SENTINEL-3 AND -6 SLR YEARLY REPORT – 2023

3RD GENERATION OF THE COPERNICUS POD SERVICE (CPOD3)

Prepared by: X Eva Terradillos Estévez 2024.02.23 13:18:23 +01'00'

CPOD Team
Project Engineer

Approved by: X Irene Raquel Spangaro 2024.02.23 13:46:33 +01'00'

I. Spangaro
Quality Manager

Authorised by: X Carlos Fernández Martín 2024.02.23 13:23:40 +01'00'

C. Fernández
Project Manager

Document ID:	GMV-CPOD-SLR-0008
DIL Code:	TD-17
Internal Code:	GMV 21268/24 V1/24
Version:	1.0
Date:	26/02/2024
ESA contract number:	4000139509/22/I-BG

DOCUMENT STATUS SHEET

Version	Date	Pages	Changes
1.0	26/02/2024	45	First version

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. PURPOSE

This document has been prepared in the frame of the project 3rd Generation of the Copernicus POD Service. It reports about the **Satellite Laser Ranging (SLR)** data of Sentinel-3A, Sentinel-3B and Sentinel-6A used by the Sentinel-3 and Sentinel-6 projects to perform periodic checks of the biases that could exist between the other tracking techniques (GNSS and DORIS), and to assess the accuracy of the operational Sentinel-3 and Sentinel-6 orbits. The covered period is year 2023.

1.2. SCOPE

This document is a deliverable by GMV to acknowledge the work of the **International Laser Ranging Service (ILRS) [RD.2]** community in supporting the Copernicus Sentinel-3 and Sentinel-6 missions. The main aspects that are highlighted herein are the data received from the ILRS, the results obtained from the SLR external validation and the Consolidated Prediction Files (CPFs) that the Copernicus POD (CPOD) Service provides to the ILRS laser stations in order to allow the tracking of the Sentinel-3 satellites.

1.3. DISCLAIMER

Sentinel-3 and Sentinel-6 missions, and in particular the CPOD Service, would like to thank the **ILRS Community** for their efforts and acknowledge the great contribution to the verification of the stringent accuracy requirements of the S-3 and S-6 altimetry missions. The SLR tracking data provided has proven to be an invaluable asset for independent orbit validation, allowing to assess the quality of the different available orbital products and ensure the best are used for the altimetry processing.

GMV, as prime contractor of the Copernicus POD Service, and the Copernicus POD Quality Working Group (QWG) members, consider satisfactory the performance of the SLR tracking. The content presented herein has been gathered with the purpose of informing the ILRS Community about the S-3 and S-6 SLR tracking statistics, the obtained residuals and how they contribute to the Sentinel-3 and Sentinel-6 orbital products validation. Those cases in which the reported results are worse than expected might either be related to a temporal problem with any given station or wrongly configured parameters at the POD processing (in particular, the station coordinates), not necessarily implying an issue with the observations themselves.

1.4. DEFINITIONS AND ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-1: Acronyms

Acronym	Definition	Acronym	Definition
AIUB	Astronomical Institute University of Bern	JPL	Jet Propulsion Laboratory
CLS	Collecte Localisation Satellites	LEO	Low Earth Orbit
CNES	Centre National d'Études Spatiales	LRR	Laser Retro-reflector
CPF	Consolidated Prediction Format	NAPEOS	NAvigation Package for Earth Orbiting Satellites
CPOD	Copernicus POD	OLCI	Ocean & Land Colour Instrument
DIL	Document Item List	PDGS	Payload Data Ground Segment
DLR	Deutsche Zentrum für Luft- und Raumfahrt	POD	Precise Orbit Determination
DORIS	Doppler Orbytography and Radiopositioning Integrated by Satellite	QWG	Quality Working Group
EGU	European Geosciences Union	RMS	Root Mean Square
ESA	European Space Agency	SAR	Synthetic Aperture Radar

Acronym	Definition	Acronym	Definition
ESOC	European Space Operation Centre	SINEX	Solution Independent Exchange
ESTEC	European Space research and TEchnology Centre	SLR	Satellite Laser Ranging
EUMETSAT	EUropean organisation for the exploitation of METeorological SATellites	SLSTR	Sea and Land Surface Temperature Radiometer
FTP	File Transfer Protocol	SRAL	SAR Radar Altimeter
GFZ	Geo Forschungs Zentrum	STC	Short Time Critical
GNSS	Global Navigation Satellite System	STD	Standard Deviation
GPS	Global Positioning System	TUD	Technische Universiteit Delft
IGS	International GNSS Service	TUM	Technische Universität München
ILRS	International Laser Ranging Service	USA	United States of America
ITRF	International Terrestrial Reference Frame		

1.5. APPLICABLE AND REFERENCE DOCUMENTS

1.5.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]:

Table 1-2: Applicable Documents

Ref.	Title	Code	Version	Date
[AD.1]	Sentinel-3A Mission Support Request Form	ESTEC_ILRS_MSRF_Sentinel-3A	1	10/11/2015
[AD.2]	Sentinel-3B Mission Support Request Form	ESTEC_ILRS_MSRF_Sentinel-3B	3	15/01/2018

1.5.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, extend or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.X]:

Table 1-3: Reference Documents

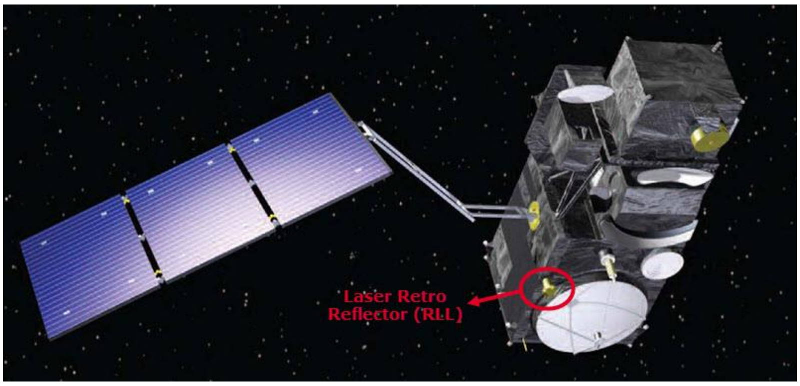
Ref.	Title	Code	Version	Date
[RD.1]	Analysis of elements for Sentinel-3 SLR tracking	GMV-GMESPOD-TN-0028	1.2	10/05/2018
[RD.2]	Pearlman M.R., Noll C.E., Pavlis E.C., Lemoine F.G., Combrink L., Degnan J.D., Kirchner G., Schreiber U. (2019). "The ILRS: approaching 20 years and planning for the future", J. Geodesy, 93, 2161-2180, https://doi.org/10.1007/s00190-019-01241-1	N/A	N/A	2019
[RD.3]	Copernicus POD Product Handbook	GMV-CPOD3-PH-0001	1.1	17/10/2023
[RD.4]	Copernicus POD Regular Service Review Jan – Dec 2023	GMV-CPOD3-RSR-0030	1.0	09/02/2023

2. GENERAL OVERVIEW

The Copernicus Precise Orbit Determination (CPOD) Service is part of the Copernicus Payload Data Ground Segment (PDGS) of the Copernicus programme, which is an Earth observation programme coordinated and managed by the European Commission in partnership with the European Space Agency (ESA).

The Copernicus programme is in charge of the Sentinel missions, a series of satellites equipped with various Earth observation instruments in order to monitor, record and analyse environmental data and events around the globe. The monitoring of such events demands high levels of orbital accuracy, which requirements are satisfied by the CPOD Service, a consortium of different centres led by GMV. Thus, the CPOD Service is in charge of the provision of precise orbital products and auxiliary data files of the Sentinel satellites to the PDGS.

One of the Sentinel missions operated by the CPOD Service is the Sentinel-3 mission. This mission is currently using two satellites (Sentinel-3A and Sentinel-3B) to measure sea surface topography, sea and land surface temperature, and ocean and land surface colour with high accuracy and reliability. To that end, Sentinel-3 satellites are equipped with many instruments, among which there are an Ocean and Land Colour Instrument (OLCI), a Sea and Land Surface Temperature Radiometer (SLSTR), a SAR Radar Altimeter (SRAL), etc. In addition, the Sentinel-3 satellites are also equipped with a Laser Retro Reflector (LRR), which allows the tracking of the Sentinel-3 satellites by using a laser ranging from a network of Satellite Laser Ranging (SLR) stations belonging to the International Laser Ranging Service (ILRS). Figure 2-1 shows the location of the LRR reflector on the payload of the Sentinel-3 satellites. This figure also summarises a few properties of the orbit described by the Sentinel-3 satellites.

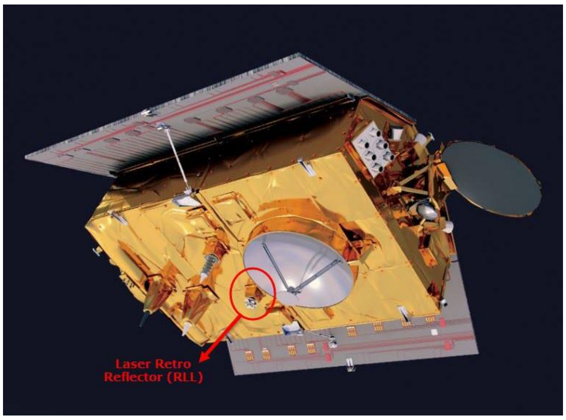


Properties of Sentinel-3 satellites

- Low Earth Orbit (LEO)
- Polar orbit
- Inclination: 98.65°
- Altitude: 814.5 km

Figure 2-1: Properties of Sentinel-3 satellites and location of the LRR

On the other hand, Sentinel-6 mission will ensure continuity to the JASON series of operational missions providing high precision ocean altimetry measurements. Figure 2-2 illustrates the location of the LRR on Sentinel-6A satellite and provides some extra information about the satellite orbit.



Properties of Sentinel-6A satellite

- Low Earth Orbit (LEO)
- Inclination: 66.0°
- Altitude: 1336 km

Figure 2-2: Properties of Sentinel-6A satellite and location of the LRR

The observations provided by the SLR stations are very valuable for the CPOD Service since they are used as an alternative source for validating the precise orbit solutions the CPOD Service generates through the Global Navigation Satellite System (GNSS) signals, especially from those obtained by means of the Global Positioning System (GPS) and Galileo (Sentinel-6A). For this, not only the CPOD Service but also ESA are very grateful for the support provided by the ILRS community, which helps at the long-term validation and valorisation of the Sentinel-3 and Sentinel-6 orbit and science products.

Not all the SLR stations may track both Sentinel-3 satellites (see [AD.1], [AD.2] and [RD.1]) since high levels of laser energy could damage some instrument on-board the Sentinel-3 satellites (e.g., the OLCI receiver). This is not the case for Sentinel-6A satellite. Figure 2-3 shows the geographical location of all SLR stations tracking both families of satellites. More information about these SLR stations can be found in Table 6-1 of the annex.

From the figure below, it can be seen that an overall good geographical coverage is obtained given the available stations, with up to five stations in the southern hemisphere.

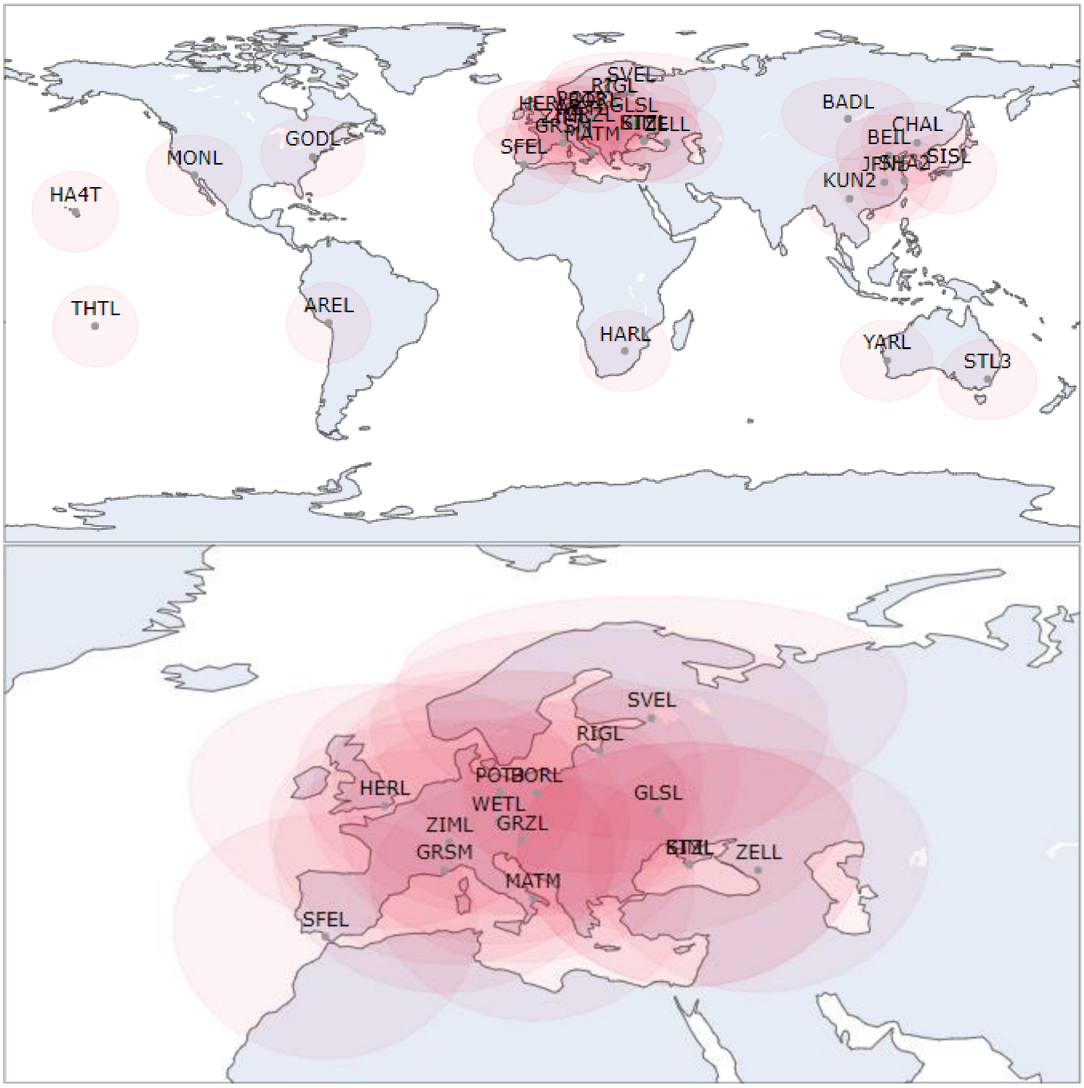


Figure 2-3: ILRS stations tracking Sentinel-3 and Sentinel-6 satellites (the field of view is depicted with a cut-off angle of 15°; below there is a zoom-in of the European region)

The tracking of the satellites from the SLR stations follows a mission priority list established by the ILRS community. This information is summarised in Figure 2-4, which particularly highlights the positions that the Sentinel-3 and Sentinel-6 satellites are occupying on the list at the time of writing this document. The complete priority list can be found in the official website of the ILRS community. As seen from the figure, Sentinel-3A, Sentinel-3B and Sentinel-6A are on the 7th, 8th and 17th position, respectively, of all satellites considered by the ILRS community. Again, both ESA and the CPOD Service are very grateful that the ILRS community not only keeps tracking both satellites but continues to keep both satellites at this priority level.

Priority	Mission	ILRS Name	COSPAR ID	SIC	Sponsor	Altitude (km)	Inclination (degrees)	Comments
1	GRACE-FO-1/2	gracefo1 gracefo2	1804701 1804702	0123 0124	NASA JPL and the German Research Centre for Geosciences (GFZ)	500	89	1-month campaign
2	ICESat-2	icesat2	1807001	6873	NASA	496	92	Restricted tracking; authorization required
3	CryoSat-2	cryosat2	1001301	8006	ESA	450-720	92	
7	Sentinel-3B	sentinel3b	1803901	8011	ESA/EUMETSAT	814.5	98.65	Restricted tracking; authorization required
8	Sentinel-3A	sentinel3a	1601101	8010	ESA/EUMETSAT	814.5	98.65	Restricted tracking; authorization required
16	Sentinel-6A/Jason-CSA	sentinel6a	2008601	4380	NASA, ESA, EUMETSAT, NOAA, CNES	1339.4-1355.9	66.042	
17	Jason-3	jason3	1600201	4379	NASA, CNES, Eumetsat, NOAA	1,336	66.0	

Figure 2-4: ILRS mission priority list at the time of writing the document

Finally, this section concludes showing a general overview of the tracking of the Sentinel-3 and Sentinel-6 satellites from the SLR stations. The statistics shown below have been obtained from the np2 monthly files provided by SLR stations. The figures show the number of passes that the SLR stations have retrieved from the Sentinel-3 and Sentinel-6 satellites during the entire satellite mission and also from the year 2023 in particular.

Figure 2-5 and Figure 2-6 show the temporal evolution on the **total number of satellite passes per GPS week** for the Sentinel-3A and Sentinel-3B. Figure 2-7 and Figure 2-8 for Sentinel-6A. This temporal evolution is shown for the entire missions in Figure 2-5 and Figure 2-7, whereas Figure 2-6 and Figure 2-8 only pays attention on the year 2023.

As seen in the figures, the number of Sentinel-3 and Sentinel-6A passes has remained quite constant (**between 50 and 150 passes**, a little bit higher for Sentinel-6A) during 2023. The number of passes is in line with the results obtained in the previous year.

