THE COPERNICUS SENTINEL-3 MISSION

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1. Abstract

Sentinel-3A, the first satellite of the Copernicus Sentinel-3 mission, was launched on 16 February 2016. The mission is jointly operated by ESA and EUMETSAT to deliver operational ocean and land observation services within the Copernicus project. Sentinel-3B, the second satellite of the Copernicus Sentinel-3 mission, is planned to be launched in spring 2018. During the commissioning phase of the satellite it will be flying only 30 s apart from Sentinel-3A for three months. After the tandem phase Sentinel-3B will be moved to its long-term orbit at a 140^o phase shift with respect to Sentinel-3A.
In addition to the main payloads the satellites carry a couple of GPS receivers, a Laser Retro Reflector (LRR), and a DORIS receiver for Precise Orbit Determination (POD). Observations from all three techniques are equally important to fulfil the stringent orbit accuracy requirements of 3 cm (with a target of 2 cm) in radial direction.
The Copernicus POD Service, a GMV-led consortium being in charge of generating precise orbital products and auxiliary data files not only for Sentinel-3 but also Sentinel-1 and -2, is in charge of computing and delivering the CPF orbit files to the ILRS community and is a main user of the Satellite Laser Ranging (SLR) measurements to compute the precise orbital products of Sentinel-3.
SLR is a key technique to validate independently the accuracy of the orbits, and to calibrate the GPS and DORIS instruments. A decent amount of SLR tracking data is needed for the entire mission life-time to perform regular checks of the biases that could exist between different tracking techniques.
The SLR measurements confirm a Sentinel-3A orbit accuracy below 2 cm RMS. However, to be able to identify biases between different tracking techniques it has to be assured that the SLR observations themselves do not have biases. Therefore, the SLR data of the 25 SLR stations providing more or less frequently observations to Sentinel-3A are regularly checked for their quality.
Status and performance of the Sentinel-3A SLR processing are presented in particular focussing on the orbit and station quality assessment. More than one year of data in the satellite's operational phase have been analysed. The excellent quality of the Sentinel-3A orbits from the Copernicus POD Service are shown as well as the evolution of the tracking in terms of number of stations and number of passes and normal points. Additionally, information and details about the commissioning phase of Sentinel-3B and the planned tandem phase of the two Sentinel-3 satellites will be presented.

2. Overview of the Copernicus POD Service

The Copernicus program is a joint initiative of the European Commission and the European Space Agency. The program aims to establish an autonomous European Earth Observation capacity with different missions from Sentinel-1 to -6. The Copernicus POD (Precise Orbit Determination) Service (Figure 1) is in charge of generating precise orbital products and auxiliary data files for Sentinel-1, -2 and -3. The service is part of the PDGS of the Sentinel missions. A GMV-led consortium has developed the service and it is operated on GMV premises in Tres Cantos, Spain. The processing is based on NAPEOS (Navigation Package for Earth Orbiting Satellites). The Copernicus POD Service is also responsible for the interface to the ILRS Community. The CPF orbit files are generated from the service and it is the main user of Satellite Laser Ranging (SLR) measurements for independent orbit validation.

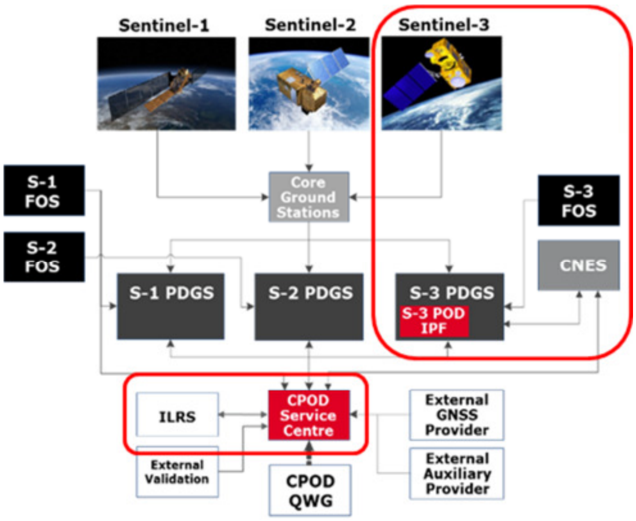

Figure 1: Overview of Copernicus POD Service

Sentinel-3A, the first satellite of the mission, was launched in 16th February 2016 and the second satellite Sentinel-3B is planned to be launched in spring 2018. The mission will be jointly operated by ESA and EUMETSAT. Both satellites are identical and for fulfilling the demanding POD requirements (2-3 cm in radial direction), they carries two GPS receivers, a DORIS receiver and a laser retro-reflector (LRR) for SLR. The main applications are the monitoring of the Earth's oceans, land, ice and atmosphere to study large-scale global dynamics and provide near-real time information for ocean and weather forecasting. The main instruments are the Radar Altimeter (SRAL), the Ocean and Land Colour Instrument (OLCI), the Sea Land Surface Temperature Radiometer (SLSRR), and the Micro Wave Radiometer (MWR). During its commissioning phase Sentinel-3B will fly only 30 s apart from Sentinel-3A for about three months. This tandem constellation will be held to calibrate several instruments, mainly the SAR altimeter. After the tandem phase, Sentinel-3B will be moved to its final orbit, shifted 140^{o} w.r.t. Sentinel-3A. The SLR tracking will be equally important for Sentinel-3A & -3B, especially during the tandem phase. Sentinel-3 project will request to ILRS for interleaved tracking of the two satellites from those SLR stations able to perform it. This scenario is similar to the one proposed for Jason-2 & -3 (see Figure 2). The other stations will be requested to alternate the tracking evenly between both satellites.

