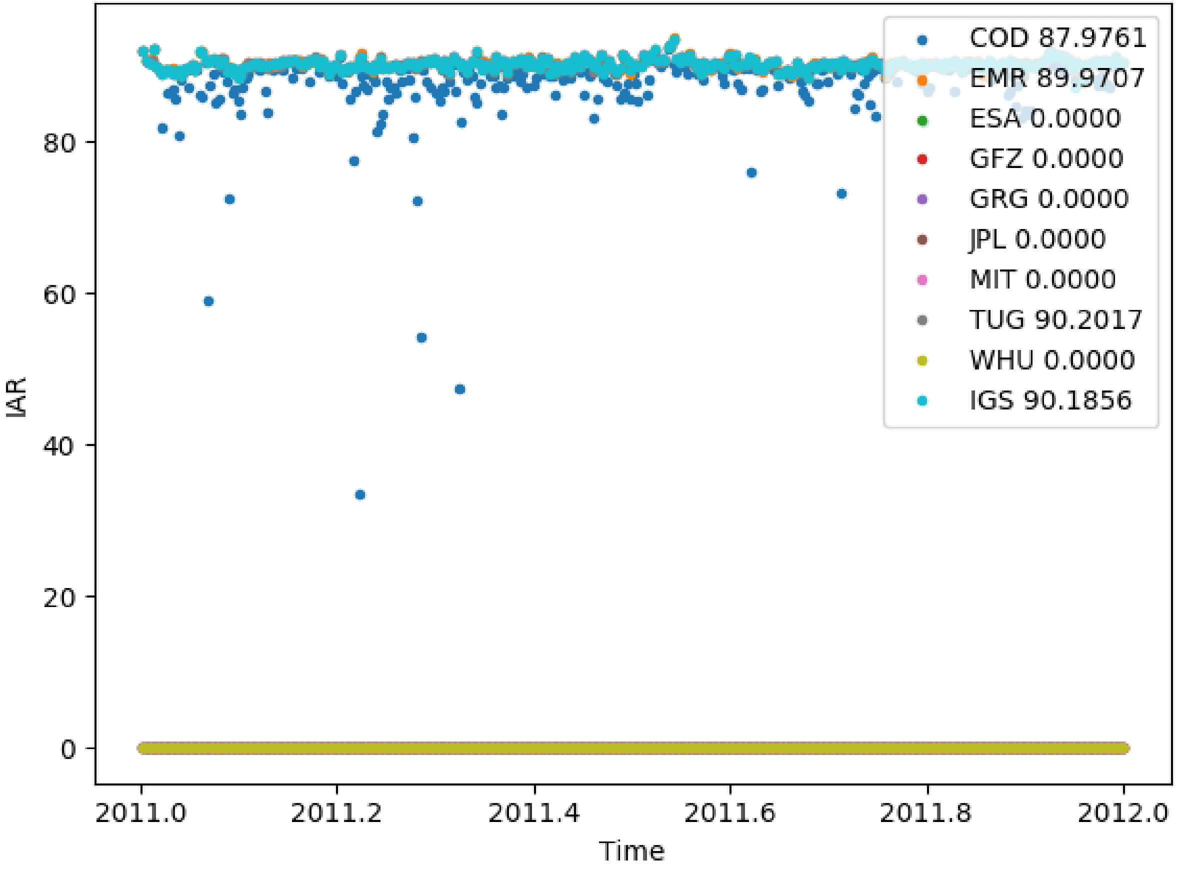




Residuals compared to daily combined SINEX; Provided by Simon Banville @ NRCan

~110 stations

GPS - Ambiguity resolution rate



Provided by Simon Banville @ NRCan

2.4 Combining multi-GNSS satellite clocks and phase biases in the PPP-AR WG

Jianghui Geng, Qiang Wen, Zhe Yan, Zhaoyan Liu, Bingqing Li
GNSS Center, Wuhan University

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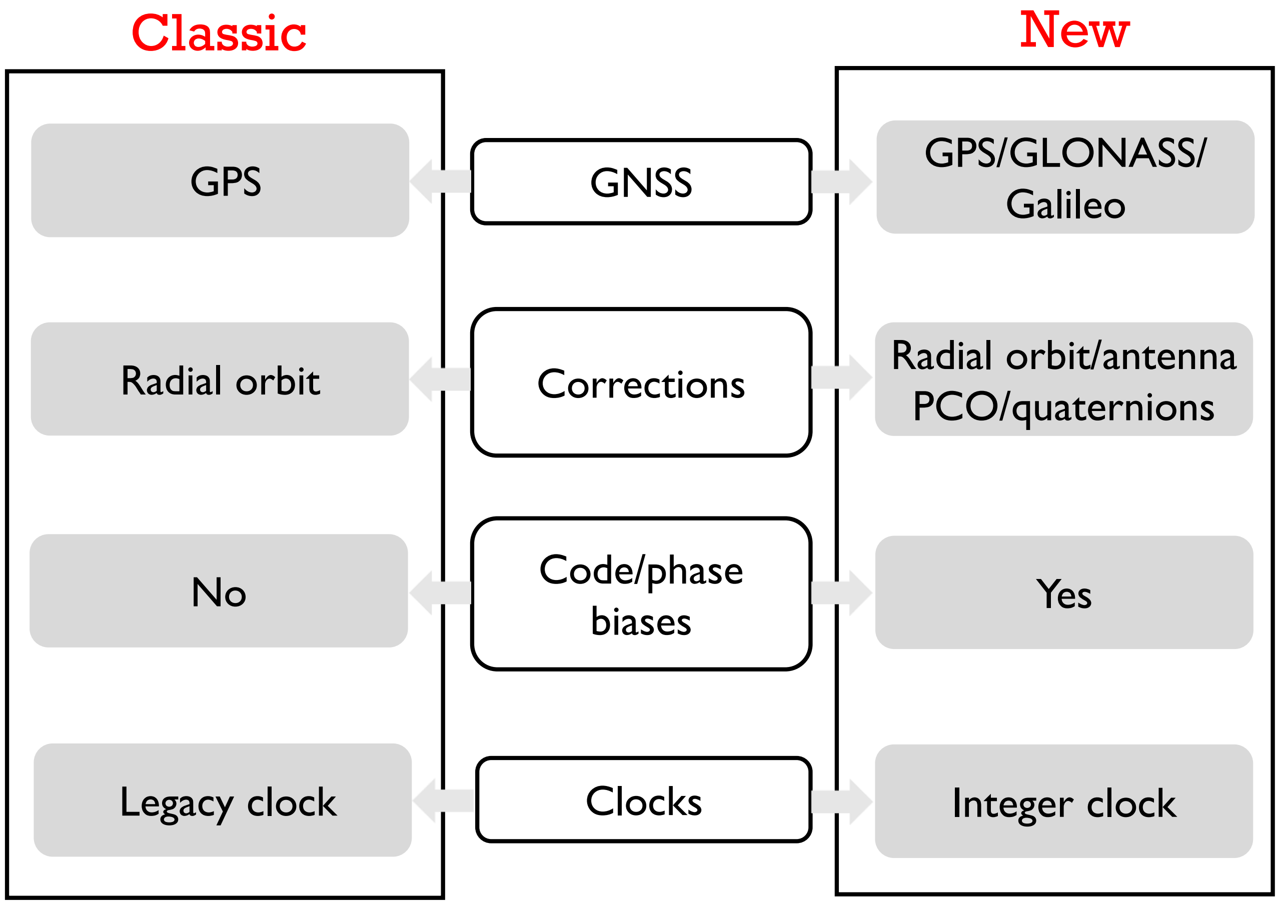
Why combine satellite clocks/phase biases?

- IGS/GA combines ACs' orbits in Repro3
  - IGS2: Satellite-specific weighting for GPS/GLONASS/Galileo combination
- Combining satellite clocks/biases to agree with combined orbits
  - to achieve more robust clock/bias solutions

AC	Orbits/Clocks	Phase biases	Quaternions
COD	GRE	GE	GRE
EMR / NGS	G	G	G
ESA	G	N/A	N/A
GFZ	G	N/A	G
GRG	GRE	GE	GRE
JPL	G	N/A	G
MIT	GE	N/A	N/A
TUG	GRE	GRE	GRE
WHU	GR	N/A	GR

New features for clock/bias combination



Banville et al. (2020)

Combination theory

- Functional model of precise satellite clocks

$$\begin{cases} P_{IF,r}^{s} = \rho_r^s + c\left(dt_r - dt^s\right) + b_{IF,r} - b_{IF}^{s} + \varepsilon_{IF,P} \\ L_{IF,r}^{s} = \rho_r^s + c\left(dt_r - dt^s\right) + B_{IF,r} - B_{IF}^{s} + \lambda N_{IF,r}^{s} + \varepsilon_{IF,L} \end{cases}$$

  - Receiver clocks are coupled with satellite clocks, a clock datum (ΔD_t^{sys}) is needed when computing satellite clocks
  - Satellite clocks will absorb modeling errors (Δm_t^s) such as orbit and attitude errors
  - To enable PPP-AR, the clock and bias products (Δb^s) should be considered simultaneously
- So precise satellite clocks comprise the following items

$$dt^s(t) = d\tilde{t}^s(t) + \Delta D_t^{sys} + \Delta m_t^s + \Delta b^s + \Delta \varepsilon_t^s$$

Combination theory

- The clock datum can be obtained by averaging clock differences among common satellites

$$\Delta D^{sys}(t) = \frac{1}{nsat}\sum_{k}^{nsat}\left(dt_{AC}^{k,sys} - dt_{ref}^{k,sys}\right)$$

- Corrections
  - Orbit corrections in radial direction

$$\Delta m_{orb}^{i}(t) = \frac{\left(\mathbf{X}_{AC}^{i}(t) - \mathbf{X}_{ref}^{i}(t)\right)\cdot \mathbf{X}_{AC}^{i}(t)}{c \cdot R^{i}(t)}$$

