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Memo: Sentinel-1 Full Mission Reprocessing (2021)
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1. INTRODUCTION

The switch of the Sentinel-1 GPS Antenna Reference Point (ARP) on the operational processing of the Copernicus POD (CPOD) Service carried out on 29th-30th July 2020 makes a reprocessing of the full time series of both satellites necessary. Sentinel-1A, being the oldest of the Copernicus Sentinel satellites, is in orbit since April 2014 and in its Routine Operational Phase (ROP) since October 2014. Not only the ARP switch but also several model and processing updates during these seven years justify a full reprocessing of the orbits.

This memorandum provides a quality assessment of the new Sentinel-1 reprocessed orbit solutions. Six centres from the CPOD Quality Working Group (QWG) have joined this Full Mission Reprocessing (FMR) activity providing their orbit solutions (see Table 1-1 for the complete list). The POD processing used by each of these centres can be found in Annex A.

Table 1-1: List of centres participating on the Sentinel-1 reprocessing campaign

Name of centre	Label of orbit solution provided
Astronomical Institute of the University of Bern (AIUB)	AIUB
Copernicus POD (CPOD) Service	CPOR
Deutsches Zentrum für Luft- und Raumfahrt (DLR)	DLRR
European Space Operation Centre (ESOC)	ESOC
Technische Universiteit Delft (TUD)	TUDF
Technische Universität München (TUM)	TUMM

The period of time for this FMR is summarised in Table 1-2. However, the quality assessment shown within this memorandum will last until 31st December 2020. The CPOD Service is currently generating same quality orbits and following the same processing scheme as used for this reprocessing. Therefore, it is ensured consistency over the transition from the reprocessed Sentinel-1 orbits to the current operational orbits, which are made available through the ESA Copernicus Open Access Hub (<https://scihub.copernicus.eu/>).

Table 1-2: Start and end dates of the Sentinel-1 FMR

Satellite	Sentinel-1 Full Mission Reprocessing	
	Start date	End date
Sentinel-1A	7 th April 2014	13 th January 2021
Sentinel-1B	28 th April 2016	13 th January 2021

This memorandum firstly describes the input data used for the reprocessing. Then, Section 3 addresses the generation of the **combined orbit solution** from which the orbit comparisons can be obtained. Section 4 performs the quality assessment of all orbit solutions participating on the

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reprocessing. And, finally, this memorandum also includes a remark for one particular event that occurred on Sentinel-1A satellite on mid-2016.

2. ANALYSIS OF THE INPUT DATA

The aim of this section is to show some statistics about the **number of orbit solutions** received from the different centres, and to perform a first analysis of these orbits from the processing metrics and estimated parameters generated during their processing.

The following tables summarise the total number of orbit solutions provided by each centre and year. There are two things that must be highlighted from the tables below:

- Firstly, there are a few days that have been left from the sum (i.e., they are not considered as expected days) since no L0 data was provided on them. These days are from the very beginning of the mission of both satellites (see Table 2-3 for the complete list). Therefore, there are no orbit solutions generated for these days in none of the centres.
- And, secondly, there are centres that do not generate orbit solutions on days with manoeuvres or even if large data gaps occur. This fact mainly explains the differences between the provided orbit solutions by each centre. Be in mind that Sentinel-1 satellites usually manoeuvre every 8-10 days.

Table 2-1: Sentinel-1A – Provided orbit solutions per year and centre

Sentinel-1A – Total number of days (% over total)							
Year	Exp. days	Orbit solution					
		AIUB	CPOR	DLRR	ESOC	TUDF	TUMM
2014	265	176 (66.4 %)	265 (100.0 %)	261 (98.5 %)	171 (64.5 %)	265 (100.0 %)	170 (64.2 %)
2015	365	299 (81.9 %)	365 (100.0 %)	364 (99.7 %)	229 (62.7 %)	365 (100.0 %)	276 (75.6 %)
2016	366	306 (83.6 %)	366 (100.0 %)	366 (100.0 %)	315 (86.1 %)	366 (100.0 %)	295 (80.6 %)
2017	365	323 (88.5 %)	365 (100.0 %)	365 (100.0 %)	345 (94.5 %)	365 (100.0 %)	321 (87.9 %)
2018	365	320 (87.7 %)	365 (100.0 %)	365 (100.0 %)	337 (92.3 %)	365 (100.0 %)	316 (86.6 %)
2019	365	318 (87.1 %)	365 (100.0 %)	365 (100.0 %)	323 (88.5 %)	365 (100.0 %)	316 (86.6 %)
2020	366	328 (89.6 %)	366 (100.0 %)	366 (100.0 %)	337 (92.1 %)	366 (100.0 %)	315 (86.1 %)
Sum	2457	2070 (84.3 %)	2457 (100.0 %)	2452 (99.8 %)	2057 (83.7 %)	2457 (100.0 %)	2009 (81.8 %)

Table 2-2: Sentinel-1B – Provided orbit solutions per year and centre

Sentinel-1B – Total number of days (% over total)							
Year	Exp. days	Orbit solution					
		AIUB	CPOR	DLRR	ESOC	TUDF	TUMM
2016	242	194 (80.2 %)	242 (100.0 %)	238 (98.3 %)	193 (79.8 %)	242 (100.0 %)	183 (75.6 %)
2017	365	316 (86.6 %)	365 (100.0 %)	365 (100.0 %)	348 (95.3 %)	365 (100.0 %)	316 (86.6 %)
2018	365	316 (86.6 %)	365 (100.0 %)	365 (100.0 %)	334 (91.5 %)	365 (100.0 %)	315 (86.3 %)
2019	365	321 (87.9 %)	365 (100.0 %)	365 (100.0 %)	326 (89.3 %)	365 (100.0 %)	319 (87.4 %)
2020	366	326 (89.1 %)	366 (100.0 %)	366 (100.0 %)	340 (92.9 %)	366 (100.0 %)	316 (86.3 %)
Sum	1703	1473 (86.5 %)	1703 (100.0 %)	1699 (99.8 %)	1541 (90.5 %)	1703 (100.0 %)	1449 (85.1 %)

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Table 2-3: Sentinel-1 – Days with missing orbit solutions due to complete gaps of L0 data

Sentinel-1A	Sentinel-1B
30/05/2014	10/05/2016
31/05/2014	11/05/2016
01/06/2014	12/05/2016
06/07/2014	22/05/2016
	31/05/2016
	05/06/2016

From the numbers above (Table 2-1 and Table 2-2), it must be highlighted that CPOD and TUD centres have been able to generate the entire set of orbit solutions for all period of time, followed very closely by DLR. The percentage of the rest of centres is above 80 %. These numbers are good news for the generation of the combined orbit solution.

2.1. PROCESSING METRICS

To analyse the quality of the input data, the processing metrics obtained during the generation of each orbit solution can be evaluated. Particularly, this subsection will focus on the **pseudo-range** and **carrier phase** residuals derived from the GPS signals.

2.1.1. PSEUDO-RANGE RESIDUALS

Figure 2-1 plots the temporal evolution of the pseudo-range residuals of each orbit solution (mean RMS). These residuals have shown to be fairly constant for all solutions, and they share similar pattern over time. The ups and downs of the curves can be mainly explained by different periods of flex power modes applied to GPS signals (see [RD.3] for further information), as it is highly correlated with the transmission power of the GPS signals.

It must be highlighted that the orbit solutions from TUD are the ones that achieve the lowest residuals with a significant distance to the rest of solutions. If these residuals are analysed per satellite (see Figure 2-2), Sentinel-1B shows similar or even lower values than Sentinel-1A depending on the orbit solution evaluated.

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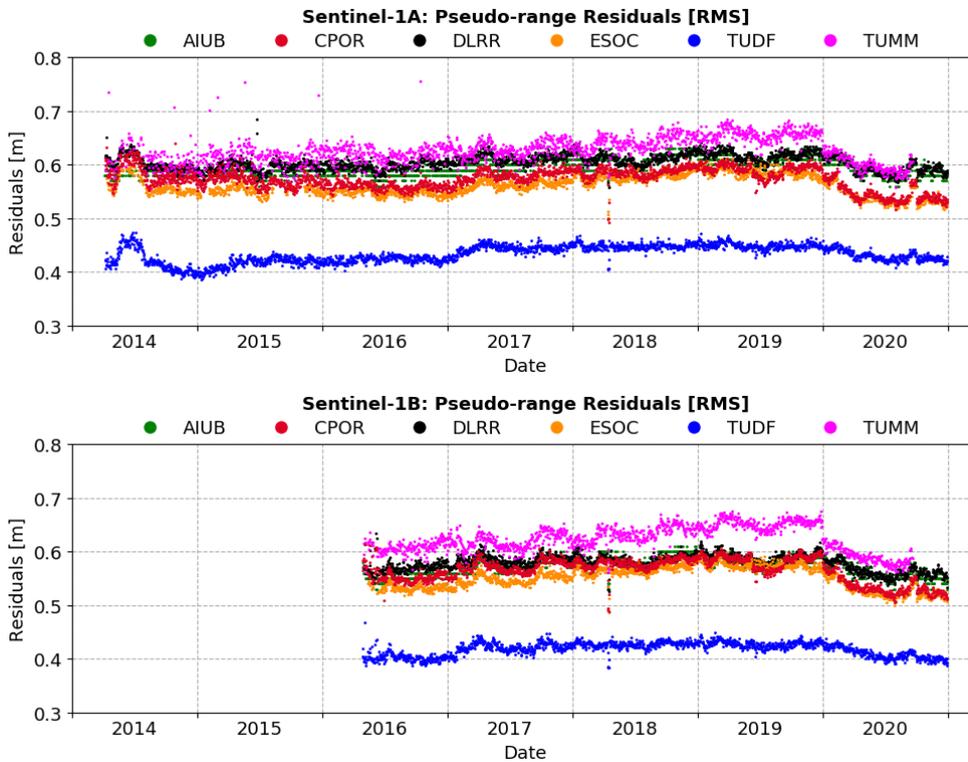


Figure 2-1: Temporal evolution of the pseudo-range residuals obtained by each orbit solution over time [RMS; m] (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

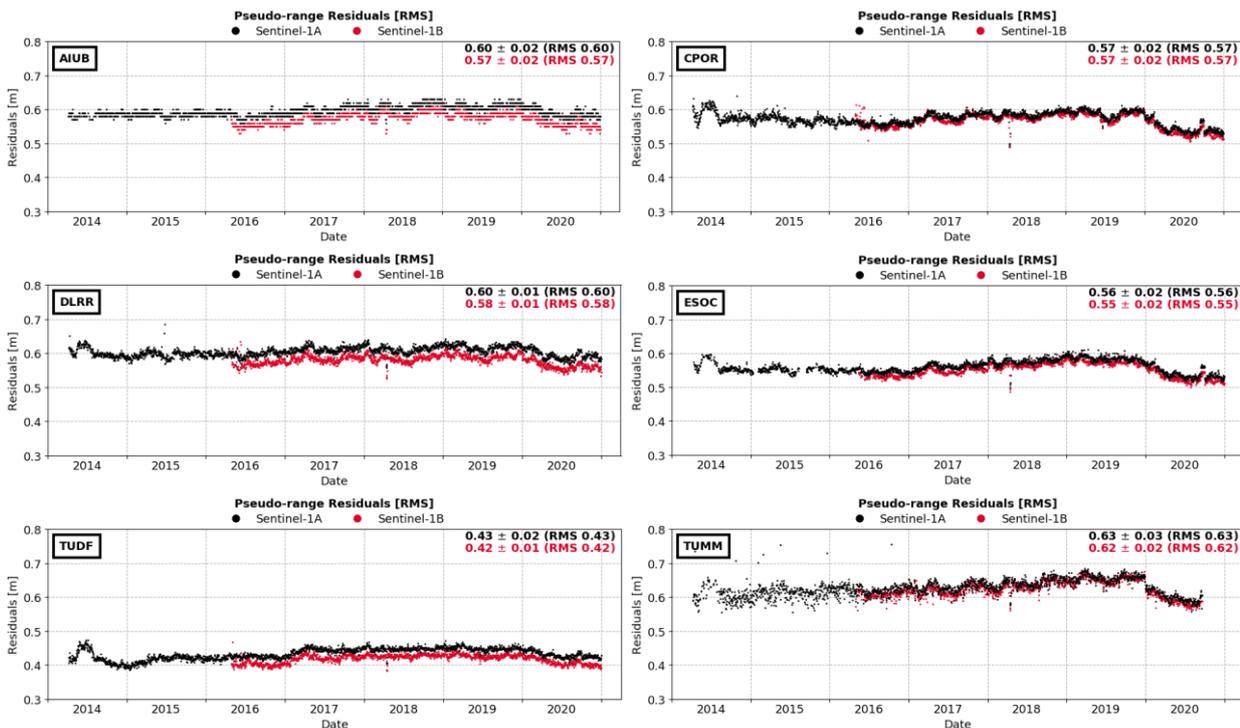


Figure 2-2: Temporal evolution per orbit solution of the pseudo-range residuals obtained by each orbit solution over time [RMS; m]

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Finally, Figure 2-3 and Table 2-4 summarise the outcome above by showing the mean and standard deviation values of the pseudo-range residuals.

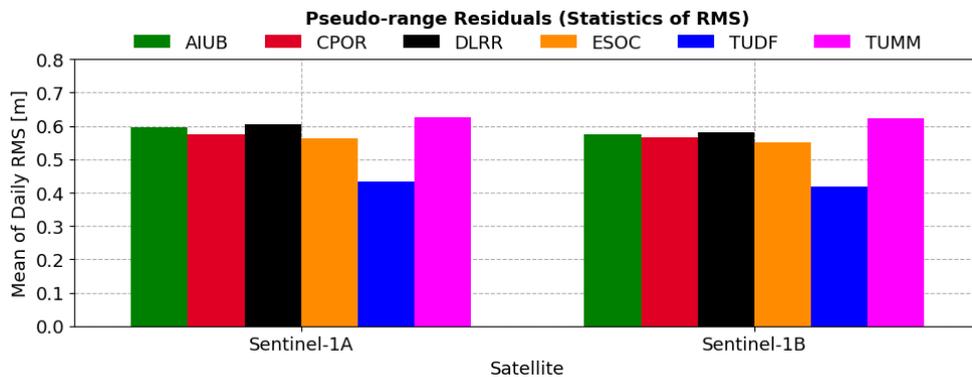


Figure 2-3: Mean [m] of the pseudo-range residuals obtained by each orbit solution

Table 2-4: Mean and standard deviation values [m] of the pseudo-range residuals obtained by each orbit solution

Pseudo-range residuals: mean +/- STD [m]		
Orbit solution	Sentinel-1A	Sentinel-1B
AIUB	0.60 +/- 0.02	0.57 +/- 0.02
CPOR	0.57 +/- 0.02	0.57 +/- 0.02
DLRR	0.60 +/- 0.01	0.58 +/- 0.01
ESOC	0.56 +/- 0.02	0.55 +/- 0.02
TUDF	0.43 +/- 0.02	0.42 +/- 0.01
TUMM	0.63 +/- 0.03	0.62 +/- 0.02

2.1.2. CARRIER PHASE RESIDUALS

Figure 2-4 depicts the temporal evolution of the carrier phase residuals of each orbit solution. There are a few things to be highlighted from the outcome of these residuals:

- The residuals obtained by the orbit solutions that use the GPS inputs from CODE are the ones showing the lowest values (probably due to the use of 5 seconds clocks). These residuals are similar amongst solutions but they present a sinusoidal pattern (see residuals from AIUB, CPOR, DLRR and TUMM solutions).
- TUDF and ESOC solutions, on the contrary, obtain higher carrier phase residuals but they are more consistent over time. The solutions from TUD are using the GPS inputs from JPL, whereas ESOC generates their own GPS inputs.
- From Figure 2-5, it can be seen that the residuals achieved from both satellites are practically identical on each orbit solution, except for the case of TUDF solution, which shows higher values on Sentinel-1B satellite.
- There is an unexpected jump on the carrier phase residuals of the CPOR solution from mid-2016 to the beginning of year 2017. This jump is also visible for DLRR orbit solution using the same GPS inputs from CODE as well. In the case of the CPOR solution, the cause can be related to some problems in the carrier phase ambiguity-fixing procedure. This issue seems to only affect the carrier phase residuals as the resulting orbit comparisons do not show any unexpected behaviour (see Section 4).

