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An experimental combination of IGS repro3 campaign's orbit products using a variance component estimation strategy

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Abstract Over the past years, the International GNSS Service (IGS) has put efforts into reprocessing campaigns, reanalyzing the entire data collected by the IGS network since 1994. Using state-of-the-art models and software, the goal is to provide a consistent set of orbits, station coordinates, and earth rotation parameters. Unlike the previous campaigns - namely: repro1 and repro2 -, the repro3 includes not only GPS and GLONASS but also the Galileo constellation. The main repro3 objective is the contribution to the next realization of the International Terrestrial Reference Frame (ITRF2020). To achieve this goal, several Analysis Centers (AC) submitted their own products to the IGS, which are combined to provide the final solutions for each product type. In this contribution, we focus on the combination of the orbit products. We present a consistent orbit solution based on a newly developed combination strategy, where the weights are determined by a Least-Squares Variance Component Estimation (LSVCE). The orbits are intended to be combined in an iterative processing: firstly, by aligning all the products via a Helmert transformation, secondly by defining which satellites will be used in the LSVCE, and finally by normalizing the inverse of the variances as weights that are used to compute a weighted mean. The combination results show an agreement between the different AC's input orbits around 10 mm for GPS, 30 mm for GLONASS. The combination also highlights the improvement of the Galileo orbit determination over the past decade, the internal precision decreasing from around 35 mm to 16 mm for the most recent weeks. We used Satellite Laser Ranging (SLR) observations for external validation. The combined orbit has one of the best RMS agreements with respect to the SLR measurements (9.1 mm for GLONASS, and 8.3 mm over the last five years of the processed period).

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1 Introduction

Over the past years, the International GNSS Service (IGS) has put efforts into reprocessing campaigns reanalyzing the full data collected by the IGS network since 1994. The goal is to provide a consistent set of orbits, station coordinates, and earth rotation parameters using state-of-the-art models. Since the end of 2020, the IGS has completed the *reprocessing 3* campaign (abbreviated as repro3). It differs from the previous campaigns (namely repro1 achieved in 2009 and repro2 in 2015) by the fact that repro3 includes not only GPS and GLONASS but also the Galileo constellation. The main repro3 objective is to provide the GNSS contribution to the next realization of the International Terrestrial Reference Frame (ITRF2020, Altamimi et al., 2021). To achieve this goal, 12 Analysis Centers (AC) joined the effort and submitted their own products to the Analysis Center Coordinator (ACC). Each product type is then combined at the solution or at the normal equation level to provide to the final user an “IGS-labeled" solution with the best accuracy possible. In this contribution, we mainly focus on the combination of the orbit products.

The strategy of combining orbits and clock offsets was developed during the early age of the IGS for two main reasons (Kouba et al., 1994):

1. to provide to the users the most reliable of all the submitted solutions and
2. to offer a feedback tool to evaluate the consistency between ACs.

The initial developments of such combination were performed by Springer and Beutler (1993) and Beutler et al. (1995), and then slightly modified by Kouba et al. (2001). However, it has evolved very little for more than 25 years. The major limitation of the current algorithm used operationally by the IGS's ACC is that it is not adapted to a multi-GNSS environment (Mansur et al., 2020b), while the new generation of satellite positioning constellations (Galileo, Beidou, QZSS, IRNSS) are coming to maturity. Therefore, an update of the combination procedure is necessary.

Thus, our research group has started to study a new combination strategy compatible with the new constellations, initially based on the legacy IGS software (Sakic et al., 2020), then by designing an *ad hoc* strategy optimised for a multi-GNSS configuration (Mansur et al., 2020b,a). These activities are carried out in parallel with the orbit combination studies performed by the ACC in the context of the IGS's Multi-GNSS Experiment (MGEX) pilot project (Sośnica et al., 2020), and the ones regarding integer clocks (Banville et al., 2020).

The present paper presents the results obtained for an orbit combination of the IGS's repro3 orbit products based on the new strategy we developed. We describe hereafter the input products integrated and the processing method. We present the results of the orbit combination results compared with each individual AC, for all satellites and for each separated constellation. We provide also a Satellite Laser Ranging (SLR) validation for an external assessment of the combination.