  - Phase wind-up corrections caused by attitude differences (quaternions)

$$\Delta m_{att}^{i}(t) = \frac{\Delta\varphi^{i}(t)}{2\pi \cdot f_{NL}^{i}}$$

Loyer et al. (2021)

Combination theory

- When combining the bias product, we should convert OSB to wide-lane and narrow-lane phase biases first

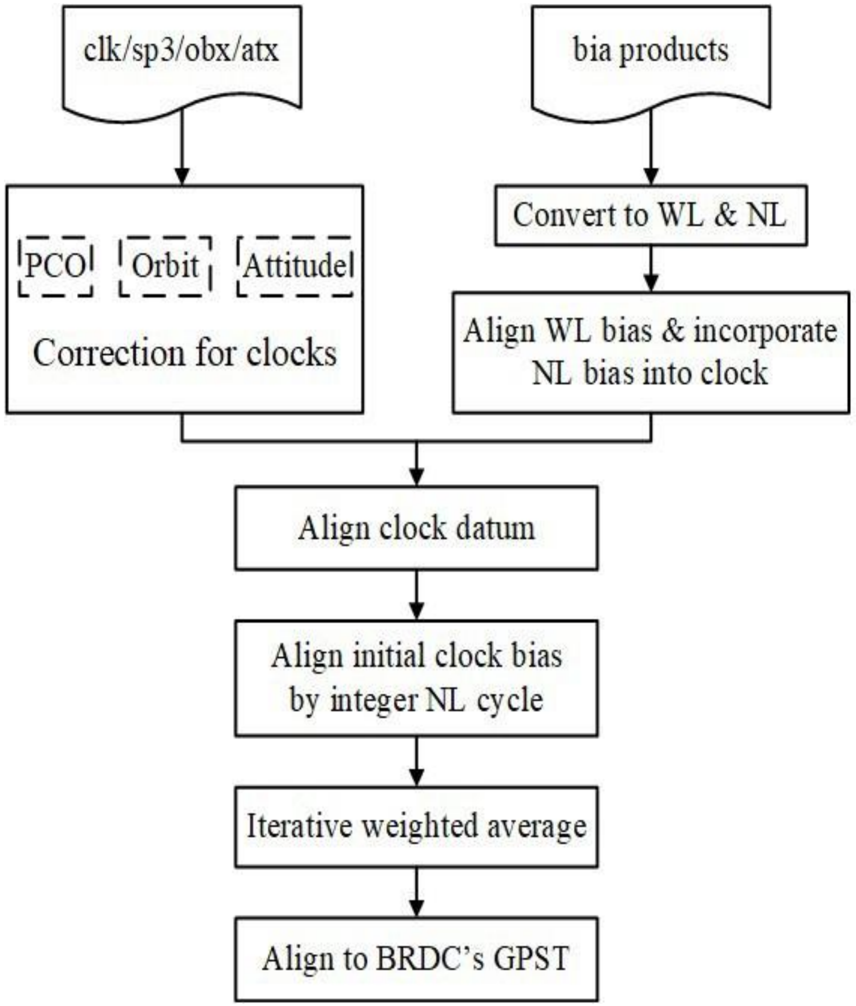
$$\begin{pmatrix} b_{WL} \\ b_{NL} \\ DCB_{P1P2} \\ D_{clk} \end{pmatrix} = \begin{pmatrix} \frac{g}{g-1} & \frac{-1}{g-1} & \frac{-g}{g+1} & \frac{-1}{g+1} \\ \alpha_{IF} & \beta_{IF} & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & \alpha_{IF} & \beta_{IF} \end{pmatrix} \begin{pmatrix} b_1 \\ b_2 \\ d_1 \\ d_2 \end{pmatrix} \qquad \begin{cases} g = \frac{f_1}{f_2} \\ \alpha_{IF} = \frac{f_1^2}{f_1^2 - f_2^2} \\ \beta_{IF} = \frac{-f_2^2}{f_1^2 - f_2^2} \end{cases}$$

- Then align DCBs and wide-lane phase biases, after which the narrow-lane phase biases are combined with satellite clocks (satellite antenna PCOs should be corrected)

$$\begin{cases} d^j_{C1W,A} - d^j_{C2W,A} = DCB^j_{CMB} + \Delta t_{C1W,C2W} + \Delta d_{PCO} \\ \alpha_{WL} b^j_{L1,A} + \beta_{WL} b^j_{L2,A} - \alpha_{NL} b^j_{C1W,A} - \beta_{NL} b^j_{C2W,A} \\ \qquad = \mathrm{UPD}^j_{WL,CMB} + \Delta t_{WL} + \lambda_{WL} N^j_{WL,A} + \Delta upd_{PCO} \\ dt^j_A - \alpha_{IF} b^j_{L1,A} - \beta_{IF} b^j_{L2,A} + \beta_{IF} \lambda_2 N^j_{WL,A} = dt^j_{CMB} - \Delta t + \lambda_{NL} N^j_{L1,A} \end{cases}$$

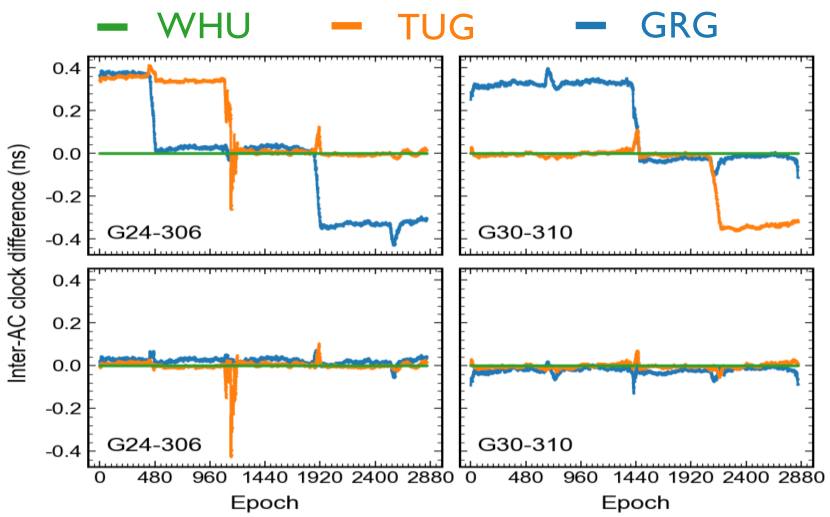
Combination procedure

- Reference attitude quaternions
  - Produced by TUG
- Clock combination
  - Code biases combined as well
  - Both legacy & integer clocks are combined without any discrimination
  - AC specific weighting



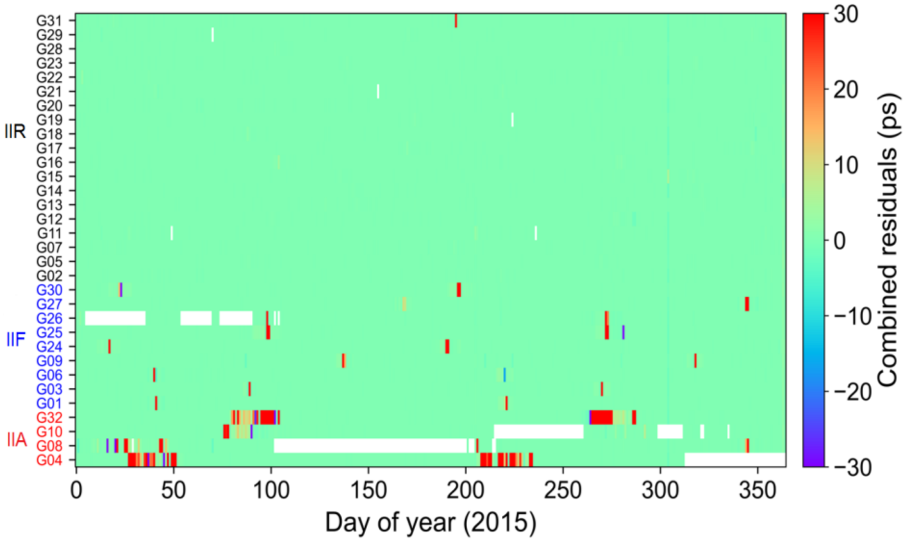
Impact of satellite attitude discrepancy

- Quaternions can diminish inter-AC clock discrepancies in eclipsing seasons



Without quaternions

With quaternions



Difference between the clock consistency with/out attitude corrections
BLOCK IIA and IIF suffer more

PCOs on code and phase biases

- Satellite & receiver antenna PCOs are usually uncorrected in the geometry-free or Melbourne-Wübbena combination
  - Usually GPS satellites have identical L1/L2 PCOs from IGS ANTEX files
  - But Block IIIA satellites have different PCOs among L1/L2 frequencies
  - Galileo have differing PCOs across frequencies