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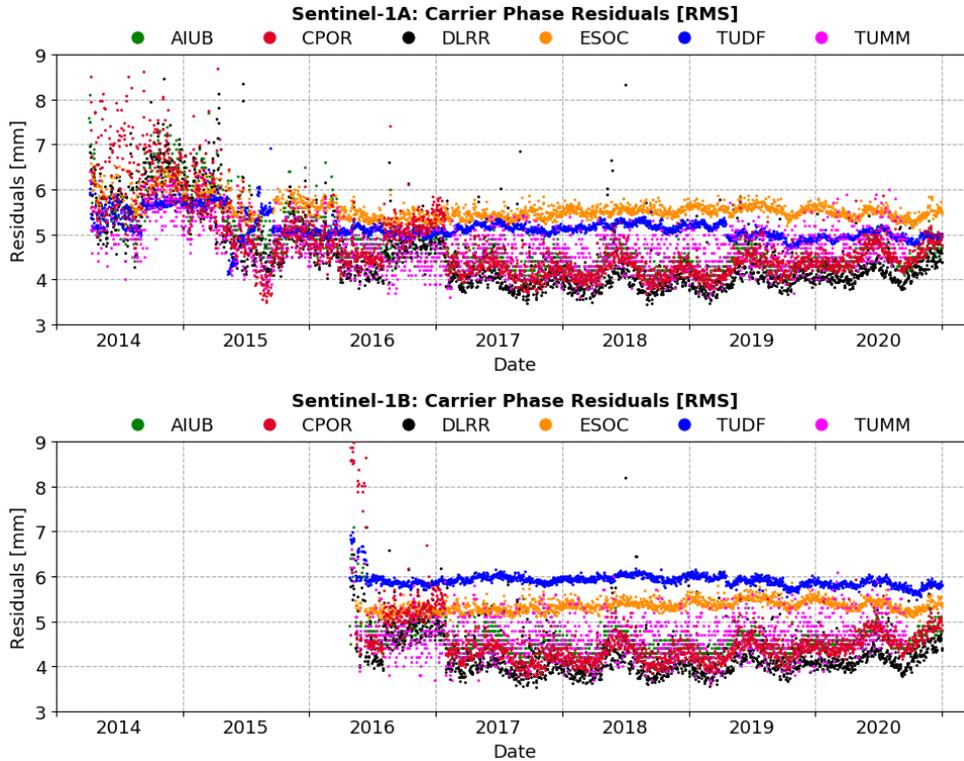


Figure 2-4: Temporal evolution of the carrier phase residuals obtained by each orbit solution over time [RMS; mm] (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

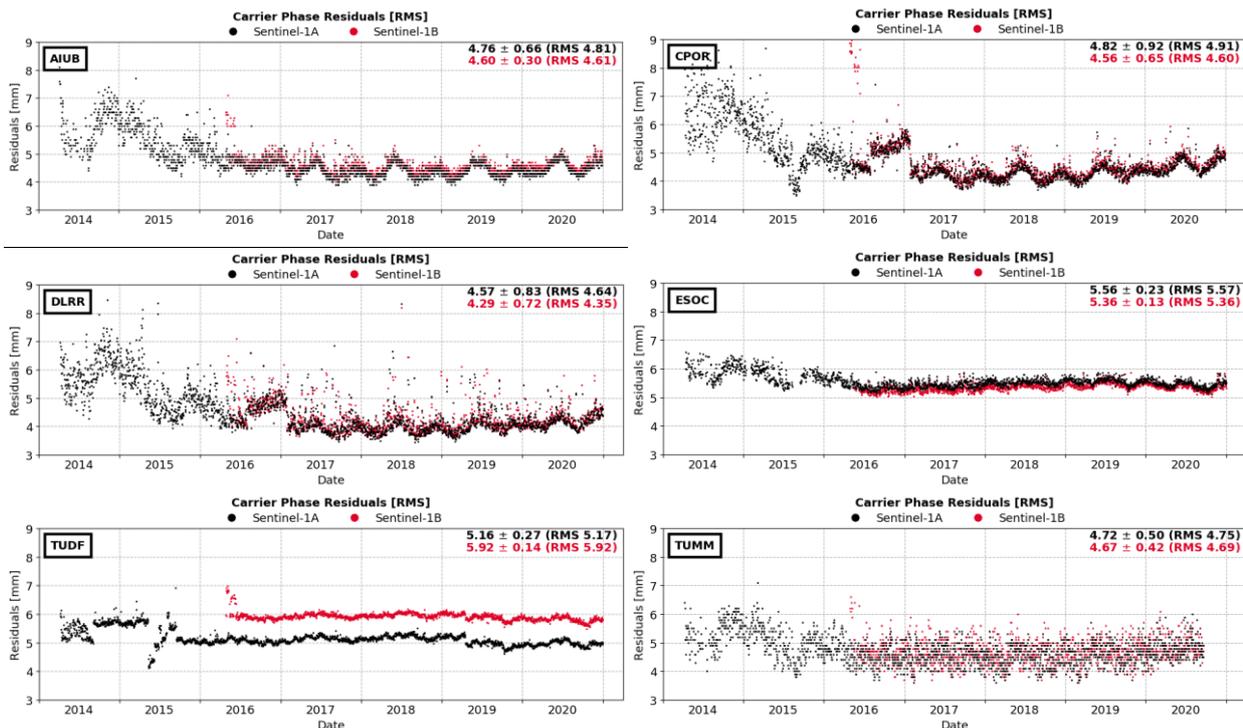


Figure 2-5: Temporal evolution per orbit solution of the carrier phase residuals obtained by each orbit solution over time [RMS; mm]

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Finally, Figure 2-6 and Table 2-5 summarise the outcome above by showing the mean and standard deviation values of the carrier phase residuals.

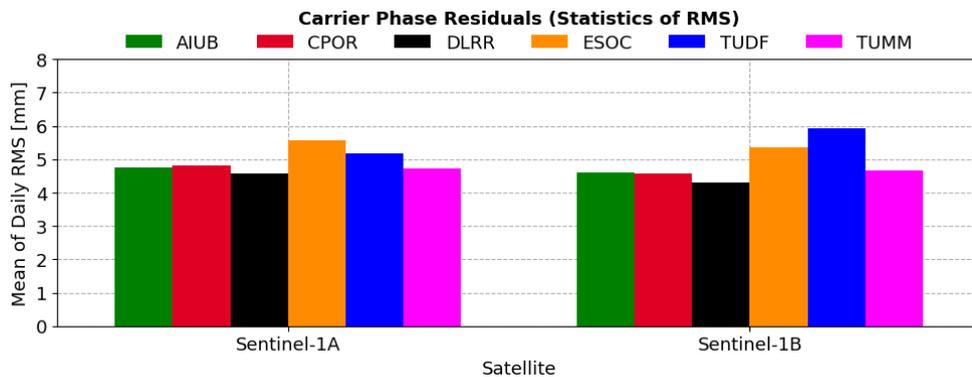


Figure 2-6: Mean [mm] of the carrier phase residuals obtained by each orbit solution

Table 2-5: Mean and standard deviation values [mm] of the carrier phase residuals obtained by each orbit solution

Carrier phase residuals: mean +/- STD [mm]		
Orbit solution	Sentinel-1A	Sentinel-1B
AIUB	4.76 +/- 0.66	4.60 +/- 0.30
CPOR	4.82 +/- 0.92	4.56 +/- 0.65
DLRR	4.57 +/- 0.83	4.29 +/- 0.72
ESOC	5.56 +/- 0.23	5.36 +/- 0.13
TUDF	5.16 +/- 0.27	5.92 +/- 0.14
TUMM	4.72 +/- 0.50	4.67 +/- 0.42

2.1.3. CPOD VS. CPOR OUTCOME

If the processing metrics of the operational Non-Time Critical (NTC) products generated by the CPOD Service during the whole Sentinel-1 mission are compared to the same metrics obtained by the reprocessed products, it can be seen a few differences:

- Although the outcome on the pseudo-range residuals for both solutions is quite similar, the results from the operational products are a little bit higher and more dispersive over time.
- On the other hand, the outcome on the carrier phase residuals is significantly different. Although the tendency of the curve is similar on both cases, the residuals achieved by the reprocessed solutions are much lower. The jump of the residuals at the end of year 2020 on the operational products is due to an update on the modelling of the orbit (including the use of ambiguity-fixing algorithms) and the non-use of GPS input clocks 5 s (GPS input clocks 30 s interpolated to the observation sampling of 10 s were used instead), while in the reprocessing 5 seconds clocks were used.

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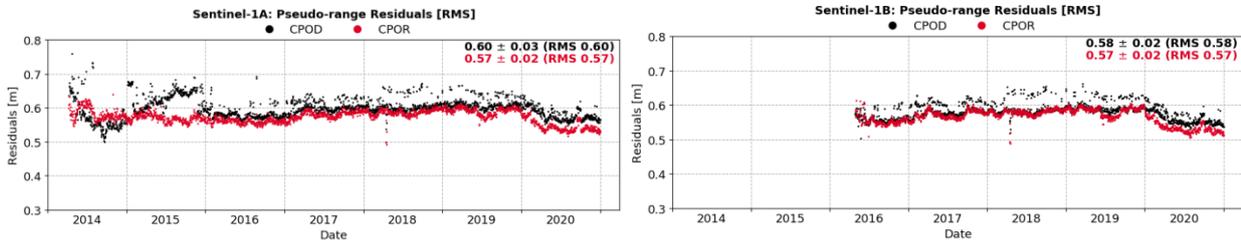


Figure 2-7: Temporal evolution of the pseudo-range residuals obtained by the operational NTC products generated by the CPOD Service and the new ones achieved from the reprocessing [RMS; m] (left plot for Sentinel-1A, right plot for Sentinel-1B)

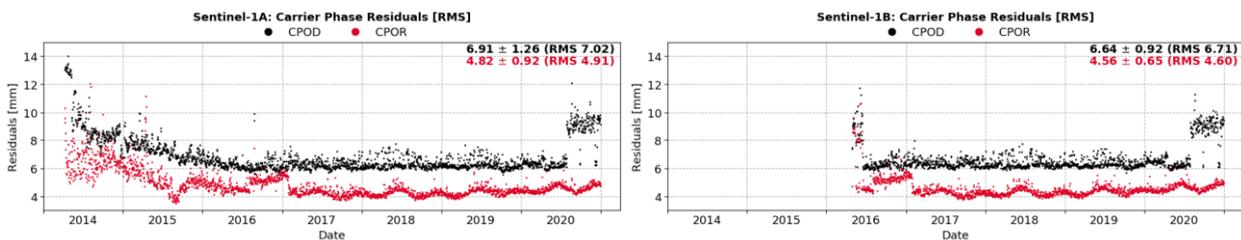


Figure 2-8: Temporal evolution of the carrier phase residuals obtained by the operational NTC products generated by the CPOD Service and the new ones achieved from the reprocessing [RMS; mm] (left plot for Sentinel-1A, right plot for Sentinel-1B)

2.2. ESTIMATED PARAMETERS

The quality of the generated orbit solutions can also be assessed by the **estimated parameters** performed during the processing of the products. Unfortunately, these parameters are only available from CPOR and TUDF solutions, and therefore, this subsection will only give information from these two solutions.

2.2.1. DRAG SCALE FACTOR

The drag scale factor is estimated once per arc determination both in CPOR and TUDF solutions. Figure 2-9 shows the temporal evolution of this estimated parameter for the CPOR case alone, and Figure 2-10 includes to the analysis the values achieved from the TUDF solution.

Two clear patterns can be distinguished from the evaluation of the CPOR solution (if years 2014 and 2015 with higher solar activity are excluded from this analysis):

- There is a period of time that the pattern of the drag remains nearly constant between 0.5 and 1.0 values. This period of time mostly coincides with the end and the beginning of the year.
- On the other hand, the estimation of the drag scale factor results in more instability on mid-year showing peaks that achieve even negative values. This period of time is where the Sentinel-1 satellites go into periods of eclipse. The drag scale factor is correlated to the along-track constant CPR (Constant-Per-Revolution) parameter (see Section 2.2.2.1), and therefore, the negative values may result from this correlation.

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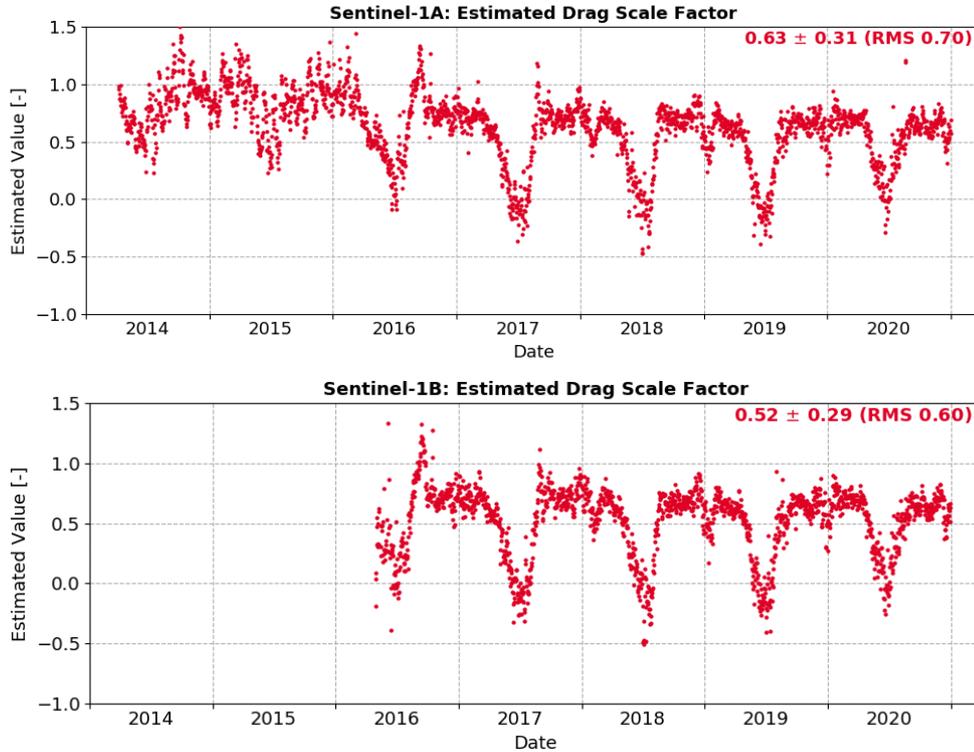


Figure 2-9: Temporal evolution of the estimated drag factor for CPOR orbit solution (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

The results from TUDF solution share similarities with the CPOR solution as the estimated drag also presents high peaks on mid-year. However, these peaks are on the opposite direction (this is something that requires further investigation). It must be remarked that the drag values are significantly biased between both solutions, and TUDF solution also shows small peaks at the very beginning of the year, which while also visible on CPOR, are smaller and displaced in time. Differences between both solutions are mainly due to differences in the orbital parametrisation, but it is interesting that both solutions visualise the same issues on the same periods, indicating that the macro-model still requires improvements.

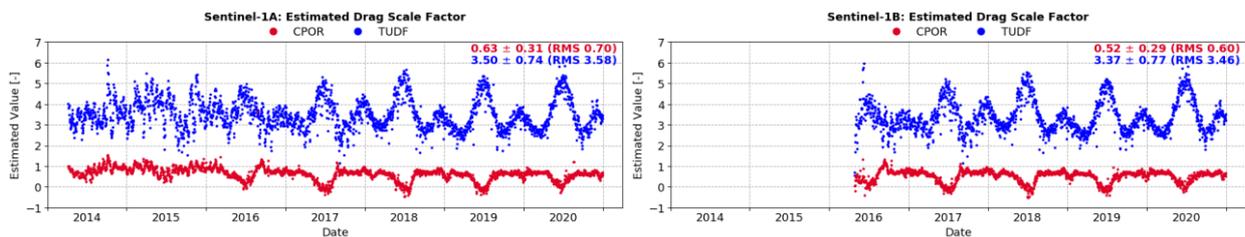


Figure 2-10: Temporal evolution of the estimated drag factor for CPOR and TUDF orbit solutions (left plot for Sentinel-1A case, right plot for Sentinel-1B)

2.2.2. CONSTANT PER REVOLUTION (CPR) PARAMETERS

The Constant per Revolution (CPR) parameters are differently estimated by CPOD and TUD centres (see Annex A for further information). Not only the number of parameters per arc is different but also the directions where they are estimated (TUDF also estimates constant CPRs in radial direction).

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Therefore, a direct comparison between the empirical parameters of both solutions cannot be done, but it is still interesting to visualise the evolution and biases.

The following subsections will focus in the along-track and cross-track directions where all matching estimated CPRs between both solutions are found.

2.2.2.1. CPRs in Along-track Direction

During the processing of a CPOR orbit solution, a total amount of 16 constant, sine and cosine CPRs are estimated for a determination arc of 32 hours. This leads to one CPR is estimated for an interval of time of 2 hours. Figure 2-11 presents the temporal evolution of the daily mean of all estimated CPRs per arc for the CPOR case alone. The same outcome but for the daily RMS is plotted in Figure 2-12.

As the drag scale factor case, there are two patterns that can be clearly identified from the outcome obtained on the CPRs:

- Firstly, a constant trend except during mid-year (eclipse period).
- And, secondly, a period of time more unstable which takes place on mid-year (eclipse period). This instability is less appreciated on the estimated sine CPRs.
- On the other hand, the RMS values do not add additional particularities, but support the previous two points.

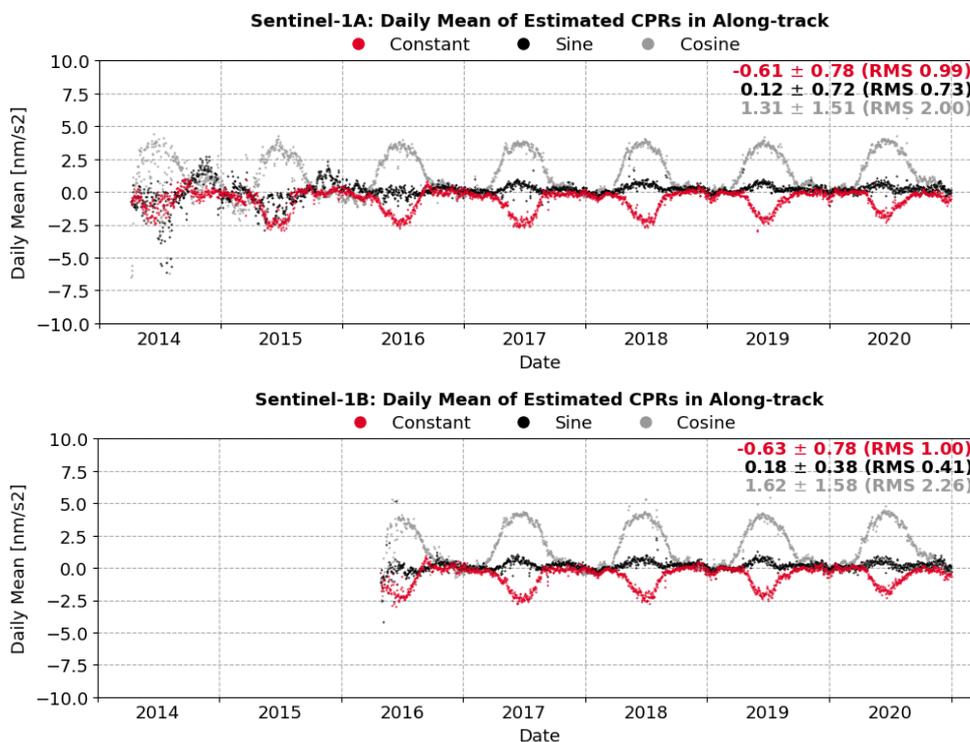


Figure 2-11: Temporal evolution of the daily mean of the estimated CPRs for CPOR orbit solution in along-track direction (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

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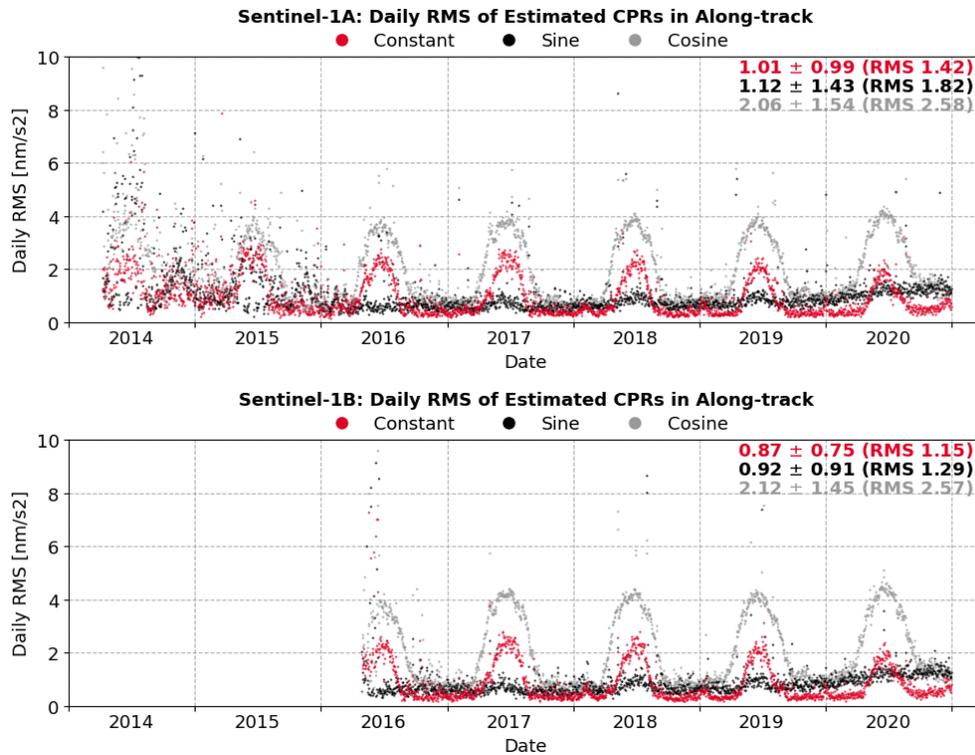


Figure 2-12: Temporal evolution of the daily RMS of the estimated CPRs for CPOR orbit solution in along-track direction (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

If the estimated CPRs from TUDF are added to the analysis (no constant CPRs in along-track are estimated by TUDF), it can be observed that there are interesting differences between both solutions (see Figure 2-13 and Figure 2-14). The estimated sine CPRs from TUDF shows a sinusoidal pattern around the New Year, which is not visible on CPOR solution. Meanwhile, the cosine CPRs of TUDF solution show a sharper sinusoidal behaviour and the amplitude is higher (here also, the definition of the empirical accelerations used by CPOR and TUDF is probably different, explaining the different sign).