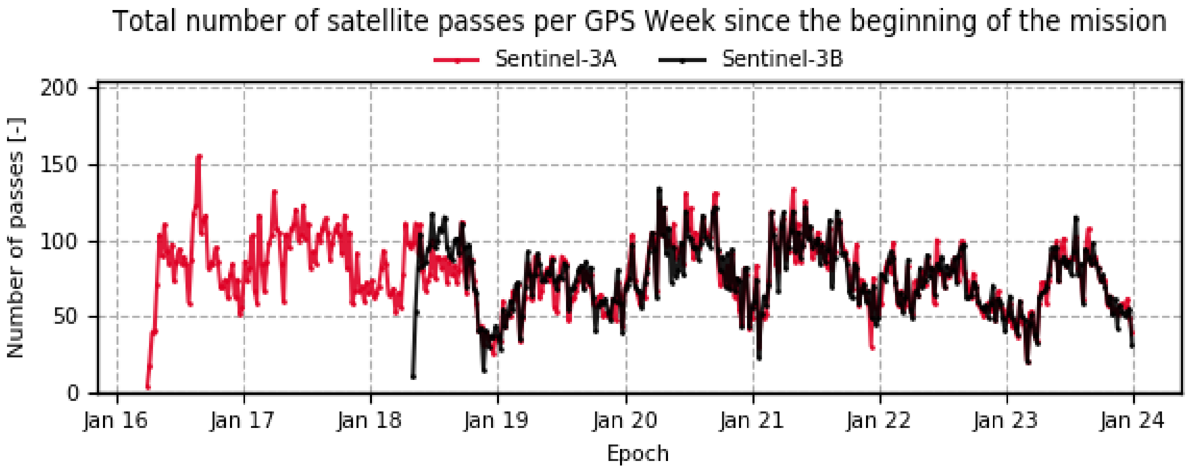


Figure 2-5: Total number of satellite passes per GPS week since the beginning of the satellite mission (Sentinel-3A and Sentinel-3B)

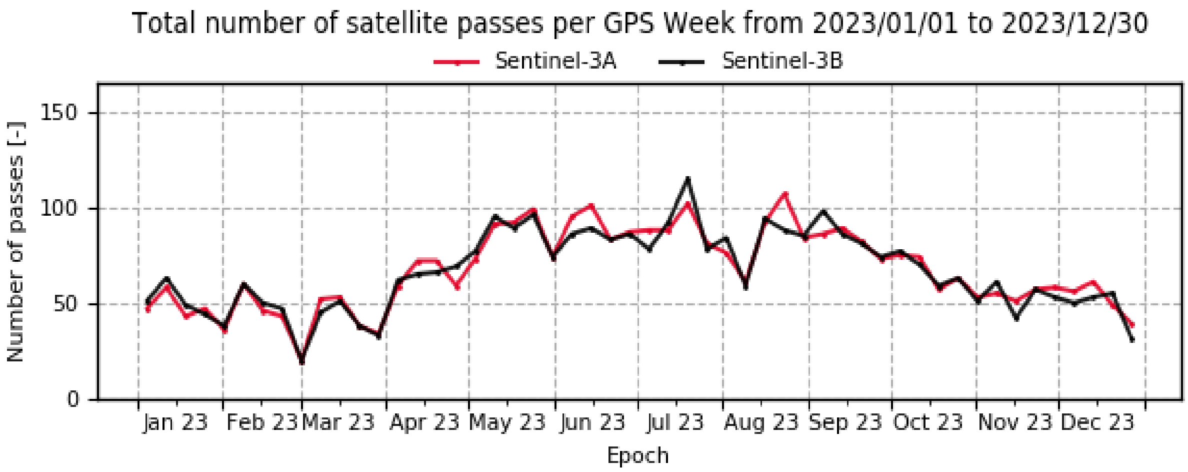


Figure 2-6: Total number of satellite passes per GPS week in 2023 (Sentinel-3A and Sentinel-3B)

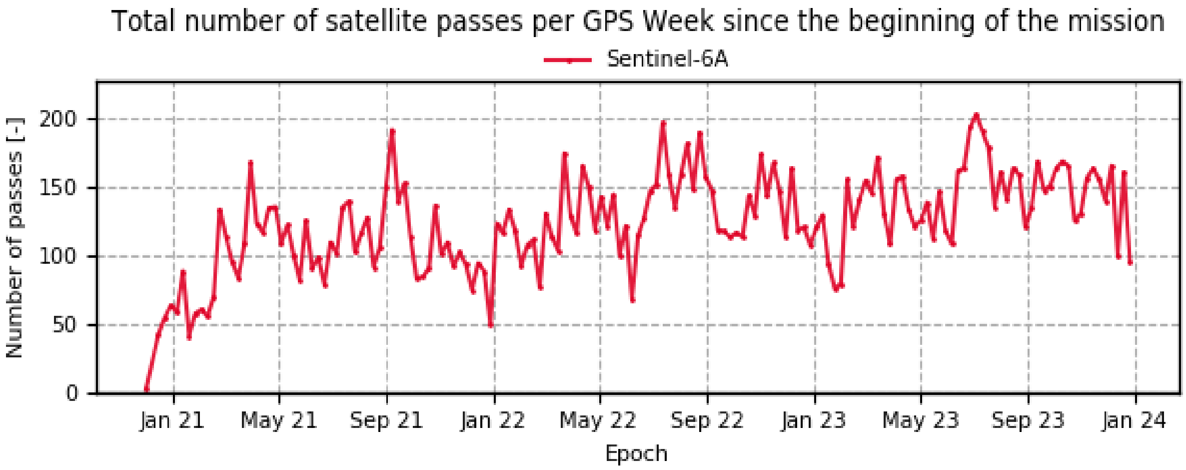


Figure 2-7: Total number of satellite passes per GPS week since the beginning of the satellite mission (Sentinel-6A)

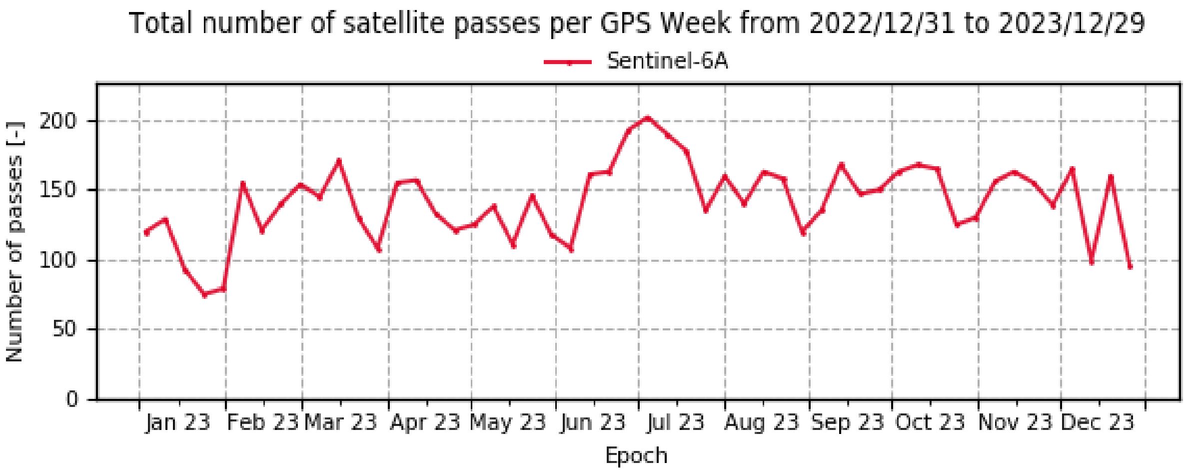


Figure 2-8: Total number of satellite passes per GPS week in 2023 (Sentinel-6A)

On the other hand, Figure 2-9 to Figure 2-12 present the **total number of satellite passes per SLR station**.

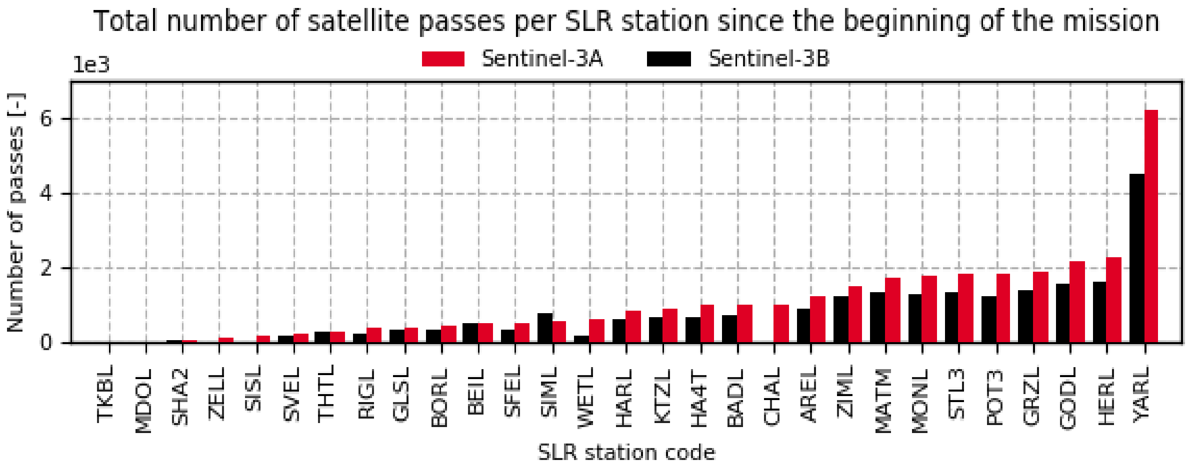


Figure 2-9: Total number of satellite passes per SLR station since the beginning of the satellite mission (Sentinel-3A and Sentinel-3B)

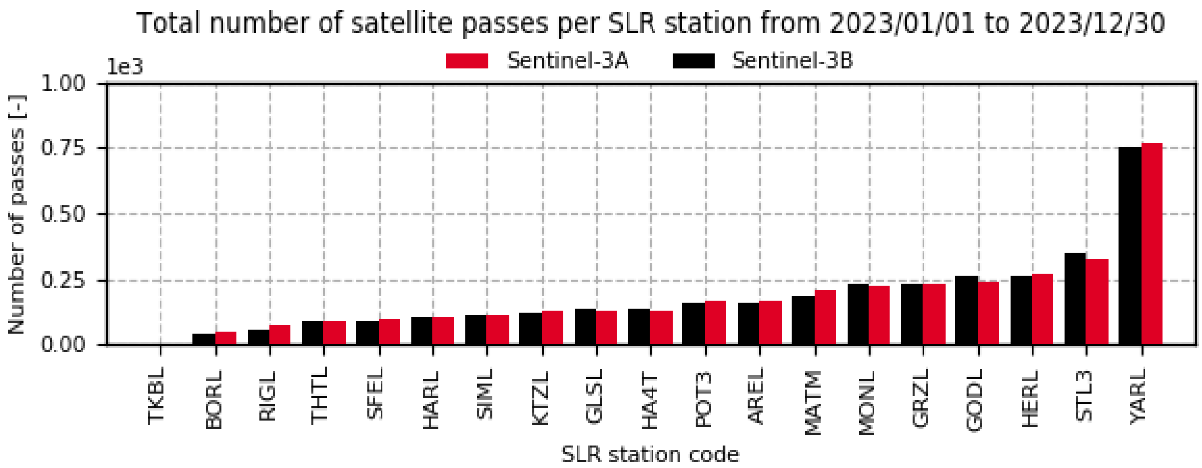


Figure 2-10: Total number of satellite passes per SLR station in 2023 (Sentinel-3A and Sentinel-3B)

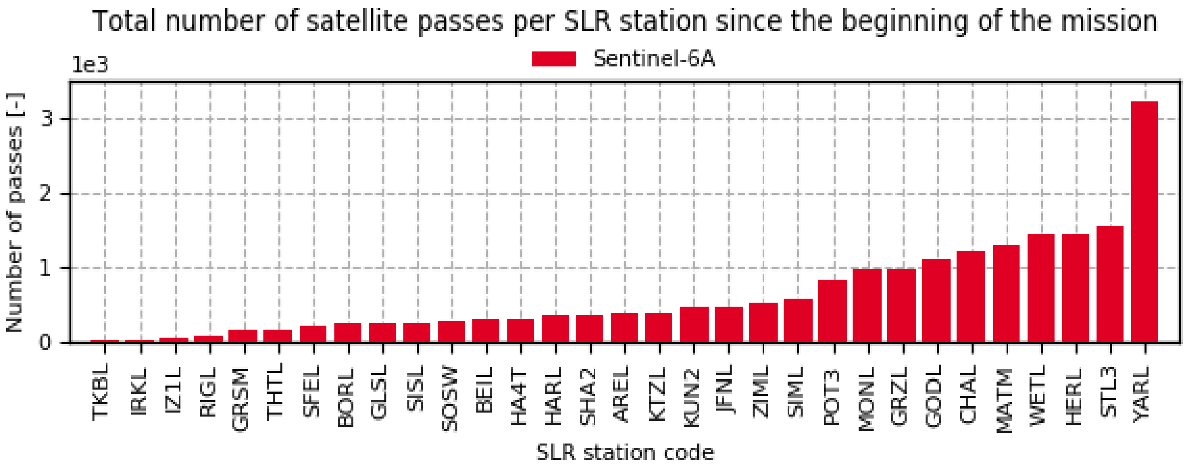


Figure 2-11: Total number of satellite passes per SLR station since the beginning of the satellite mission (Sentinel-6A)

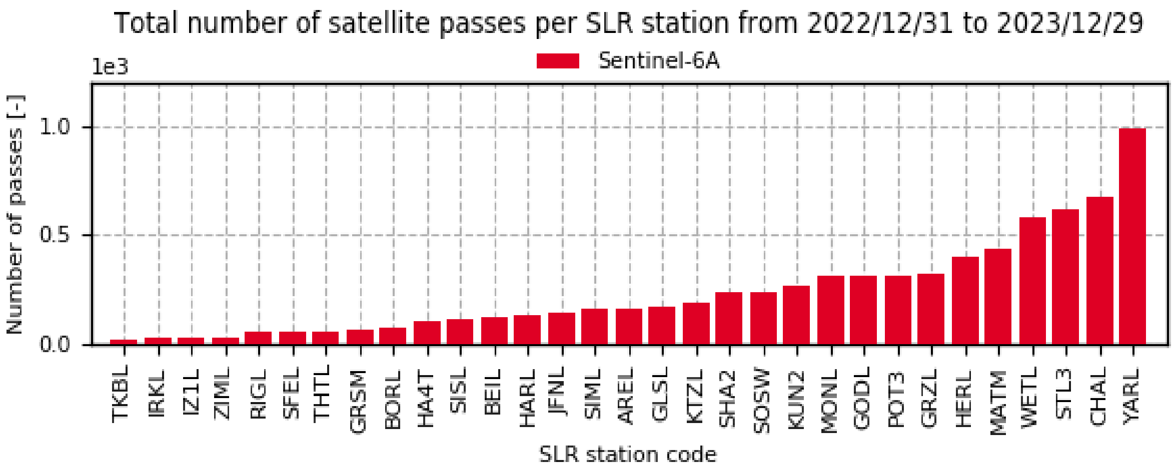


Figure 2-12: Total number of satellite passes per SLR station in 2023 (Sentinel-6A)

3. VALIDATION OF THE SENTINEL-3 AND -6A ORBIT SOLUTIONS

The SLR observations provided by the SLR stations have proven to be of high value in order to validate the precise Sentinel-3 and -6 orbit solutions being generated, for example, by the CPOD Service among others. However, not only the CPOD Service may benefit of an independent orbit validation given by the ILRS community but also the ILRS community itself may also receive some feedback in return about such validation, which may be used to improve the configuration network of the SLR stations.

This section has two main objectives: (a) validate the Sentinel-3 and -6 orbit solutions created on different centres, which do not make use of SLR data for generating their solutions, and (b) prove that including an estimated range bias on each SLR station may benefit the final validation outcome.

To that end, the section will be organised as follows:

- Firstly, a Sentinel-3 and -6 combined orbit solution for each satellite will be generated by merging appropriately all Sentinel-3 and -6 orbit solutions given by different centres.
- Secondly, the accepted observation that the SLR stations have retrieved from the tracking of Sentinel-3 and -6 during the reported period will be computed.
- Then, an estimation of the range biases of each SLR station will be performed from the combined orbit solutions previously obtained. These biases are computed for elevations higher than 10 degrees and estimating a single value using data from all three satellites per month.
- Finally, the validation of all Sentinel-3 and -6 orbit solutions will be evaluated by using the estimated range biases.

3.1. CALCULATION OF THE SENTINEL-3 AND -6A COMBINED ORBIT SOLUTION

The Sentinel-3 and -6 orbit solutions are currently being computed by several centres that conform the Copernicus POD Quality Working Group (QWG), which is intended to ensure the good quality of the products generated by the CPOD Service. The centres contributing to the combined solution are: AIUB, CNES, CPOD, DLR, ESOC, GFZ, JPL, TUD, TUG and TUM.

Table 3-1 lists all the Sentinel-3 and -6 orbit solutions that will be used in the present analysis. These orbit solutions are based on very similar GNSS processing strategies, although using different processing schemes, models and software:

- The CNES orbit solution includes DORIS observations along with the GPS data.
- The CPOF is a solution reprocessed by the CPOD Service to overcome the typical problems that arise operationally. It incorporates the latest models: ITRF2020 seasonal geocenter motion model, COST-G model and a yaw bias correction for Sentinel-6A. Further details on the operational CPOD modelling standards are available in the CPOD Product Handbook [RD.3].
- The combined orbit solution (labelled as COMB) is then obtained from a combination of all orbit solutions of the centres mentioned above. These orbit solutions are properly weighted by following an IGS-like approach used by the International GNSS Service (IGS) to finally generate the COMB orbit solution. Further details on the algorithm to compute the combined solution are available in the CPOD Regular Service Review report [RD.4].

None of the centres uses the SLR observations in the determination process, which allow the SLR data to be used as an independent means to validate the orbital accuracy of the orbit solutions of all centres. Moreover, CNES and CPOF stand out because they are the operational providers of orbit solutions for S3 and S6 missions.

Table 3-1: List of the centres providing orbit solutions for the generation of the combined orbit solution (labelled as COMB) of the Sentinel-3 and -6 satellites

Name of centre	Label/s of the orbit solution/s provided
Centre National d'Études Spatiales (CNES)	CNES
Copernicus Precise Orbit Determination (CPOD) Service	CPOF
Combined, using orbits from: AIUB, CNES, CPOD, DLR, ESOC, GFZ, JPL, TUD, TUG and TUM	COMB

Figure 3-1, Figure 3-3 and Figure 3-5 show the orbital comparisons (3D RMS) between the CNES and CPOF orbit solutions of all centres and the final COMB orbit solution calculated from them for Sentinel-3A, Sentinel-3B and Sentinel-6A satellites, respectively. The statistical outcome of such comparisons has been gathered in Figure 3-2, Figure 3-4 and Figure 3-6 for the corresponding satellites. From the analysis of these figures, it can be said that the vast majority of the orbit solutions are close to the COMB orbit solution (between 0.5 and 1.5 cm in mean). It can be concluded that all orbit solutions are of good quality.

The notable difference between the results obtained for both solutions is due to a different geocenter motion model, not because of a lower quality of the CNES solution:

- Combined solution is generated from orbits mostly in center of mass (CoM), in which no solution incorporates any seasonal geocenter motion model except for CNES.
- CNES applies a different seasonal geocenter motion model, which is not removed for orbital comparisons or accounted for in the combination.
- In this sense, the CPOF solution is more aligned to the COMB solution whereas the CNES solution shows the different center of mass realisation due to their modelling.

More information on the orbit validation can be found in [RD.4].