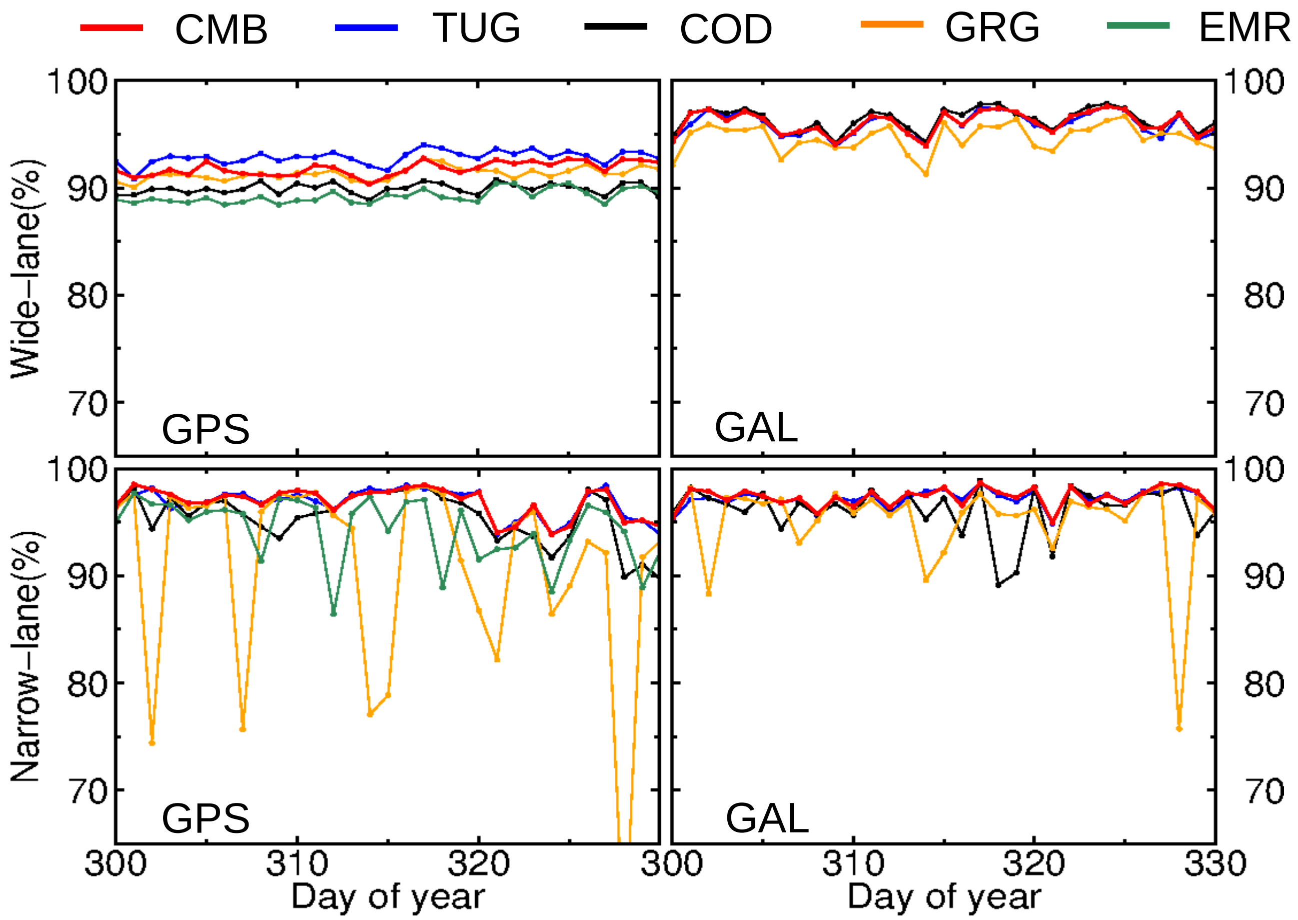
- DCBs and wide-lane phase biases differ among AC products

			tug	emr	gbm
18	G18	DCB	3.316	1.807	2.562
19	G19	DCB	6.251	6.419	6.335
20	G20	DCB	1.677	1.929	1.803
21	G21	DCB	2.486	2.831	2.659
22	G22	DCB	7.648	8.080	7.864
23	G23	DCB	3.281	1.874	2.578

			cod	esa	gbm	grg	tug
58	G18	WL	0.019	0.052	0.050	0.012	0.226
59	G19	WL	0.127	0.125	0.124	0.122	0.104
60	G20	WL	-0.429	-0.415	-0.416	-0.442	-0.463
61	G21	WL	-0.123	-0.130	-0.129	-0.145	-0.136
62	G22	WL	-0.086	-0.075	-0.075	-0.108	-0.127
63	G23	WL	0.219	0.245	0.245	0.204	0.425

GPS/Galileo combined phase biases

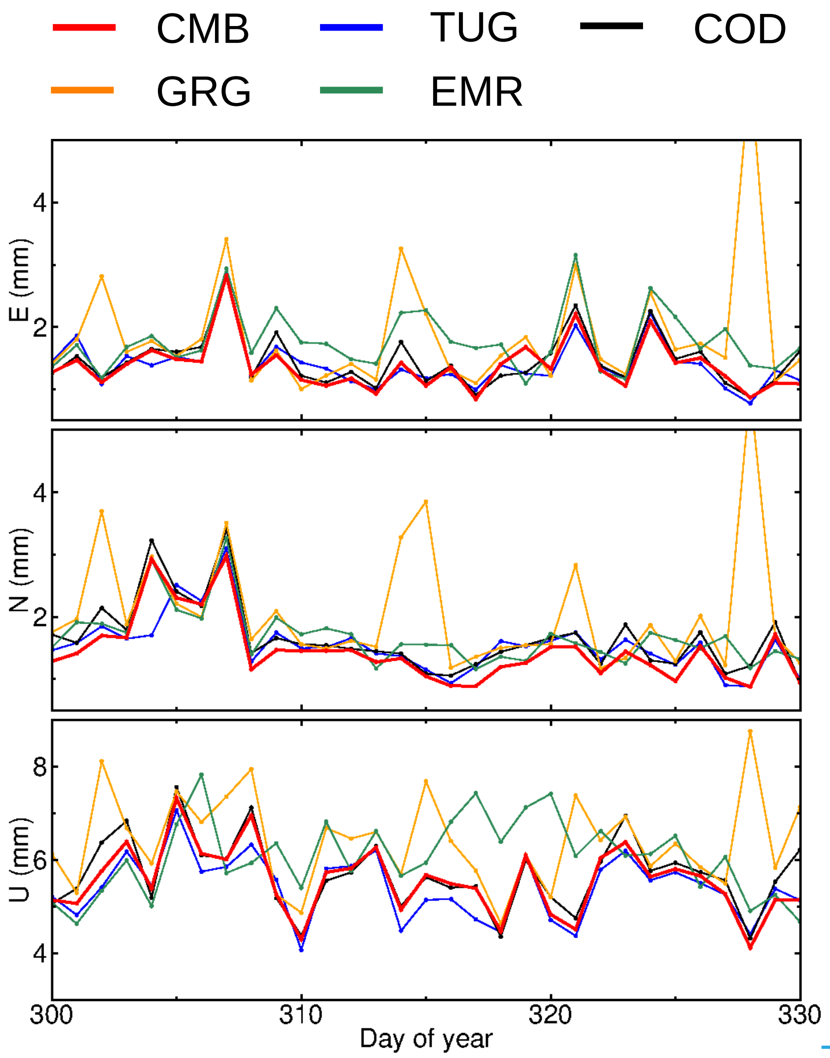
- GPS/Galileo PPP ambiguity fixing rates (day 300-330, 2020)



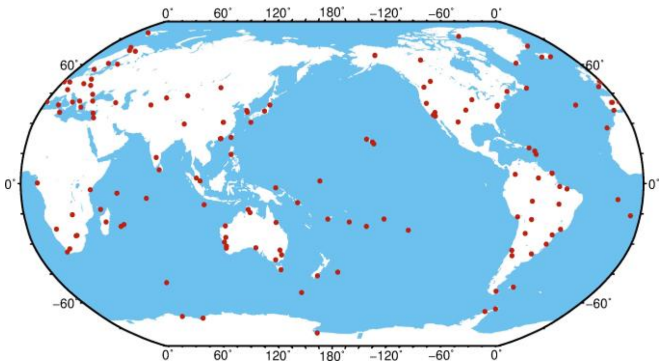
CMB products rank the top roughly in terms of ambiguity fixing rates

GPS/Galileo combined phase biases

- Daily position repeatabilities (mm) after PPP-AR (day 300-330, 2020)



AC	Mean (mm)		
	E	N	U
COD	1.5	1.7	5.7
EMR	1.8	1.7	6.1
GRG	1.9	2.1	6.4
TUG	1.4	1.5	5.5
CMB	1.4	1.6	5.5



PRIDE Lab

武漢大學

Summary

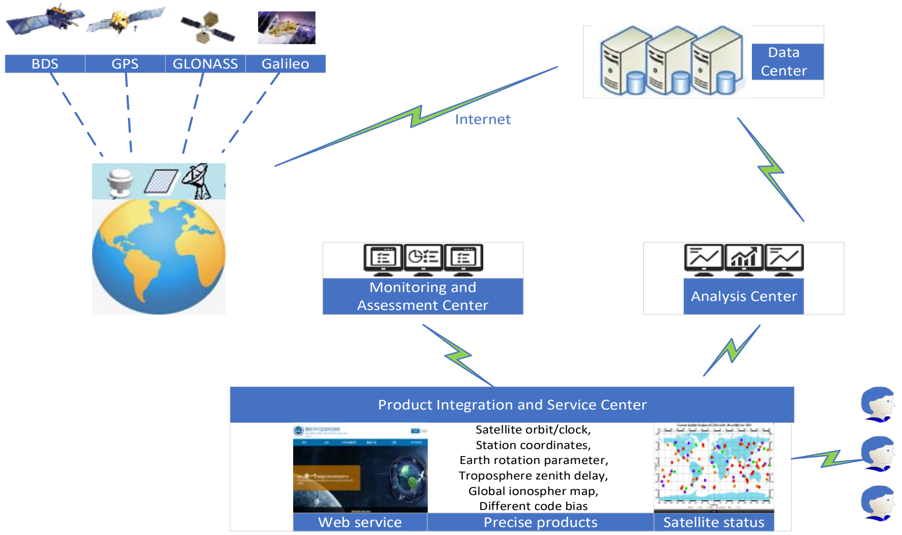
- The new clock combination differs from the classic one by incorporating multi-GNSS phase biases and satellite attitude quaternions to achieve integer clocks
- Satellite antenna PCOs should be corrected on code and phase biases to improve consistency among ACs especially for GPS BLOCK IIIA and Galileo satellites
- Combination improves the robustness of satellite products with the highest possible ambiguity fixing rates and positioning precisions among all AC specific products

2.5 iGMAS orbit and clock combination

Guo Chen, Wuhan University

iGMAS

- The international GNSS Monitoring and Assessment System (iGMAS) was proposed in 2007 to assess the performance of multi-GNSS broadcast ephemerides and provide precise products for global users.
- iGMAS consists of 30 global tracking stations, 3 data centers (DC), 12 analysis centers (AC), 1 information combination and service center (ISC), 1 monitoring and assessment center (MAC), and 1 operation control & management center(OCMC).



http://www.igmas.org/

iGMAS

- The ISC is the center of iGMAS products reprocessing, which evaluates the quality of GNSS products submitted by analysis centers, and then reprocesses them to generate combined products.
- Robust precise combined orbit and clock solutions are conducted by iGMAS to assess the broadcast ephemerides of BDS and other GNSSs.