2 Material and methods

The new combination strategy elaborated by our working group, based on a Least-Squares Variance Component Estimation (LSVCE) weighting, is described in detail in Mansur et al. (2020a). It is developed within the framework of the Python *GeodeZYX Toolbox* software (Sakic et al., 2019).

general workflow can be summarized as follow:

1. A simple arithmetic mean of all the input AC's orbits is computed.
2. Helmert transformations are performed between this mean and the ACs' solutions.
3. A set of so-called "core satellites" is defined. The goal is to get the common satellites present in all the input AC's solutions. During this step, an improved outlier detection scheme is applied: a Modified Z-Score approach (Iglewicz and Hoaglin, 1993) is used to test the radial, along-track, and cross-track components of each set of AC coordinates for all satellites. If one satellite's component is detected as outlier, the satellite is excluded from the set of core satellites.
4. The variance components are estimated based on the theory of Amiri-Simkooei et al. (2007), using only the set of core satellites as defined before. The detailed mathematical development is available in Mansur et al. (2020a).
5. The variance components σ^2 are normalized and used as weights using the formula:

$$\hat{\mathbf{X}}_{\mathrm{c}} = \frac{1}{\sum_{ac=1}^{AC} \frac{1}{\sigma_{ac}^2}} \cdot \sum_{ac=1}^{AC} \frac{1}{\sigma_{ac}^2} \cdot \bar{\mathbf{X}}_{ac}, \quad (1)$$

Where $\bar{\mathbf{X}}_{ac}$ are the input coordinate vectors of the ACs, σ_{ac}^2 is the variance for each AC, and $\hat{\mathbf{X}}_{\mathrm{c}}$ is the combined coordinate vector.

The process is repeated iteratively until the 3D-RMS difference between two iterations is bellow 1 mm. This occurs usually at the fifth iteration.

The algorithm has been designed to realize a weighting based on the different AC only, or based on both the ACs and the different constellations. For the present study, we adopted the so-called *AC plus constellation* strategy.

We considered all the orbit products provided by the different ACs which participated to the repro3 efforts. The campaign period ranges from GPS week 730 (1994-01-02) to 2138 (2020-12-31). Table 1 summarizes the different AC products used and their contribution period.

The orbits are described in the SP3d format (Hilla, 2016) and were retrieved from the Crustal Dynamics Data Information System (CDDIS) server (Noll, 2010).

3 Results

To evaluate the compatibility between the combination and the input orbit products, we compute the Root Mean Square (RMS) differences using the formulas described in Kouba et al. (1994):

$$RMS_{ac} = \sqrt{\frac{1}{Nsat_{ac}} \sum_{sat}^{Nsat_{ac}} (RMS_{ac}^{sat})^2} \quad (2)$$

Analysis Center	Abrev.	Const.	First epoch (calendar)	First epoch (GPS week)	Products and/or software
Center for Orbit Determination in Europe	cod	GRE	1994-01-02	730	Selmke et al. (2020) Dach et al. (2015)
European Space Agency	esa	GRE	1995-01-01	782	Schoenemann et al. (2021)
GeoForschungsZentrum	gfz	GRE	1994-01-02	730	Männel et al. (2020, 2021)
Groupe de Recherche en Géodésie Spatiale	grg	GRE	2000-05-03	1060	Katsigianni et al. (2019)
Jet Propulsion Laboratory	jpl	G	1994-01-01	729	Bertiger et al. (2020)
Massachusetts Institute of Technology	mit	GE	2000-01-02	1043	Herring et al. (2018)
National Geodetic Survey	ngs	G	1994-01-02	730	Damiani and Freeman (2019)
Graz University of Technology	tug	GRE	1994-01-01	729	Strasser and Mayer-Gürr (2021) Mayer-Gürr et al. (2021)
Wuhan University	whu	GR	2008-01-01	1460	Guo et al. (2016)

Table 1 Summary of the different input orbit products. *Abrev.* stands for the AC abbreviation, *Const.* for the GNSS constellations computed by each AC: G for GPS, R for GLONASS, E for Galileo.