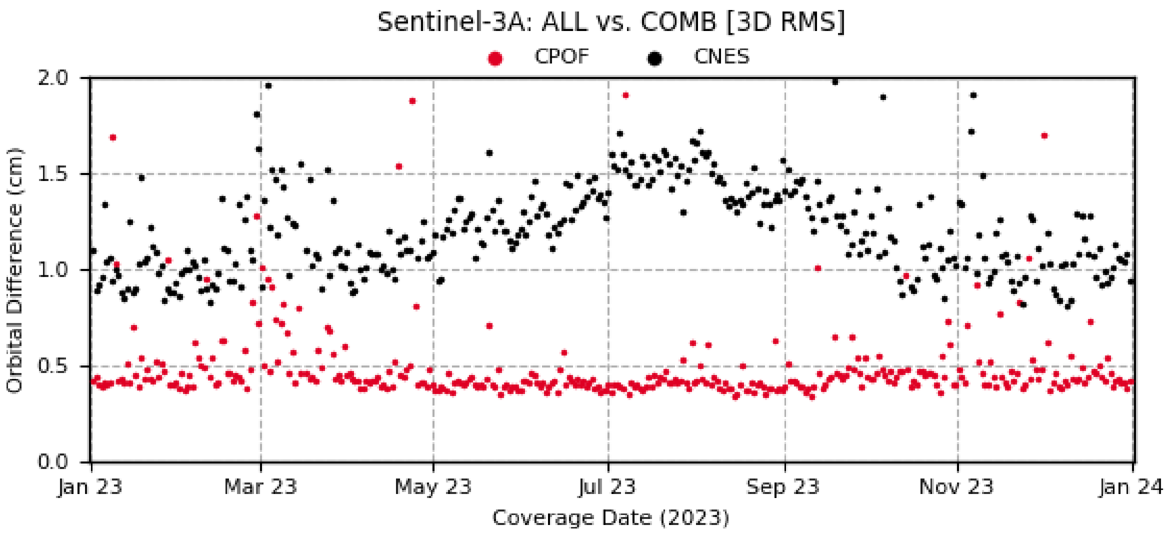


Figure 3-1: Orbital comparisons [3D RMS; cm] between CPOF and CNES Sentinel-3A orbit solution and the Sentinel-3A combined orbit solution

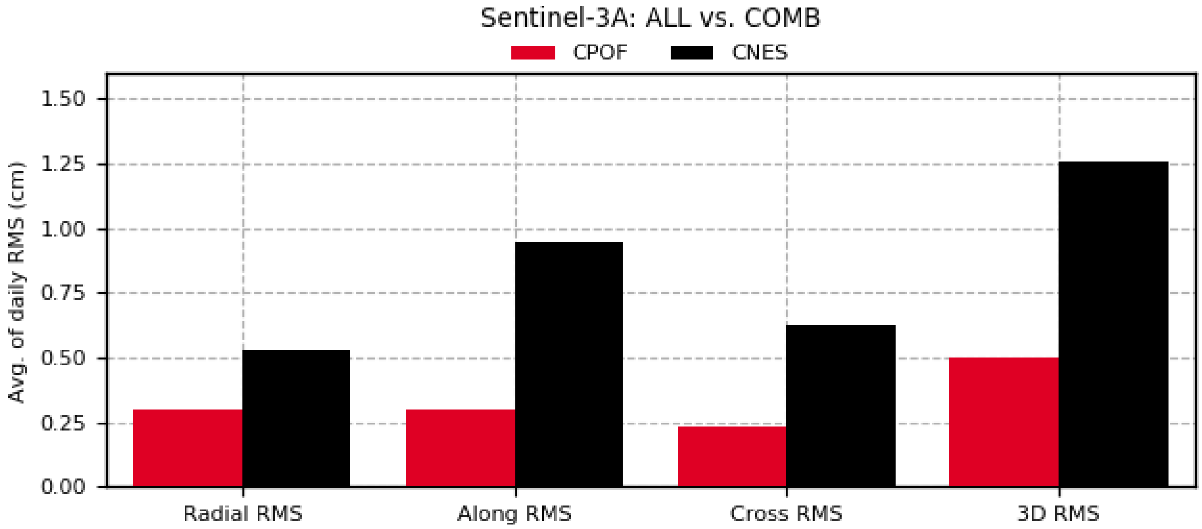


Figure 3-2: Mean and STD of the orbital comparisons [3D RMS; cm] between CPOF and CNES Sentinel-3A orbit solution and the Sentinel-3A combined orbit solution

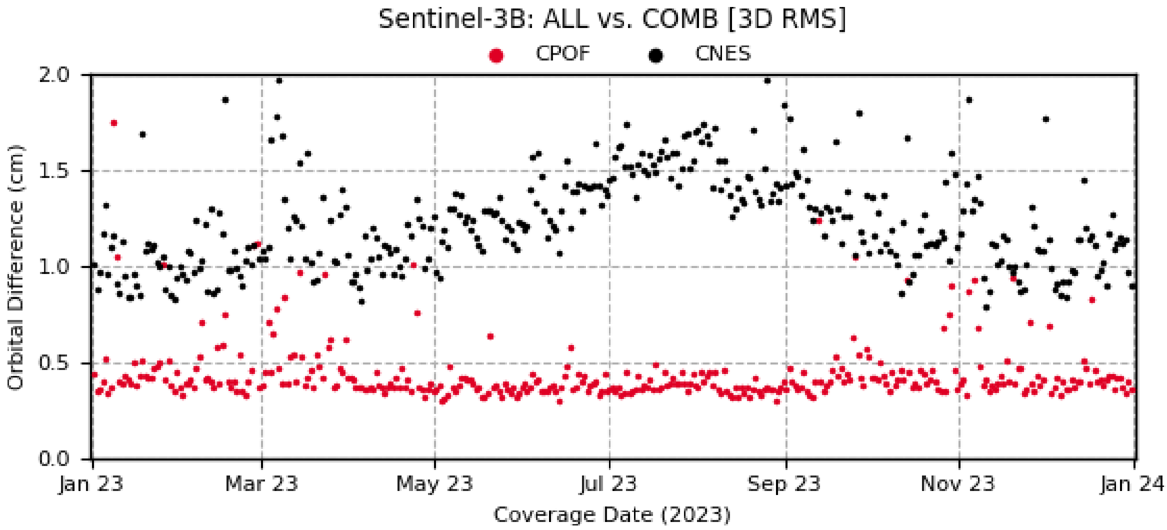


Figure 3-3: Orbital comparisons [3D RMS; cm] between CPOF and CNES Sentinel-3B orbit solution and the Sentinel-3B combined orbit solution

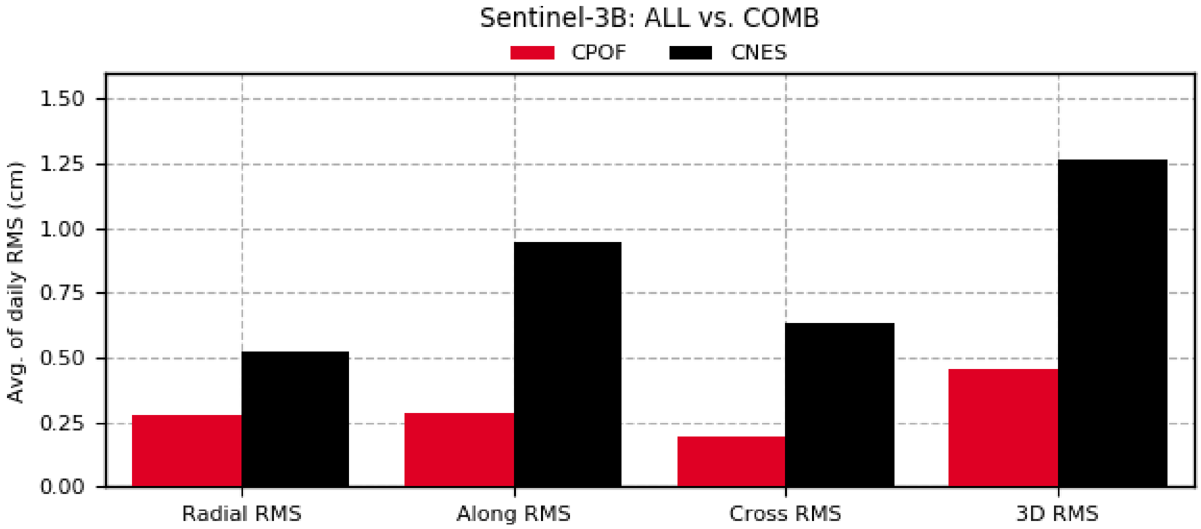


Figure 3-4: Mean and STD of the orbital comparisons [3D RMS; cm] between CPOF and CNES Sentinel-3B orbit solution and the Sentinel-3B combined orbit solution

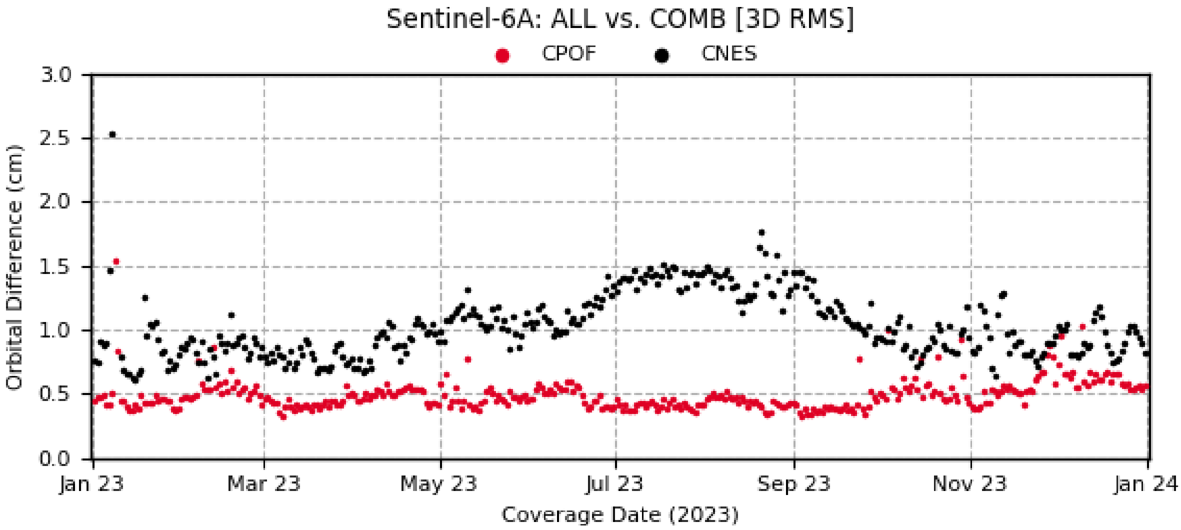


Figure 3-5: Orbital comparisons [3D RMS; cm] between CPOF and CNES Sentinel-6A orbit solution and the Sentinel-6A combined orbit solution

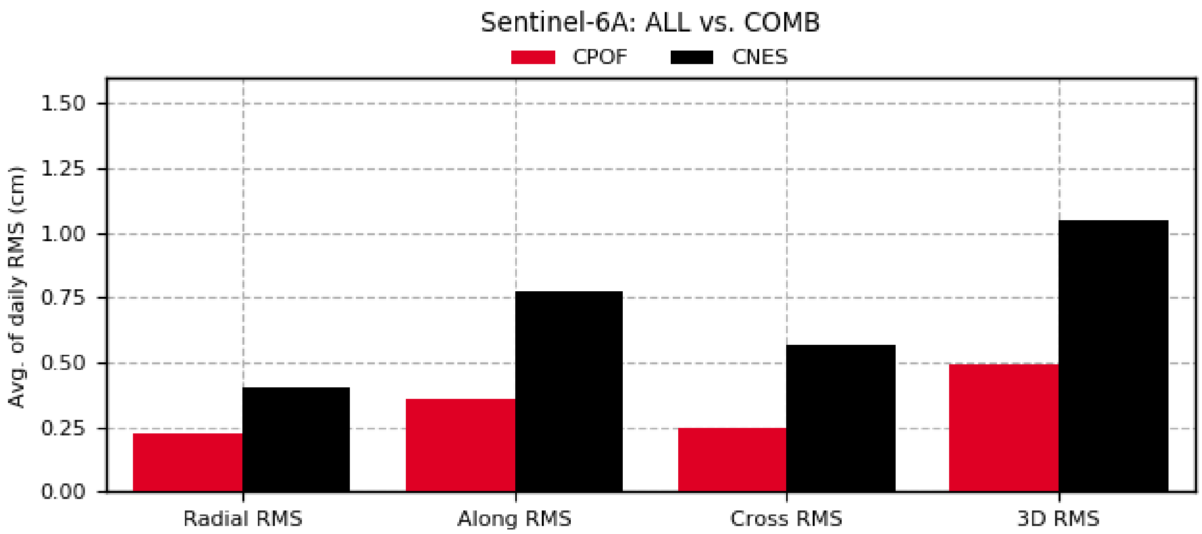


Figure 3-6: Mean and STD of the orbital comparisons [3D RMS; cm] between CPOF and CNES Sentinel-6A orbit solution and the Sentinel-6A combined orbit solution

The following tables gather the statistical outcome of the previous figures adding the results for each satellite component. Note that the Sentinel-3 and Sentinel-6A orbit solutions must present high accuracy on the radial component as the altimetry applications demand it.

Table 3-2: Summary of the mean, and STD values per satellite component of the orbital comparisons between CPOF and CNES Sentinel-3A orbit solution and the Sentinel-3A combined orbit solution during 2023

Orbit solution	Sentinel-3A [cm]							
	Radial RMS		Along-track RMS		Cross-track RMS		3D RMS	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
CPOF	0.30	0.09	0.30	0.28	0.23	0.07	0.50	0.28
CNES	0.53	0.16	0.94	0.42	0.62	0.10	1.26	0.43

Table 3-3: Summary of the mean, and STD values per satellite component of the orbital comparisons between CPOF and CNES Sentinel-3B orbit solution and the Sentinel-3B combined orbit solution during 2023

Orbit solution	Sentinel-3B [cm]							
	Radial RMS		Along-track RMS		Cross-track RMS		3D RMS	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
CPOF	0.27	0.10	0.28	0.24	0.20	0.06	0.45	0.25
CNES	0.52	0.14	0.95	0.34	0.63	0.07	1.26	0.33

Table 3-4: Summary of the mean, and STD values per satellite component of the orbital comparisons between CPOF and CNES Sentinel-6A orbit solution and the Sentinel-6A combined orbit solution during 2023

Orbit solution	Sentinel-6A [cm]							
	Radial RMS		Along-track RMS		Cross-track RMS		3D RMS	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
CPOF	0.22	0.05	0.36	0.11	0.24	0.06	0.49	0.12
CNES	0.41	0.10	0.77	0.24	0.57	0.28	1.05	0.35

3.2. SLR OBSERVATIONS

Since all orbit solutions are computed using the same set of observations from GNSS, an independent technique such as the SLR is needed to guarantee that the previous orbit solutions have no systematic biases affecting them all equally. An analysis of the SLR residuals can consequently be used to identify these possible biases. Keep in mind that the SLR residuals are nothing more than the differences between the SLR observations that would be obtained for a specific orbit solution and those SLR observations provided by the SLR stations themselves. The following figures show the amount of the SLR observations delivered by the SLR stations during the time period evaluated.

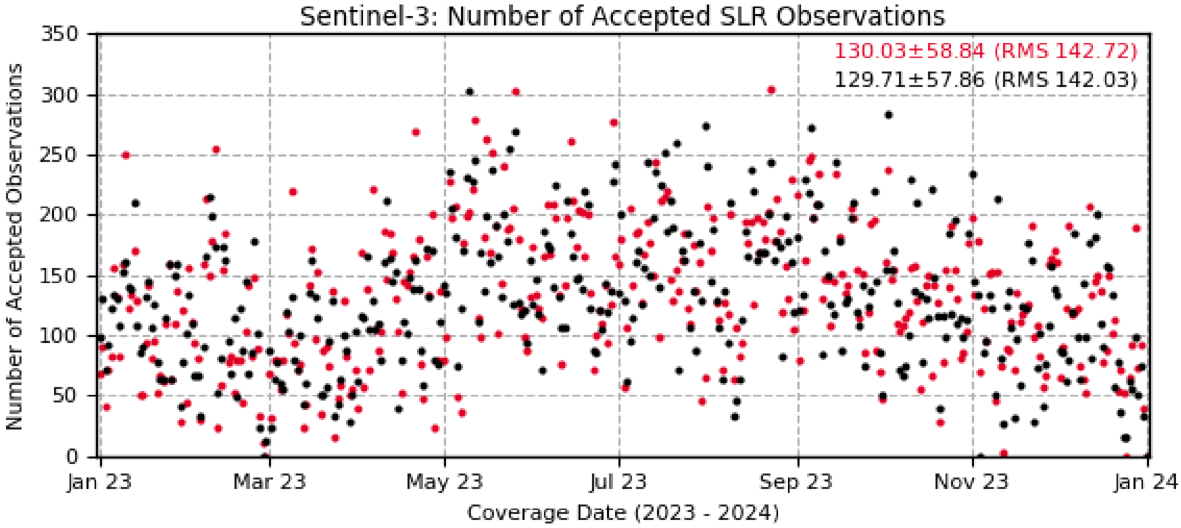


Figure 3-7: Daily total number of the accepted SLR observations of all SLR stations tracking Sentinel-3A and Sentinel-3B satellites in 2023

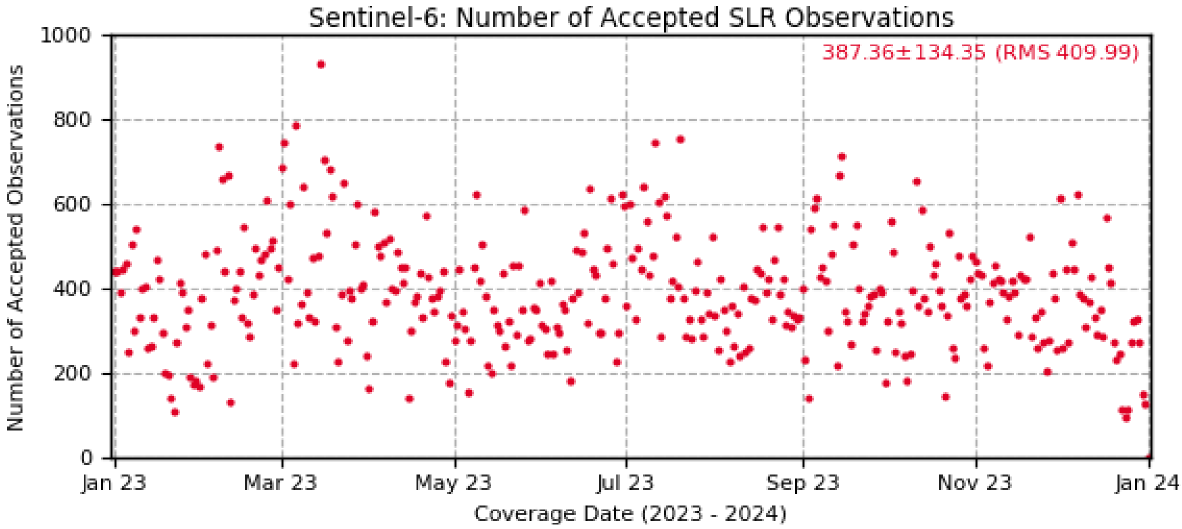


Figure 3-8: Daily total number of the accepted SLR observations of all SLR stations tracking Sentinel-6A satellite in 2023

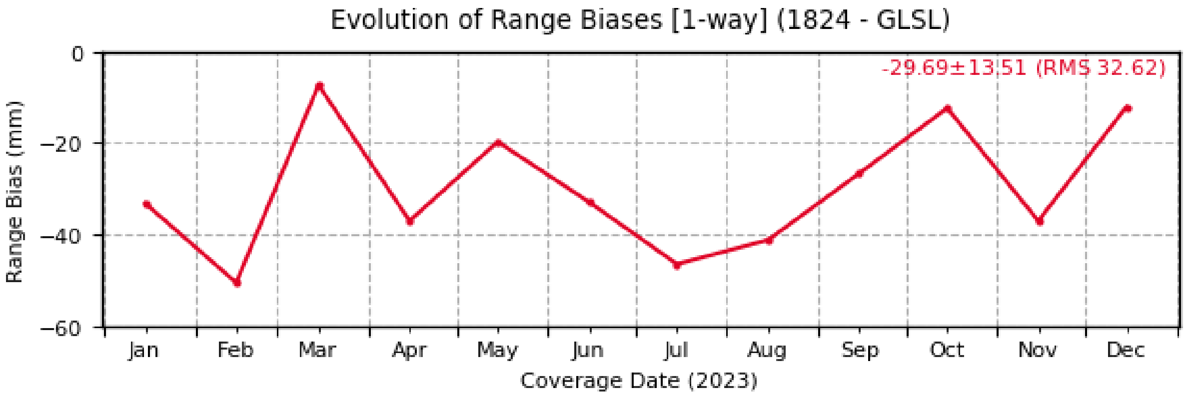
Prior to the calculation of the SLR residuals, it has been deemed worth to estimate a range bias for each SLR station in order to improve the statistical outcome on the residuals.