AC	Description
BAC	Beijing Aerospace Control Center
CGS	Chinese Academy of Surveying and mapping
CHD	Chang'an University
CUM	China University of Mining and Technology
IGG	Institute of Geodesy and Geophysics
LSN	Information Engineering University
NTS	National Time Service Center
SHA	Shanghai Astronomical Observatory
TJU	Tongji University
WHU	Wuhan University
XRS	Xi'an Research Institute of Surveying and Mapping
XSC	Xi'an Satellite Control Center

Product	Time delay	Updates interval
Ultra-rapid :SP3, CLK, ERP, TRO	**Real-time (pre)**	**6 hour**
	3 hour (obs)	**6 hour**
Rapid :SP3, CLK, ERP, IONO	**17 hours**	**1 day**
	1 day	**1 day (IONO)**
Final: SP3, CLK, ERP, SNX, IONO, TRO, DCB	**12 days**	**1 day**
	20 hours	**1 month (DCB)**

Part I: Overview of iGMAS

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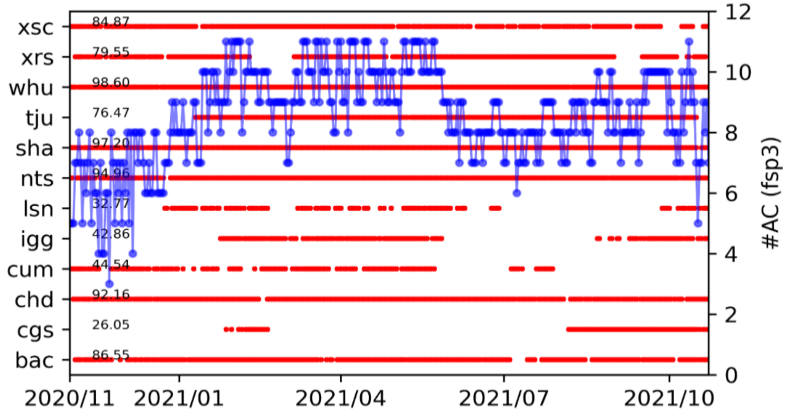
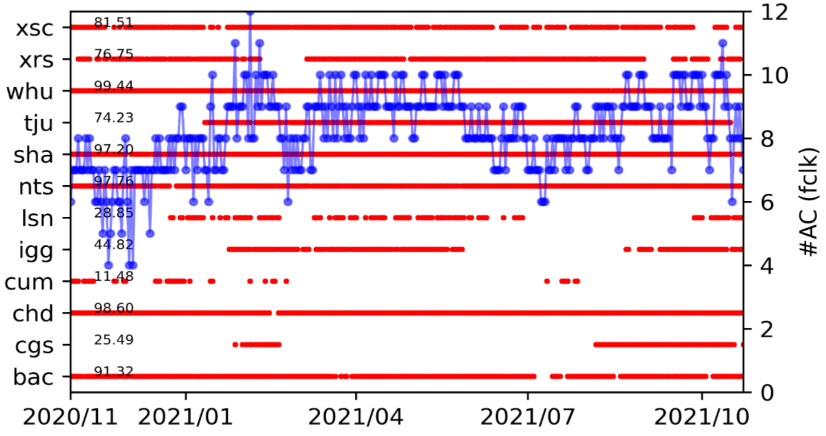
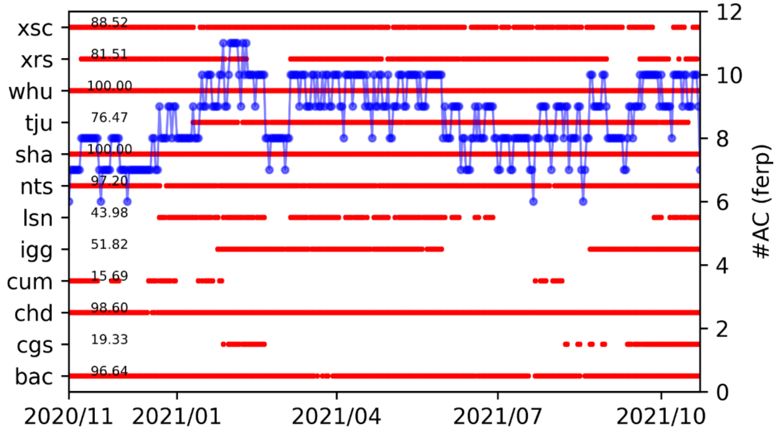
Final orbit/clock/ERP submitted by ACs



90% :4 ACs Orbit 80%:6 ACs



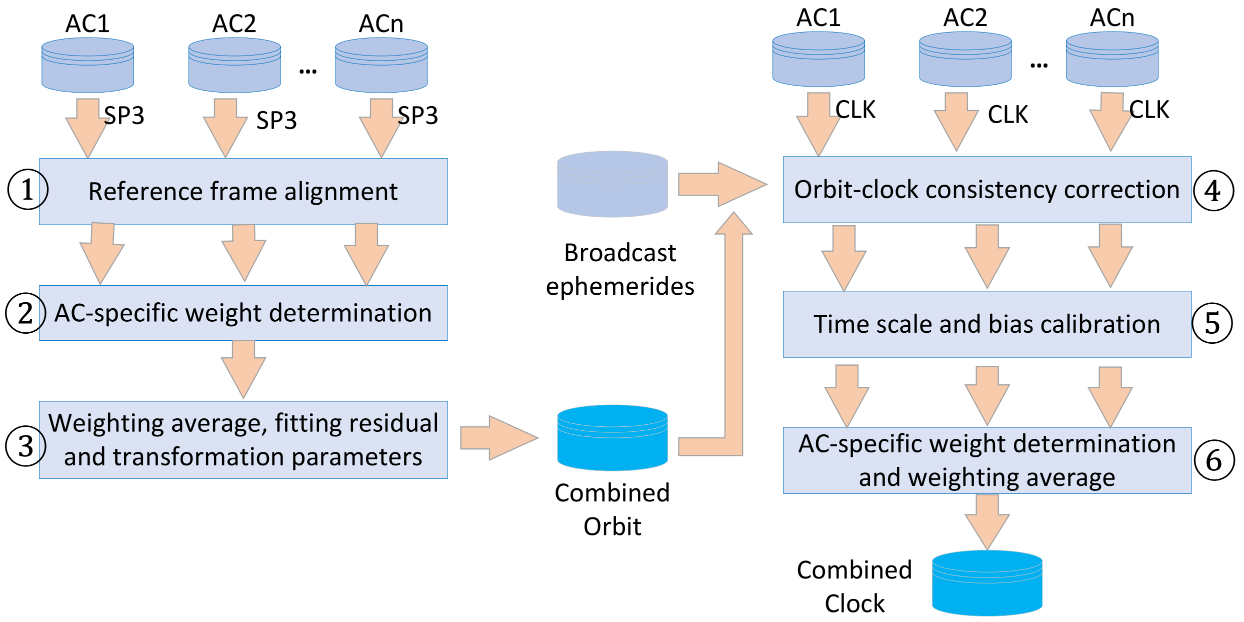
90%:5 ACs Clock 80%: 6 ACs

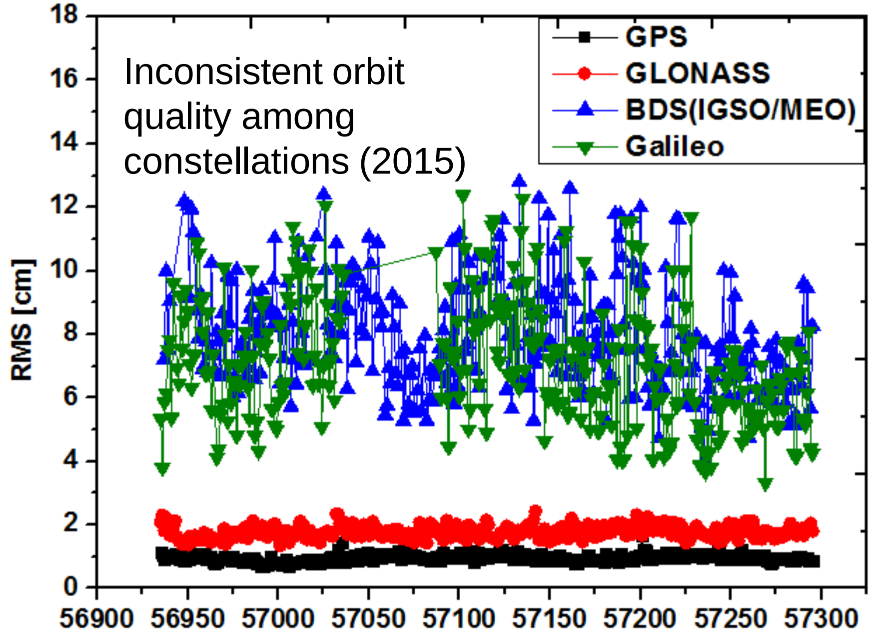


90%:5 ACs ERP 80%:7 ACs

Product submitted failure occurs frequently for some ACs, and continuous and robust combined products are expected using solutions from multi-AC.