However, considering that TUDF solution does not estimate the constant CPRs in the along-track direction, it is not possible to derive any conclusion from this direct comparison.

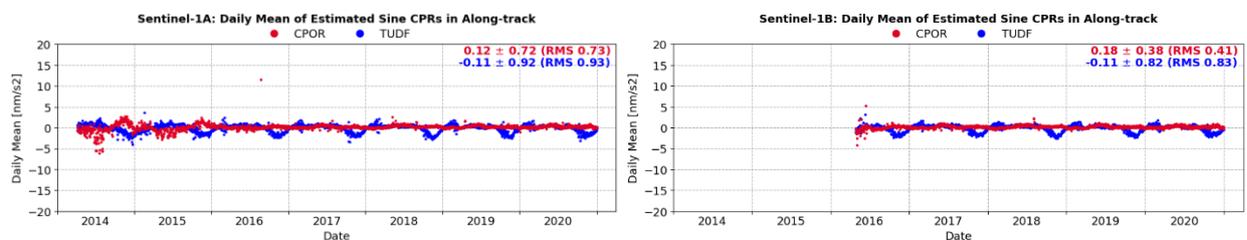


Figure 2-13: Temporal evolution of the daily mean of the estimated sine CPRs for CPOR and TUDF orbit solutions in along-track direction (left plot for Sentinel-1A case, right plot for Sentinel-1B)

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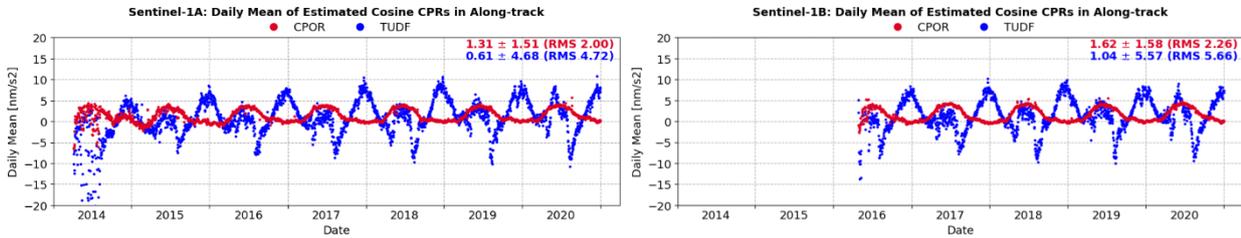


Figure 2-14: Temporal evolution of the daily mean of the estimated cosine CPRs for CPOR and TUDF orbit solutions in along-track direction (left plot for Sentinel-1A case, right plot for Sentinel-1B)

2.2.2.2. CPRs in Cross-Track Direction

The same approach for estimating CPRs in the cross-track direction as for the along-track case is followed by the CPOD Service. Figure 2-15 and Figure 2-16 depict the temporal evolution of the daily mean and daily RMS, respectively, of all estimated CPRs per arc for the CPOR case alone.

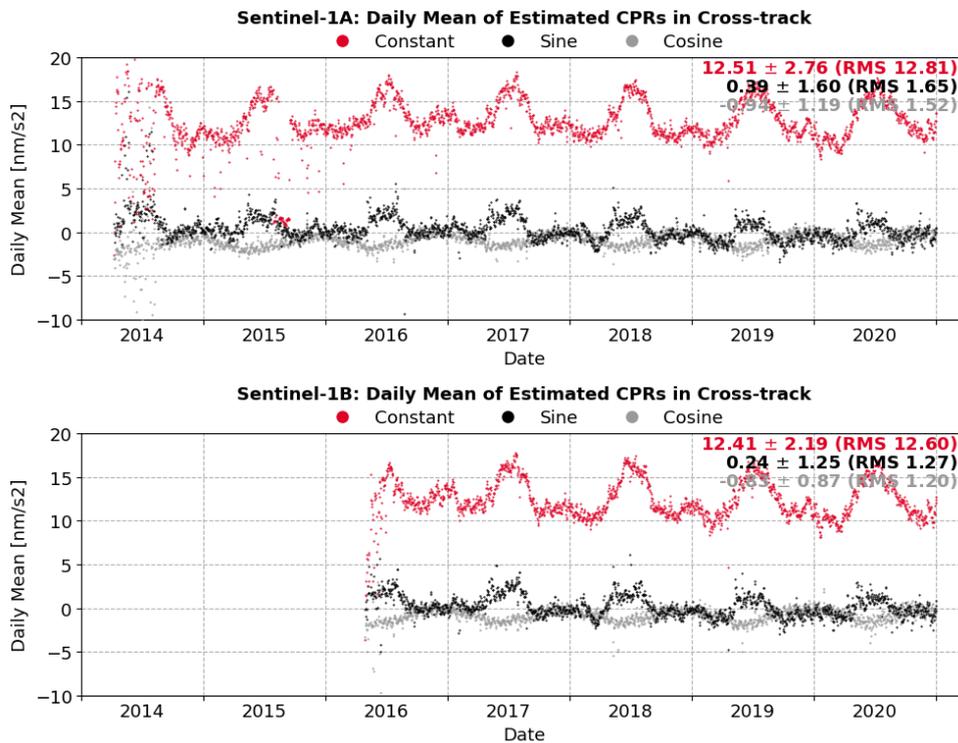


Figure 2-15: Temporal evolution of the daily mean of the estimated CPRs for CPOR orbit solution in cross-track direction (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

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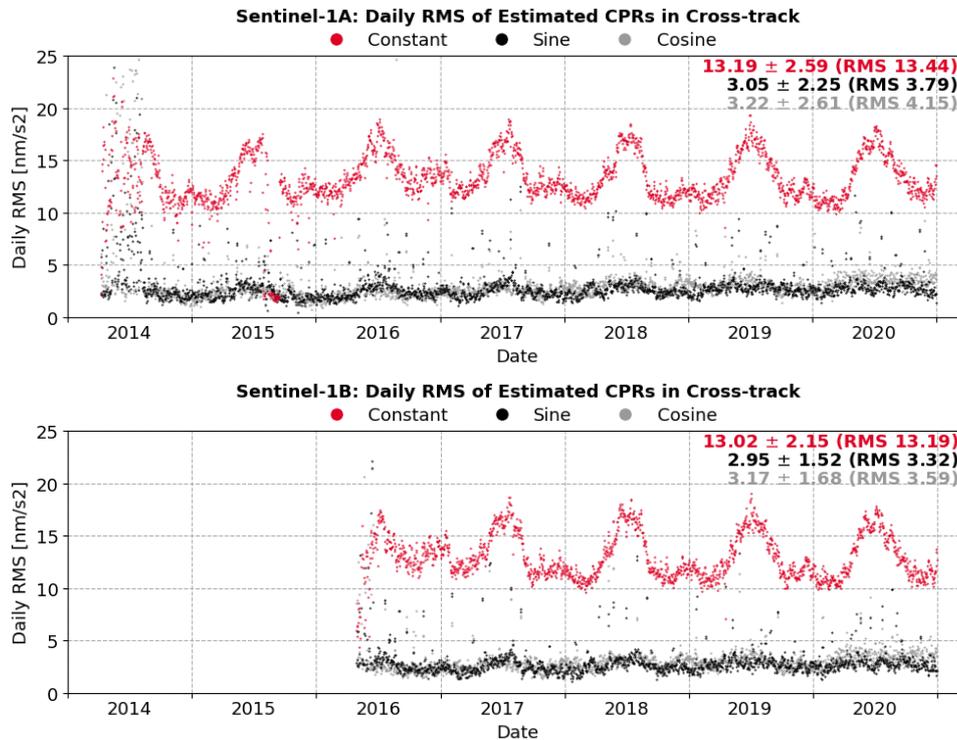


Figure 2-16: Temporal evolution of the daily RMS of the estimated CPRs for CPOR orbit solution in cross-track direction (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

In addition to what has been already commented in the previous subsection, the estimation of the CPRs in cross-track direction includes two more issues:

- Firstly, the constant CPR values show a significant bias with respect to the estimated values given by sine and cosine CPRs. This is probably due to a miss-modelling in the macro-model of the satellite. This issue is currently being investigated.
- And, secondly, there is jump on the estimated constant CPRs during the third quarter of 2015 as a result of the activation of the redundant receiver. During approximately 40 days, the redundant receiver was the receiver activated on Sentinel-1A. The amount of data retrieved from this period of time was not as large as required in order to estimate the antenna Phase Centre Offset (PCO) and Phase Centre Variation (PCV) values of the redundant receiver precisely. Thus, it was expected that the figures shown within this period of time presented a different behaviour as they do, especially on the cross-track direction.

The outcome from TUDF is quite similar on sine and cosine CPRs with respect to the CPOR solution (similar patterns are shown, but with different sign, which is probably due to a different definition of the empirical accelerations), and it is significantly different for the constant CPRs. In this case, the estimated constant CPRs from TUDF does not show any clear bias as the CPOR solution does, but the amplitude of the curve is significantly higher. TUDF is also estimating a scale factor for solar radiation pressure, which is strongly correlated to the cross-track direction in the case of Sentinel-1. In the case of the CPOR solution, the scale factor for the solar radiation pressure is fixed to 1.0. This might be the reason for the large differences in the estimates of the constant CPRs between CPOR and TUDF.

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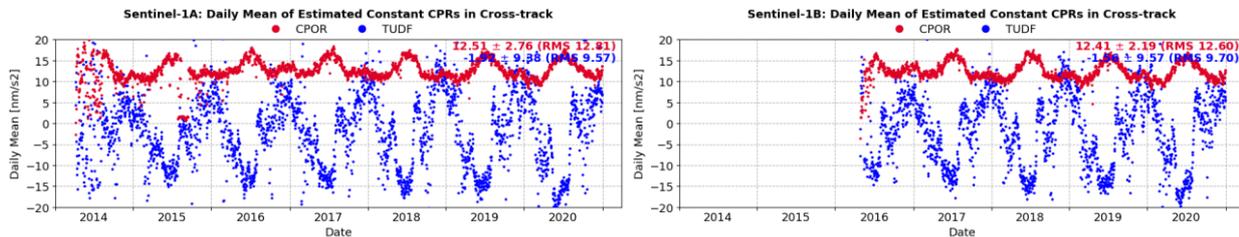


Figure 2-17: Temporal evolution of the daily mean of the estimated constant CPRs for CPOR and TUDF orbit solutions in cross-track direction (left plot for Sentinel-1A case, right plot for Sentinel-1B)

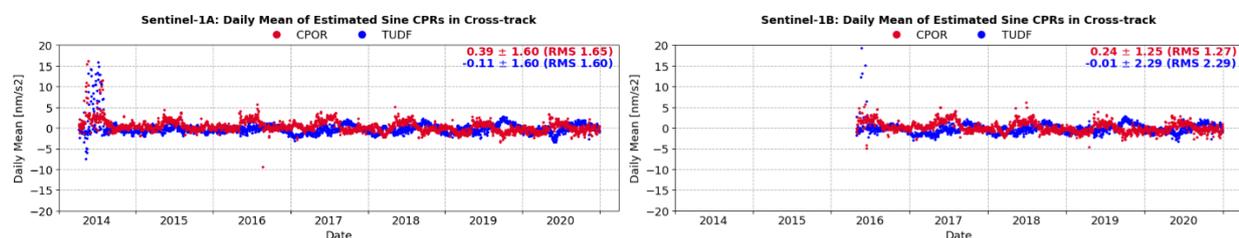


Figure 2-18: Temporal evolution of the daily mean of the estimated sine CPRs for CPOR and TUDF orbit solutions in cross-track direction (left plot for Sentinel-1A case, right plot for Sentinel-1B)

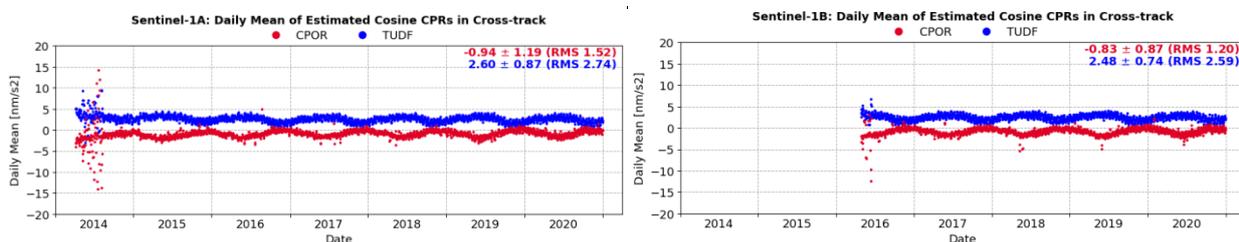


Figure 2-19: Temporal evolution of the daily mean of the estimated cosine CPRs for CPOR and TUDF orbit solutions in cross-track direction (left plot for Sentinel-1A case, right plot for Sentinel-1B)

The analysis of the estimated parameters has therefore revealed that there are still some things to be improved on the orbit modelling of both satellites. The peaks on mid-year show some inconsistencies between periods where the satellites are in eclipse and periods of time where they are not. This might probably be related to the macro-model currently used. Thus, further studies will be carried out on this direction in order to minimise the estimated orbit parameters and to finally improve the quality of the orbit solutions.

3. COMBINED ORBIT SOLUTION (COMB)

The combined orbit solution (COMB) is a weighted mean of all orbital solutions available. This combination follows a similar approach used by the International GNSS Service (IGS) when generating their final solutions. A brief description of how the weights of the COMB solution are obtained is detailed in Annex B.

It is necessary to highlight that a combined solution is not always better than each of the individual solutions. This combined solution is just a weighted mean, which means that if all except one individual solution are biased with respect to the reality, the combined solution will also be biased, and therefore, the individual comparisons will indicate a worse performance of the better (unbiased) solution. However, considering that all orbital solutions are of similar quality, and without an

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independent method for orbit quality control (e.g., Satellite Laser Ranging, SLR, data), this approach was selected for quality control purposes.

Although the desired approach is to use all available orbit solutions for the combination, there is a limitation on the current tool performing such task that prevents the use of the complete set of orbits provided by the different centres. If one of these orbit solutions at any particular day contains a gap of data at the beginning or at the end of the day (e.g. due to the lack of GPS data), the resulting combined orbit solution is generated with such gap of data. To avoid this issue and in order to have consistent COMB solutions over the entire period of time, some orbit solutions have been excluded from the combination (see Annex C for the complete list).

Taking into account the previous comment, a first generation of the COMB orbit solution has been carried out. The analysis of the orbit comparisons between all solutions against this COMB solution has revealed a few *outliers*. These *outliers* might be the result of a wrong combination, and therefore, they have been carefully analysed. As this analysis is not short enough to be included within this section, a specific annex has been added at the end of this memorandum in order to address this issue (see Annex D).

The following tables and figures aim to reflect the final status of the generation of the COMB solution. Firstly, Table 3-1 and Figure 3-1 provide the complete overview on the amount of orbit solutions used for the generation of the COMB orbit solution.

Table 3-1: Number of orbit solutions used for the generation of the COMB orbit solution (includes the legend of Figure 3-1)

Number of orbit solutions used for the COMB					
Number of orbit solutions	Sentinel-1A		Sentinel-1B		
	Total number	%	Total number	%	
1 orbit	5	0.20	3	0.18	
2 orbits	20	0.81	14	0.82	
3 orbits	221	8.99	105	6.17	
4 orbits	188	7.65	122	7.16	
5 orbits	145	5.90	47	2.76	
6 orbits	1878	76.43	1412	82.91	
Sum	2457	100.00	1703	100.00	

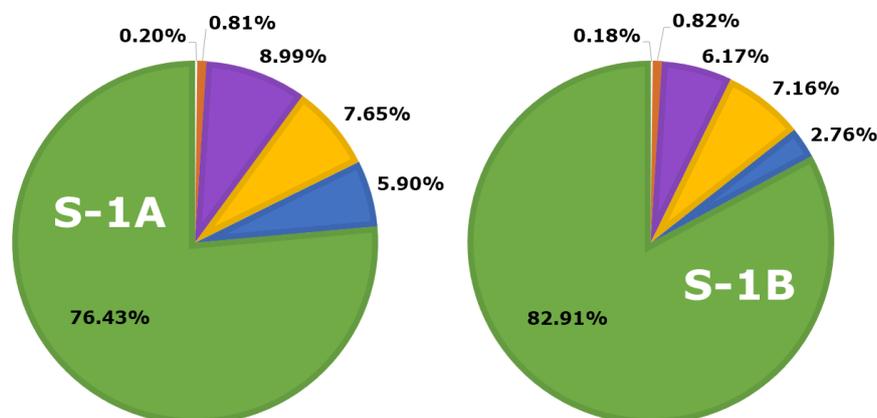


Figure 3-1: Number of orbit solutions used for the generation of the COMB orbit solution in percentage (the legend is given in Table 3-1)

Memo: Sentinel-1 Full Mission Reprocessing (2021)

The outcome presented above shows that, on the vast majority of cases, all orbit solutions have been used for the combination despite the fact that not all centres have generated the entire set of orbits for the whole period of time of the reprocessing. In addition, it should be remarked that only 1 % of the COMB solutions have been created by means of 1 or 2 orbit solutions (these are typically cases with large data gaps or manoeuvres, which in any case will not generate precise orbit solutions).

Figure 3-2 depicts the weight values given to each orbit solution during the generation of the COMB orbit solution. It must be highlighted that the higher is the weight, the higher is the contribution on the COMB solution.