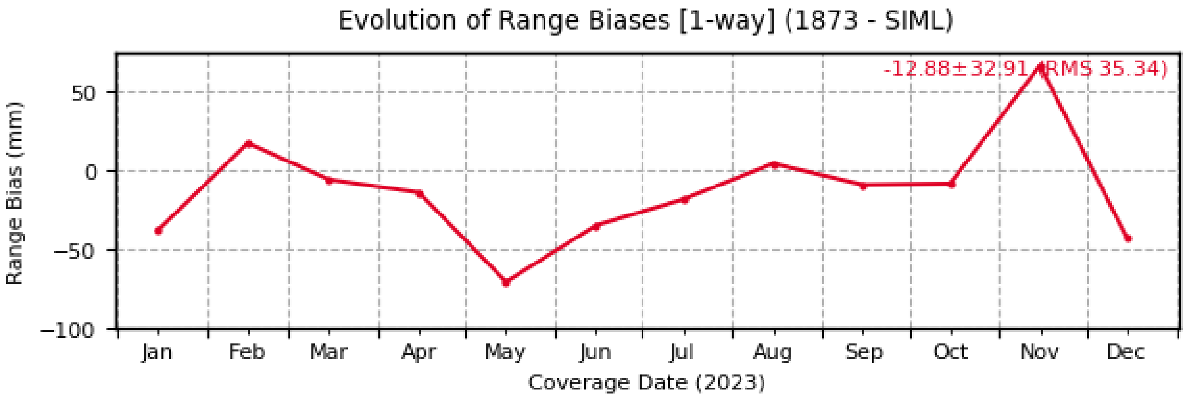
3.3. ESTIMATION OF THE RANGE BIASES FOR ALL SLR STATIONS

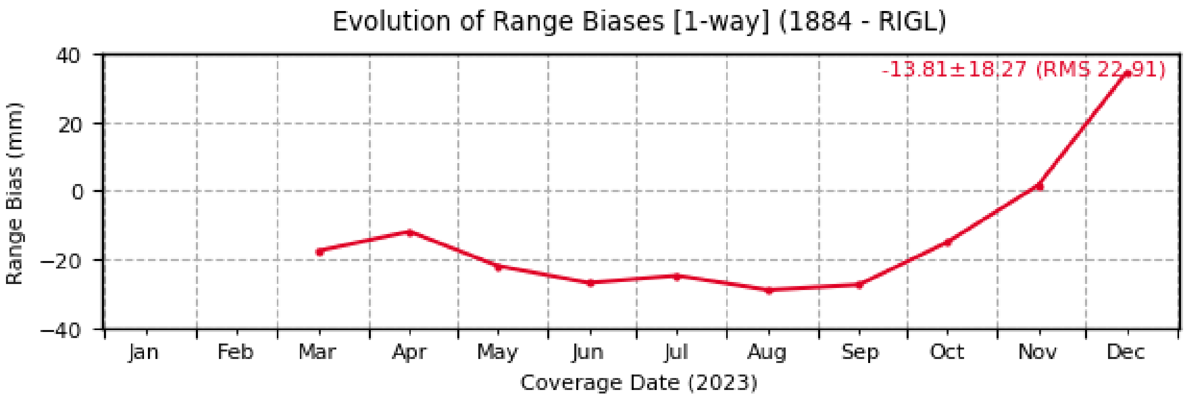
A range bias per station is estimated by fixing the Sentinel-3 and -6A combined orbit solution (COMB) and estimating the range bias of the SLR observations over one month. Coordinates from **SLR2020** standard are used. Eccentricities have been applied to the coordinates of the stations accordingly (see Section 6). Moreover, in the residual computation and in the estimation of the range biases, no seasonal geocenter motion model has been included, because this is still under evaluation by the CPOD QWG.

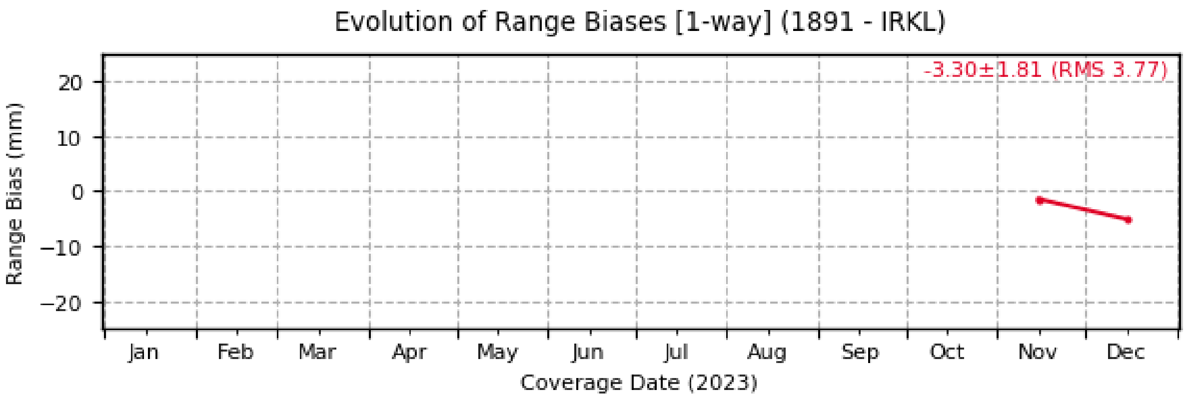
The following figure includes the plots of the temporal evolution of these estimated range biases for each SLR station assessed. These biases are computed using the COMB solution, for elevations higher than 10 degrees, and estimating a single value for all satellites per month.

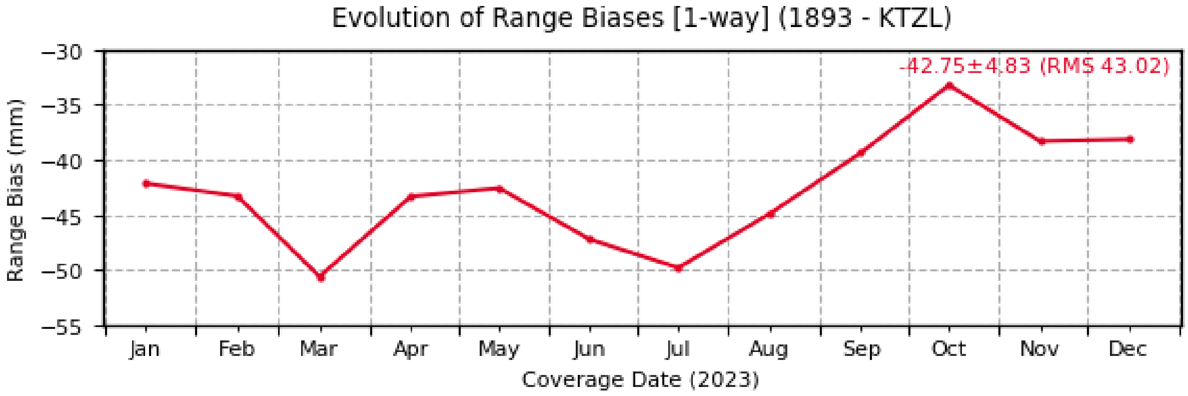
It is important to remark that there are some stations that have a particular behavior. On the one hand, we have observed that not all observations from the station **7306 – TKBL** have the same frequency for the year 2023. Two different frequencies were used: 532Hz, for most of the days; and 1064Hz, for a few observations. During the bias estimation process, this resulted in two different biases being computed because of internal SW considerations. In order to obtain only one bias, we discarded the observations for the 1064Hz frequency since they were only present in one day. Therefore, we only used the observations corresponding to the frequency of 532 Hz to obtain the TKBL bias. On the other hand, station **7810 – ZIML** does not appear in these plots because all its observations were rejected during the bias estimation process because of global rejection criteria, so no bias has been estimated.


Evolution of Range Biases [1-way] (1824 - GLSL)
-29.69±13.51 (RMS 32.62)
Range Bias (mm)
0
−20
−40
−60
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Coverage Date (2023)

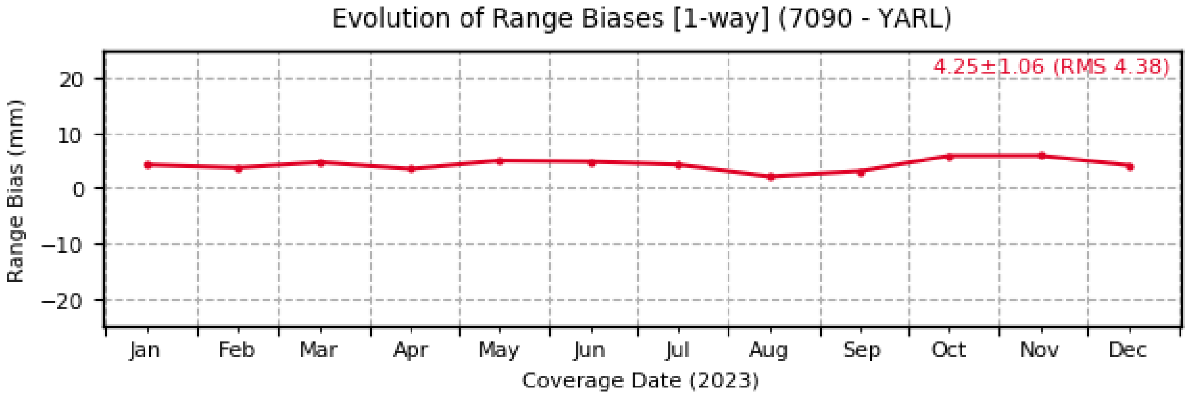

Evolution of Range Biases [1-way] (1873 - SIML)
-12.88±32.91 (RMS 35.34)
Range Bias (mm)
50
0
−50
−100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Coverage Date (2023)


Evolution of Range Biases [1-way] (1884 - RIGL)
-13.81±18.27 (RMS 22.91)
Range Bias (mm)
40
20
0
−20
−40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Coverage Date (2023)

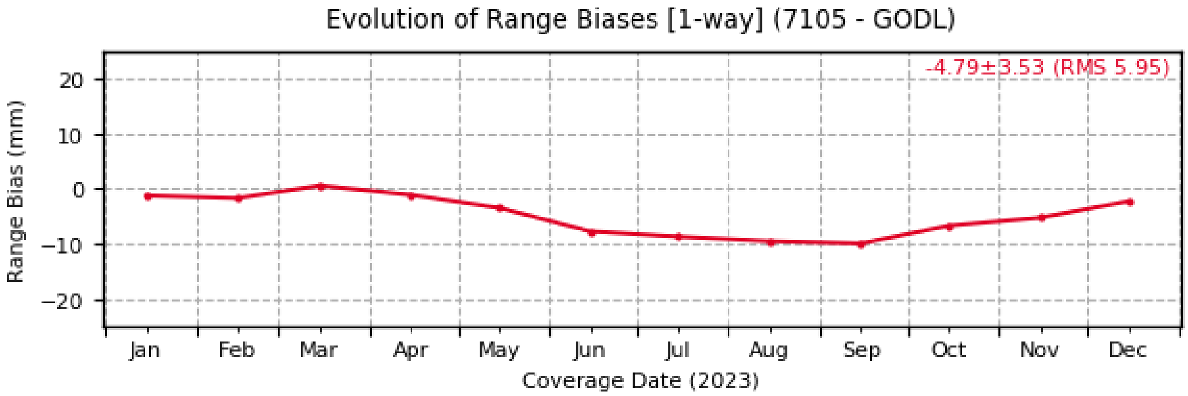

Evolution of Range Biases [1-way] (1891 - IRKL)
-3.30±1.81 (RMS 3.77)
Range Bias (mm)
20
10
0
−10
−20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Coverage Date (2023)



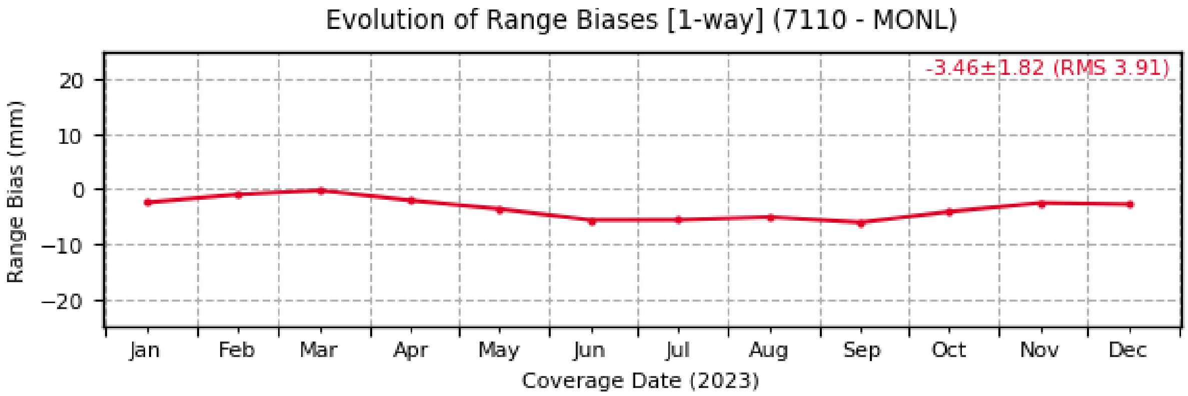
Evolution of Range Biases [1-way] (1893 - KTZL)
-42.75±4.83 (RMS 43.02)
Range Bias (mm)
−30
−35
−40
−45
−50
−55
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Coverage Date (2023)



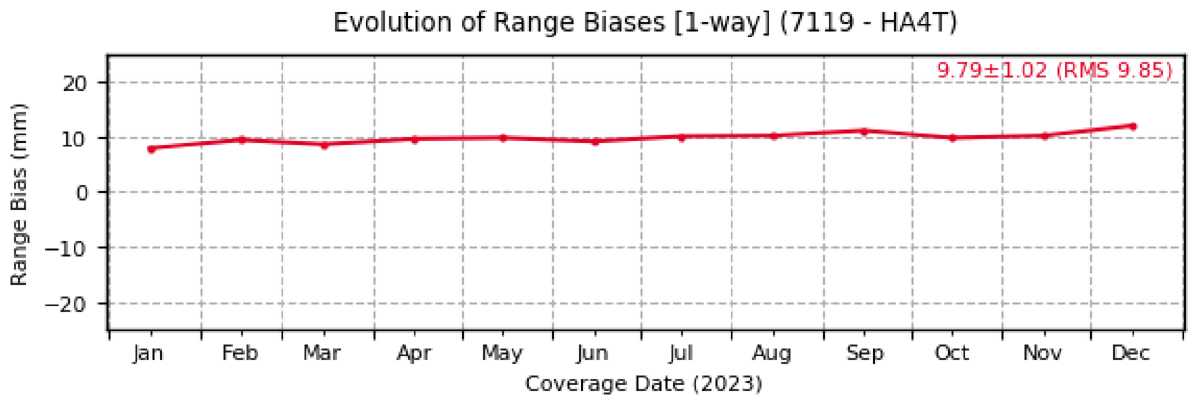
Evolution of Range Biases [1-way] (7090 - YARL)
4.25±1.06 (RMS 4.38)
Range Bias (mm)
20
10
0
−10
−20
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Coverage Date (2023)

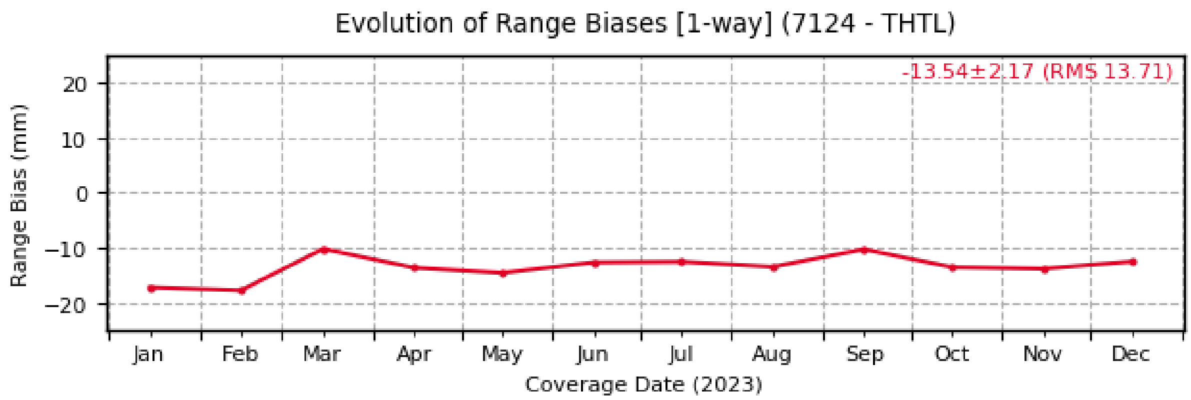


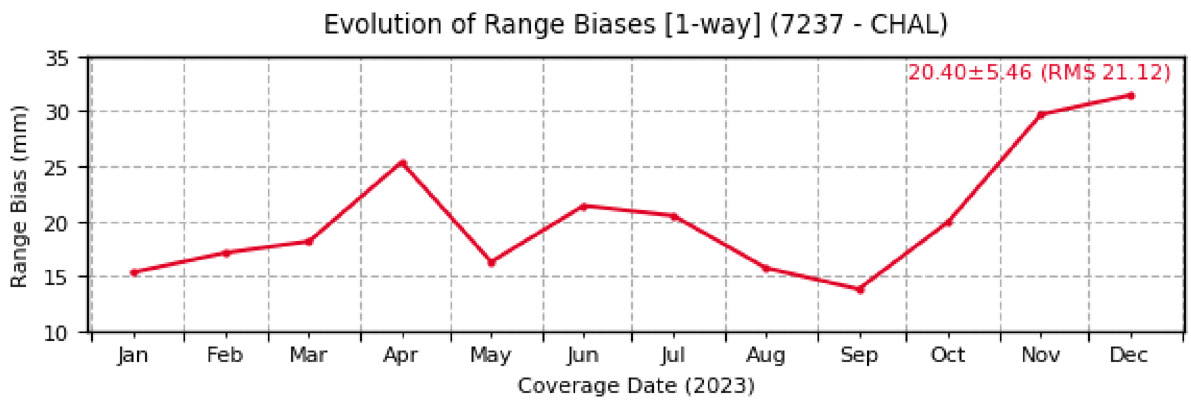
Evolution of Range Biases [1-way] (7105 - GODL)
-4.79±3.53 (RMS 5.95)
Range Bias (mm)
20
10
0
−10
−20
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Coverage Date (2023)