iGMAS orbit and clock combination





Step 1

$$\begin{cases} dO^{isat}_{X,AC} = -dX_p O^{isat}_{Z,AC} \\ dO^{isat}_{Y,AC} = dY_p O^{isat}_{Z,AC} \\ dO^{isat}_{Z,AC} = dX_p O^{isat}_{X,AC} - dY_p O^{isat}_{Y,AC} \end{cases}$$

$$O^{sys}_{AC} + v^{sys}_{AC} = O^{sys}_{cmb} + D^{sys}_{AC} + S^{sys}_{AC} + R_{AC} O^{sys}_{cmb}$$

Step 2

$$RMS^{sys}_{AC} = \sqrt{\frac{(v^{sys}_{AC,cor})^T P^{sys,Last}_{AC} v^{sys}_{AC,cor}}{3 \cdot np^{sys}_{AC} - 7}}$$

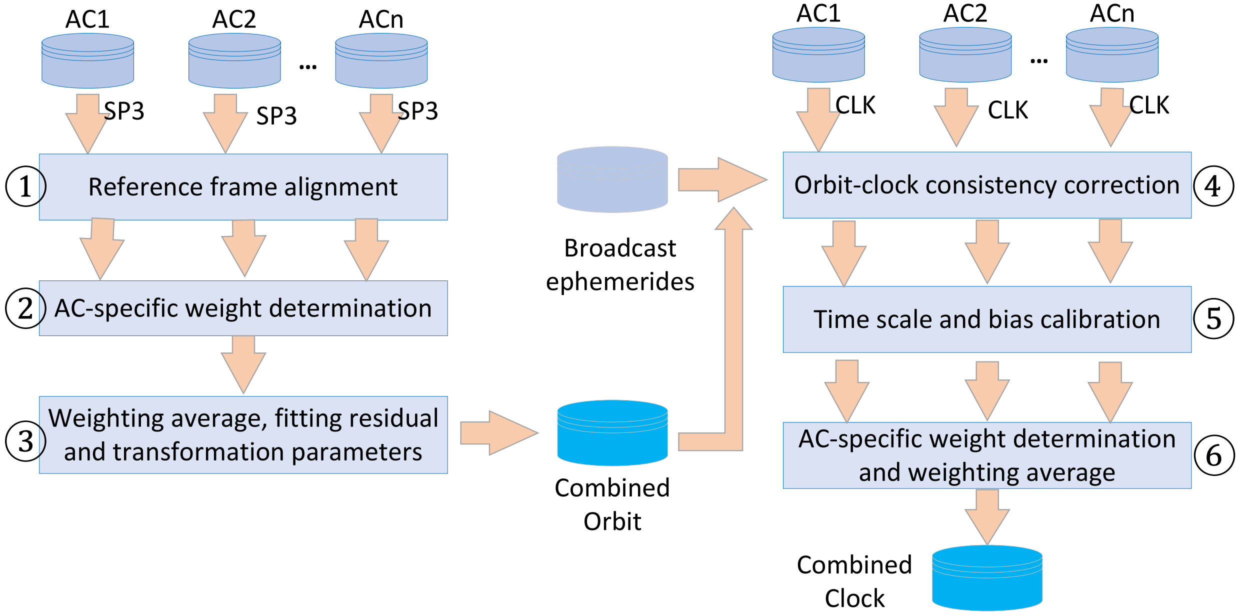
$$P^{sys}_{AC} = \frac{1 / RMS^{sys}_{AC}}{\sum_{i=1}^{nac} 1 / RMS^{sys}_{i}}$$

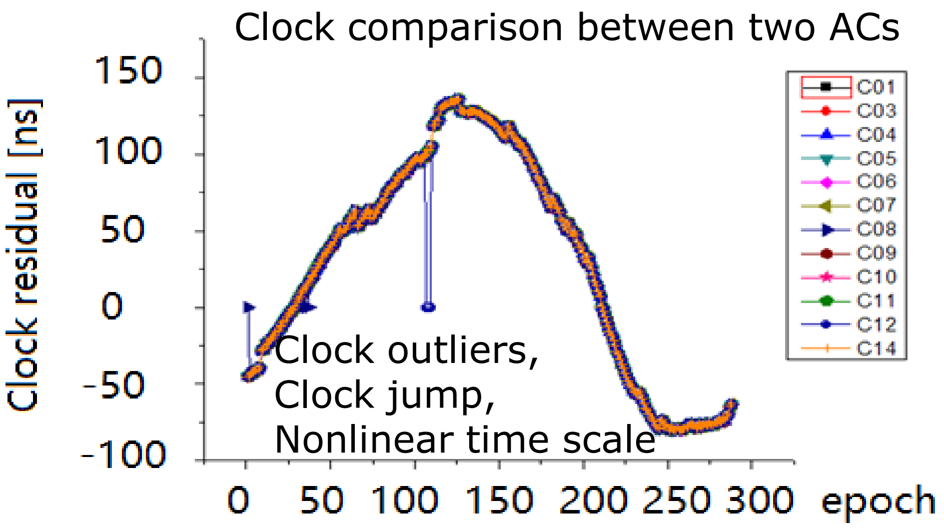
$$P^{sys,isat}_{AC} = \begin{cases} 1, & RMS^{sys,isat}_{AC} < k_1 \cdot RMS^{sys,med}_{AC} \\ \bar{P}^{sys,isat}_{AC}, & k_1 \cdot RMS^{sys,med}_{AC} \le RMS^{sys,isat}_{AC} < k_2 \cdot RMS^{sys,med}_{AC} \\ 0, & RMS^{sys,isat}_{AC} \ge k_2 \cdot RMS^{sys,med}_{AC} \end{cases}$$

Step 3

$$O^{sys,isat}_{cmb} = \frac{\sum_{i=1}^{nac} P^{sys}_{i} \{ O^{sys,isat}_{AC,cor} - (D^{sys}_{i} + S^{sys}_{i} + R_i O^{sys,isat}_{cor}) \}}{\sum_{i=1}^{nac} P^{sys}_{i}}$$

iGMAS orbit and clock combination





Step 4

$$\begin{cases} dC_{AC}^{sys,isat} = e\cdot\left(O_{AC}^{sys,isat} - O_{cmb}^{sys,isat}\right) \\ e = \begin{bmatrix} e_X \\ e_Y \\ e_Z \end{bmatrix}, e_X = \dfrac{O_{X,cmb}^{sys,isat}}{\rho_0}, e_Y = \dfrac{O_{Y,cmb}^{sys,isat}}{\rho_0}, e_Z = \dfrac{O_{Z,cmb}^{sys,isat}}{\rho_0} \end{cases}$$

Step 5

$$C_{brd,t_k}^{sys} = C_{AC,t_k}^{sys} + a_{o,AC}^{sys} + a_{1,AC}^{sys}\Delta t_k \qquad C_{ref,t_k}^{sys,isat} = C_{AC,t_k}^{sys,isat} + a_{o,AC}^{sys,isat} + a_{1,AC}^{sys,isat}\Delta t_k$$

$$C_{comb,t_k}^{sys} = C_{AC,t_k}^{sys} + a_{o,AC}^{sys} + a_{1,AC}^{sys}\Delta t_k$$