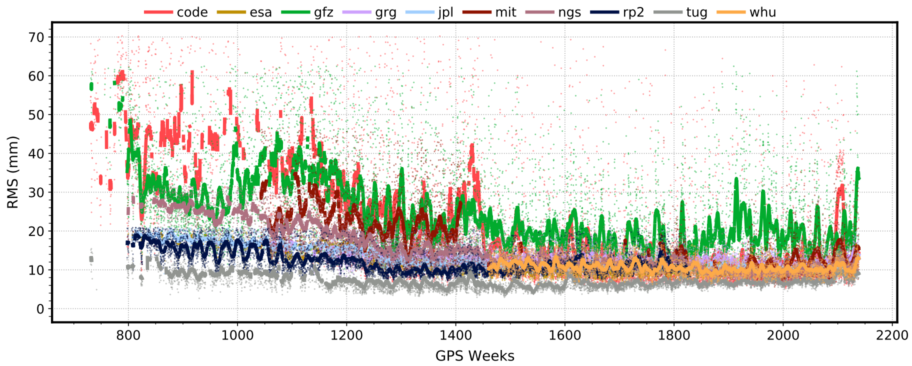
$$RMS_{ac}^{sat} = \sqrt{\frac{\sum_{i}^{Nepoch_{ac}^{sat}} \left\| \bar{\mathbf{X}}_{ac} - \hat{\mathbf{X}}_{c} \right\|_{i}^{2}}{3 \cdot Nepoch_{ac}^{sat} - 7}} \quad (3)$$

where RMS_{ac} is the center's RMS, RMS_{ac}^{sat} is the satellite's RMS per center, $Nsat_{ac}$ is the number of satellites per center and $Nepoch_{ac}^{sat}$ is the number of determined orbit positions per center per satellite.

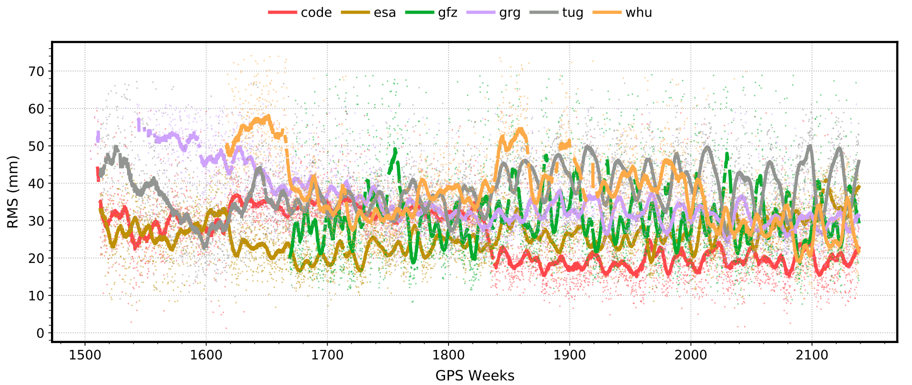
The results are shown in Figure 1. We also adopt a similar graphical representation as the one usually presented by the IGS's ACC (e.g. Griffiths, 2019): dots representing the daily RMS, and a smoothing curve based on a 14-day window Gaussian filter. We perform also a comparison with respect to the previous combined orbits generated at the end of the previous repro2 campaign (Griffiths, 2019). The repro2 products, used only for comparison purposes and based on GPS-only orbits, are identified as *rp2* in Figure 1. We also indicate in Table 2 the mean RMS for each AC for the three processed constellations, and subdivided into two columns, one for the full-time range and the other for the last year (2020) only.

	G (full)	G (2020)	R (full)	R (2020)	E (full)	E (2020)
cod	66.88	22.14	35.08	23.18	37.85	16.39
esa	25.42	18.91	27.74	34.34	16.80	13.78
gfz	48.09	20.19	56.80	37.51	154.41	33.55
grg	30.47	16.82	52.50	30.96	22.79	23.25
jpl	18.72	11.51	N/A	N/A	N/A	N/A
mit	28.66	13.85	N/A	N/A	24.69	21.64
ngs	41.84	11.67	N/A	N/A	N/A	N/A
tug	18.96	8.96	48.07	41.59	36.69	12.24
whu	11.48	14.76	198.74	25.75	N/A	N/A