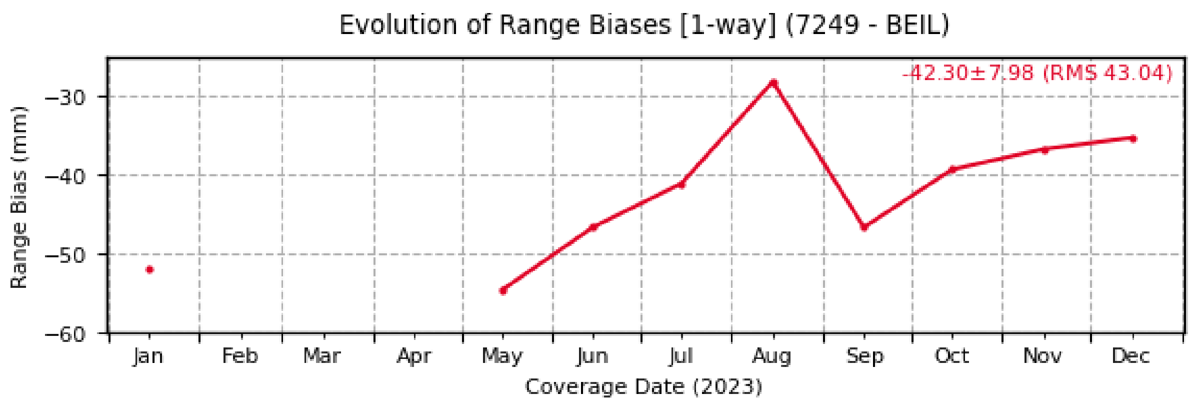


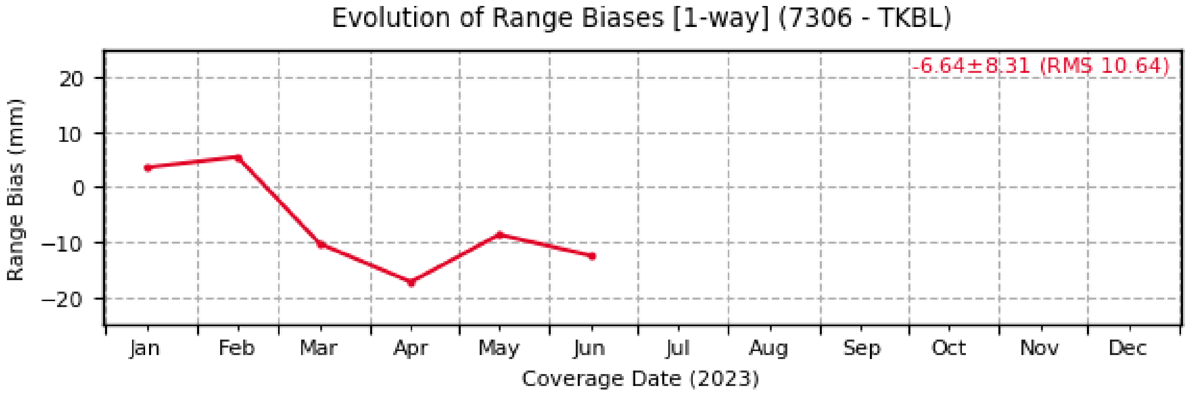
Evolution of Range Biases [1-way] (7110 - MONL)
-3.46±1.82 (RMS 3.91)
Range Bias (mm)
20
10
0
−10
−20
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Coverage Date (2023)

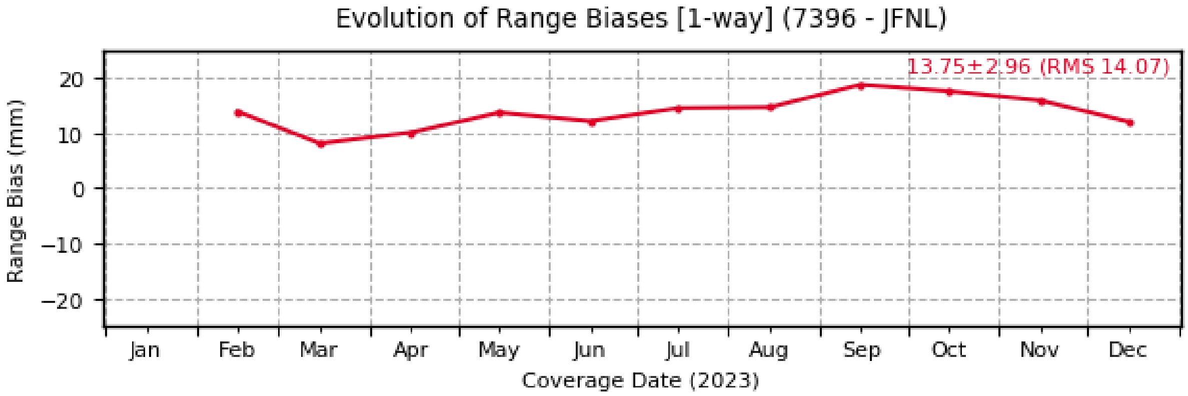

Evolution of Range Biases [1-way] (7119 - HA4T)
9.79±1.02 (RMS 9.85)
Range Bias (mm)
Coverage Date (2023)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

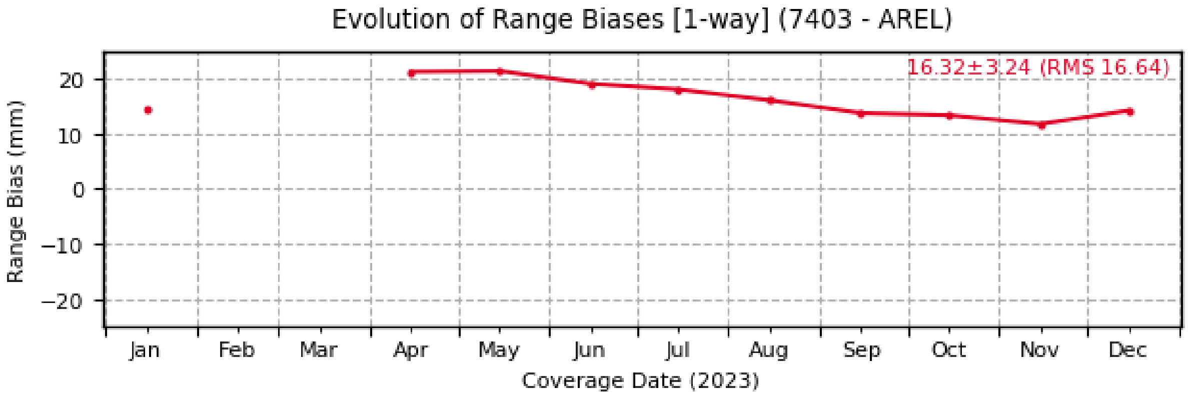

Evolution of Range Biases [1-way] (7124 - THTL)
-13.54±2.17 (RMS 13.71)
Range Bias (mm)
Coverage Date (2023)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

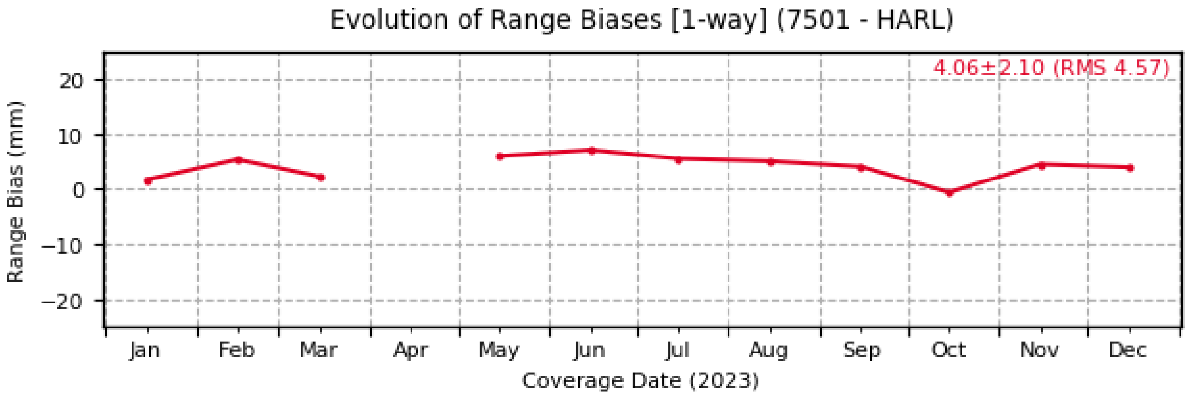

Evolution of Range Biases [1-way] (7237 - CHAL)
20.40±5.46 (RMS 21.12)
Range Bias (mm)
Coverage Date (2023)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

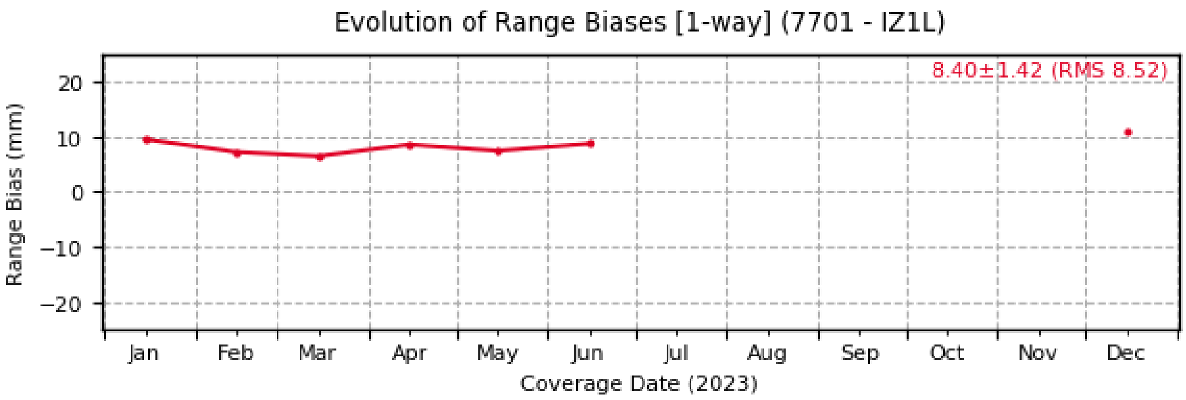

Evolution of Range Biases [1-way] (7249 - BEIL)
-42.30±7.98 (RMS 43.04)
Range Bias (mm)
Coverage Date (2023)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

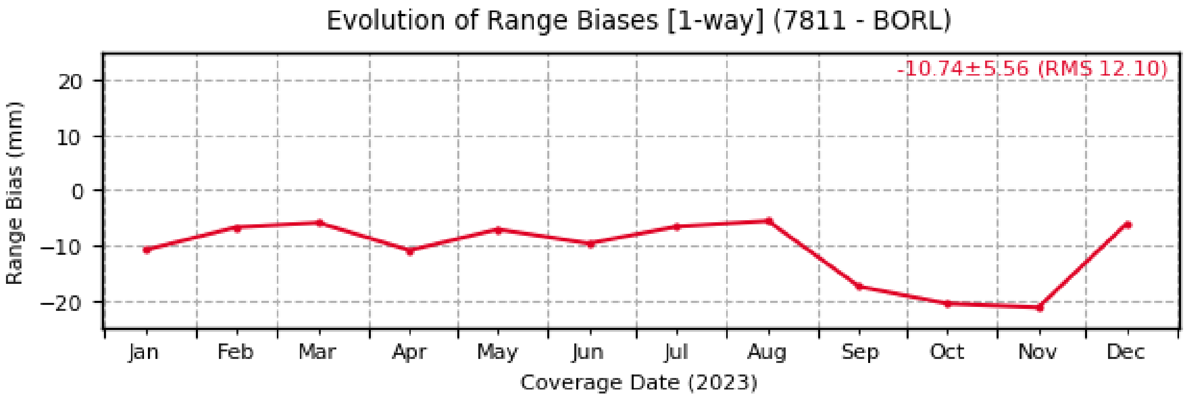

Evolution of Range Biases [1-way] (7306 - TKBL)
-6.64±8.31 (RMS 10.64)
Range Bias (mm)
Coverage Date (2023)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

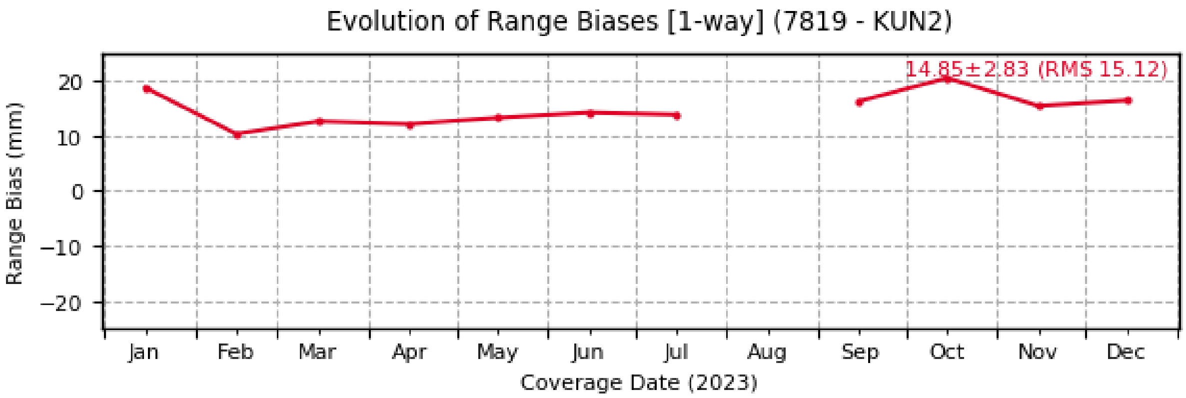

Evolution of Range Biases [1-way] (7396 - JFNL)
13.75±2.96 (RMS 14.07)
Range Bias (mm)
Coverage Date (2023)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

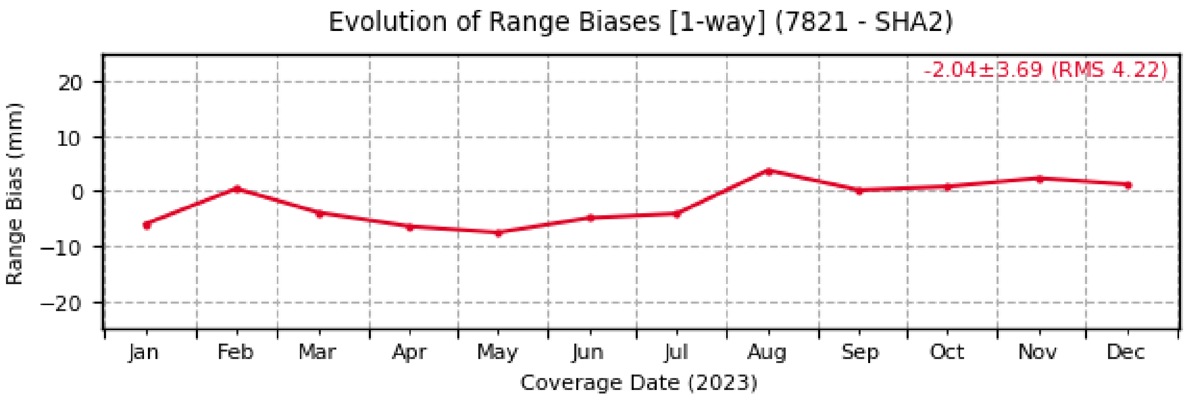

Evolution of Range Biases [1-way] (7403 - AREL)
16.32±3.24 (RMS 16.64)
Range Bias (mm)
Coverage Date (2023)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

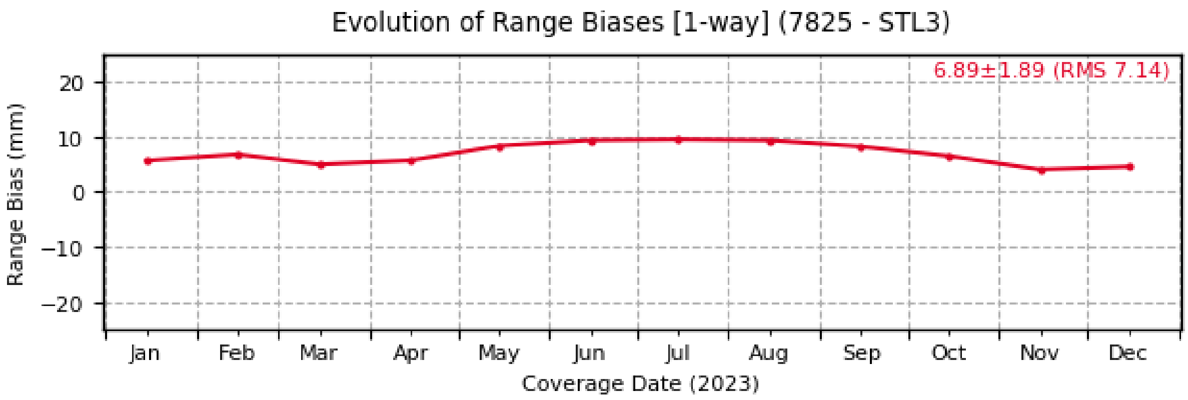

Evolution of Range Biases [1-way] (7501 - HARL)
4.06±2.10 (RMS 4.57)
Range Bias (mm)
Coverage Date (2023)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

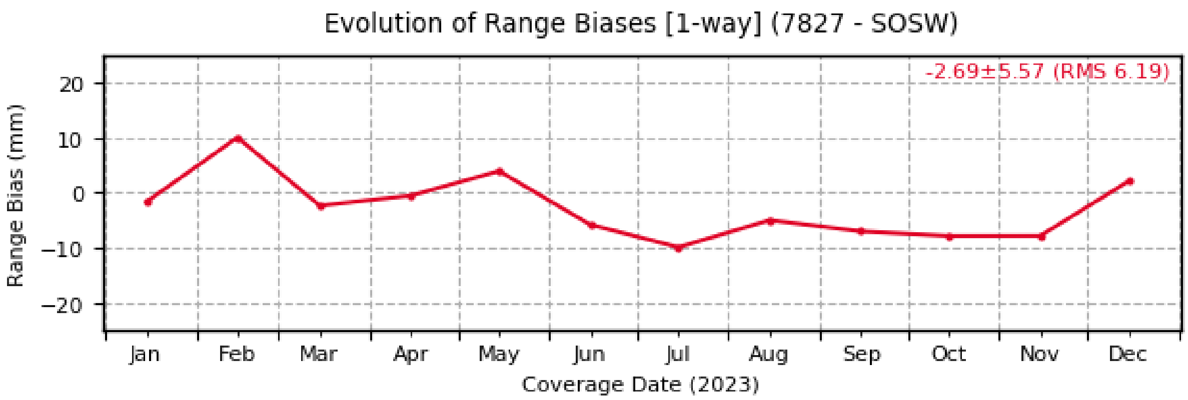

Evolution of Range Biases [1-way] (7701 - IZ1L)
8.40±1.42 (RMS 8.52)
Range Bias (mm)
20
10
0
−10
−20
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Coverage Date (2023)

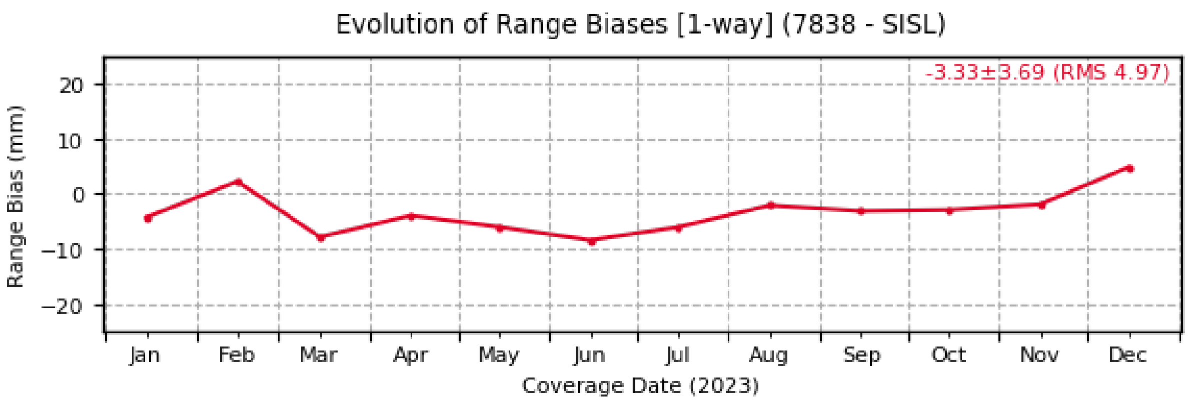

Evolution of Range Biases [1-way] (7811 - BORL)
-10.74±5.56 (RMS 12.10)
Range Bias (mm)
20
10
0
−10
−20
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Coverage Date (2023)