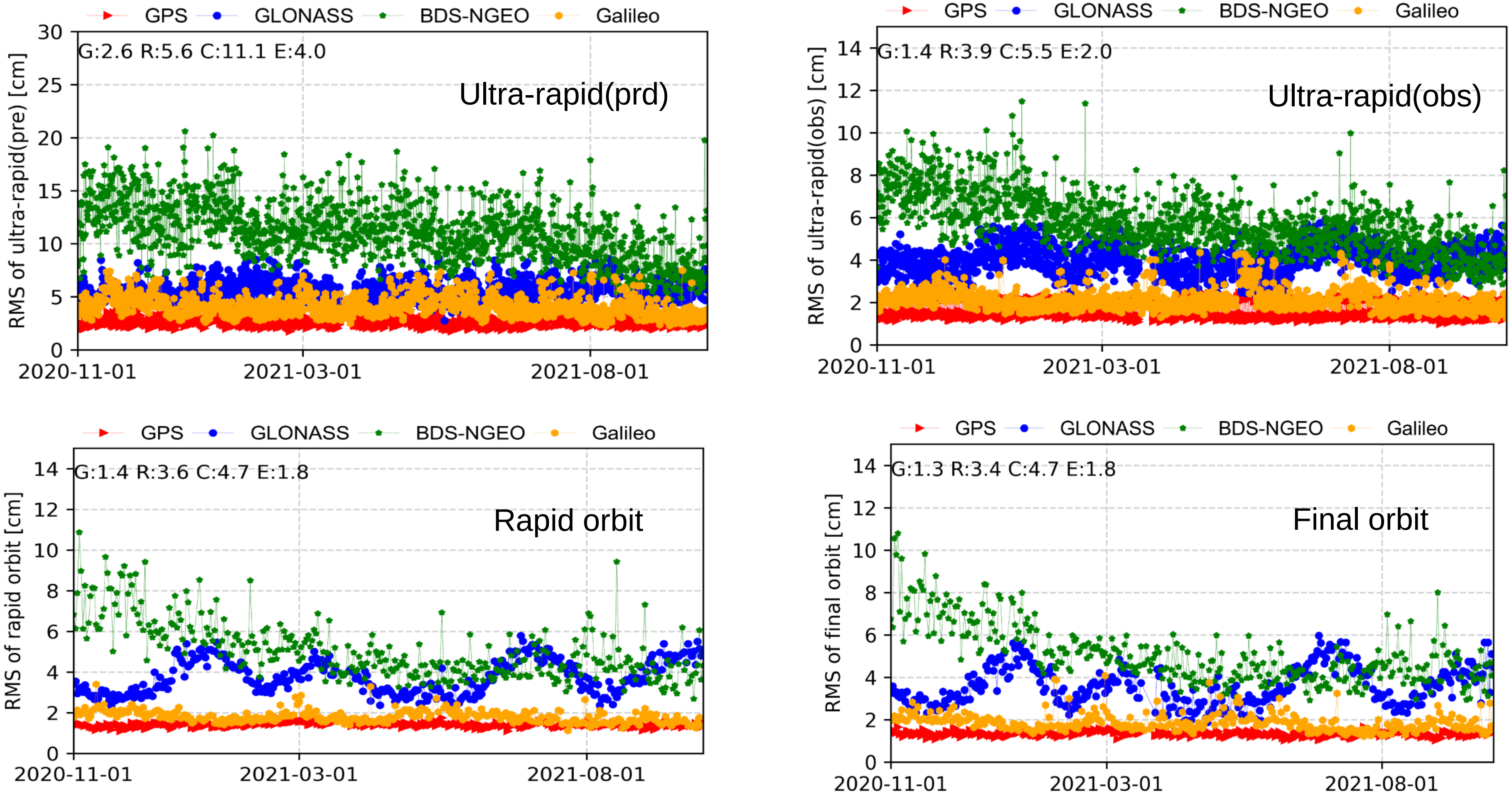
$$p_{i,k}^{j} = \begin{cases} 1, & \left|v_{i,k}^{j}\right| < k_0\sigma_{i,0}\sqrt{q_{i,k}^{j}} \\ \dfrac{k_0}{\left|v_{i,k}^{j}\right|}\left(\dfrac{k_1\sigma_{i,0}\sqrt{q_{i,k}^{j}} - \left|v_{i,k}^{j}\right|}{k_1 - k_0}\right), & k_0\sigma_{i,0}\sqrt{q_{i,k}^{j}} \le \left|v_{i,k}^{j}\right| < k_1\sigma_{i,0}\sqrt{q_{i,k}^{j}} \\ 0, & \left|v_{i,k}^{j}\right| > k_1\sigma_{i,0}\sqrt{q_{i,k}^{j}} \end{cases}$$

Step 6

$$w_i = \frac{1}{\left(C_{i,RMS}^{sys}\right)^2}$$

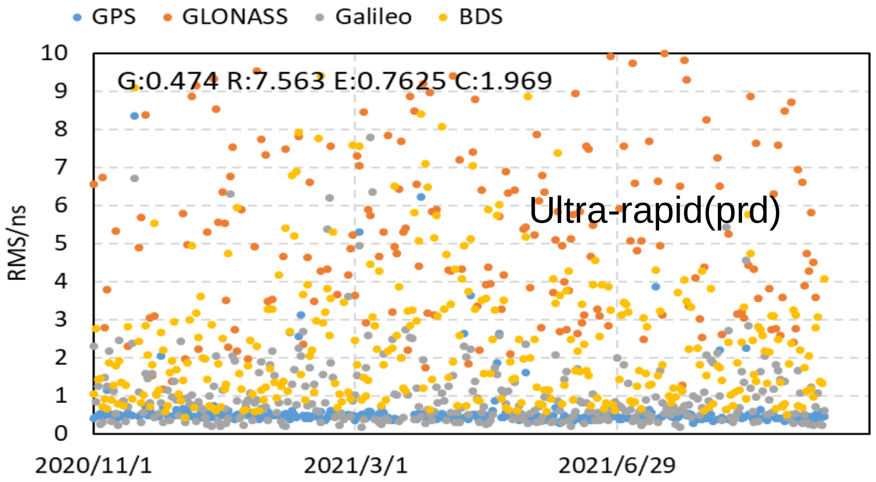
$$C_{cmb,k}^{j} = \frac{\sum_{i=1}^{nac} w_i \bar{C}_{i,k}^{j}}{\sum_{i=1}^{nac} w_i}$$

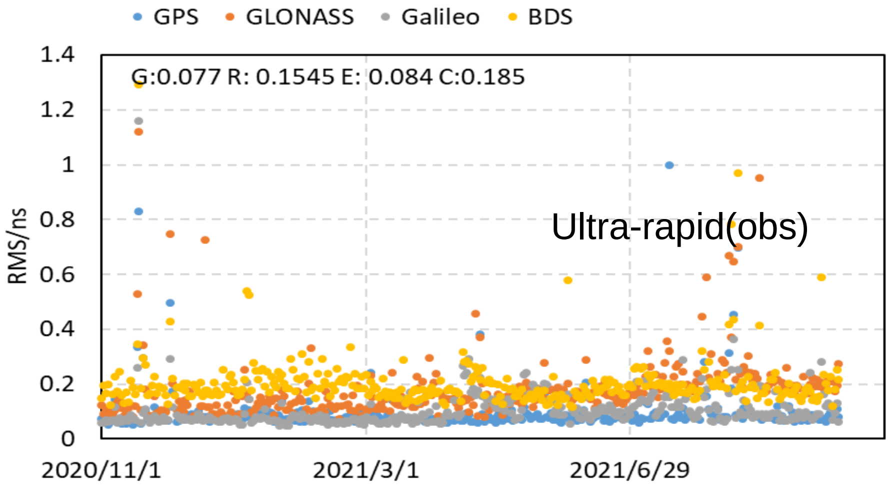
iGMAS orbit



The GPS and GLONASS orbits are compared to the IGS combination, the BDS and Galileo orbits are compared to the products of GFZ.