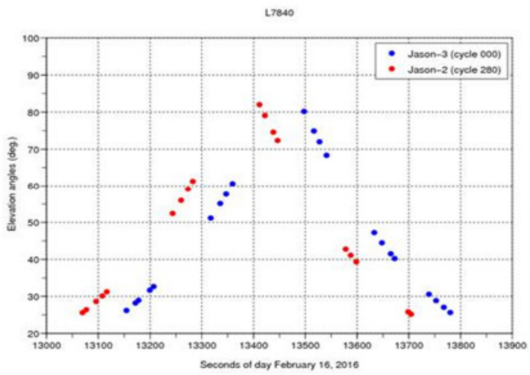

Figure 2 Interleaved SLR from station 7840 (Herstmonceux) to Jason-2 and -3 during their tandem phase

3. SLR station quality assessment

SLR is a key technique to calibrate the GPS and DORIS instruments and the overall POD processing chain. A decent amount of SLR tracking data is needed for the entire mission to perform regular checks of the biases that could exist between different tracking techniques.
More than one year of operational data (1 April 2016 – 31 May 2017) has been analysed for this purpose.

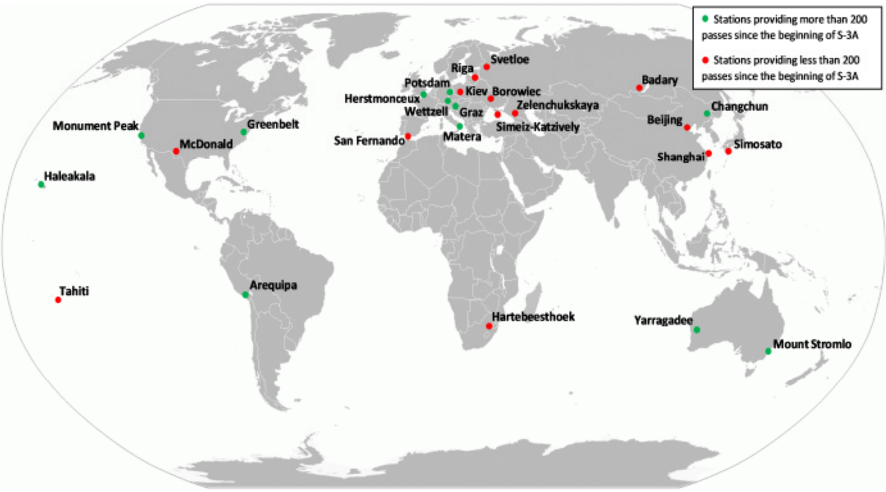

Figure 3: ILRS station network tracking Sentinel-3A. Coloured points according to number of passes provided by the stations

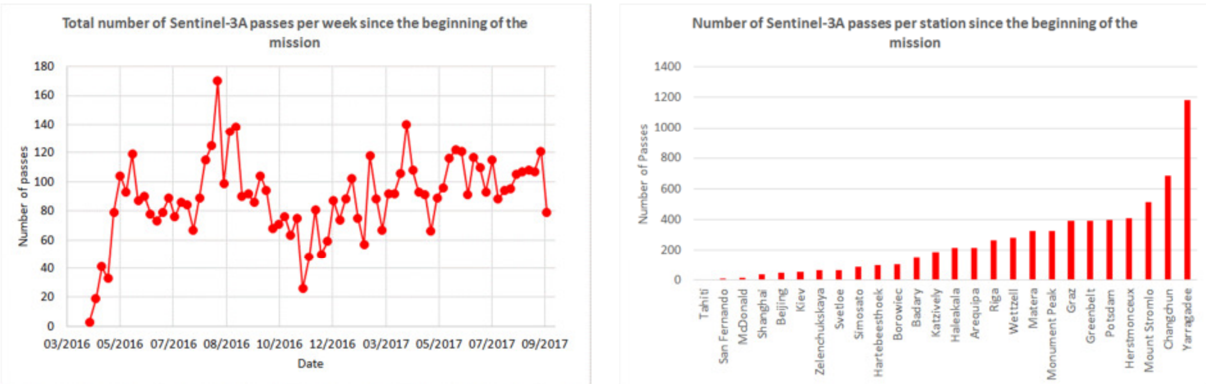

Figure 4: Total number of Sentinel-3A passes (per week on left plot; per station on right plot)

Since the beginning of the mission 25 stations all around the world have been tracking Sentinel-3A (see Figure 3). Figure 4 shows the number of tracked passes per week (left) and increasing per station (right).
The daily standard deviations from the SLR validation of all 25 stations are displayed in Figure 5 for the 14 months period. The proper application of the Post-Seismic Displacement (PSD) file in connection with the SLRF2014 coordinates has been implemented for this. The PSD file has been applied for the stations marked with "P". Table 1 shows the corresponding mean offsets and mean standard deviations of this analysis. The numbers in parentheses are obtained w/o applying the PSD file. The standard deviation of four stations affected by PSD is improved whereas it is slightly worse for two of them.
Moreover, the quality of the SLR stations has been assessed based on the statistics from ILRS analysis centres of other satellites' observations (such as Lageos 2) to estimate the station range biases and on analysis of Jason-2 residuals (both analyses not shown here).