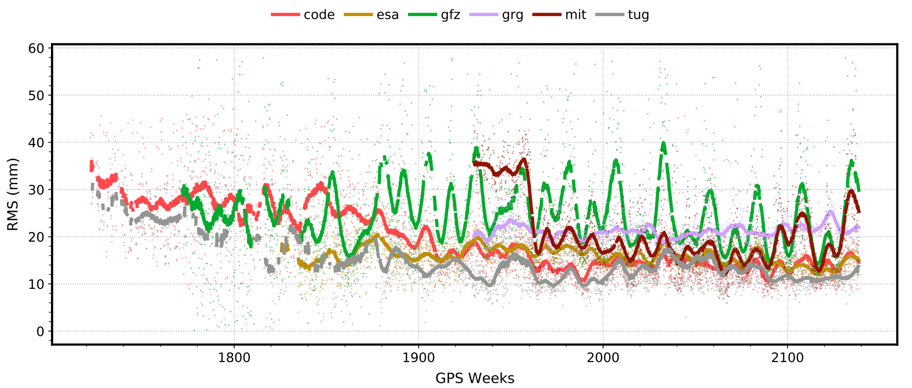
Table 2 Mean RMS for each AC for the three processed constellations, for the full period (*full* column) and the last year (*2020* column).



(a) GPS



(b) GLONASS



(c) Galileo

Fig. 1 3D-RMS difference of individual AC orbit solutions w.r.t the combined solution. Please note that the y-axis scales are different for each figure.

For GPS, the differences of individual ACs with respect to the combination reach 60 mm for the early weeks of the repro3 period. It stabilizes after GPS week 1400 at around 25 mm for the ACs with the highest RMS, and around 10 mm for the majority of the ACs. The best RMS values along with the best stability is achieved by the TUG solution around 6 mm. A noticeable difference with the repro2 solution is visible, ranging from 18 mm for the early weeks to 10 mm after GPS week 1250. This difference can be seen as a general improvement in the accuracy of the repro3 orbits compared to the previous reprocessing campaign.

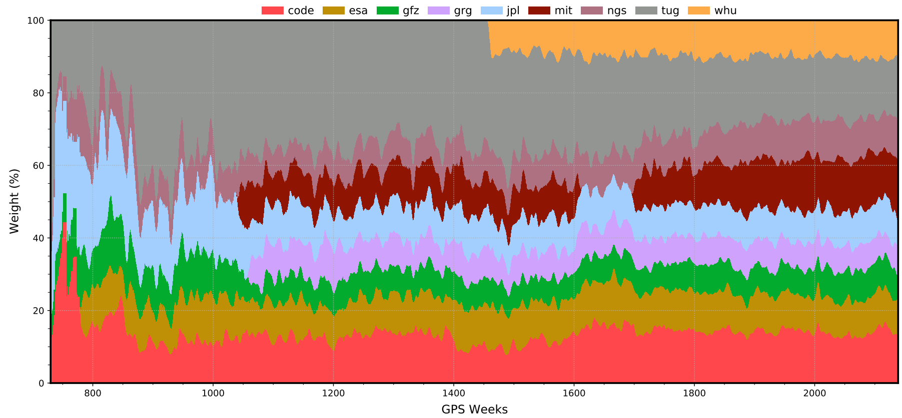
For GLONASS, the differences are centered around 30 mm for the complete period, with a dispersion between 55 mm and 20 mm, with the latter achieved by CODE. Regarding Galileo, the differences range from about 35 mm from GPS week 1745 (date of the first Galileo satellite activation) to a stabilized value of 16 mm after GPS week 1900. For the European constellation, it is also remarkable that half of the ACs (namely CODE, ESA and TUG) have the same level of agreement for their provided orbits, since their RMS differences with respect to the combination are similar (to the level of 5 mm).

The weights derived from the LSVCE are represented on Figure 2. They are the corollary of the RMS difference plots, since the ACs with the smallest RMS present the highest weights. For most AC's the weights are stable over time as expected for a consistent re-processing. Short-term (periodic) fluctuation represents differences related to the individual orbit modeling approaches.