iGMAS clock



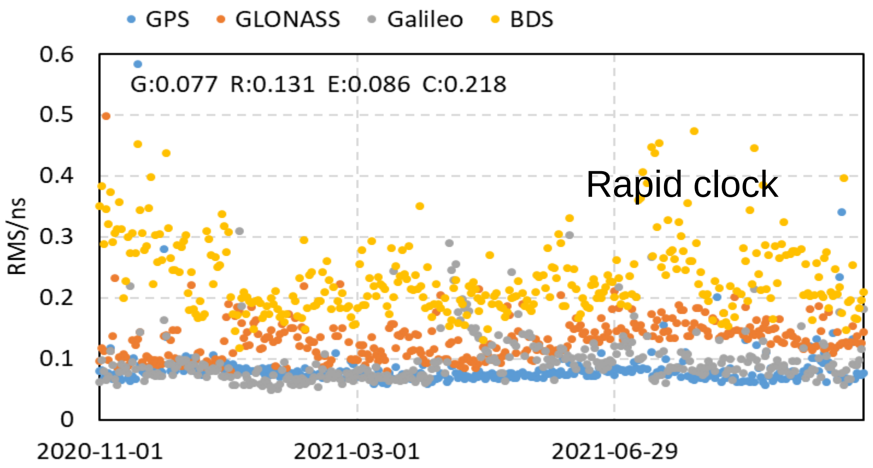


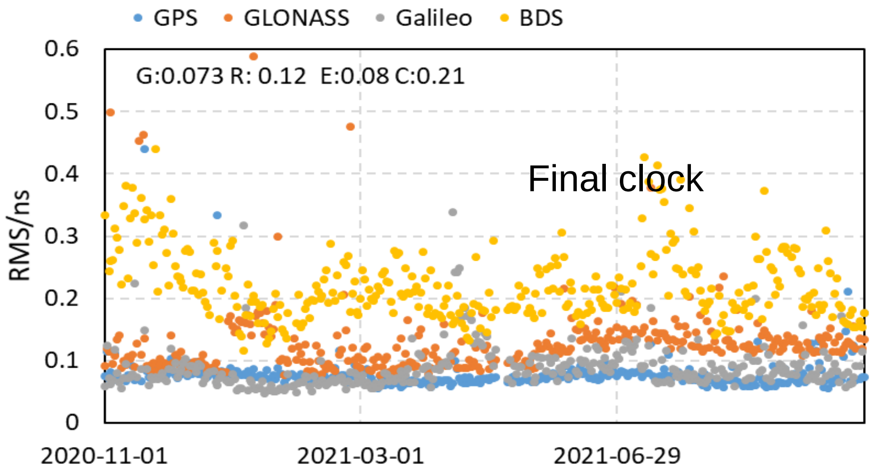
GPS : ISC .VS. IGS

GLONASS : ISC .VS. GFZ

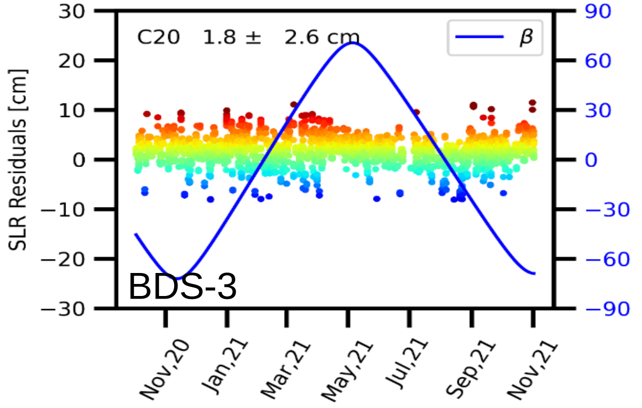
BDS : ISC .VS. GFZ

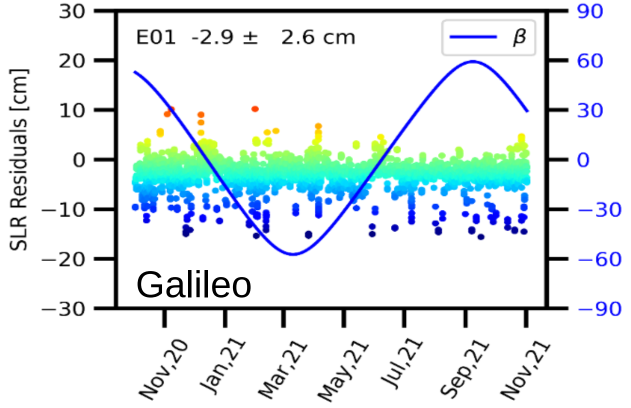
Galileo : ISC .VS. GFZ

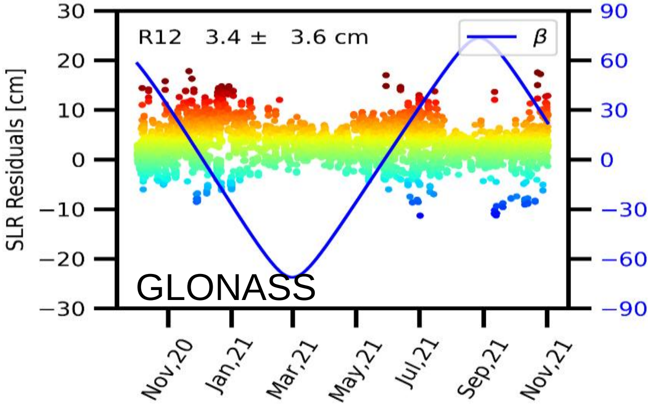




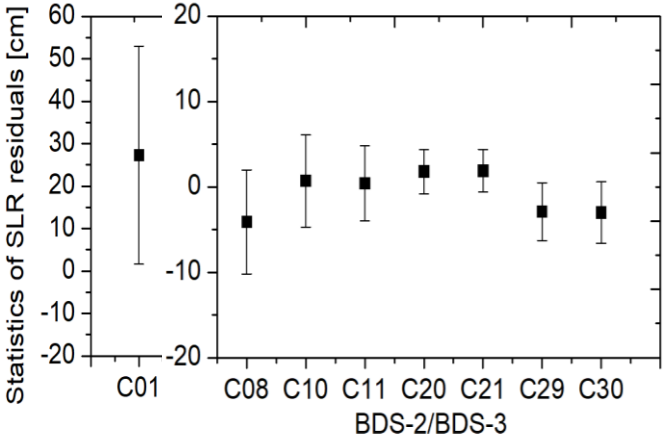
SLR validation of final orbit

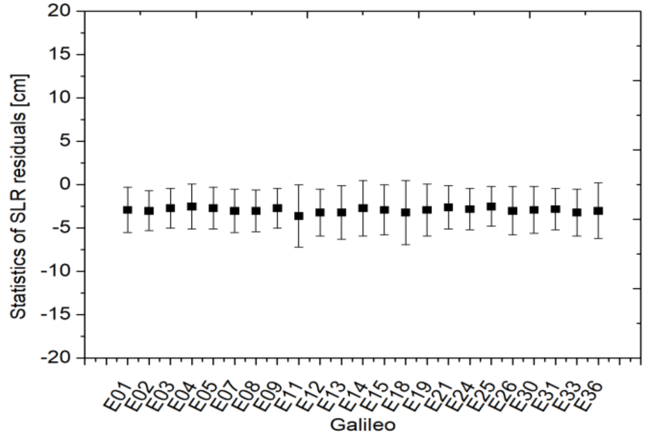


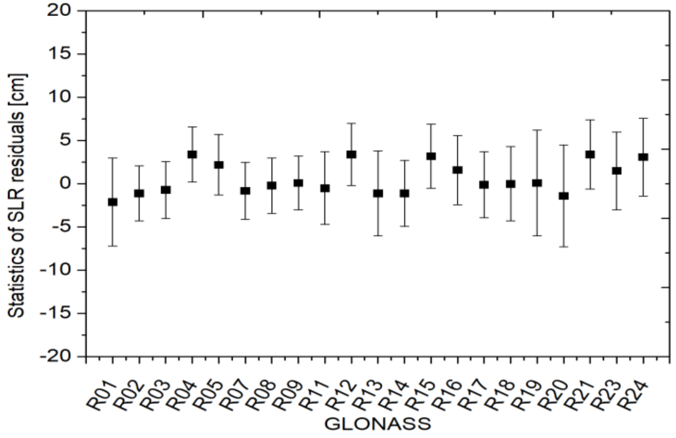




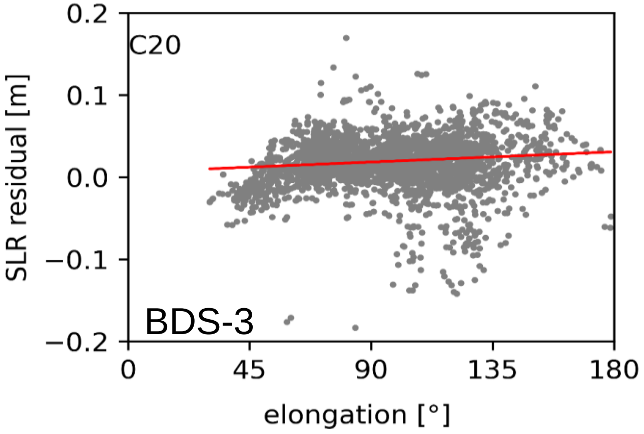
- Overall, the standard deviations of BDS-3 MEO and Galileo satellites are at the same level (i.e, 3.0 cm), smaller than the values of GLONASS (i.e. 4-6 cm).
- The statistics of SLR residuals show consistent bias of -3 cm for Galileo satellites.