From the figure below, it is visible that the orbit solutions are clustered in two groups. In one group, there are AIUB, CPOR, DLRR and TUDF (with a higher weight), and, in a second group, there are ESOC and TUMM (with a lower weight). This just indicates that the solutions from the first group are more similar among them, and therefore, as they are 4 out of 6, they have higher weight. This is not an indication of real orbit quality.

The pattern followed by each orbit solution can be better seen in Figure 3-3, where the weights per orbit solution are plotted. As seen from the figure, similar outcome is achieved on both satellites for all solutions, and the figures remain fairly consistent over time. It can be remarked that the TUDF orbit solution seems to gain importance over time, whereas the CPOR solution is losing it.

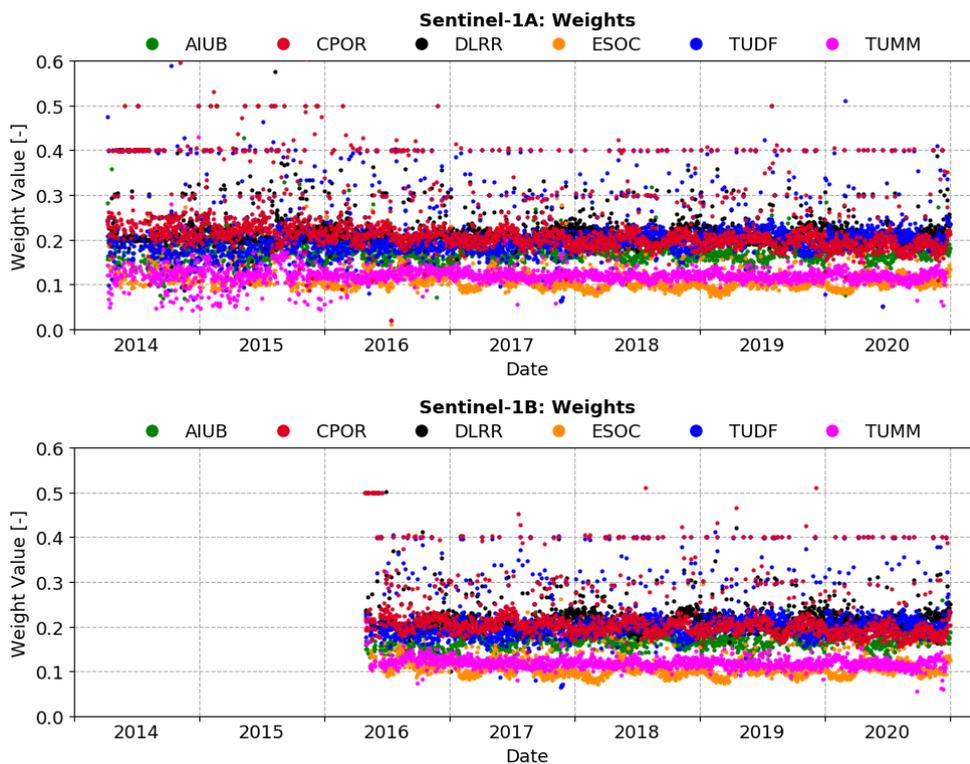


Figure 3-2: Temporal evolution of the weights given to each orbit solution for the generation of the COMB orbit solution (upper plot for Sentinel-1A case, and lower plot for Sentinel-1B)

Memo: Sentinel-1 Full Mission Reprocessing (2021)

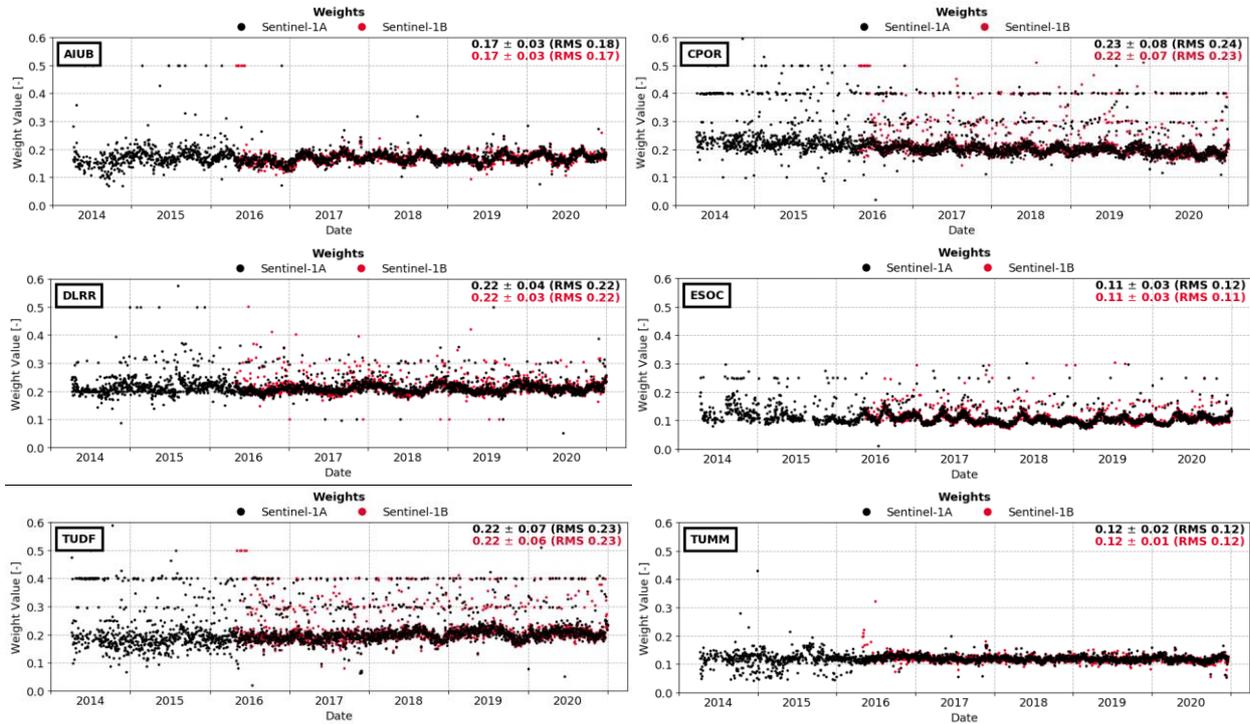


Figure 3-3: Temporal evolution per orbit solution of the weights given to each orbit solution for the generation of the COMB orbit solution

Finally, Figure 3-4 and Table 3-2 summarise the outcome above by showing the mean and standard deviation values of the weights.

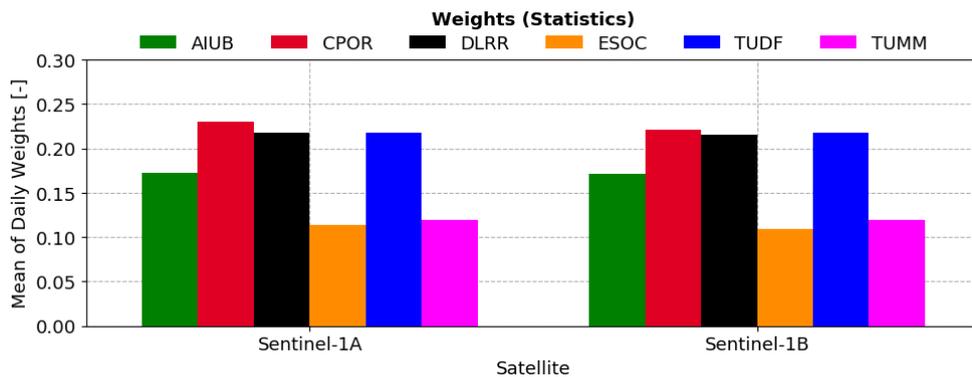


Figure 3-4: Mean of the weights given to each orbit solution for the generation of the COMB orbit solution

Table 3-2: Mean and standard deviation values of the weights given to each orbit solution for the generation of the COMB orbit solution

Weights: mean +/- STD [-]		
Orbit solution	Sentinel-1A	Sentinel-1B
AIUB	0.17 +/- 0.03	0.17 +/- 0.03

Memo: Sentinel-1 Full Mission Reprocessing (2021)

Weights: mean +/- STD [-]		
Orbit solution	Sentinel-1A	Sentinel-1B
CPOR	0.23 +/- 0.08	0.22 +/- 0.07
DLRR	0.22 +/- 0.04	0.22 +/- 0.03
ESOC	0.11 +/- 0.03	0.11 +/- 0.03
TUDF	0.22 +/- 0.07	0.22 +/- 0.06
TUMM	0.12 +/- 0.02	0.12 +/- 0.01

4. QUALITY ASSESSMENT

The following subsections show the outcome on the orbit comparisons calculated between each orbit solution participating on the Sentinel-1 reprocessing campaign against the COMB orbit solution generated on the previous step. Statistics about daily RMS and daily mean will be addressed.

As commented in the previous section, the COMB orbit solution cannot be considered the reality, or even the best solution. However, it is a reasonable approach to perform a relatively *fair* orbit quality control, in absence of independent methods (e.g. SLR observations)

It must be remarked that the outliers shown in Annex D have been filtered out from the orbit comparisons in order not to harm the final statistics. In addition, the orbit comparisons have been calculated without considering the periods of time when either manoeuvres or gaps of data occurred plus a safety margin of time before and after the event (5 minutes on each side). Thus, possible degradations on the orbit solutions as a consequence of any of the two events are minimised.

4.1. ROOT MEAN SQUARE (RMS) OF DAILY COMPARISONS

Figure 4-1 and Figure 4-2 show the temporal evolution of the daily RMS of the calculated orbit comparisons and considering all three satellites components together. The first figure depicts all orbit solutions on the same plot, whereas the results of each orbit solution are plotted alone on the second figure. From the analysis of these figures, some conclusions can be drawn:

- The vast majority of orbit comparisons is below 1.5 cm [3D RMS]. It must be highlighted that the position accuracy requirement for the S-1 POEORB (NTC) products on Sentinel-1 mission is of 5 cm [3D RMS]. The comparisons show that all independent orbit solutions agree between them much better than the required accuracy.
- AIUB, CPOR, DLRR and TUDF orbit solutions are the closest to the COMB orbit solution. This result is in line with the outcome shown for the weights of the COMB orbit solution.
- The results provided by CPOR and TUDF orbit solutions are very consistent over time. DLRR solution follows this performance very closely.
- In years 2014 and 2015, the solar activity was high. This fact may explain the dispersion shown by the resulting orbit comparisons during those days. It must be also taken into account that, during the first months after the launch of Sentinel-1A satellite, many manoeuvres were performed on the satellite increasing the difficulty to generate accurate orbits.
- There is some degradation (i.e., a few millimetres) on the orbit comparisons during the third quarter of year 2015 on all orbit solutions. As commented on a previous section, the redundant receiver was activated during this period of time whereas the nominal receiver remained deactivated. The PCO and PCV values from the redundant receiver are not well-enough calibrated as there is no sufficient data for a proper calibration, and therefore, some degradation was even a priori expected.
- Despite being the only float ambiguity solution, the outcome of ESOC orbit solution is not far from the results achieved by the rest of solutions. This is perhaps the main difference in the observation modelling between the ESOC and the other solutions.

Memo: Sentinel-1 Full Mission Reprocessing (2021)

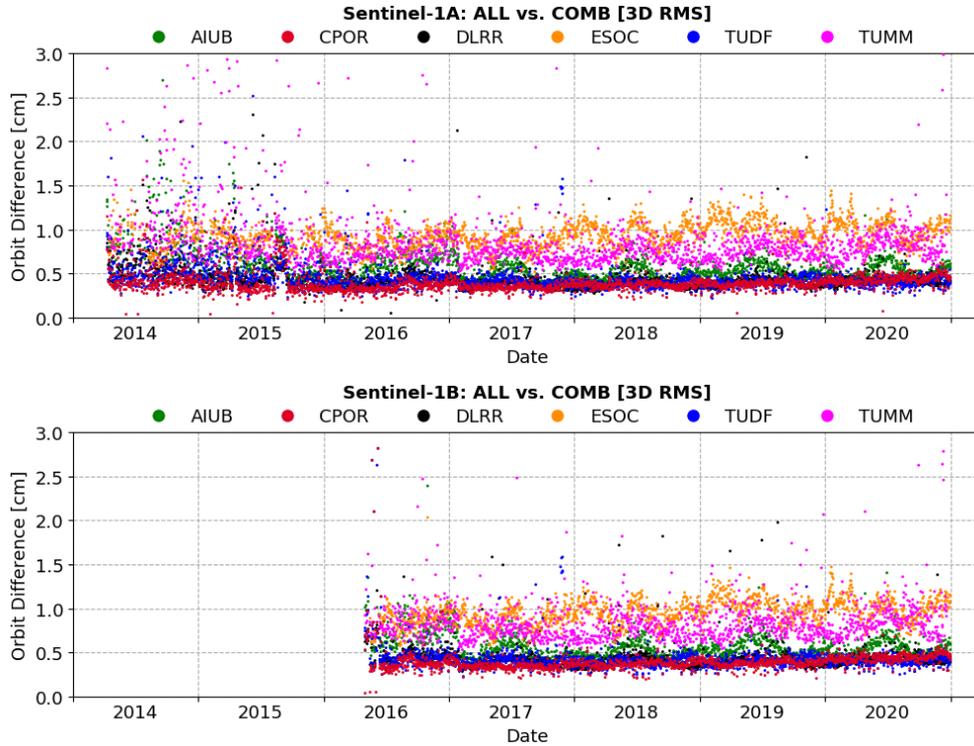


Figure 4-1: Temporal evolution of the orbit comparisons between all orbit solutions against the COMB orbit solution [3D RMS; cm] (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

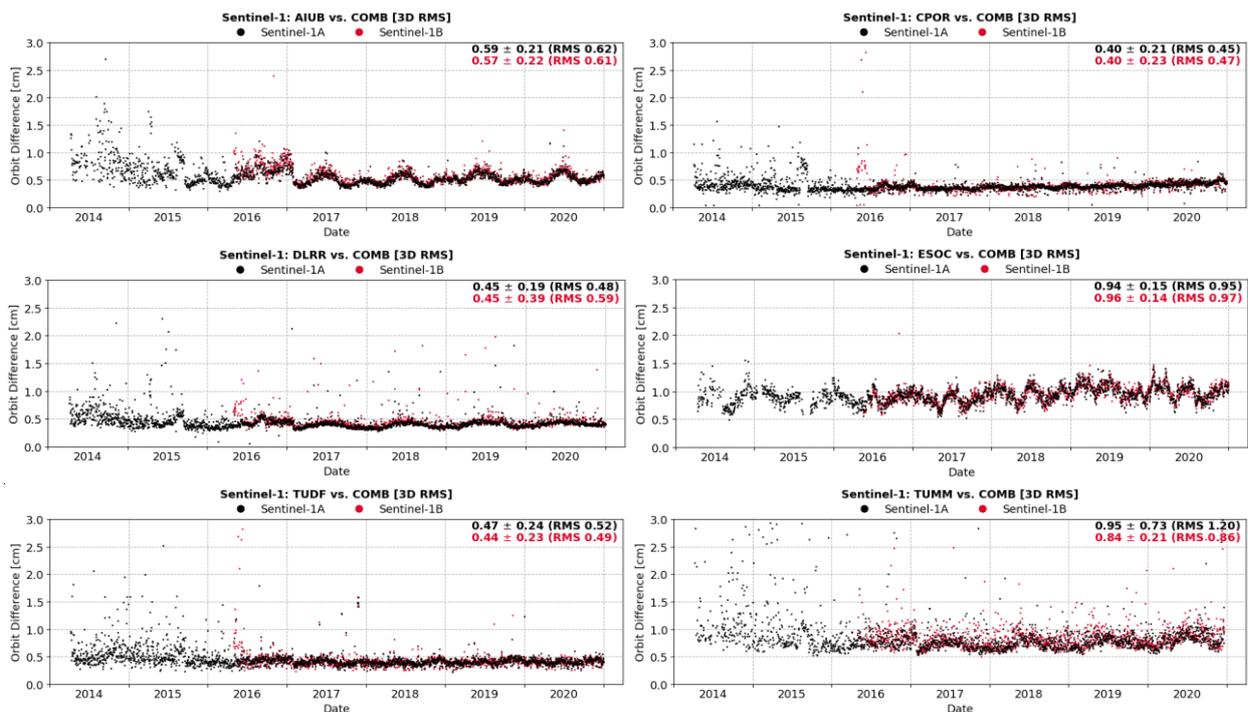


Figure 4-2: Temporal evolution per orbit solution of the orbit comparisons against the COMB orbit solution [3D RMS; cm]

Memo: Sentinel-1 Full Mission Reprocessing (2021)

The following figures show the outcome on the orbit comparisons but split by satellite component. The analysis of these figures concludes that the greatest differences among the orbit solutions are in the along-track (drag) and cross-track (solar radiation) directions.