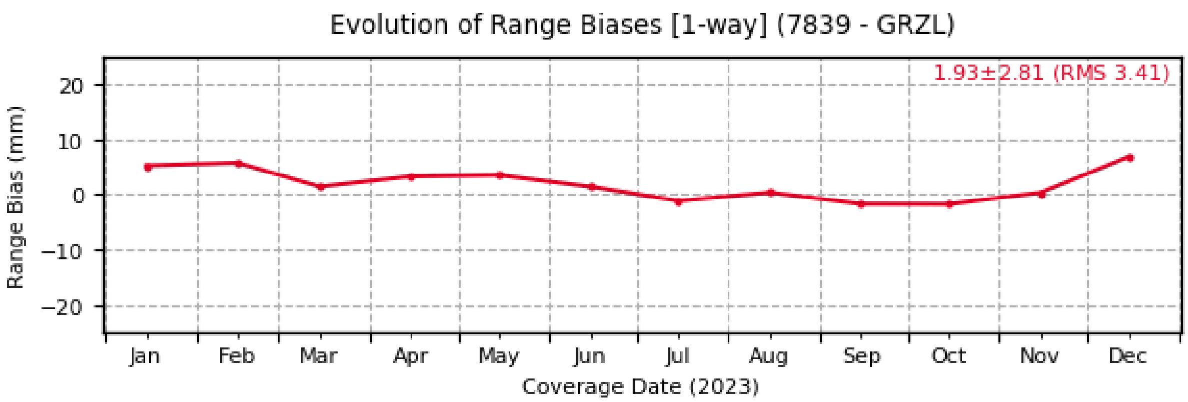

Evolution of Range Biases [1-way] (7819 - KUN2)
14.85±2.83 (RMS 15.12)
Range Bias (mm)
20
10
0
−10
−20
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Coverage Date (2023)

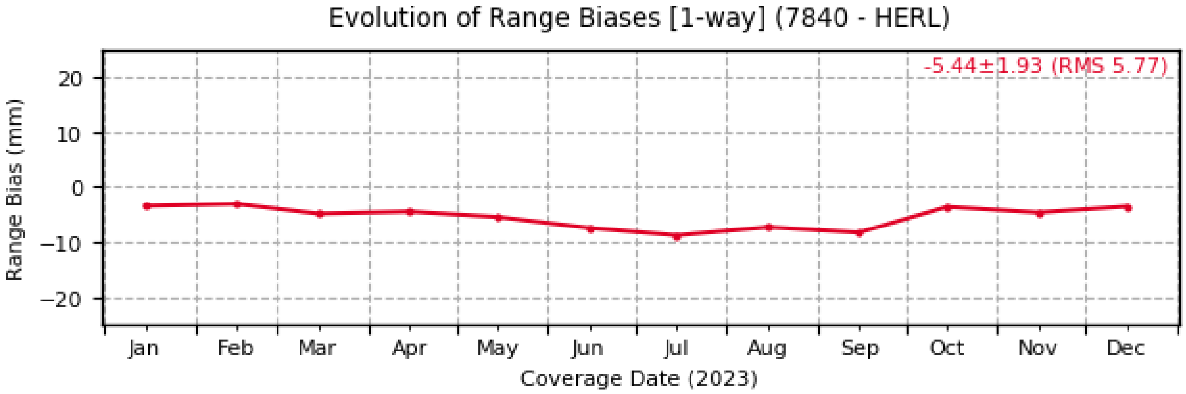

Evolution of Range Biases [1-way] (7821 - SHA2)
-2.04±3.69 (RMS 4.22)
Range Bias (mm)
20
10
0
−10
−20
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Coverage Date (2023)

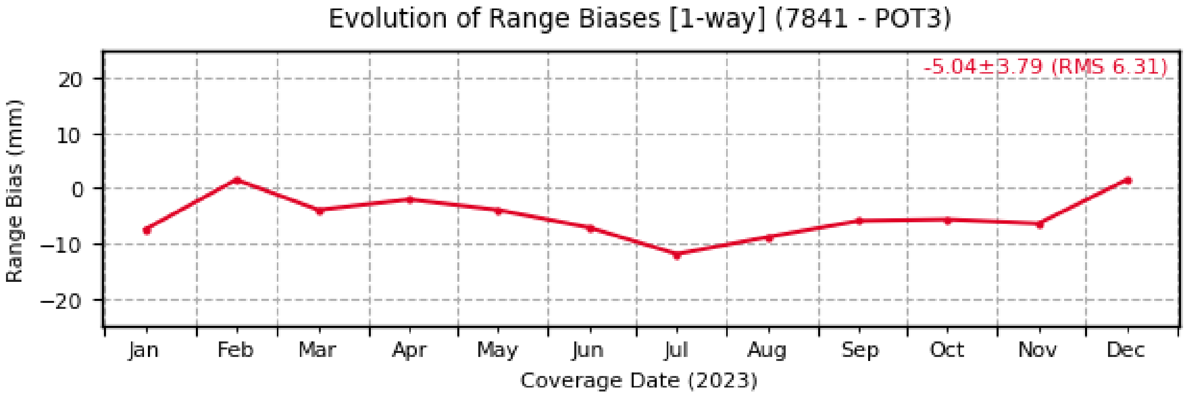

Evolution of Range Biases [1-way] (7825 - STL3)
6.89±1.89 (RMS 7.14)
Range Bias (mm)
Coverage Date (2023)

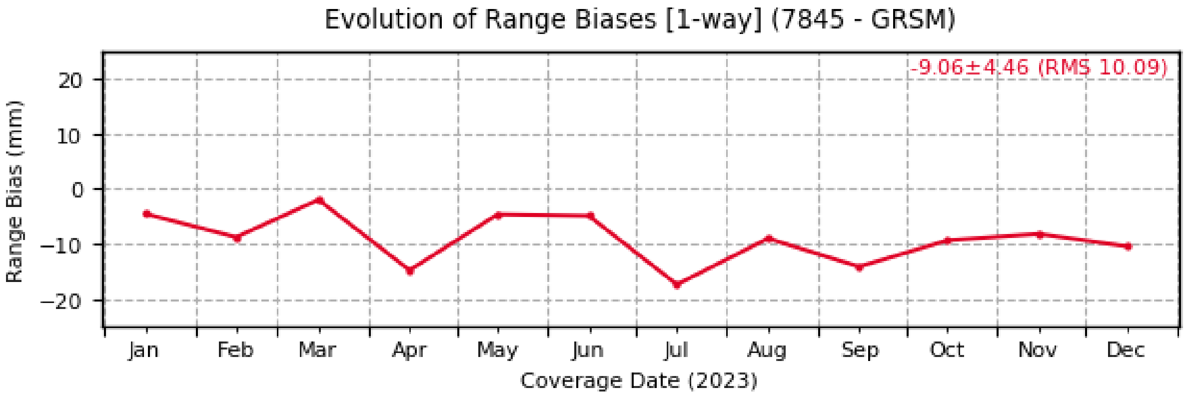

Evolution of Range Biases [1-way] (7827 - SOSW)
-2.69±5.57 (RMS 6.19)
Range Bias (mm)
Coverage Date (2023)


Evolution of Range Biases [1-way] (7838 - SISL)
-3.33±3.69 (RMS 4.97)
Range Bias (mm)
Coverage Date (2023)


Evolution of Range Biases [1-way] (7839 - GRZL)
1.93±2.81 (RMS 3.41)
Range Bias (mm)
Coverage Date (2023)


Evolution of Range Biases [1-way] (7840 - HERL)
-5.44±1.93 (RMS 5.77)
Range Bias (mm)
Coverage Date (2023)


Evolution of Range Biases [1-way] (7841 - POT3)
-5.04±3.79 (RMS 6.31)
Range Bias (mm)
Coverage Date (2023)


Evolution of Range Biases [1-way] (7845 - GRSM)
-9.06±4.46 (RMS 10.09)
Range Bias (mm)
Coverage Date (2023)

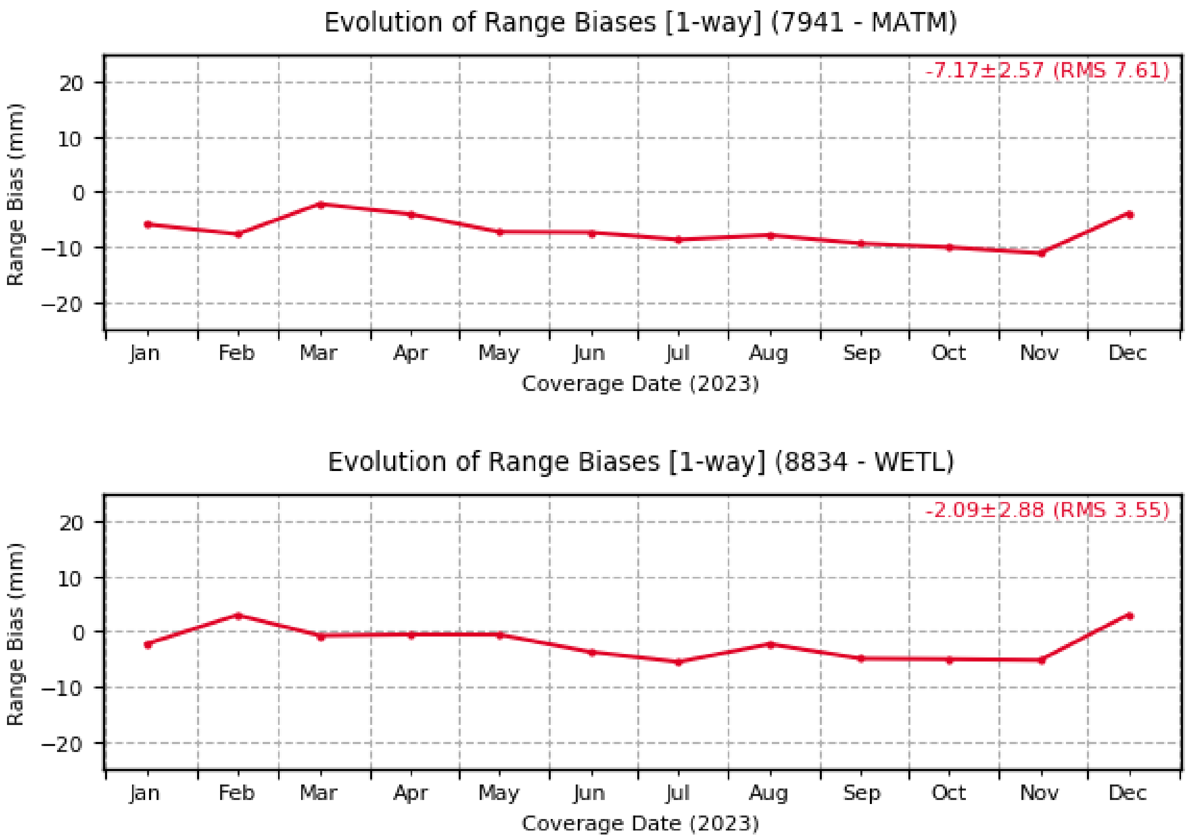
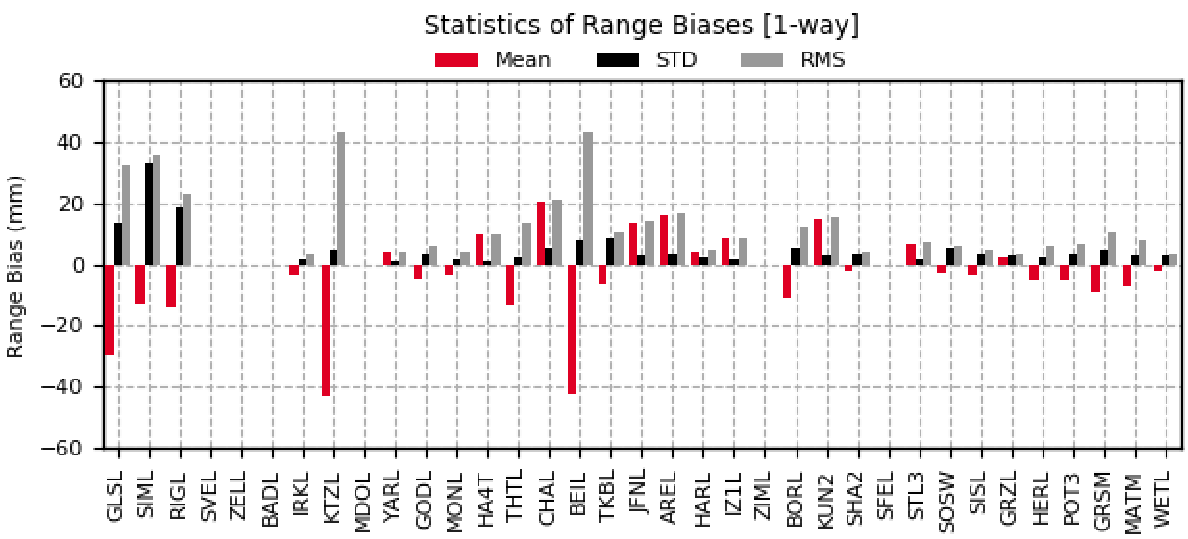


Figure 3-9: Evolution of the range biases [1-way; mm] calculated for each SLR station in 2023

The outcome of this figure is summarised in the following figure, where the mean, standard deviation and root mean square statistics of the range biases estimated above are shown. As seen in the figures, the vast majority of the SLR stations obtains statistical figures below 1.5 cm (in absolute value). There are only three SLR stations that present unusual values.



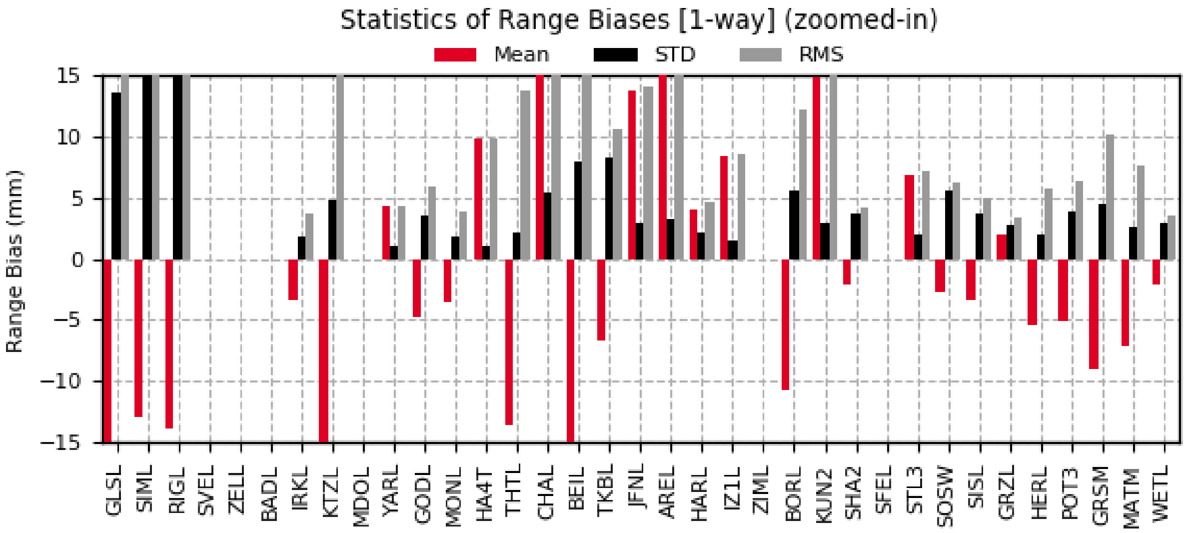


Figure 3-10: Mean, STD and RMS of the range biases [1-way; mm] of each SLR station (the figure below is a zoomed-in of the figure above)

Finally, following table gathers the mean value of the range biases estimated for each SLR station. These values have been fixed together with the corresponding COMB orbit solution on the processing to retrieve the SLR residuals shown in the following sub section.

Table 3-5: Mean value of the range biases [1-way; mm] of each SLR station in 2023 used to calculate the SLR residuals

SLR station		Mean value [mm]
Monument	Code	
1824	GLSL	-29.69
1873	SIML	-12.88
1884	RIGL	-13.81
1888	SVEL	-
1889	ZELL	-
1890	BADL	-
1891	IRKL	-3.30
1893	KTZL	-42.75
7080	MDOL	-
7090	YARL	4.25
7105	GODL	-4.79
7110	MONL	-3.46
7119	HA4T	9.79
7124	THTL	-13.54
7237	CHAL	20.40
7249	BEIL	-42.30
7306	TKBL	-6.64
7396	JFNL	13.75
7403	AREL	16.32
7501	HARL	4.06
7701	IZ1L	8.40

SLR station		Mean value [mm]
Monument	Code	
7810	ZIML	-
7811	BORL	-10.74
7819	KUN2	14.85
7821	SHA2	-2.04
7824	SFEL	-
7825	STL3	6.89
7827	SOSW	-2.69
7838	SISL	-3.33
7839	GRZL	1.93
7840	HERL	-5.44
7841	POT3	-5.04
7845	GRSM	-9.06
7941	MATM	-7.17
8834	WETL	-2.09

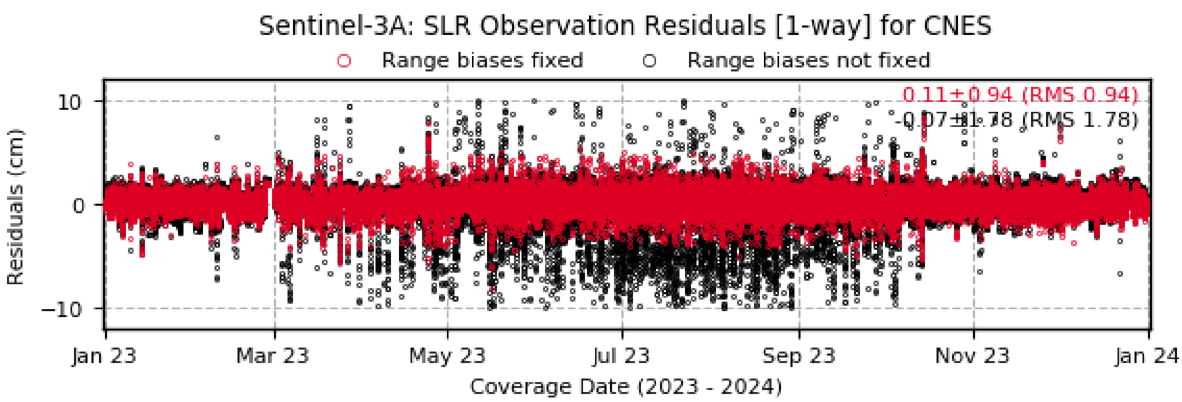
3.4. SLR RESIDUALS PER ORBIT SOLUTION

This subsection shows the SLR residuals obtained by the CNES, CPOF and COMB orbit solution, before and after applying the range biases estimated above.

Note that a filtering criterion has been applied to the calculation of the SLR residuals in order not to harm the final statistics obtained for each orbit solution. If there are white gaps of data on particular days in any plot, it is as a result of missing orbit solutions due to either manoeuvres or gaps of data.

From the analysis of the figures below, it can be said that removing the range biases has a positive effect on the standard deviation and root mean square statistics of all orbit solutions. After having fixed them, all orbit solutions have obtained reduced figures on such statistics. In addition, removing the range biases has led the mean value of the different orbit solutions to alternate more between positive and negative values. Note that the vast majority of the mean values are only positive if the range biases are not fixed.

Therefore, it can be concluded that the validation of the different Sentinel-3 and Sentinel-6A orbit solutions improves if the range biases of the SLR stations are fixed.