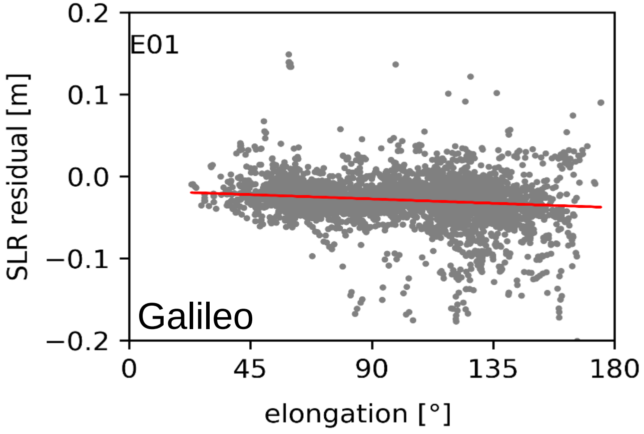


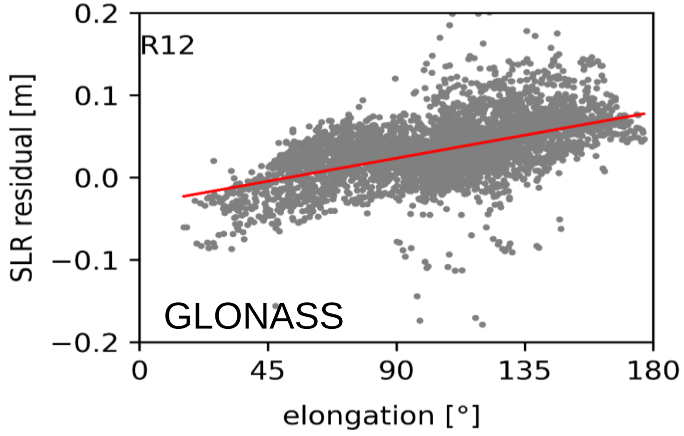


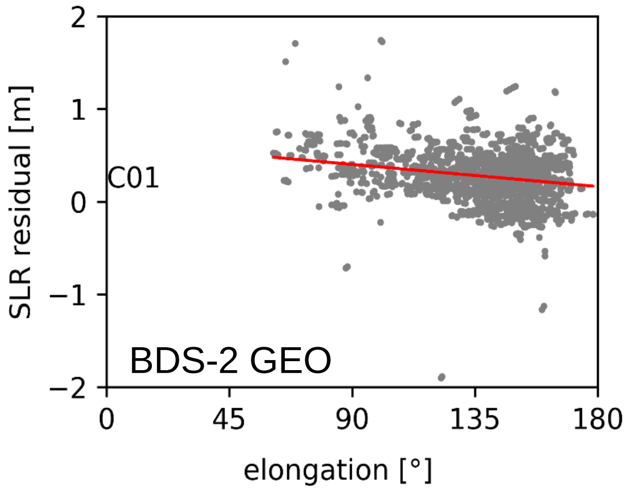


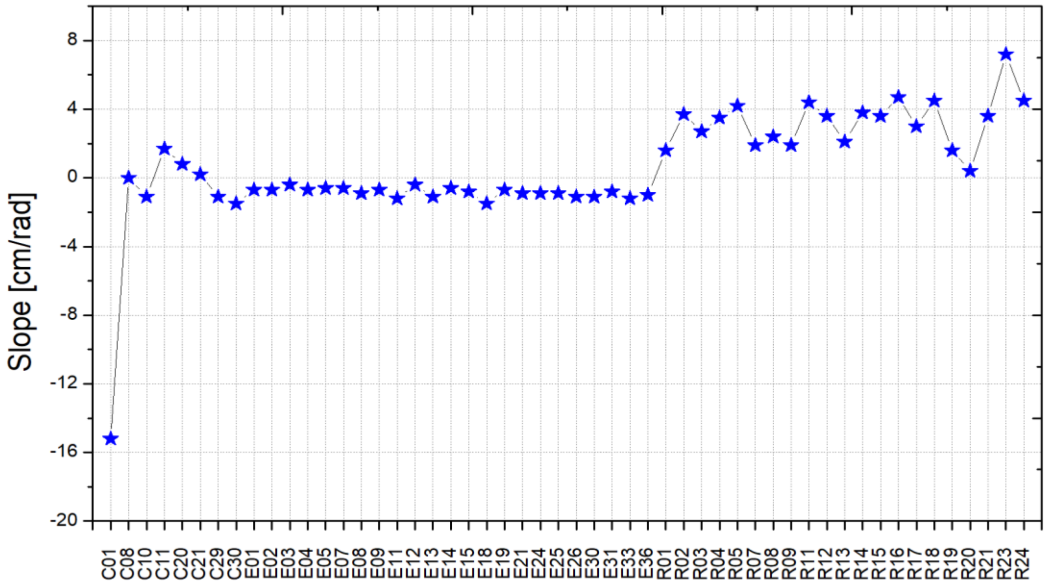
SLR validation of final orbit





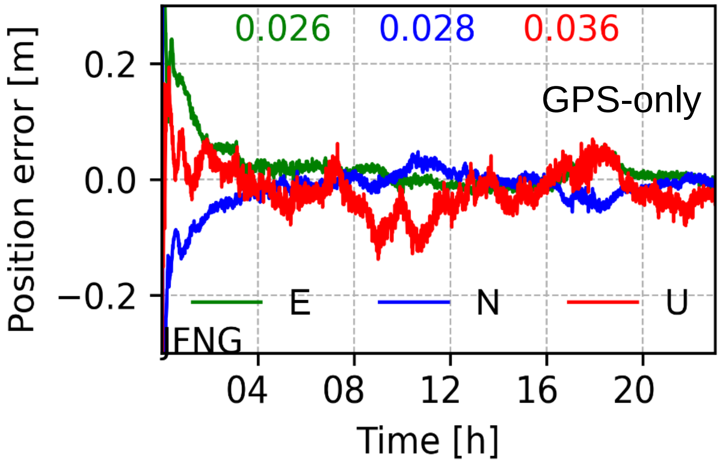


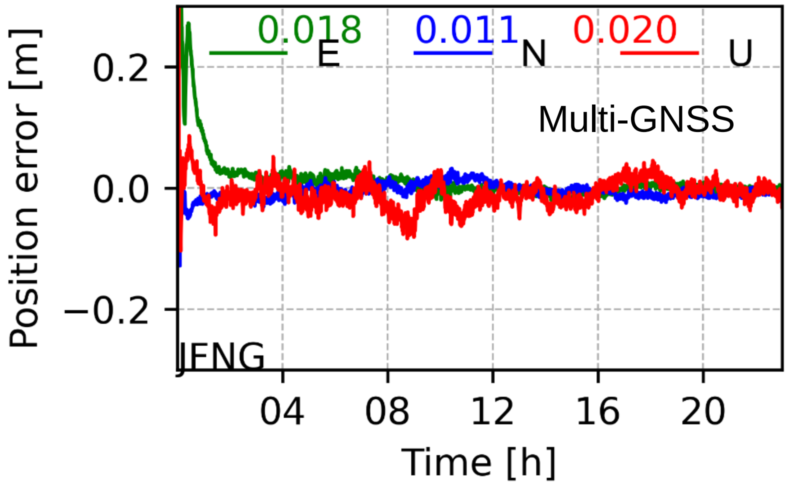




Obvious relationship between SLR residuals and elongation angle is noticed for C01 and most of GLONASS satellites

PPP validation of final orbit and clock





SITE	GPS			GPS+GLONASS+BDS+Galileo		
	E	N	U	E	N	U
ABPO	4.4	1.6	4.4	1	0.6	2.6
BRST	4.6	3.5	8.3	1.4	1.4	3
CHPI	2.8	1.3	4.6	1.1	0.7	2.9
CUT0	2.8	2.1	4.5	1.7	1.3	2.2
JFNG	2.6	2.8	3.6	1.8	1.1	2
KOKB	1.4	1.1	4.3	0.9	0.7	3.1
SAVO	4.9	3.5	7.1	2.7	3	5.6
UNB3	1.7	1.6	2.2	0.8	0.8	1.6
Average	3.2	2.2	4.9	1.4	1.2	2.9

Compared to the GPS-only result, the accuracy of 1.4 (E), 1.2 (N) and 2.9 cm (U) for quad-constellation integrated PPP, and an improvement of 57 (E), 45 (N) and 41% (U) is achieved, which also indicates the consistency level of multi-GNSS combined orbit/clock.

Summary

- The GPS combined orbits and clocks achieve the best consistency with IGS solutions, followed by Galileo, GLONASS and BDS are comparable. The consistency of BDS is getting better, and it can reach 3-4 cm at the end of 2021.
- The consistency between combined orbit and clock is also evaluated by kinematic PPP, and the positioning accuracy of 1.4 (East), 1.2 (North) and 2.9 cm (Up) is obtained for the quad-constellation integrated PPP.
- In the future, further work should be done :

  - More robust combination strategy are expected when products submitted by not sufficient ACs (e.g. 2-4 ACs).

  - Improved solar radiation pressure, earth albedo, antenna thrust model, should be considered during the POD of ACs.

2.6 Discussion

All

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MGEX Product Combination Needs

- Understand quality and possible deficits of current multi-GNSS products
    - Systematic comparison and assessment
- Understand/consolidate IGS multi-GNSS product combination requirements
    - Required harmonization of products (e.g. models, single- vs multi-step, orbit/clock rates, EOPs)
    - Preferred concept for multi-GNSS orbit combination (constellations and satellites, EOP alignment, common vs single-constellation Helmert, iterated/uniterated VCE, screening of bad satellites)
    - Clock and bias combination concept (system time scale, GLONASS handling)
- Tools and proceses
    - Design and implementation
    - Timeline
    - Responsibilities

Task force

- Rationale
  - Multi-GNSS product combination is a need & responsibility across multiple IGS entities
  - Need to move forward without further delays
- Proposal
  - Establish multi-GNSS product combination task force integrating experts, volunteers, stakeholders from IGS community and selected externals
  - Can be coordinated by MGWG Chair or other lead
- Tasks
  - Assessment and review of multi-GNSS product quality
  - Requirements analysis for combination tools
  - Tool chain definition and implementation
  - Setup of operational process chain

Satellite Metadata File

Peter Steigenberger, Oliver Montenbruck

IGS INTERNATIONAL GNSS SERVICE

Satellite Metadata

- Satellite metadata essential for GNSS data processing
  - Unique identifier: SVN, NORADID, COSPAR ID
  - Satellite mass
  - Center of mass
  - Sensor eccentricities (navigation payload antennas, laser retroreflector arrays)
  - …
- "IGS White Paper on Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products" published in 2017, updated in 2020
- Publications of satellite metadata by system providers (e.g., Galileo, QZSS) and manufacturers (e.g., Lockheed Martin for GPS III)
- IGS satellite metadata file as centralized interface

Satellite Metadata File

- Maintained by DLR/GSOC, available at https://files.igs.org/pub/station/general/igs_satellite_metadata.snx
- SINEX style format, examples available at MGEX website

Name	Description
SATELLITE/IDENTIFIER	Satellite designations (static)
SATELLITE/PRN	PRN assignment
SATELLITE/FREQUENCY_CHANNEL	GLONASS frequency channel
SATELLITE/MASS	Spacecraft mass
SATELLITE/CENTER_OF_MASS	Center-of-mass position
SATELLITE/ECCENTRICITY	Equipment positions
SATELLITE/TX_POWER	Transmit power

```
+SATELLITE/MASS
*
*SVN_ Valid_From____ Valid_To______ Mass_[kg]
*
 E223 2021:339:00000 0000:000:00000   716.376
 E224 2021:339:00000 0000:000:00000   713.182
 ...
 J004 2021:009:82121 2021:191:38791  2297.000
 J004 2021:191:38791 2022:005:64638  2287.000
 J004 2022:005:64638 0000:000:00000  2278.000
```

Discussion

- Draft format description distributed to WG members and available on IGS website
- Recommendation: Approval of format description by GB
- Possible extensions:
  - Active clock (already included in draft but no data yet)
  - **`BAND_POWER`** and **`SIGNAL_POWER`** blocks
    - already included in draft but no data yet
    - Information might be incomplete, no replacement of **`TX_POWER`** block
  - Geometry and surface properties

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Resources

- IGS Whitepaper Version 2017/07/25
- IGS Whitepaper Version 2020/02/04
- Galileo Satellite Metadata
- BeiDou Satellite Parameters
- GPS Technical References
- QZSS Satellite Information (satellite property information and operational history information)

GPS L5 Support

Oliver Montenbruck

MULTI-GNSS

IGS INTERNATIONAL GNSS SERVICE

GPS L5 Support

- Growing number of L5-capable satellites, 24 satellites expected by 2027
- Aviation and spaceborne GNSS users (ESA!) moving to L1/E1+L1/E5a receivers
- Expected needs
  - ANTEX update for IIF satellites (add “tweaked” L5* to obtain IF(L1,L5) from IF(L1/L2,L5*))
  - Independent L1/L5 (phase) clock product
  - L5 phase biases
- Can IGS support these users (and does it want to)?

Multi-GNSS Working Group
Recommendations

Recommendations

- Relocate all MGEX products to standard IGS products directory

  Notes: currently products implementation by all DCs coordinated by DCC (Pat and Markus); target date for completion 30 Sep 2023; 2 months lead notice to all users via IGS mail

- Request GB approval for Satellite Metadata SINEX File Format and Product

  Notes: standardized I/F for satellite metadata for ACs and IGS users, maintained by DLR/GSOC, prototype available from files.igs.org/pub/station/general/ or igs.org/mgex since Jan 2021

- Establish a Task Force to define and implement a tool chain for multi-GNSS orbit/clock/(bias) combination and to establish an operational product.

  Notes: cross-WG taskforce composed of invited specialists/volunteers/stakeholders

- Study options for supporting the GPS L1/L5 user community through dedicated IGS clock or bias products