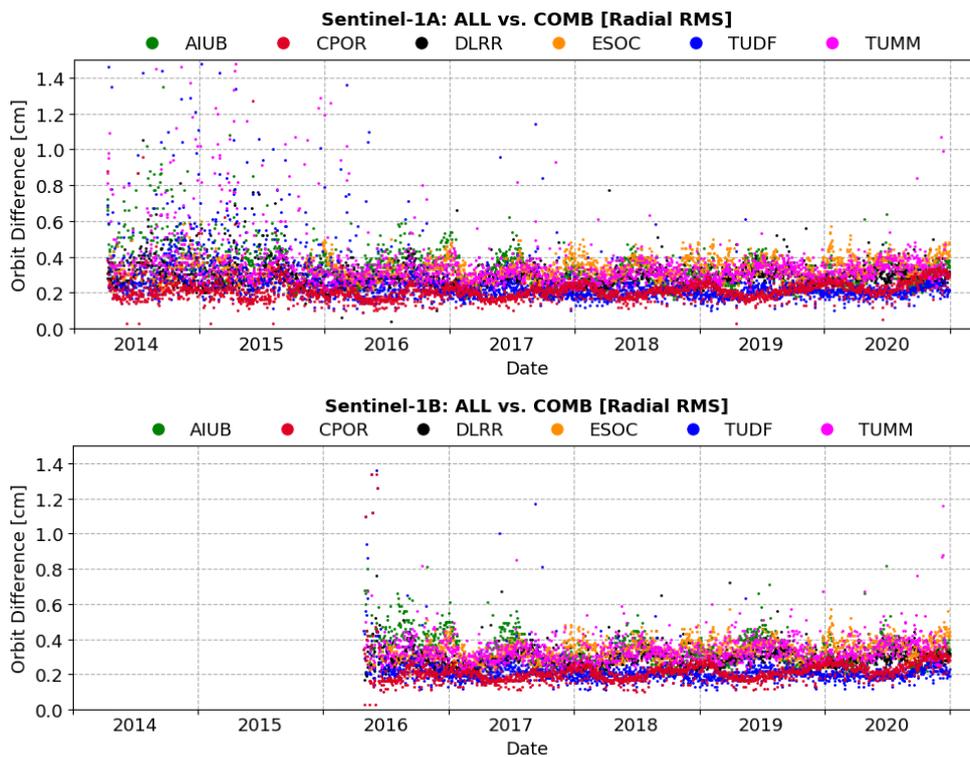


Figure 4-3: Temporal evolution of the orbit comparisons between all orbit solutions against the COMB orbit solution [radial RMS; cm] (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

Memo: Sentinel-1 Full Mission Reprocessing (2021)

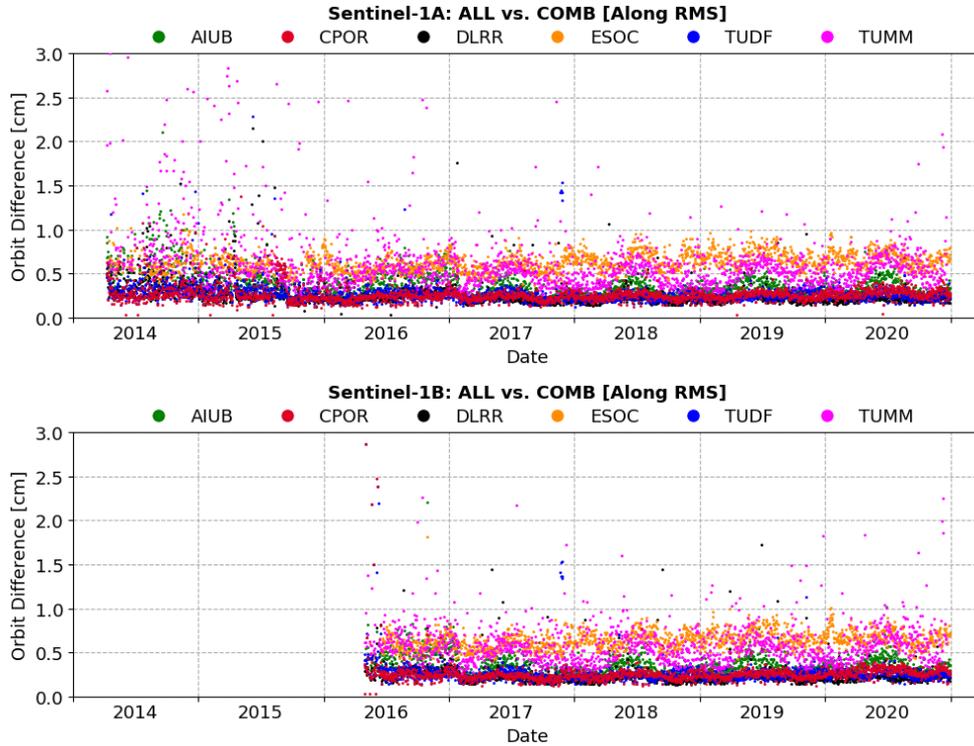


Figure 4-4: Temporal evolution of the orbit comparisons between all orbit solutions against the COMB orbit solution [along RMS; cm] (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

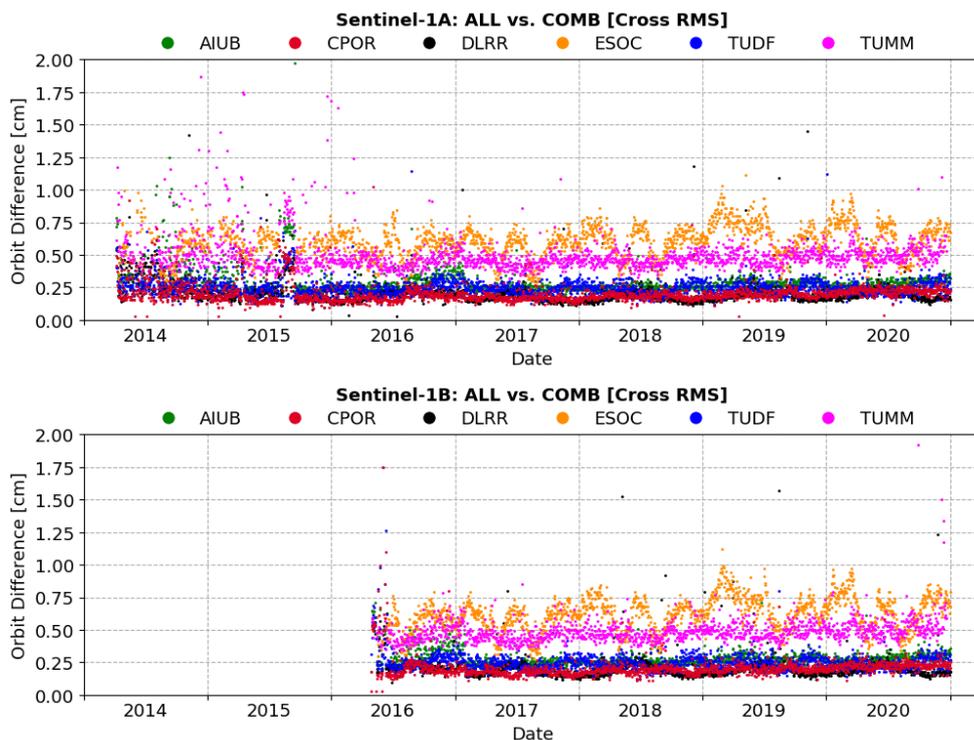


Figure 4-5: Temporal evolution of the orbit comparisons between all orbit solutions against the COMB orbit solution [cross RMS; cm] (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

Memo: Sentinel-1 Full Mission Reprocessing (2021)

Finally, Figure 4-6, Table 4-1 and Table 4-2 summarise the outcome above by showing the mean and standard deviation values of the daily RMS of the orbit comparisons per satellite component. It has to be emphasised again that a 3D RMS of lower than 1 cm could be achieved in the orbit comparisons over the entire mission time for both Sentinel-1 satellites.

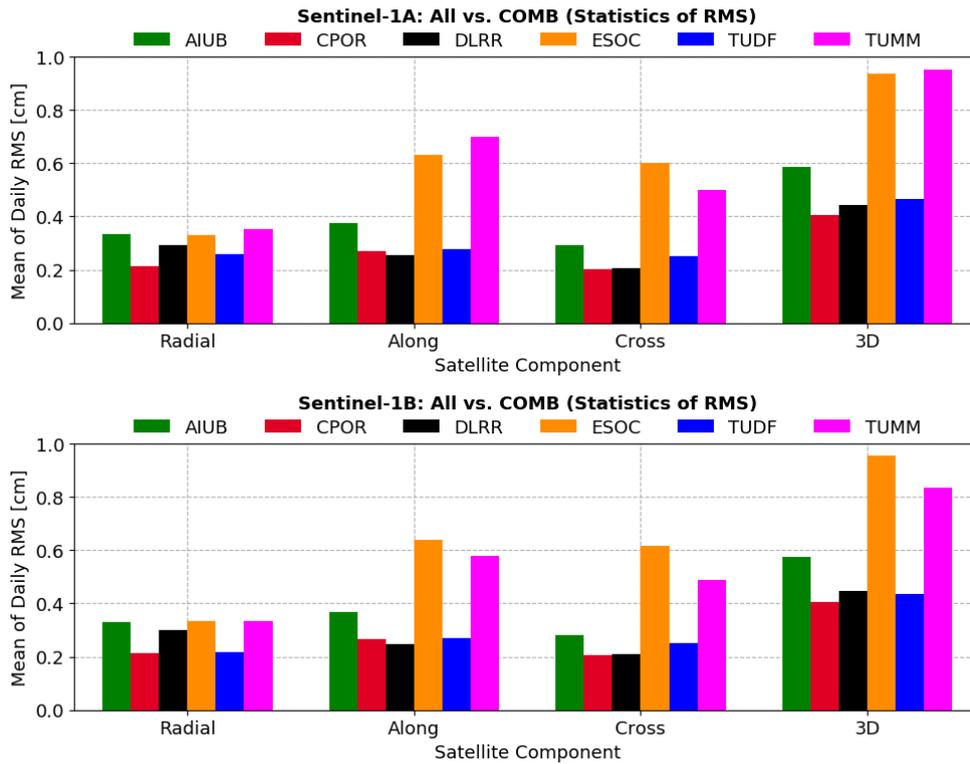


Figure 4-6: Mean of daily RMS [cm] of the orbit comparisons between all orbit solutions against the COMB orbit solution (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

Table 4-1: Mean and standard deviation values of daily RMS [cm] of the orbit comparisons between all orbit solutions against the COMB orbit solution (Sentinel-1A)

Sentinel-1A daily RMS of orbit comparisons: mean +/- STD [cm]				
Orbit solution	Satellite component			
	Radial	Along-track	Cross-track	3D
AIUB	0.33 +/- 0.11	0.38 +/- 0.17	0.29 +/- 0.15	0.59 +/- 0.21
CPOR	0.21 +/- 0.07	0.27 +/- 0.19	0.20 +/- 0.08	0.40 +/- 0.21
DLRR	0.29 +/- 0.06	0.25 +/- 0.17	0.21 +/- 0.09	0.45 +/- 0.19
ESOC	0.33 +/- 0.06	0.63 +/- 0.11	0.60 +/- 0.13	0.94 +/- 0.15
TUDF	0.26 +/- 0.16	0.28 +/- 0.19	0.25 +/- 0.07	0.47 +/- 0.24
TUMM	0.35 +/- 0.15	0.70 +/- 0.73	0.50 +/- 0.15	0.95 +/- 0.73

Memo: Sentinel-1 Full Mission Reprocessing (2021)

Table 4-2: Mean and standard deviation values of daily RMS [cm] of the orbit comparisons between all orbit solutions against the COMB orbit solution (Sentinel-1B)

Sentinel-1B daily RMS of orbit comparisons: mean +/- STD [cm]				
Orbit solution	Satellite component			
	Radial	Along-track	Cross-track	3D
AIUB	0.33 +/- 0.09	0.37 +/- 0.21	0.28 +/- 0.06	0.57 +/- 0.22
CPOR	0.21 +/- 0.09	0.27 +/- 0.21	0.21 +/- 0.08	0.40 +/- 0.23
DLRR	0.30 +/- 0.16	0.25 +/- 0.33	0.21 +/- 0.16	0.45 +/- 0.39
ESOC	0.33 +/- 0.06	0.64 +/- 0.10	0.62 +/- 0.13	0.96 +/- 0.14
TUDF	0.22 +/- 0.10	0.27 +/- 0.21	0.25 +/- 0.07	0.44 +/- 0.23
TUMM	0.33 +/- 0.07	0.58 +/- 0.21	0.49 +/- 0.09	0.84 +/- 0.21

4.2. MEAN OF DAILY COMPARISONS

The aim of this subsection is to find out if any of the orbit solutions generated presents systematic or periodic biases with respect to the others. The following figures plot the temporal evolution of the daily mean of the orbit comparisons. These figures are directly split per satellite component.

As seen in the figures, the values on the daily mean confirm that there is not any particular bias on the orbit solutions. The only issue to be remarked is a curve with an amplitude of +/-0.5 cm for the ESOC orbit solution in the cross-track direction, which may be the result of being a float ambiguity solution.

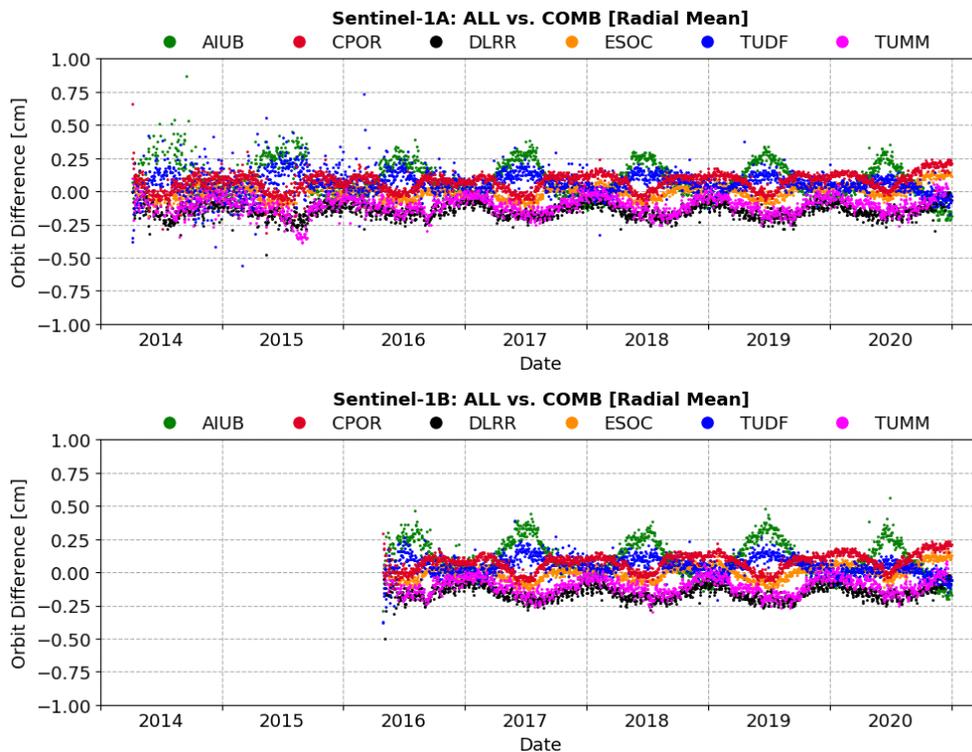


Figure 4-7: Temporal evolution of the orbit comparisons between all orbit solutions against the COMB orbit solution [radial mean; cm] (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

Memo: Sentinel-1 Full Mission Reprocessing (2021)

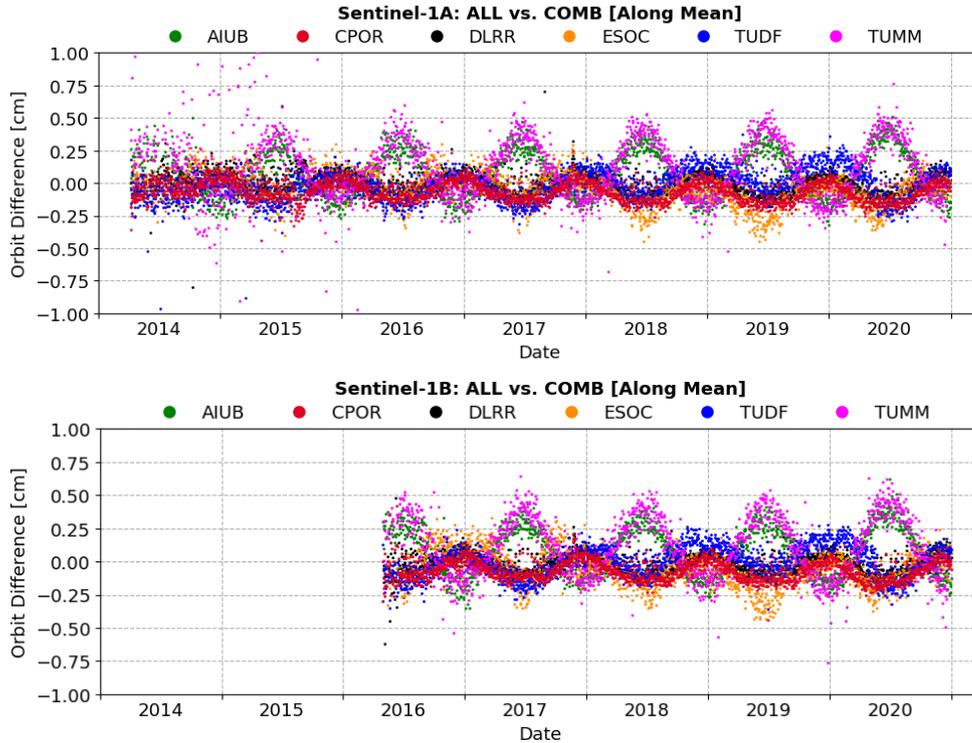


Figure 4-8: Temporal evolution of the orbit comparisons between all orbit solutions against the COMB orbit solution [along mean; cm] (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

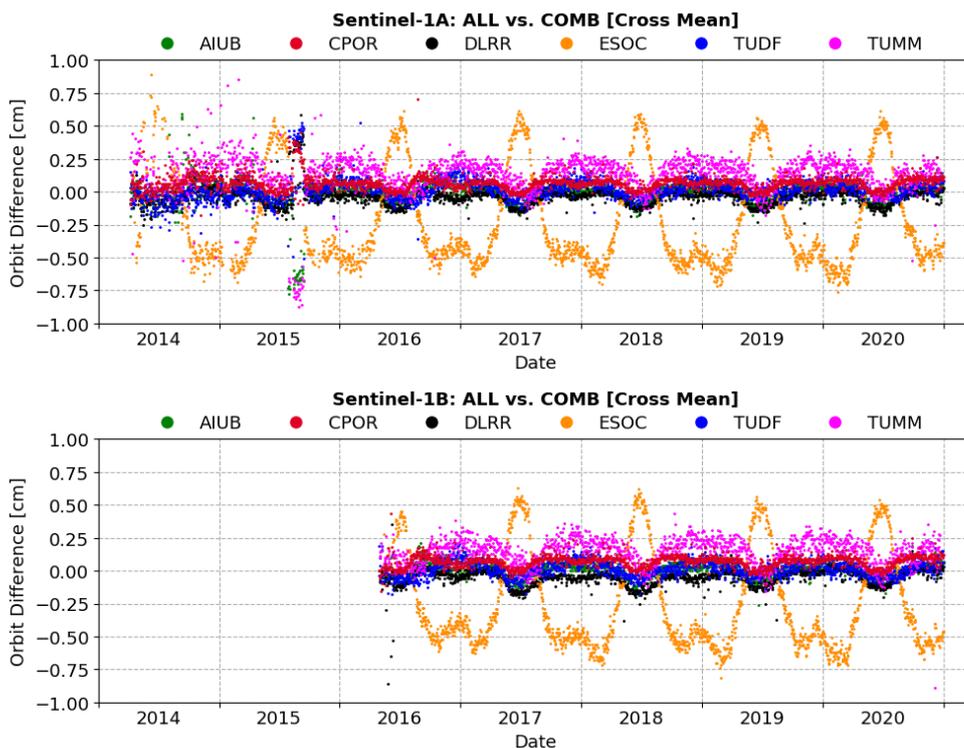


Figure 4-9: Temporal evolution of the orbit comparisons between all orbit solutions against the COMB orbit solution [cross mean; cm] (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

Memo: Sentinel-1 Full Mission Reprocessing (2021)

Finally, Figure 4-10, Table 4-3 and Table 4-4 summarise the outcome above by showing the mean and standard deviation values of the daily mean of the orbit comparisons per satellite component.