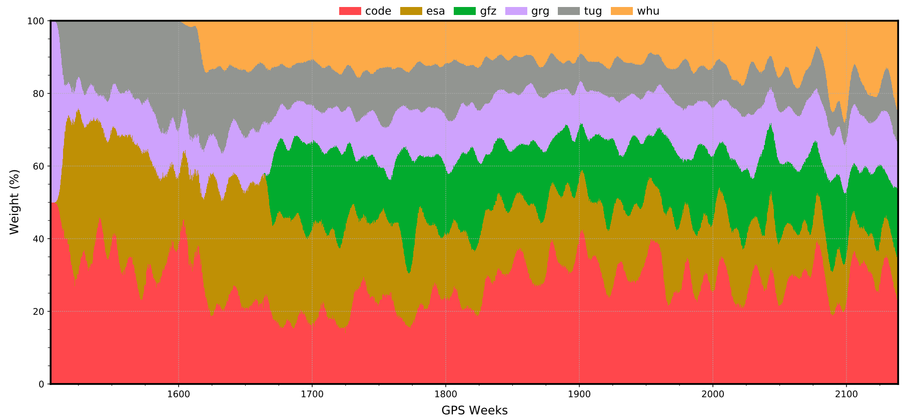
4 SLR external validation

To perform an independent quality assessment of the combination, we performed an external validation using SLR observations. Indeed, all Galileo and the most of the GLONASS satellites (GLONASS-M and GLONASS-K generations) are equipped with Laser Retroreflector Arrays (LRA, Dell'Agnello et al., 2011) and thus are suited for such operation. We use as observation input the normal points provided by the International Laser Ranging Service (ILRS, Pearlman et al., 2002). The processing is performed with GFZ's EPOS-P8 software (Uhlemann et al., 2015), designed for GNSS precise orbit determination, precise point positioning, and orbit validation using SLR. SLR station coordinates are fixed to the SLRF2014 (Luceri et al., 2015). Ocean tidal loading is corrected from the station positions using the FES2004 model (Lyard et al., 2006). An outlier threshold for residuals over 0.5 m is applied. Daily averaged residuals and a smoothing curve based on a 14-day window Gaussian filter for each AC are shown in Figure 3. The validation is performed starting from GPS week 1745, when the first Galileo satellites were available. Table 3 summarizes the mean residuals and the associated standard deviation for each AC and both constellations.

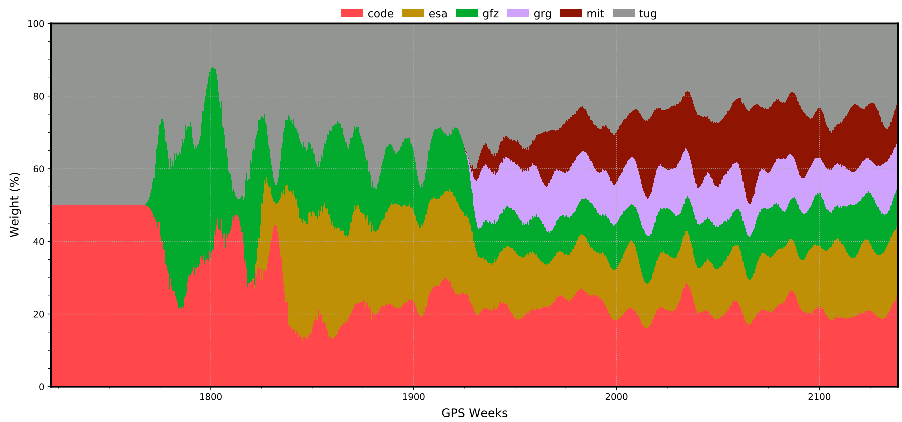
The combined solution shows one of the best agreements with the SLR measurement (-2.63 mm mean residuals for Galileo, 0.84 mm for GLONASS). It shows also the second smallest dispersion for GLONASS (std. = 9.10 mm for GLONASS). For Galileo, the combination dispersion is not significantly reduced over the whole tested period ("E, full" in Table 3) due to the input solutions' high residuals during the early weeks. But if we consider the residuals on a reduced period only after the GPS week 1890 ("E, red." in Table 3), the combination shows the second smallest dispersion (std. = 8.15 mm). This external validation illustrates that the combi-



(a) GPS



(b) GLONASS



(c) Galileo

Fig. 2 Weights derived from the LSVCE for each AC solution per constellation

Const.	AC	Mean	Std.	RMS
R	cod	0.04	9.61	9.61
R	esa	1.26	8.89	8.97
R	gfz	0.79	16.47	16.48
R	grg	7.67	9.15	11.94
R	tug	-5.03	9.14	10.43
R	whu	3.54	23.13	23.40
R	rp3	0.84	9.10	9.14
E, full	cod	-6.31	13.08	14.52
E, full	esa	-5.84	8.58	10.38
E, full	gfz	-14.37	14.69	20.55
E, full	grg	21.34	8.53	22.98
E, full	mit	-0.12	10.97	10.97
E, full	tug	2.37	22.87	22.99
E, full	rp3	-2.63	14.56	14.79
E, red.	cod	-4.26	8.42	9.43
E, red.	esa	-6.58	7.15	9.71
E, red.	gfz	-14.16	12.25	18.73
E, red.	grg	21.34	8.53	22.98
E, red.	mit	-0.12	10.97	10.97
E, red.	tug	10.84	8.65	13.87
E, red.	rp3	1.55	8.15	8.30