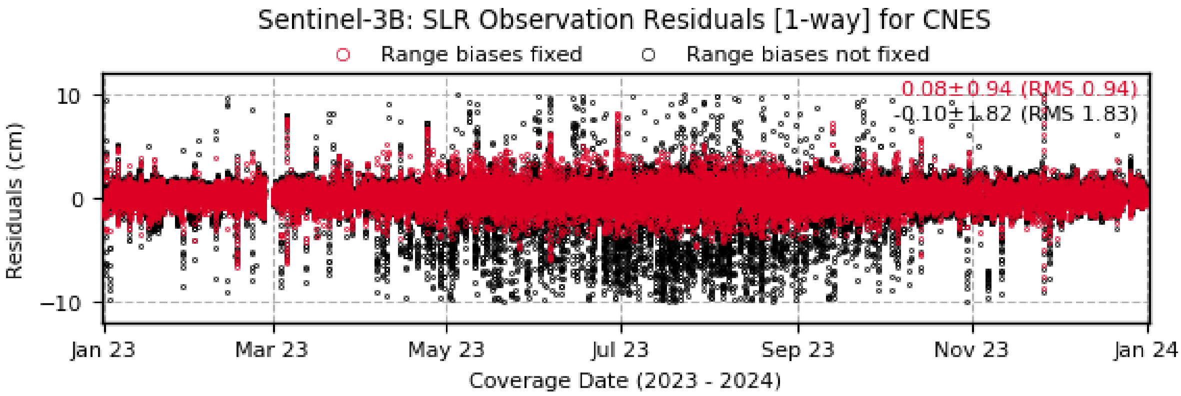


Figure 3-11: SLR observation residuals [1-way; cm] obtained for CNES orbit solution in 2023 (above Sentinel-3A, and below Sentinel-3B)

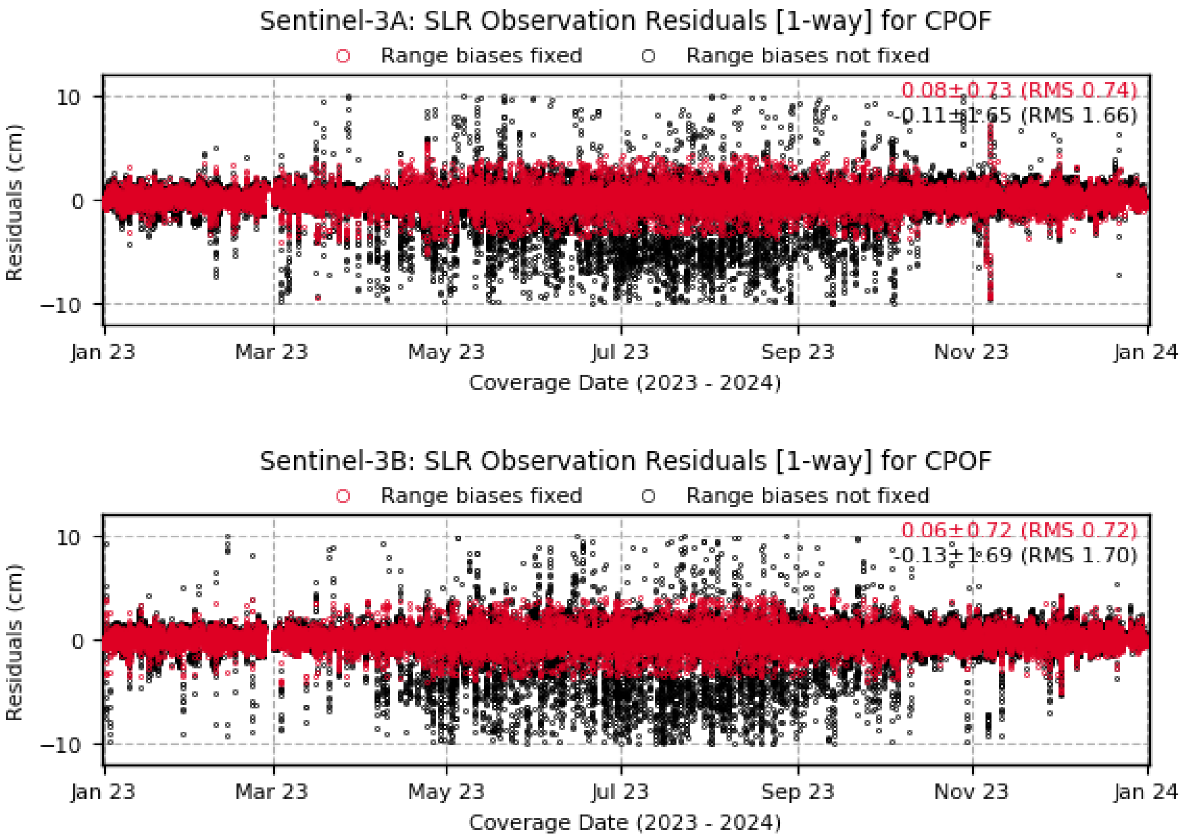


Figure 3-12: SLR observation residuals [1-way; cm] obtained for CPOF orbit solution in 2023 (above Sentinel-3A, and below Sentinel-3B)

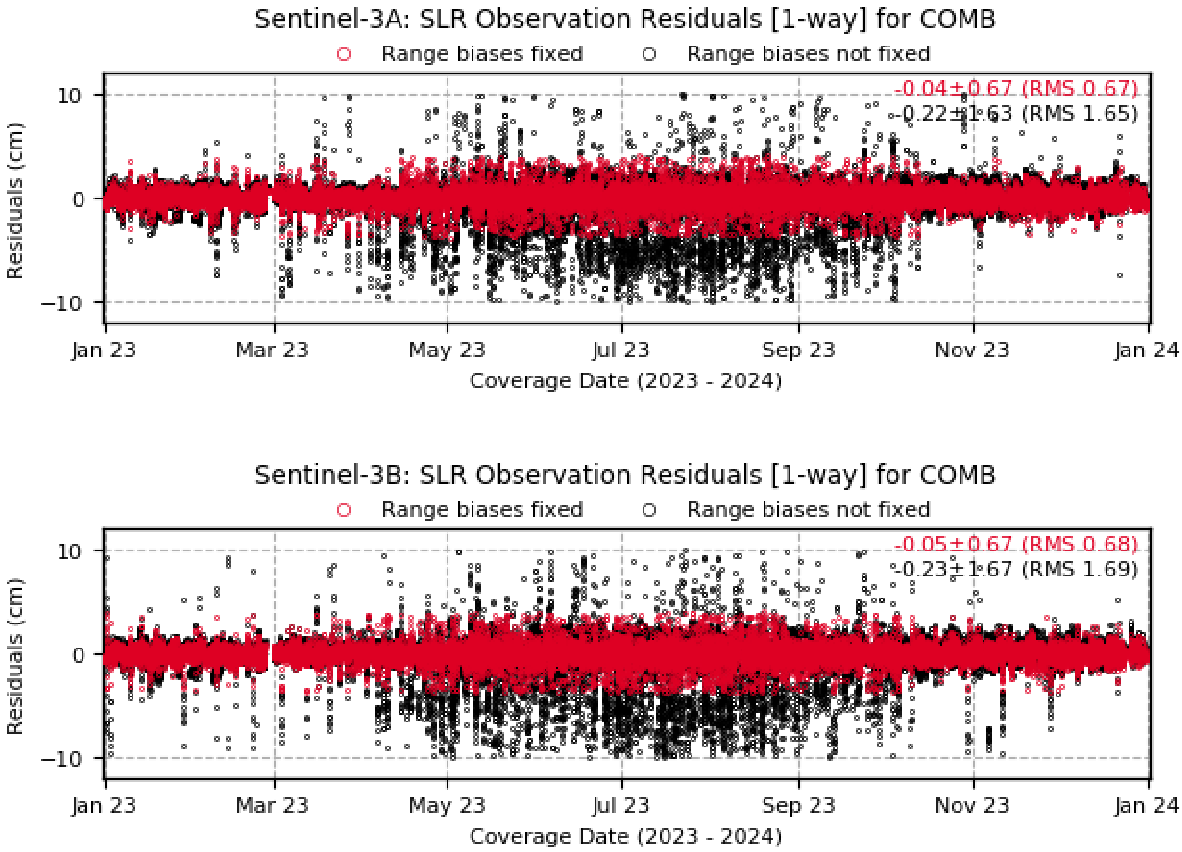


Figure 3-13: SLR observation residuals [1-way; cm] obtained for COMB orbit solution in 2023 (above Sentinel-3A, and below Sentinel-3B)

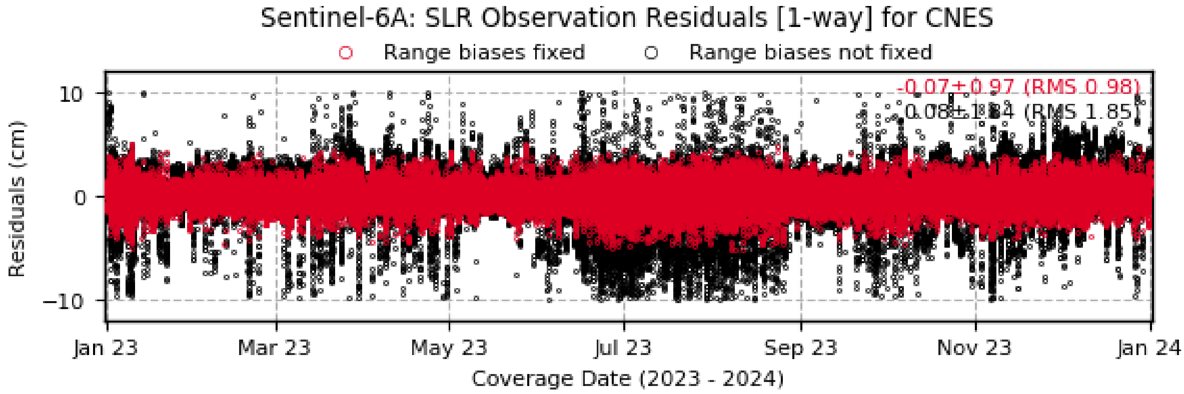


Figure 3-14: SLR observation residuals [1-way; cm] obtained for CNES orbit solution in 2023 (Sentinel-6A)

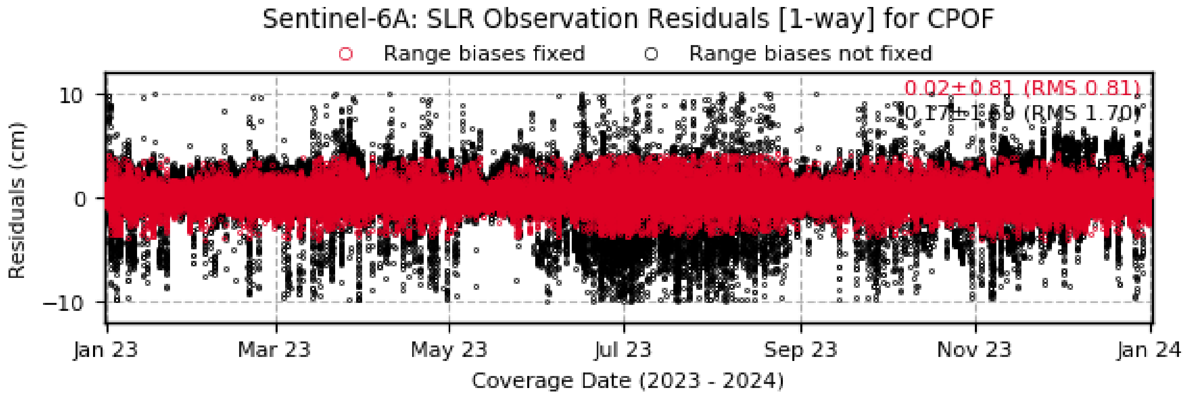


Figure 3-15: SLR observation residuals [1-way; cm] obtained for CPOF orbit solution in 2023 (Sentinel-6A)

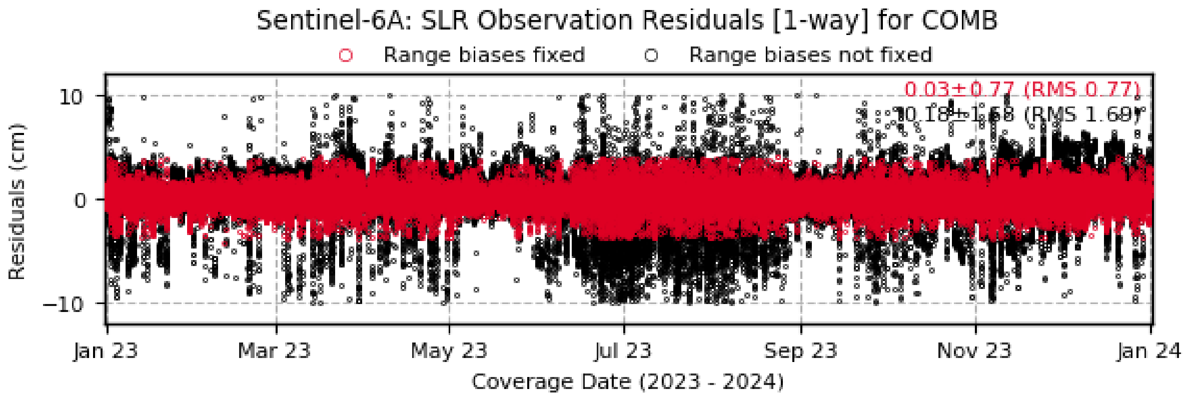


Figure 3-16: SLR observation residuals [1-way; cm] obtained for COMB orbit solution in 2023 (Sentinel-6A)

Finally, the information of the SLR residuals presented above has been summarised in the following two figures and Table 3-6 by showing the mean, standard deviation and root mean square statistics altogether per Sentinel-3 and Sentinel-6A satellites.

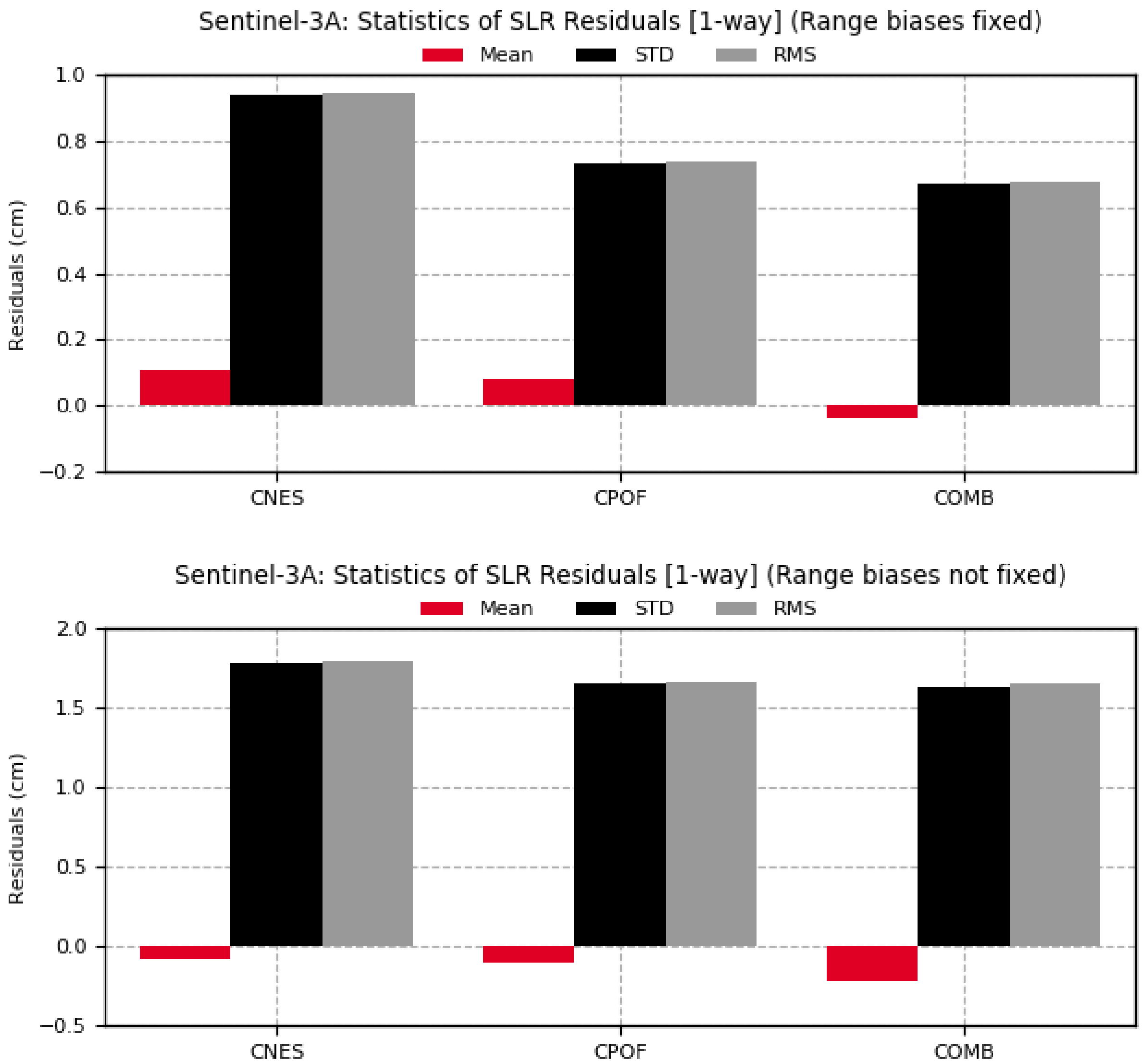


Figure 3-17: Mean, STD and RMS of the Sentinel-3A SLR observation residuals [1-way; cm] from all orbit solutions in 2023 (above the range biases have not been fixed, below the range biases have been fixed)

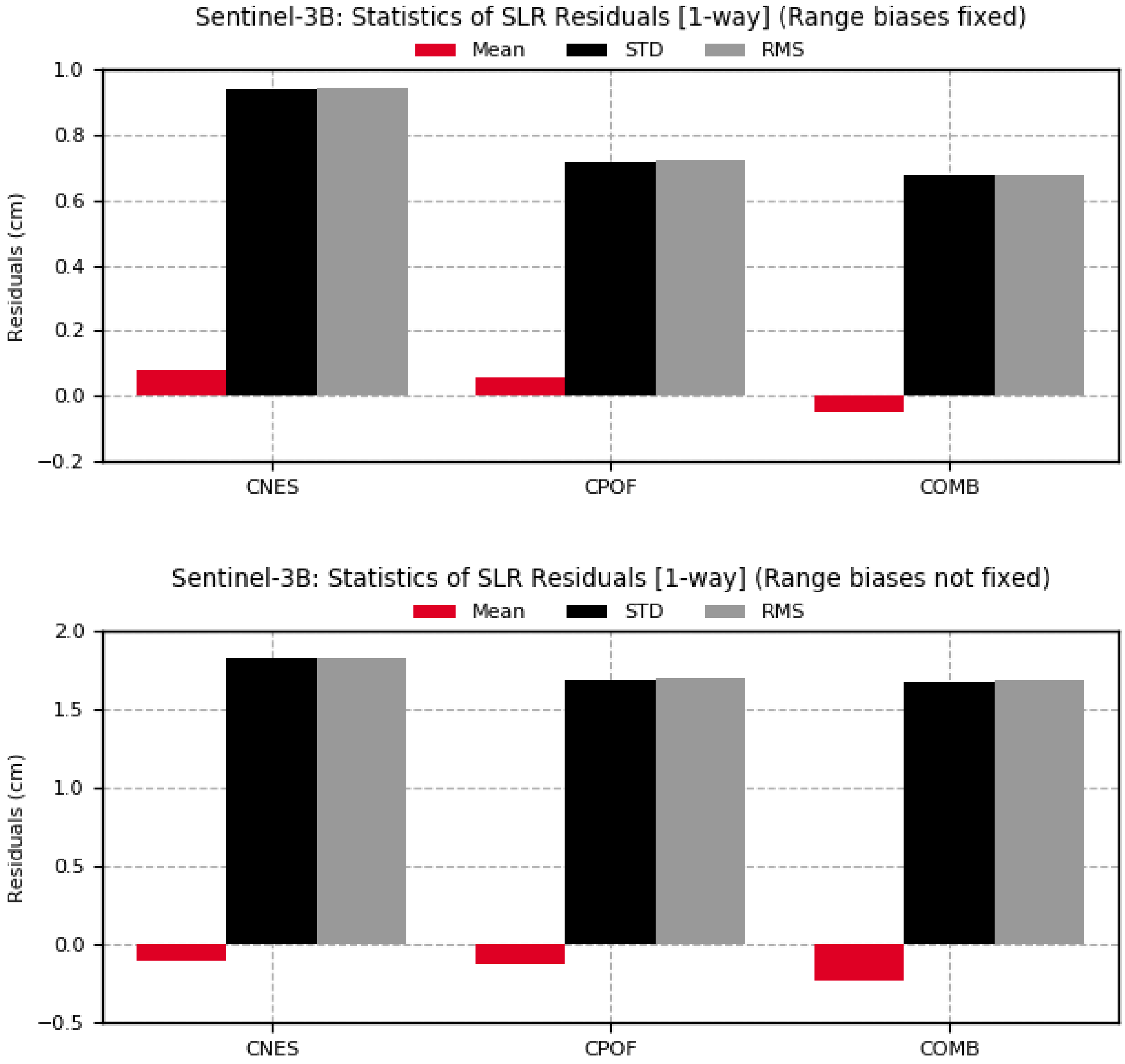


Figure 3-18: Mean, STD and RMS of the Sentinel-3B SLR observation residuals [1-way; cm] from all orbit solutions in 2023 (above the range biases have not been fixed, below the range biases have been fixed)