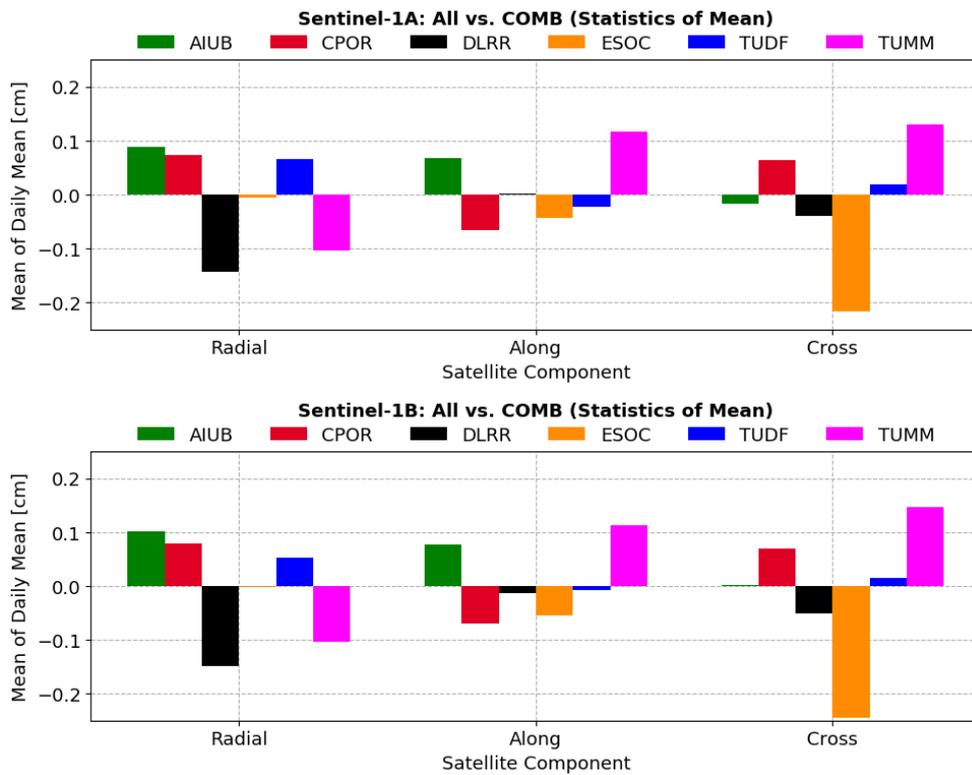


Figure 4-10: Mean of daily mean [cm] of the orbit comparisons between all orbit solutions against the COMB orbit solution (upper plot for Sentinel-1A case, lower plot for Sentinel-1B)

Table 4-3: Mean and standard deviation values of daily mean [cm] of the orbit comparisons between all orbit solutions against the COMB orbit solution (Sentinel-1A)

Sentinel-1A daily mean of orbit comparisons: mean +/- STD [cm]			
Orbit solution	Satellite component		
	Radial	Along-track	Cross-track
AIUB	0.09 +/- 0.14	0.07 +/- 0.18	-0.02 +/- 0.10
CPOR	0.07 +/- 0.07	-0.07 +/- 0.09	0.06 +/- 0.06
DLRR	-0.14 +/- 0.05	0.00 +/- 0.08	-0.04 +/- 0.07
ESOC	-0.01 +/- 0.05	-0.04 +/- 0.12	-0.22 +/- 0.37
TUDF	0.07 +/- 0.09	-0.02 +/- 0.13	0.02 +/- 0.08
TUMM	-0.10 +/- 0.07	0.12 +/- 0.26	0.13 +/- 0.17

Memo: Sentinel-1 Full Mission Reprocessing (2021)

Table 4-4: Mean and standard deviation values of daily mean [cm] of the orbit comparisons between all orbit solutions against the COMB orbit solution (Sentinel-1B)

Sentinel-1B daily mean of orbit comparisons: mean +/- STD [cm]			
Orbit solution	Satellite component		
	Radial	Along-track	Cross-track
AIUB	0.10 +/- 0.14	0.08 +/- 0.18	0.00 +/- 0.06
CPOR	0.08 +/- 0.06	-0.07 +/- 0.07	0.07 +/- 0.04
DLRR	-0.15 +/- 0.05	-0.01 +/- 0.08	-0.05 +/- 0.06
ESOC	-0.00 +/- 0.05	-0.05 +/- 0.14	-0.25 +/- 0.37
TUDF	0.05 +/- 0.07	-0.01 +/- 0.14	0.01 +/- 0.06
TUMM	-0.10 +/- 0.06	0.11 +/- 0.22	0.15 +/- 0.11

4.3. GEOGRAPHICAL ANALYSIS

To conclude the quality assessment, the following figures show the geographical distribution of the orbit comparisons between each orbit solution and the COMB solution. Only the mean of the 3D RMS is shown for both satellites. The plots have been scaled to the same value in order that the differences between orbit solutions can be better appreciated. By using these plots, inconsistencies of the orbit solutions around the globe may be evaluated.

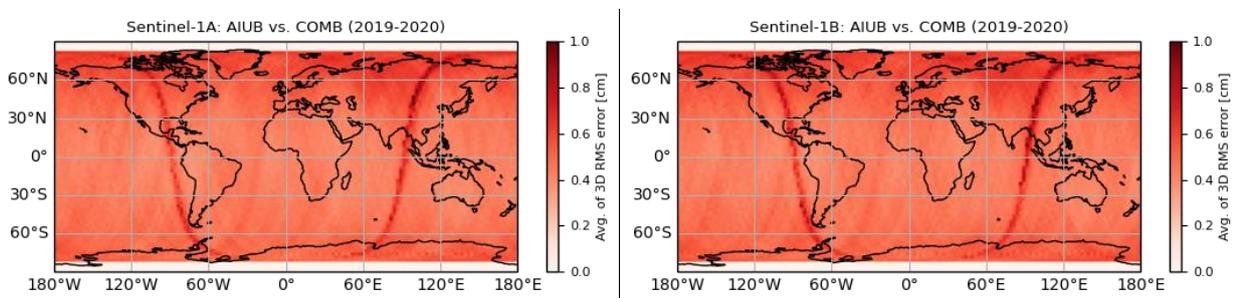


Figure 4-11: Geographical distribution of the orbit comparisons between AIUB and COMB orbit solutions [Mean of 3D RMS; cm] (left plot for Sentinel-1A case, right plot for Sentinel-1B)

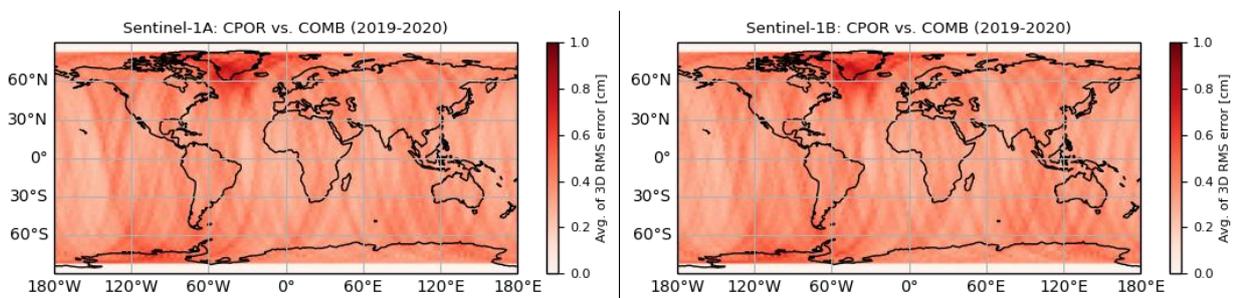


Figure 4-12: Geographical distribution of the orbit comparisons between CPOR and COMB orbit solutions [Mean of 3D RMS; cm] (left plot for Sentinel-1A case, right plot for Sentinel-1B)

Memo: Sentinel-1 Full Mission Reprocessing (2021)

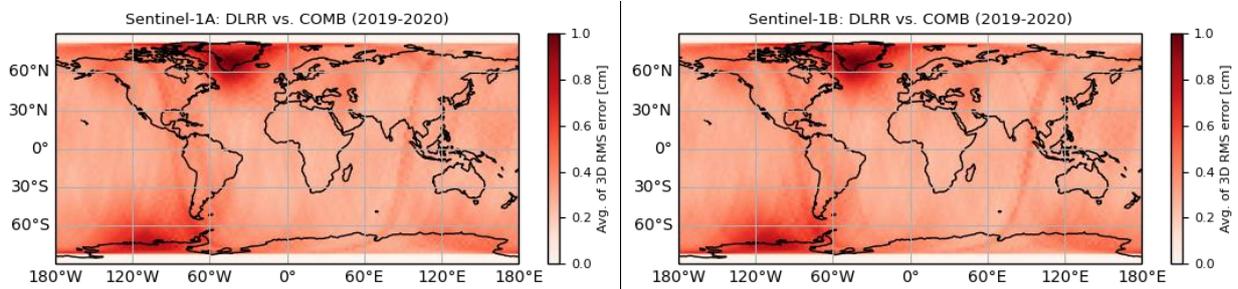


Figure 4-13: Geographical distribution of the orbit comparisons between DLRR and COMB orbit solutions [Mean of 3D RMS; cm] (left plot for Sentinel-1A case, right plot for Sentinel-1B)

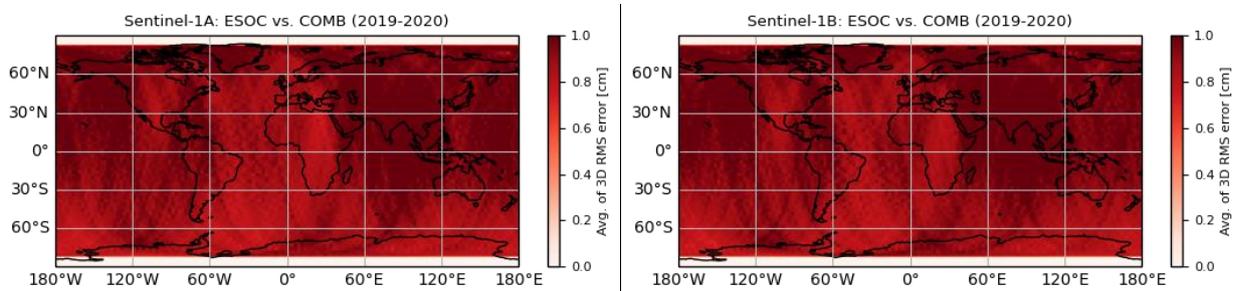


Figure 4-14: Geographical distribution of the orbit comparisons between ESOC and COMB orbit solutions [Mean of 3D RMS; cm] (left plot for Sentinel-1A case, right plot for Sentinel-1B)

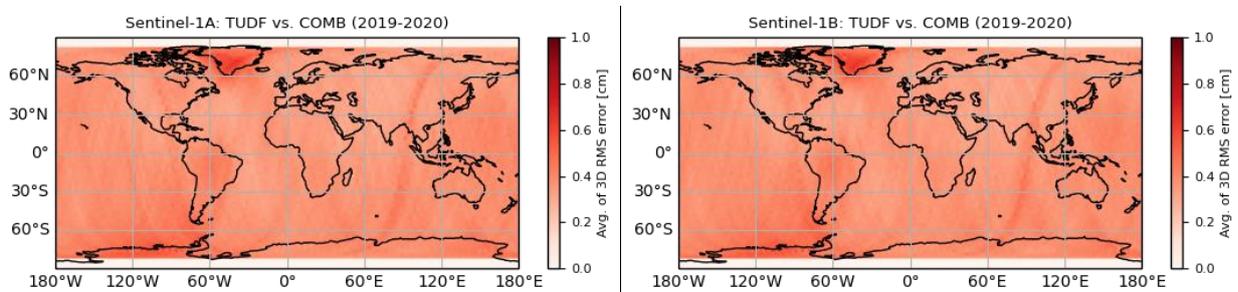


Figure 4-15: Geographical distribution of the orbit comparisons between TUDF and COMB orbit solutions [Mean of 3D RMS; cm] (left plot for Sentinel-1A case, right plot for Sentinel-1B)

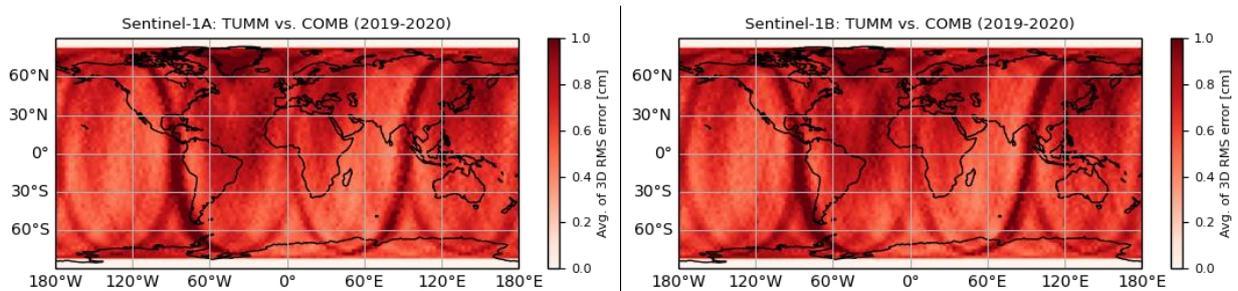


Figure 4-16: Geographical distribution of the orbit comparisons between TUMM and COMB orbit solutions [Mean of 3D RMS; cm] (left plot for Sentinel-1A case, right plot for Sentinel-1B)

Memo: Sentinel-1 Full Mission Reprocessing (2021)

5. SPACE PARTICLE HIT ON SOLAR PANEL (SENTINEL-1A)

On 23rd August 2016, the solar panel array of Sentinel-1A was hit by a space particle [RD.4]. Figure 5-1 shows the orbital cross-comparisons between the different orbit solutions on this day. The CPOR orbit solution did not modelled any manoeuvre on this day in order to simulate any change on the satellite's trajectory after the hit; at least TUDF modelled it as a manoeuvre. This may explain the larger values obtained on the cross comparisons when the CPOR orbit solution is involved.

Further analysis could be done on the CPOD Service side in order to reduce the impact of this event on the current orbit solution generated.

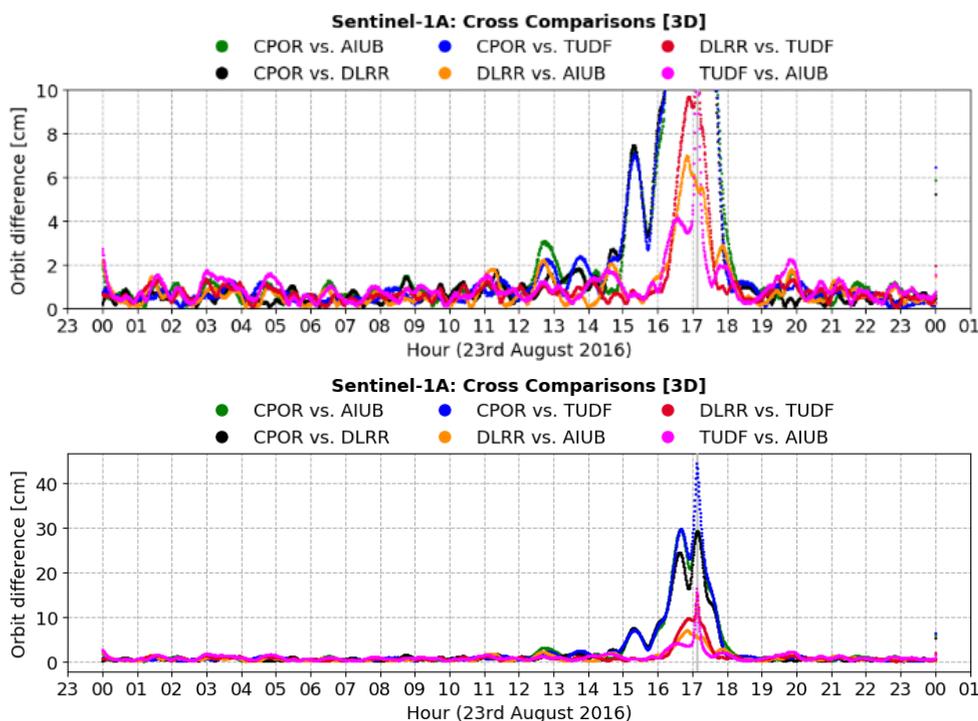


Figure 5-1: Sentinel-1A – Temporal evolution of the cross-comparisons on 23rd August 2016 [3D; cm] (the vertical grey line stands for the time when the particle hit the solar panel)

6. CONCLUSIONS

The reprocessed Sentinel-1A and -1B orbit solutions analysed within this memorandum show an excellent performance. The resulting mean of the daily 3D RMS of the orbit comparisons is below 1 cm for all orbit solutions (below 0.5 cm for those solutions presenting the best performance). This outcome is well below the position accuracy requirement for NTC products of the Sentinel-1 mission (i.e., 5 cm [3D RMS]).

13/04/2021

Memo: Sentinel-1 Full Mission Reprocessing (2021)

ANNEX A. DESCRIPTION OF THE POD PROCESSING

The following table summarises the POD processing used by each centre participating on the Sentinel-1 reprocessing campaign.