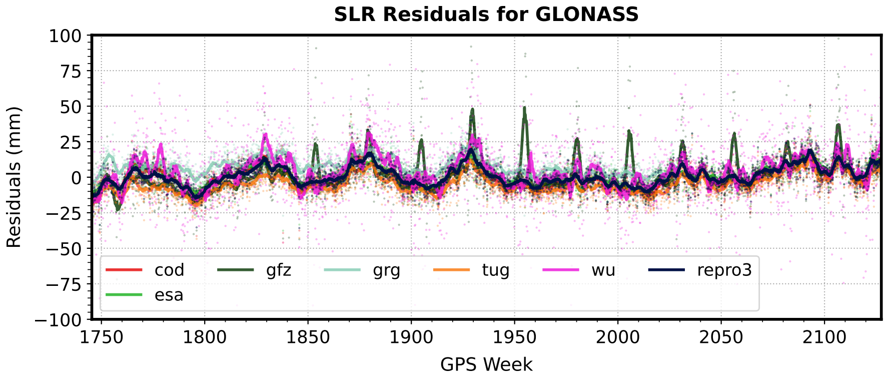
Table 3 Mean residuals, standard deviation, and Root Mean Square w.r.t. 0 in mm for each input AC for GLONASS (R) and Galileo (E). For Galileo, the statistics are split into two ranges: a full period ("E, full" column) and a reduced period ("E, red." column) starting from GPS week 1890.

nation provides both the best accuracy and precision level out of the individual input solutions.

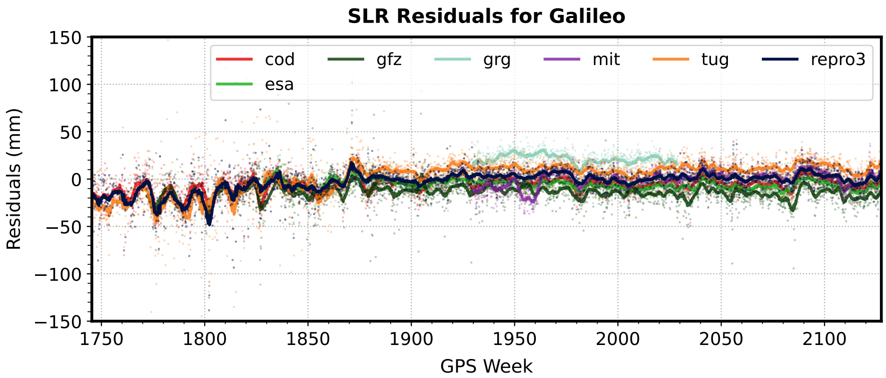
5 Discussion and perspectives

We developed a new GNSS orbit combination strategy based on a Least-Squares Variance Component Estimation, and an improved detection for outlier satellites (Mansur et al., 2020a). This algorithm can also handle the different constellations separately. It corrects the weaknesses of the legacy software used routinely by the IGS's ACC, which have been raised during a preliminary study investigating the possibilities to improve it for a multi-GNSS environment (Sakic et al., 2020). We tested this new algorithm with the recent set of orbit products generated by the different IGS ACs in the framework of the repro3 reprocessing campaign. A 10 mm internal precision is achieved for GPS, 30 mm for GLONASS, and 16 mm for Galileo at the end of the reprocessed period (2020-12-31). The SLR validation shows that the combination has one of the best agreements with the laser measurements and also the smallest residual dispersion, then confirming its robustness with an external technique. The results can be a useful tool for the ACs to identify potential weaknesses in their processing. The present work can also be a support for cross-comparison and validation of the orbit combination currently performed by the IGS's ACC (Masoumi and Moore, 2021).

Data Availability



(a) GLONASS



(b) Galileo

Fig. 3 Average SLR Residuals per constellation for each AC solution and the combination

The data used for this work are publicly and freely available on the CDDIS server. The combined products described in this study can be provided for free on demand.

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