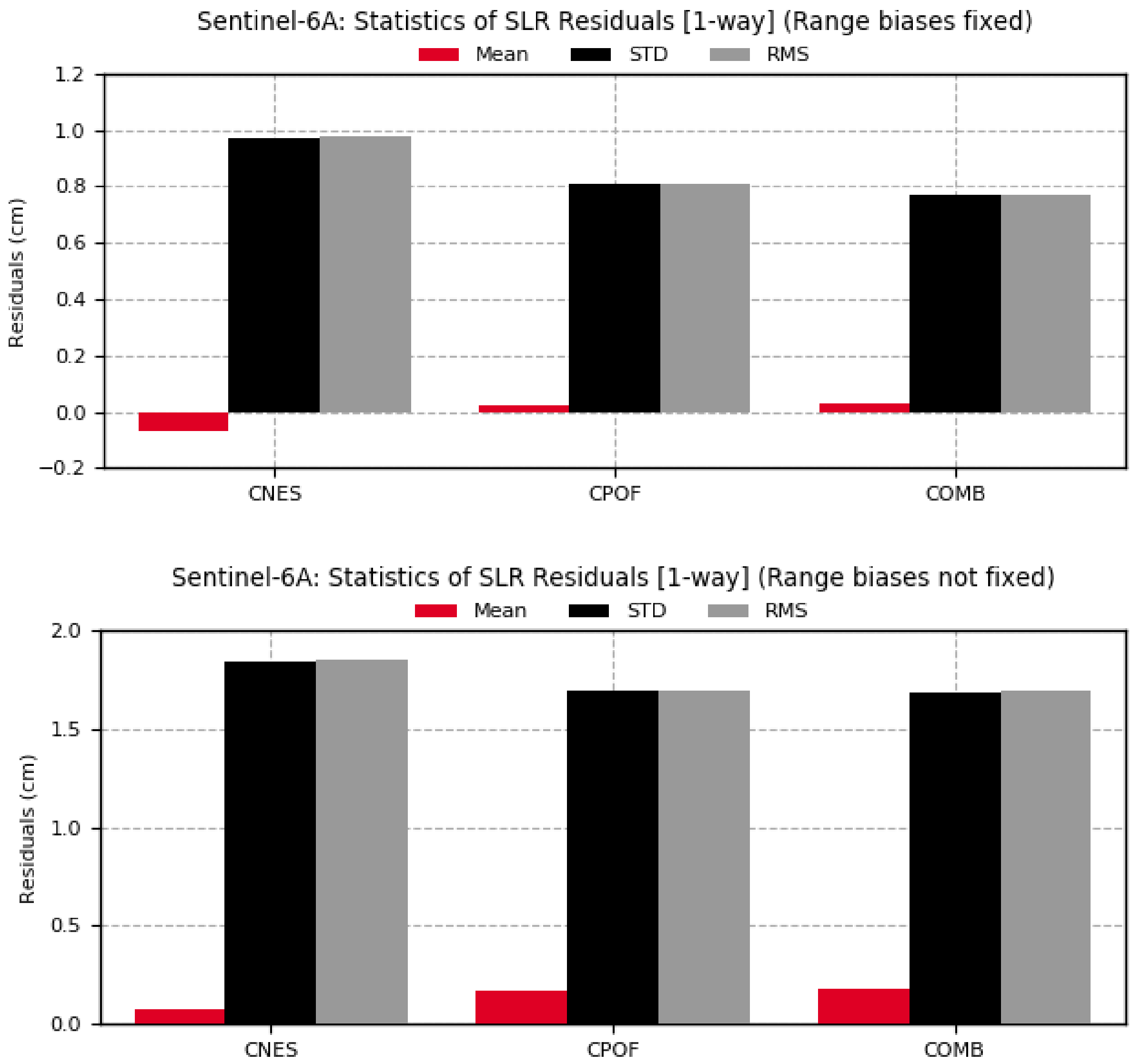


Figure 3-19: Mean, STD and RMS of the Sentinel-6A SLR observation residuals [1-way; cm] from all orbit solutions in 2023 (above the range biases have not been fixed, below the range biases have been fixed)

Finally, all the statistics of the sub section have been gathered in Table 3-6 and Table 3-7.

Table 3-6: Summary of the mean, STD and RMS of the Sentinel-3A and Sentinel-3B SLR observation residuals [1-way; cm] obtained from all orbit solutions in 2023

Orbit solution	Sentinel-3A [1-way; cm]						Sentinel-3B [1-way; cm]					
	Mean		STD		RMS		Mean		STD		RMS	
	Range biases not fixed	Range biases fixed	Range biases not fixed	Range biases fixed	Range biases not fixed	Range biases fixed	Range biases not fixed	Range biases fixed	Range biases not fixed	Range biases fixed	Range biases not fixed	Range biases fixed
CNES	-0.07	0.11	1.78	0.94	1.78	0.94	-0.10	0.08	1.82	0.94	1.83	0.94
CPOF	-0.11	0.08	1.65	0.73	1.66	0.74	-0.13	0.06	1.69	0.72	1.70	0.72
COMB	-0.22	-0.04	1.63	0.67	1.65	0.67	-0.23	-0.05	1.67	0.67	1.69	0.68

Table 3-7: Summary of the mean, STD and RMS of the Sentinel-6A SLR observation residuals [1-way; cm] obtained from all orbit solutions in 2023

Orbit solution	Sentinel-6A [1-way; cm]					
	Mean		STD		RMS	
	Range biases not fixed	Range biases fixed	Range biases not fixed	Range biases fixed	Range biases not fixed	Range biases fixed
CNES	0.08	-0.07	1.84	0.97	1.85	0.98
CPOF	0.17	0.02	1.69	0.81	1.70	0.81
COMB	0.18	0.03	1.68	0.77	1.69	0.77

4. CPF PREDICTIONS

To allow the SLR tracking of the Sentinel-3 satellites, the CPOD Service makes available the so-called **Consolidated Prediction Files (CPFs)** to the SLR stations, which contain the orbital prediction of the Sentinel-3 satellites. These files are daily created after the generation of the Sentinel-3 CPOD Short-Time Critical (STC) products and contain a 7-day prediction with respect to the generation time. On 2023, the number of generated CPF predictions was **365/365** for each of the Sentinel-3A/B satellites, which coincides with the total number of the expected files.

It is important to point out that the CPOD Service informs the ILRS community about possible degraded CPF prediction files as a result of satellite manoeuvres. The CPF files generated on manoeuvre days might be generated with a significant loss of accuracy in the prediction, and this fact might consequently pose a difficulty for the tracking of both satellites. The list of days were Sentinel-3 satellites were manoeuvred in 2023 is summarised in Table 4-1.

Table 4-1: Manoeuvre days on the Sentinel-3 satellites during 2023

Sentinel-3A	Sentinel-3B
2023/01/18	2023/01/12
2023/02/16	2023/01/23
2023/03/01	2023/02/16
2023/03/14	2023/03/07
2023/04/05	2023/03/13
2023/04/26	2023/03/13
2023/05/16	2023/03/22
2023/06/14	2023/04/05
2023/07/05	2023/04/20
2023/07/27	2023/05/11
2023/07/30	2023/06/06
2023/07/30	2023/06/29
2023/08/17	2023/07/27
2023/08/31	2023/08/10
2023/09/27	2023/08/16
2023/10/16	2023/08/31
2023/10/31	2023/09/20
2023/11/09	2023/09/28
2023/11/28	2023/10/13
2023/11/30	2023/11/01
2023/12/10	2023/11/03
	2023/11/03
	2023/11/15
	2023/11/17
	2023/11/17
	2023/12/07

Figure 4-1 shows the quality of the CPF predicted files delivered by the CPOD Service, as compared against the Sentinel-3 CPOD STC products. It must be considered that the CPF files contain predictions of the satellite orbit, whereas the STC products are determinations of the satellite orbit. As the CPF files are daily delivered, the figure below only takes into account the first predicted orbit to perform the comparisons, and the outcome is only shown for the 3D RMS. The statistical results for each component are summarised in Table 4-2.

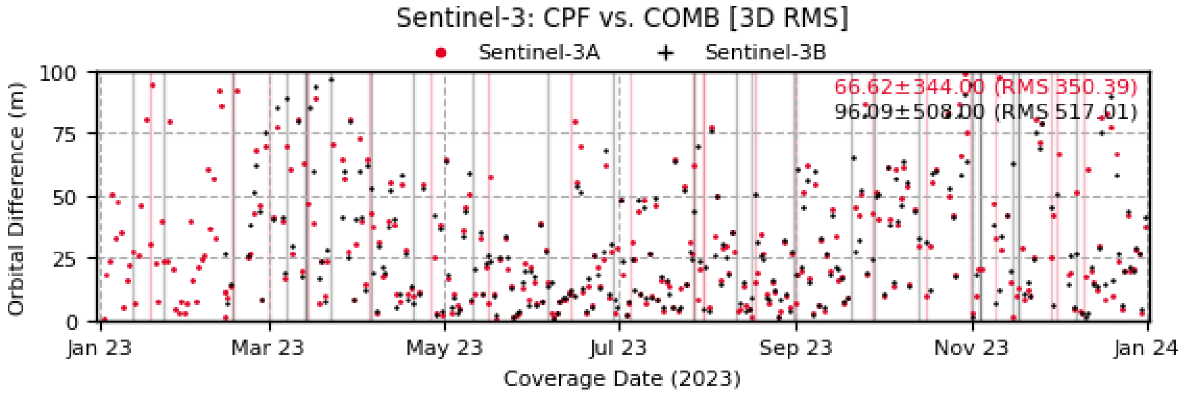


Figure 4-1: Orbital comparisons [3D RMS; m] between the Sentinel-3 CPF predictions and COMB products during 2023

Table 4-2: Summary of the mean, STD and RMS of the orbital comparisons between the Sentinel-3 CPF predictions and the Sentinel-3 CPOD STC products during 2023

	Radial RMS [m]			Along-track RMS [m]			Cross-track RMS [m]			3D RMS [m]		
	Mean	STD	RMS	Mean	STD	RMS	Mean	STD	RMS	Mean	STD	RMS
Sentinel-3A	1.03	4.12	4.24	25.85	133.76	136.23	61.38	316.91	322.79	66.62	344.00	350.39
Sentinel-3B	1.51	6.38	6.55	37.29	198.26	201.73	88.53	467.68	475.99	96.09	508.00	517.01

From the data above, it can be said that the accuracy of the CPF files is below 10 m in mean (3D RMS) for S-3B, with S-3A presenting such high value due to an outlier caused by a cancelled manoeuvre, the update of which was delivered late. The along-track is less accurate than the other components, as it is highly correlated with uncertainties on the drag modelling.

Finally, Table 4-3 gathers the percentage of the CPF files that have achieved a certain accuracy criterion, which complements the results previously shown.

Table 4-3: Percentiles of the orbital comparisons [3D RMS] between the Sentinel-3 CPF predictions and the COMB products during 2023

Product Accuracy		
Threshold	Percentage of Fulfilment	
	Sentinel-3A	Sentinel-3B
< 1 m	0.55 %	0.31 %
< 5 m	10.11 %	9.01 %
< 10 m	22.95 %	21.12 %
< 50 m	71.04 %	67.39 %
< 100 m	88.80 %	85.09 %
< 200 m	95.36 %	92.55 %
< 400 m	98.91 %	97.52 %

5. CONCLUSIONS

This document gathers the 2023 yearly results related to the tracking of the Sentinel-3 and Sentinel-6A satellites from the SLR stations. The document is meant to stress the importance of the ILRS Community in the frame of the Sentinel-3 and Sentinel-6 missions. The main aspects to be highlighted are:

- The ILRS stations cooperate with the Copernicus POD (CPOD) Service and its QWG by tracking both Sentinels-3 and Sentinel-6A and supplying ranging measurements. Due to the number of available stations, an overall good geographical coverage is attained.
- The total number of satellite passes during 2023 has shown values between 50 and 150 passes for both Sentinel-3 satellites and slightly higher for Sentinel-6A.
- The observations provided by the ILRS stations are used by the CPOD QWG as an independent means to validate the orbital accuracy of the POD orbits. The comparisons have revealed a good agreement between them (keeping the 3D RMS of the residuals below 1.5 cm in mean), which improves the reliability of the CPOD products.
- A monthly range bias has been calculated per each SLR station in order to improve the statistical outcome of the SLR residuals. It has been shown that the use of these range biases benefits the final outcome.

6. ANNEX: STATIONS COORDINATE LIST

The following table lists all SLR stations that have tracked any of the two Sentinel-3 or Sentinel-6A satellites at least once during the complete satellite missions, and have been analysed in this document. The table includes not only the identification of the SLR stations but also the station coordinates and the eccentricities used for the calculation of the statistics throughout the document. The station coordinates are based on the SLRF2020 reference frame, particularly they have been extracted from the SINEX file "**SLRF2020_POS+VEL_2023.10.02.SNX**" published in the International Terrestrial Reference Frame (ITRF) website. Eccentricities are subtracted from SINEX file "ecc_une.snx" published in the ILRS website[1].

Table 6-1: Geographical location and coordinates (SLRF2014) of all SLR stations that have ever tracked Sentinel-3 and Sentinel-6 satellites

Monument	Code	Location Name (Country)	Station Coordinates [m]			Eccentricities [m]			Allowed to Track S-3 Satellites
			X	Y	Z	North	East	Up	
1824	GLSL	Golosiiv (Ukraine)	3512988.994	2068968.978	4888817.456	0	0	0	X
1873	SIML	Simeiz (Ukraine)	3783902.060	2551405.202	4441257.591	0	0	0	X
1884	RIGL	Riga (Latvia)	3183895.606	1421497.304	5322803.924	0	0	0	X
1888	SVEL	Svetloe (Russia)	2730138.820	1562328.820	5529998.709	0	0	0	X
1889	ZELL	Zelenchukskaya (Russia)	3451135.877	3060335.286	4391970.361	0	0	0	X
1890	BADL	Badary (Russia)	-838300.107	3865738.863	4987640.890	0	0	0	X
1891	IRKL	Irkutsk (Russia)	- 968340.368	3794415.098	5018178.117	0	0	0	
1893	KTZL	Katsively (Ukraine)	3785944.240	2550780.871	4439461.420	0	0	0	X
7080	MDOL	McDonald Observatory, TX (USA)	-1330021.294	-5328401.839	3236480.697	-0.0030	-0.0060	1.7630	
7090	YARL	Yarragadee (Australia)	-2389007.770	5043329.486	-3078523.971	-0.0064	0.0194	3.1827	X
7105	GODL	Greenbelt, MD (USA)	1130719.363	-4831350.575	3994106.585	-0.0087	-0.0327	3.1379	X
7110	MONL	Monument Peak, CA (USA)	-2386278.768	-4802353.672	3444881.847	-0.0242	-0.0148	3.1895	X
7119	HA4T	Haleakala, Hawaii (USA)	-5466065.623	-2404337.715	2242108.553	0.0029	0.0032	2.6304	X
7124	THTL	Tahiti (French Polynesia)	-5246407.504	-3077284.050	-1913813.591	-0.0150	0.0100	3.1410	X

[1] https://ilrs.gsfc.nasa.gov/network/site_procedures/eccentricity.html

Monument	Code	Location Name (Country)	Station Coordinates [m]			Eccentricities [m]			Allowed to Track S-3 Satellites
			X	Y	Z	North	East	Up	
7237	CHAL	Changchun (China)	-2674387.291	3757189.142	4391508.240	0	0	0	
7249	BEIL	Beijing (China)	-2148760.919	4426759.516	4044509.560	0	0	0	X
7306	TKBL	Tsukuba (Japan)	-3961640.925	3308774.677	3734291.473	0	0	0	
7396	JFNL	Wuhan (China)	-2279755.841	5004737.429	3219791.739	0	0	0	
7403	AREL	Arequipa (Peru)	1942807.880	-5804069.660	-1796915.546	0.0140	-0.0020	2.6790	X
7501	HARL	Hartebeesthoek (South Africa)	5085401.091	2668330.429	-2768688.574	-0.0029	-0.0071	3.2236	X
7701	IZ1L	Izaña (Tenerife), Spain	5390375.929	-1597788.199	3006931.800	0	0	0	
7810	ZIML	Zimmerwald (Switzerland)	4331283.421	567550.071	4633140.477	0	0	0	X
7811	BORL	Borowiec (Poland)	3738332.513	1148246.773	5021816.187	0	0	0	X
7819	KUN2	Kunming (China)	-1281301.395	5640724.415	2682905.491	0	0	0	
7821	SHA2	Shanghai (China)	-2830744.756	4676580.173	3275072.735	0	0	0	X
7824	SFEL	San Fernando (Spain)	5105473.821	-555110.398	3769893.061	0	0	0	X
7825	STL3	Mt. Stromlo (Australia)	-4467064.966	2683034.891	-3667007.095	0	0	0	X
7827	SOSW	Wettzell, Germany	4075530.921	931782.013	4801620.050	0	0	0	
7838	SISL	Simosato (Japan)	-3822388.305	3699363.655	3507573.044	0	0	0	
7839	GRZL	Graz (Austria)	4194426.213	1162694.357	4647246.843	0	0	0	X
7840	HERL	Herstmonceux (UK)	4033463.476	23662.787	4924305.351	0	0	0	X
7841	POT3	Potsdam (Germany)	3800432.021	881692.254	5029030.226	0	0	0	X
7845	GRSM	Grasse, (France)	4581691.939	556196.368	4389355.287	0	0	0	
7941	MATM	Matera (Italy)	4641978.524	1393067.820	4133249.696	0	0	0	X
8834	WETL	Wettzell (Germany)	4075576.573	931785.766	4801583.752	0	0	0	

END OF DOCUMENT