Table A-1: Data processing summary (I)

Data Processing Summary						
Parameter/Model	Analysis Centre (Orbit Solution)					
	AIUB (AIUB)	CPOD (CPOR)	DLR (DLRR)	ESOC (ESOC)	TU Delft (TUDF)	TUM (TUMM)
Software						
Name and version	Bernese GNSS Software v5.3	NAPEOS	GHOST 2276	NAPEOS 4.2.1	GIPSY-X (v1.5)	Bernese GNSS Software v5.3 (mod)
Arc Cut						
Arc lengths	24 h	32 h	30 h	30 h	30 h	30 h
Handle of manoeuvres	Only days processed w/o manoeuvres	Manoeuvres are calibrated in the POD process	Only days processed w/o manoeuvres			
Handle of data gaps	No	Yes	Yes	Yes	Yes	No
Reference System						
Polar motion and UT1	CODE final products	IERS finals2000A.data	igs96p02.erp	IERS Bulletin A (IERS rapids)	JPL Final products	IERS finals2000A.data
Pole model	IERS 2010 Conventions	IERS 2010 Conventions	n/a	IERS 2010 Conventions	IERS 2010 Conventions	IERS 2010 Conventions
Precession/Nutation	IERS 2010 Conventions	IERS 2010 Conventions	IERS 2010 Conventions	IERS 2010 Conventions	IERS 2010 Conventions	IERS 2010 Conventions
Satellite Reference						
Mass and centre of gravity	Variable with input from FOS	Variable with input from FOS	Variable with input from FOS	Variable with input from FOS	Variable with input from FOS	Variable with input from FOS
Attitude model	Nominal attitude law	Quaternions	Nominal attitude law	Nominal attitude law	Quaternions	Nominal attitude law

Memo: Sentinel-1 Full Mission Reprocessing (2021)

Data Processing Summary						
Parameter/Model	Analysis Centre (Orbit Solution)					
	AIUB (AIUB)	CPOD (CPOR)	DLR (DLRR)	ESOC (ESOC)	TU Delft (TUDF)	TUM (TUMM)
GPS antenna reference point (X,Y,Z)	[RD.1]	[RD.1]	[RD.1]	[RD.1]	[RD.1]	[RD.1]
GPS antenna orientation (Euler angles, Z,Y,X)	[RD.1]	[RD.1]	[RD.1]	[RD.1]	[RD.1]	[RD.1]
Gravity						
Gravity field (static)	GOCO05s (120x120)	EIGEN.GRGS.RL04 TVG (120x120)	GOCO03S (100x100)	EIGEN.GRGS.RL04.MEAN-FIELD with quadratic_mean_pole	EIGEN.GRGS.RL04.MEAN-FIELD with quadratic_mean_pole (200X200)	EIGEN GL04C (120x120)
Gravity field (time varying)	IERS 2010 Conventions	Drift/annual/semi-annual piece wise linear terms up to degree/order 90	n/a	Drift/annual/semi-annual piece wise linear terms up to degree/order 80	Drift/annual/semi-annual piece wise linear terms up to degree/order 90	Drift of 20, 30, 40
Solid Earth tides	Applied (IERS 2010)	Applied (IERS 2010)	Applied	Applied (IERS 2010)	Applied (IERS 2010)	Applied (IERS 2010)
Ocean tides	EOT11A (50x50)	FES2014 (100x100, 142 tidal constituents)	Applied (FES 2004)	EOT11a (50x50)	Applied (FES2004)	FES2004 (50x50)
Atmospheric gravity	None	AOD1B RL06 (100x100)	n/a	AOD1B RL06 (100x100)	AOD1B RL06 (180x180)	None
Atmospheric tides	None	AOD1B RL06 (100x100)	n/a	Ray-Ponte 2003	n/a	None
Earth pole tide	IERS 2010	IERS 2010	n/a	IERS 2010	IERS 2010	IERS 2010
Ocean pole tide	IERS 2010	IERS 2010	n/a	IERS 2010	IERS 2010	IERS 2010
Third bodies	Sun, Moon, Planets DE405	Sun, Moon, Planets DE421	Sun, Moon (analytical series)	Sun, Moon, Planets DE405	Sun, Moon, Planets (IERS 2010)	Sun, Moon, Planets DE405
Surface Forces and Empiricals						
Radiation pressure model	No explicit modelling	Box-wing model (with re-radiation)	Macro-model	Box-wing model	Box-wing model	Box-wing model
Earth radiation	No explicit modelling	Albedo and Infra-red applied	n/a	Albedo and Infra-red applied	Albedo	Box-wing for Albedo and Infra-red

Memo: Sentinel-1 Full Mission Reprocessing (2021)

Data Processing Summary						
Parameter/Model	Analysis Centre (Orbit Solution)					
	AIUB (AIUB)	CPOD (CPOR)	DLR (DLRR)	ESOC (ESOC)	TU Delft (TUDF)	TUM (TUMM)
Atmospheric density model	No explicit modelling	msise00	NRLMSISE-00, macro model, drag, lift	msise90	DTM2000	MSISE-90
Radiation pressure coefficient	No explicit modelling	Fixed 1 coefficient to 1.0	1 per arc (estimated)	Fixed	1 per arc (estimated)	1 per arc (estimated)
Drag coefficients	No explicit modelling	Estimated 1 coefficient per arc (constrained with 0.3)	1 per arc (estimated)	1 per day	1 per arc (estimated)	1 per arc (estimated)
1/rev empiricals	n/a	Estimated 16 sets per arc: Alo: constant, sine, cosine Cro: constant, sine, cosine (constrained with 10e-12 km/s ² [con], 10e-11 km/s ² [sin/cos])	n/a	18 sets in along and cross track direction (constant/sine/cosine)	In along-track and cross-track directions (sine/cosine), constrained 5e-9 m/s ²	2 sets in along-track and cross-track direction (with sin/cos signals)
Other empiricals	Piecewise constant empiricals in R,S,W, every 6' (constrained)	n/a	Constant empirical accelerations in RTN at 10 min intervals (constrained to zero)	n/a	Constant empirical accelerations in radial, cross-track and along-track directions, updated every 10 minutes (constrained 5e-9 m/s ² , daily biases removed)	Stoch. velocity changes every 15 min (constr. 5e-7m/s ²)
GPS Measurements						
Relativity	Applied	Applied (IERS 2010)	Applied	Applied (IERS 2010)	Applied	Applied
Sampling	10 s	10 s	30 s	10 s	30 s	10 s
Observations	Iono-free linear combination of phase measurements (pseudo-range used only for clock synchronisation)	Iono-free linear combinations of phase and pseudo-range measurements	Iono-free linear combinations of phase and pseudo-range measurements (undifferenced)	Iono-free linear combinations of phase and pseudo-range measurements	Iono-free linear combinations of phase and pseudo-range measurements (undifferenced)	Iono-free linear combinations of phase and pseudo-range measurements
Weight	n/a	0.8 m (pseudo-range) / 10 mm (carrier-phase)	1 m (pseudo-ranges), 10 mm (carrier-phase)	1.0 m (pseudo-range) / 10 mm (carrier-phase)	1.0 m (pseudo range) / 10 mm (carrier-phase)	n/a
Elevation angle cut-off	0 deg	7 deg	0 deg	7 deg	0 deg	0 deg

Memo: Sentinel-1 Full Mission Reprocessing (2021)

Data Processing Summary						
Parameter/Model	Analysis Centre (Orbit Solution)					
	AIUB (AIUB)	CPOD (CPOR)	DLR (DLRR)	ESOC (ESOC)	TU Delft (TUDF)	TUM (TUMM)
Down-weighting law	None	None	None	None	None	None
Antenna phase-centre wind-up correction	Applied	Applied	Applied	Applied	Applied (IGS model)	Applied (IGS model)
Antenna phase-centre variation	Applied (AIUB maps)	Applied (sen08_2146.atx)	Applied (sen08_2146.atx)	Applied (sen08_2146.atx)	Applied (sen08_2146.atx)	Applied (sen08_2146.atx)
GPS Parameters						
Receiver clocks	Per epoch, every 10 s	Per epoch, every 10 s	Per epoch, every 10 s	Per epoch, every 10 s	Per epoch, every 30 s (no relativistic corrections applied)	Per epoch, every 10 s
Receiver ambiguities	Estimated (integer)	Estimated (fixed)	Estimated (integer)	Estimated (float)	Estimated (resolved, typically 85%)	Estimated (resolved, typically more than 95%)
GPS orbits	Fixed (CODE repro/final products ^(*))	Fixed (CODE repro/final products ^(**))	Fixed (CODE repro/final products ^(**))	Fixed (ESOC COP Final)	Fixed (JPL Final / IGS14)	Fixed (CODE repro/final products ^(**))
GPS clocks	Fixed (CODE repro/final products ^(*) , 5 s)	Fixed (CODE repro/final products ^(**) , 5 s)	Fixed (CODE repro/final products ^(**) , 5 s)	Fixed (ESOC COP Final)	Fixed (JPL Final / IGS14, 30 s clocks)	Fixed (CODE repro/final products ^(**) , 5 s)
GPS satellite biases	n/a	CODE repro/final ^(**)	CODE repro/final ^(**)	n/a	n/a	n/a
<p>^(*) The CODE repro products [RD.2] have been used for the interval of time between the start of the mission until 31/12/2018, whereas the CODE final products have been used on 2019/2020.</p> <p>^(**) The CODE repro products [RD.2] have been used for the interval of time between the start of the mission until 31/12/2019, whereas the CODE final products have been used on 2020. The CODE final products have also been used on mid-2019 from 9th June to 7th September (both included) due to a problem with the reprocessed products.</p>						

13/04/2021

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ANNEX B. CALCULATION OF THE COMB ORBIT SOLUTION

This annex describes how the combined orbit solution is generated from the calculation of the weights given to the orbit solutions involved within the combination.

The combined orbit solution for a particular satellite and day is computed by averaging the state vectors that contain the position and velocity of the satellite at time t^* , $\mathbf{SV}(t^*) = [\mathbf{r}(t^*) \mathbf{v}(t^*)]^T$, of the different orbit solutions as follows:

$$\mathbf{SV}_{comb}(t^*) = \frac{\sum_j \mathbf{SV}_j(t^*)/w_j}{\sum_j 1/w_j},$$

where $1/w_j$ denotes the weight associated to each orbit solution j on a particular day. These weights are a measurement of the (inverse) distance between the orbits of each centre and the simple arithmetic mean combination (i.e., a priori combined solution setting $1/w_j = 1$).

Let d_j be the module of the distance between the position of the a priori combined solution, \mathbf{r}_0 , and the position of the solution of centre j , \mathbf{r}_j , at time t^* . This is:

$$d_j(t^*) = |\mathbf{r}_0(t^*) - \mathbf{r}_j(t^*)|$$

If \mathbf{d}_j is the vector built from the distances d_j computed for every t^* of the temporal discretisation (defined by the combination step, which value can be selected by the user), a value \bar{w}_j has been defined as the median of \mathbf{d}_j (the mean is not used in order to avoid overlaps). To ease their usage, these values are scaled with the following scaling factor:

$$sc = \max\{\bar{w}_1, \bar{w}_2, \dots, \bar{w}_j, \dots\}$$

If w_j is computed as $w_j = \bar{w}_j/sc$, the desired weight, $1/w_j$, corresponding to a particular day of centre j is obtained.

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ANNEX C. ORBIT SOLUTIONS EXCLUDED FROM THE COMBINATION

The following table provides the complete list of orbit solutions that have not been considered for the generation of the COMB orbit solution. These solutions present gaps of data at the start or the end of the day due to large GPS data gaps occurring on those days. As the current tool in charge of the combination has a limitation when combining orbits with less data than 24 hours, the orbit solutions provided below have been excluded from the combination. However, these orbits solutions have been included for the quality assessment of Section 4.

In addition to this list, there are several days (Table 2-3) on which no orbit solutions were generated as there was no GPS data for the whole day.

Table C-1: Orbit solutions excluded from the combination

Sat.	Date	Orbit Solution/s	Comment
S-1A	29/05/2014	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 29/05/2014 14:49:35 h (UTC) to 02/06/2014 07:52:19 h (UTC)
S-1A	02/06/2014	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 29/05/2014 14:49:35 h (UTC) to 02/06/2014 07:52:19 h (UTC)
S-1A	05/07/2014	TUDF	Orbit solution incomplete due to a gap of L0 data from 05/07/2014 05:15:38 h (UTC) to 07/07/2014 09:30:58 h (UTC)
S-1A	07/07/2014	TUDF	Orbit solution incomplete due to a gap of L0 data from 05/07/2014 05:15:38 h (UTC) to 07/07/2014 09:30:58 h (UTC)
S-1A	29/12/2014	TUDF	Orbit solution incomplete due to a gap of L0 data from 29/12/2014 20:45:54 h (UTC) to 30/12/2014 09:54:04 h (UTC)
S-1A	30/12/2014	TUDF	Orbit solution incomplete due to a gap of L0 data from 29/12/2014 20:45:54 h (UTC) to 30/12/2014 09:54:04 h (UTC)
S-1A	01/02/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 01/02/2015 07:48:01 h (UTC) to 02/02/2015 10:12:41 h (UTC)
S-1A	02/02/2015	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 01/02/2015 07:48:01 h (UTC) to 02/02/2015 10:12:41 h (UTC)
S-1A	19/02/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 19/02/2015 17:45:21 h (UTC) to 20/02/2015 09:18:11 h (UTC)
S-1A	20/02/2015	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 19/02/2015 17:45:21 h (UTC) to 20/02/2015 09:18:11 h (UTC)
S-1A	20/06/2015	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 20/06/2015 15:38:57 h (UTC) to 21/06/2015 11:37:57 h (UTC)
S-1A	21/06/2015	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 20/06/2015 15:38:57 h (UTC) to 21/06/2015 11:37:57 h (UTC)
S-1A	28/07/2015	DLRR	-
S-1A	03/08/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 03/08/2015 01:39:56 h (UTC) to 03/08/2015 14:46:28 h (UTC), and a gap of L0 data from 03/08/2015 17:47:47 h (UTC) to 04/08/2015 12:14:31 h (UTC)
S-1A	04/08/2015	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 03/08/2015 17:47:47 h (UTC) to 04/08/2015 12:14:31 h (UTC), and a gap of L0 data from 04/08/2015 23:44:31 h (UTC) to 05/08/2015 11:16:51 h (UTC)
S-1A	05/08/2015	DLRR	Orbit solution incomplete due to a gap of L0 data from 04/08/2015 23:44:31 h (UTC) to 05/08/2015 11:16:51 h (UTC)
S-1A	09/08/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 09/08/2015 20:31:21 h (UTC) to 10/08/2015 14:38:15 h (UTC)

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Sat.	Date	Orbit Solution/s	Comment
S-1A	10/08/2015	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 09/08/2015 20:31:21 h (UTC) to 10/08/2015 14:38:15 h (UTC)
S-1A	04/09/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 04/09/2015 16:43:30 h (UTC) to 05/09/2015 09:34:38 h (UTC)
S-1A	05/09/2015	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 04/09/2015 16:43:30 h (UTC) to 05/09/2015 09:34:38 h (UTC)
S-1A	05/11/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 05/11/2015 16:27:13 h (UTC) to 06/11/2015 06:33:37 h (UTC)
S-1A	06/11/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 05/11/2015 16:27:13 h (UTC) to 06/11/2015 06:33:37 h (UTC)
S-1A	07/11/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 07/11/2015 17:47:49 h (UTC) to 08/11/2015 12:10:27 h (UTC)
S-1A	08/11/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 07/11/2015 17:47:49 h (UTC) to 08/11/2015 12:10:27 h (UTC)
S-1A	10/12/2015	TUDF	Orbit solution incomplete due to a gap of L0 data from 10/12/2015 19:15:43 h (UTC) to 11/12/2015 13:28:57 h (UTC)
S-1A	11/12/2015	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 10/12/2015 19:15:43 h (UTC) to 11/12/2015 13:28:57 h (UTC)
S-1A	21/02/2016	TUDF	Orbit solution incomplete due to a gap of L0 data from 21/02/2016 18:03:30 h (UTC) to 22/02/2016 09:19:17 h (UTC)
S-1A	22/02/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 21/02/2016 18:03:30 h (UTC) to 22/02/2016 09:19:17 h (UTC)
S-1A	24/11/2016	TUDF	Orbit solution incomplete due to a gap of L0 data from 24/11/2016 18:58:47 h (UTC) to 25/11/2016 09:50:47 h (UTC)
S-1A	25/11/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 24/11/2016 18:58:47 h (UTC) to 25/11/2016 09:50:47 h (UTC)
S-1B	28/04/2016	TUDF	Orbit solution incomplete due to a gap of L0 data from 28/04/2016 16:44:34 h (UTC) to 29/04/2016 10:44:14 h (UTC)
S-1B	29/04/2016	TUDF	Orbit solution incomplete due to a gap of L0 data from 28/04/2016 16:44:34 h (UTC) to 29/04/2016 10:44:14 h (UTC)
S-1B	05/05/2016	TUDF	Orbit solution incomplete due to a gap of L0 data from 05/05/2016 15:03:47 h (UTC) to 06/05/2016 07:55:35 h (UTC)
S-1B	06/05/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 05/05/2016 15:03:47 h (UTC) to 06/05/2016 07:55:35 h (UTC)
S-1B	09/05/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 09/05/2016 14:36:29 h (UTC) to 13/05/2016 01:39:01 h (UTC)
S-1B	13/05/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 09/05/2016 14:36:29 h (UTC) to 13/05/2016 01:39:01 h (UTC)
S-1B	21/05/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 21/05/2016 06:53:01 h (UTC) to 23/05/2016 11:17:11 h (UTC)
S-1B	23/05/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 21/05/2016 06:53:01 h (UTC) to 23/05/2016 11:17:11 h (UTC)
S-1B	30/05/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 30/05/2016 17:38:13 h (UTC) to 01/06/2016 11:55:41 h (UTC)
S-1B	01/06/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 30/05/2016 17:38:13 h (UTC) to 01/06/2016 11:55:41 h (UTC)

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Sat.	Date	Orbit Solution/s	Comment
S-1B	04/06/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 04/06/2016 05:04:31 h (UTC) to 06/06/2016 00:13:41 h (UTC)
S-1B	06/06/2016	DLRR and TUDF	Orbit solutions incomplete due to a gap of L0 data from 04/06/2016 05:04:31 h (UTC) to 06/06/2016 00:13:41 h (UTC)
S-1B	28/06/2016	TUDF	Orbit solution incomplete due to a gap of L0 data from 28/06/2016 19:40:17 h (UTC) to 29/06/2016 09:00:15 h (UTC)
S-1B	29/06/2016	TUDF	Orbit solution incomplete due to a gap of L0 data from 28/06/2016 19:40:17 h (UTC) to 29/06/2016 09:00:15 h (UTC)

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ANNEX D. FIRST ANALYSIS OF THE ORBIT CROSS-COMPARISONS

A few orbit comparisons between the orbit solutions provided by the different centres participating on the Sentinel-1 reprocessing campaign against the COMB orbit solution showed unexpected values after a first analysis of the generated COMB orbit solution. Table D-1 lists these outliers. They typically correspond to the presence of manoeuvres or data gaps. That is why not all solutions are available.

Table D-1: Outliers from first analysis of the COMB orbit solution

Sat.	Date	COMB generated from	Orbit comparison: solution vs. COMB [3D RMS; cm]					
			AIUB	CPOR	DLRR	ESOC	TUDF	TUMM
S-1A	13/05/2015	CPOR, DLRR and TUDF	n/a	351.3	351.3	n/a	879.1	n/a
S-1A	28/07/2015	AIUB, CPOR and TUDF	90.3	22.4	33.6	n/a	22.4	n/a
S-1A	03/08/2015	CPOR and AIUB	680.6	680.6	n/a	n/a	n/a	n/a
S-1A	14/09/2015	AIUB, CPOR, DLRR and TUDF	81.7	NO outlier	NO outlier	n/a	NO outlier	n/a
S-1A	18/04/2019	CPOR, DLRR and TUDF	n/a	NO outlier	15.5	n/a	NO outlier	n/a
S-1A	31/07/2019	CPOR, DLRR and TUDF	n/a	209.8	209.5	n/a	676.1	n/a
S-1B	03/05/2016	CPOR, DLRR and TUDF	n/a	NO outlier	19.1	n/a	NO outlier	n/a
S-1B	19/05/2016	CPOR, DLRR and TUDF	n/a	NO outlier	10.2	n/a	NO outlier	n/a
S-1B	24/05/2016	CPOR, DLRR and TUDF	n/a	NO outlier	11.1	n/a	NO outlier	n/a
S-1B	07/06/2016	CPOR, DLRR and TUDF	n/a	NO outlier	11.5	n/a	NO outlier	n/a

From the figures above, it can be assumed that one of the solutions is harming somehow the generation of the COMB orbit solution. The following subsections are going to analyse each of the previous cases by showing the temporal evolution of the cross-comparisons amongst all solutions involved into the generation of the COMB orbit solution.

SENTINEL-1A

On 13th May 2015, two large manoeuvres were carried out at the end of the day on Sentinel-1A satellite. From Figure D-1, it can be seen that the cross-comparisons against TUDF orbit solution show large differences after the first manoeuvre. This explains why the differences with respect to the COMB solution are high in Table D-1. In this case, it was decided to exclude the TUDF from the orbit comparison, so the COMB solution is just the mean of CPOR and DLRR. Differences in orbit modelling, in particular if the manoeuvres are large, can explain these large differences.

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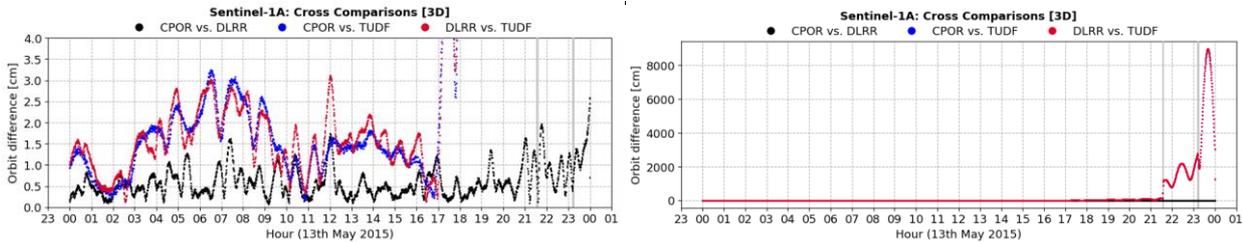


Figure D-1: Sentinel-1A – Temporal evolution of the cross-comparisons on 13th May 2015 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

On 28th July 2015, there was neither a manoeuvre nor a gap of data. However, the orbit comparisons against the COMB orbit solution present high values, especially the one from AIUB solution. In Figure D-2, it can be seen that the cross-comparisons against the AIUB solution results in large differences on the first half of the day. This fact leads to the generation of a degraded COMB orbit solution and degraded orbit comparisons. The AIUB solution was removed from the combination of this day. Considering that two other centres (ESOC and TUMM) did not generate orbit solutions on that day, there was probably some wrong data.

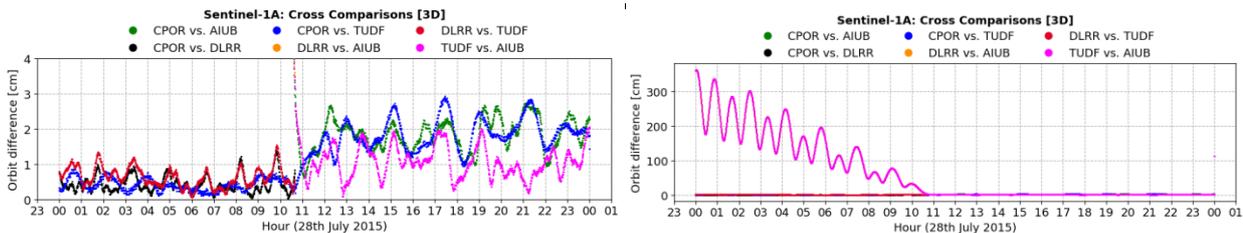


Figure D-2: Sentinel-1A – Temporal evolution of the cross-comparisons on 28th July 2015 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

On 3rd August 2015, there were two large gaps of L0 data, which affected almost the entire day. Although the interval of time with available data is small, Figure D-3 shows agreement between CPOR and TUDF orbits, whereas the cross-comparisons against the AIUB solution results in degradation. Considering these facts, the orbit solution from AIUB should be excluded from the combination. It has to be clarified that, in the presence of data gaps, some centres decide not to deliver an orbit solution, while others decide to propagate dynamically the orbit, a procedure that cannot guarantee the required accuracy. Therefore, the orbit solution of this day cannot be considered too accurate in any case.

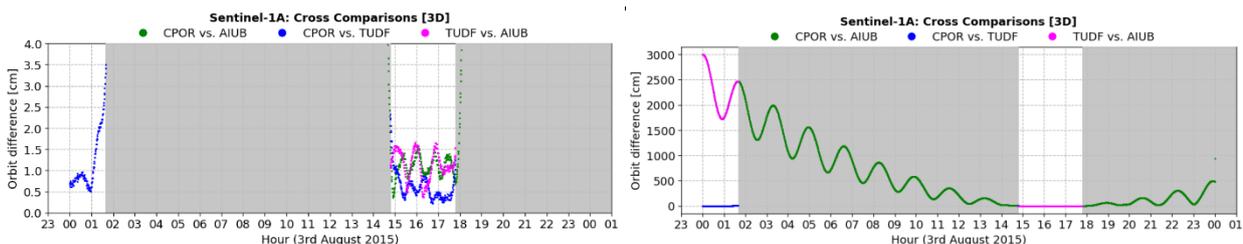


Figure D-3: Sentinel-1A – Temporal evolution of the cross-comparisons on 3rd August 2015 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

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On 14th September 2015, there was neither a manoeuvre nor a gap of data. The cross-comparisons against the AIUB solution though present large differences on the second half of the day (see Figure D-4). It may be concluded that something is wrong with this solution, and therefore, it should not be used for the combination on this day. It is worth to mention that ESOC and TUMM did not generate an orbit solution on that day, so probably there was some problem with the data.

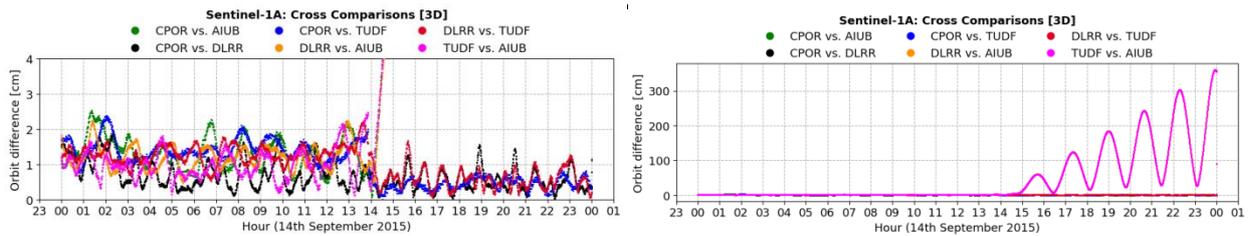


Figure D-4: Sentinel-1A – Temporal evolution of the cross-comparisons on 14th September 2015 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

On 18th April 2019, there was a large gap of L0 data. From the analysis of Figure D-5, it must be observed that there is agreement between CPOR and TUDF solutions outside the gap of data (DLRR solution seems not to converge with them). On the other hand, the cross-comparisons show huge degradation when the gap of data occurs. In this case, it was decided to just use the CPOR for the COMB solution, but it is clear that the orbit quality cannot be guaranteed in the presence of large data gaps like this one.

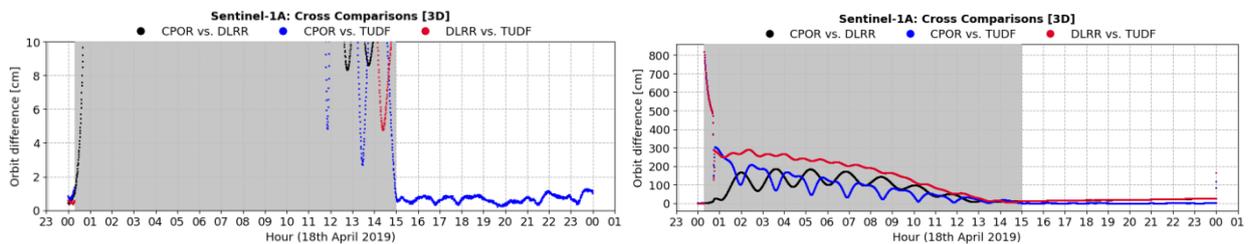


Figure D-5: Sentinel-1A – Temporal evolution of the cross-comparisons on 18th April 2019 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

On 31st July 2019, there was a large manoeuvre at the end of the interval. The cross-comparisons showed large differences with respect to TUDF, and also against DLRR but smaller (see Figure D-6). These differences are probably due to different manoeuvre modelling. It was decided to exclude TUDF from the combination to avoid the outlier, even if it is not clear which centre modelled better the manoeuvre.

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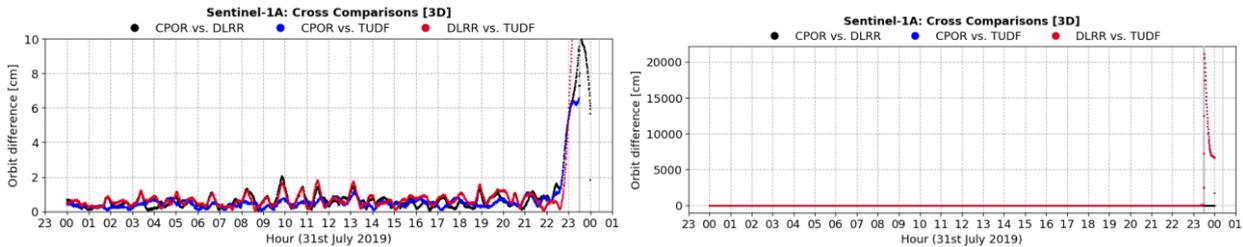


Figure D-6: Sentinel-1A – Temporal evolution of the cross-comparisons on 31st July 2019 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

Once the mentioned orbit solutions have been removed from the combination, the degraded orbit comparisons only remain for those orbit solutions that have been excluded. The other orbit comparisons, on the other hand, obtain nominal values. See Table D-2 for the updated values of Table D-1 for the Sentinel-1A case. As described above, all these cases represent anomalies due to manoeuvres, data gaps, or other problems, so it is not possible to do a complete orbit quality control.

Table D-2: Outliers update after first analysis of the COMB orbit solution (Sentinel-1A)

Sat.	Date	COMB generated from	Orbit comparison: solution vs. COMB [3D RMS; cm]					
			AIUB	CPOR	DLRR	ESOC	TUDF	TUMM
S-1A	13/05/2015	CPOR and DLRR	n/a	NO outlier	NO outlier	n/a	1230.4	n/a
S-1A	28/07/2015	CPOR and TUDF	112.7	NO outlier	NO outlier	n/a	NO outlier	n/a
S-1A	03/08/2015	CPOR	1361.2	NO outlier	n/a	n/a	n/a	n/a
S-1A	14/09/2015	CPOR, DLRR and TUDF	90.8	NO outlier	NO outlier	n/a	NO outlier	n/a
S-1A	18/04/2019	CPOR	n/a	NO outlier	19.3	n/a	NO outlier	n/a
S-1A	31/07/2019	CPOR and DLRR	n/a	NO outlier	NO outlier	n/a	885.8	n/a

SENTINEL-1B

The four cases showing outliers for Sentinel-1B follow the same pattern: there is a large manoeuvre occurring on midday approximately that showed larger differences with DLRR in this case. In all these cases, it was decided to exclude the DLRR solutions from the combination to avoid large differences with respect to the COMB solution, especially from the period of time around the manoeuvre. Table D-3 updates the values shown in Table D-1 for the Sentinel-1B case. However, it is worth to mention that by no means this implies that DLR manoeuvre handling is worse than others. This requires much detail assessment, which is beyond the scope of this memorandum.

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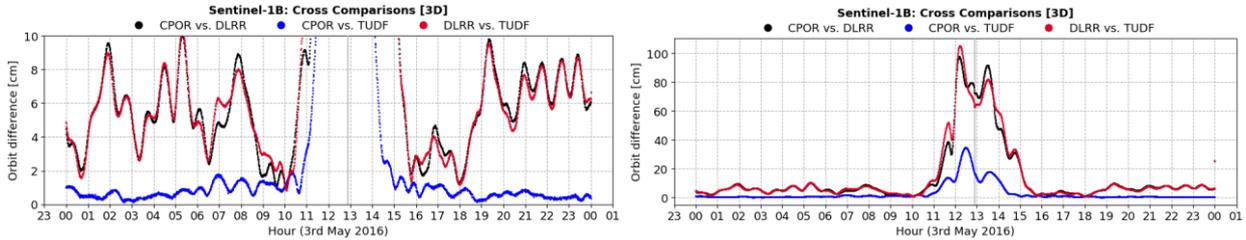


Figure D-7: Sentinel-1B – Temporal evolution of the cross-comparisons on 3rd May 2016 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

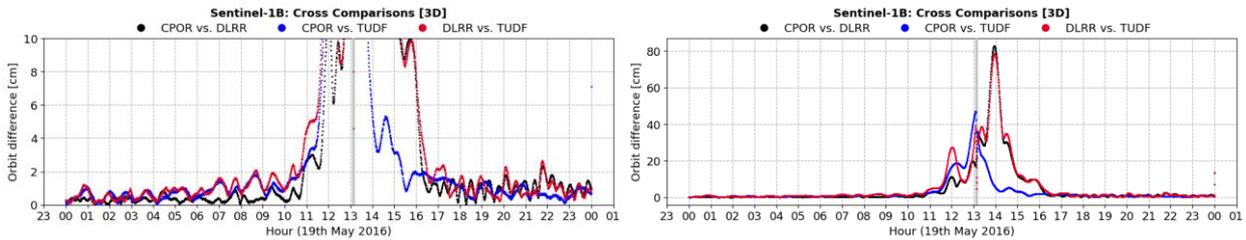


Figure D-8: Sentinel-1B – Temporal evolution of the cross-comparisons on 19th May 2016 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

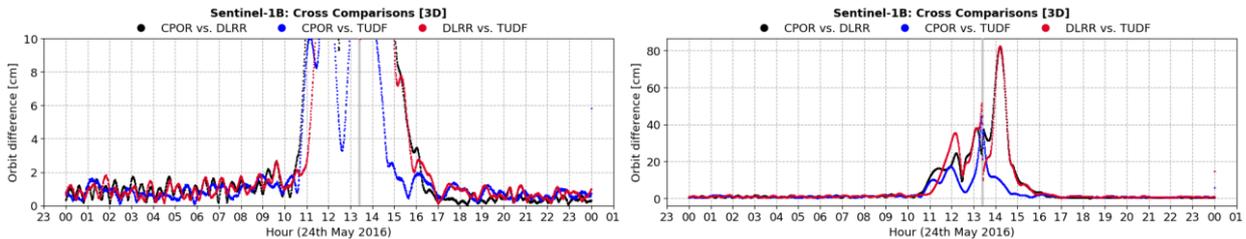


Figure D-9: Sentinel-1B – Temporal evolution of the cross-comparisons on 24th May 2016 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

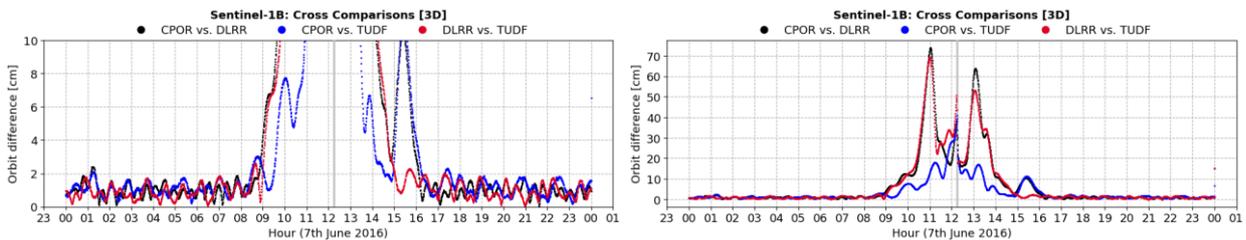


Figure D-10: Sentinel-1B – Temporal evolution of the cross-comparisons on 7th June 2016 [3D; cm] (vertical grey lines stand for either manoeuvres or gaps of data and their widths are related to the duration of the event)

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Table D-3: Outliers update after first analysis of the COMB orbit solution (Sentinel-1B)

Sat.	Date	COMB generated from	Orbit comparison: solution vs. COMB [3D RMS; cm]					
			AIUB	CPOR	DLRR	ESOC	TUDF	TUMM
S-1B	03/05/2016	CPOR, DLRR and TUDF	n/a	NO outlier	23.9	n/a	NO outlier	n/a
S-1B	19/05/2016	CPOR, DLRR and TUDF	n/a	NO outlier	12.7	n/a	NO outlier	n/a
S-1B	24/05/2016	CPOR, DLRR and TUDF	n/a	NO outlier	13.8	n/a	NO outlier	n/a
S-1B	07/06/2016	CPOR, DLRR and TUDF	n/a	NO outlier	14.4	n/a	NO outlier	n/a

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ANNEX E. LIST OF ACRONYMS

The following table lists all acronyms used within this memorandum.

Table E-1: List of acronyms

Acronym	Definition
AIUB	Astronomical Institute University of Bern
ARP	Antenna Reference Point
CODE	Center for Orbit Determination in Europe
CPOD	Copernicus POD
CPR	Constant Per Revolution
DLR	Deutsche Zentrum für Luft- und Raumfahrt
EIGEN	European Improved Gravity model of the Earth by New techniques
ESA	European Space Agency
ESOC	European Space Operation Centre
FES	Finite Element Solution
FMR	Full Mission Reprocessing
FOS	Flight Operations System
GHOST	GPS High Precision Orbit Determination Software Tools
GIPSY	GNSS-Inferred Positioning System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRGS	Groupe de Recherche de Géodésie Spatiale
IERS	International Earth Rotation Service
IGS	International GNSS Service
JPL	Jet Propulsion Laboratory
NAPEOS	Navigation Package for Earth Orbiting Satellites
NTC	Non-Time Critical
PCO	Phase Centre Offset
PCV	Phase Centre Variation
POD	Precise Orbit Determination
QWG	Quality Working Group
RMS	Root Mean Square
ROP	Routine Operations Phase
SLR	Satellite Laser Ranging
STD	Standard Deviation
TUD	Technische Universiteit Delft
TUM	Technische Universität München
UTC	Coordinated Universal Time

Memo: Sentinel-1 Full Mission Reprocessing (2021)

ANNEX F. REFERENCE DOCUMENTS

[RD.1] Sentinel-1 properties for GPS POD

(<https://sentinel.esa.int/documents/247904/3455957/Sentinel-1-properties-for-GPS-POD>)

[RD.2] CODE IGB14 reprocessed GPS orbits, clocks (5s) and frequency-dependent code and phase biases (doi:10.7892/boris.146753) available at ftp://ftp.aiub.unibe.ch/REPRO_I20/<yyyy>

[RD.3] <https://insidegnss.com/the-new-flex-power-mode-from-gps-iir-m-and-iif-satellites-with-extended-coverage-area/>

[RD.4] http://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Copernicus_Sentinel-1A_satellite_hit_by_space_particle