To make the SLR analysis comparable within the Copernicus POD Quality Working Group (QWG), a common list of nine SLR stations (marked in bold letters and dark green background in Table 1) is selected based on the following criteria:

- Number of normal points in the Sentinle-3A lifetime
- Standard deviation of Sentinel-3A orbit validation with SLR
- Range biases of Lageos 2 analysis
- Mean of Jason-2 SLR residuals
- Exclusion of stations affected by PSD (for the time being, because not yet all QWG members have implemented the application in their SW packages).

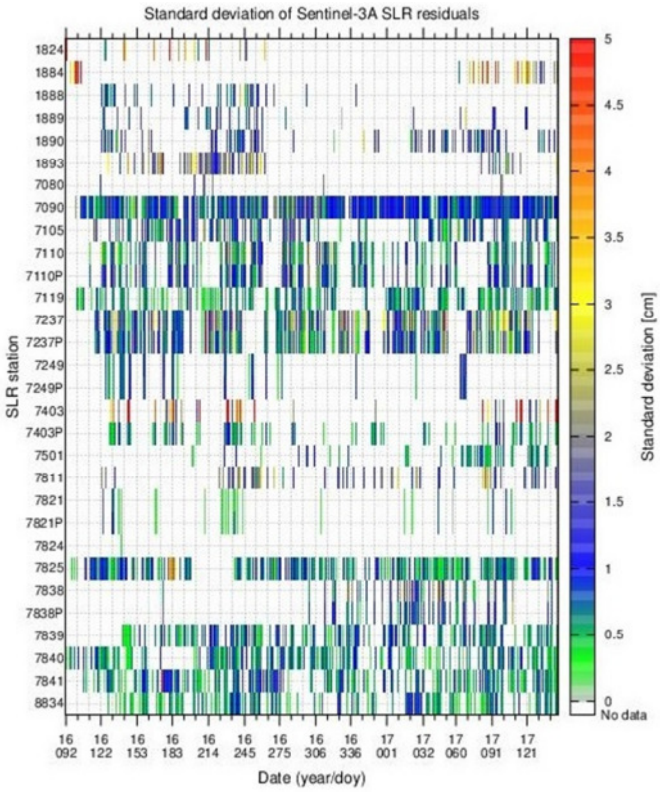

Figure 5 Daily standard deviations (cm) for all 25 SLR stations. For stations marked with P the PSD file has been applied.

Table 1 List of ILRS stations tracking Sentinel-3A, mean (cm) and standard deviation (cm) of SLR orbit validation from 1 April 2016 – 31 May 2017, values in parentheses are obtained w/o applying PSD file

Station number	Station Name	Mean (cm)	Standard dev. (cm)
7824	San Fernando, Spain	-2.13	0.40
7840	**Herstmonceux, U. K.**	0.61	0.90
7941	**Matera, Italy**	-0.18	1.05
7501	**Hartebeesthoek, South Africa**	0.32	1.08
7839	**Graz, Austria**	0.79	1.09
8834	**Wettzell, Germany**	-1.40	1.09
7841	**Potsdam, Germany**	-0.06	1.10
7090	**Yarragadee, Australia**	0.70	1.29
7825	Mt Stromlo, Australia	0.67	1.29
7821	Shanghai, China	(-0.89) -1.02	(1.22) 1.31
7403	Arequipa, Peru	(-1.28) 0.95	(8.98) 1.32
7119	**Haleakala, U.S.A.**	1.07	1.35
7110	Monument Peak, U.S.A.	(0.93) 0.59	(1.83) 1.48

Station number	Station Name	Mean (cm)	Standard dev. (cm)
7105	**Greenbelt, U.S.A.**	0.04	1.52
1888	Svetloe, Russia	-0.42	1.53
7249	Beijing, China	(-0.33) -0.80	(1.44) 1.54
1889	Zelenchukskya, Russia	1.12	1.76
7838	Simosato, Japan	(0.75) 1.41	(3.99) 1.76
7237	Changchun, China	(-0.09) -0.77	(2.18) 1.78
1890	Badary, Russia	-0.22	1.89
7080	McDonald Observatory, U.S.A.	-2.89	1.96
1893	Katzively, Ukraine	-2.13	2.26
7811	Borowiec, Poland	-2.52	2.55
1824	Golosiiv, Ukraine	0.06	4.56
1884	Riga, Latvia	9.52	4.58

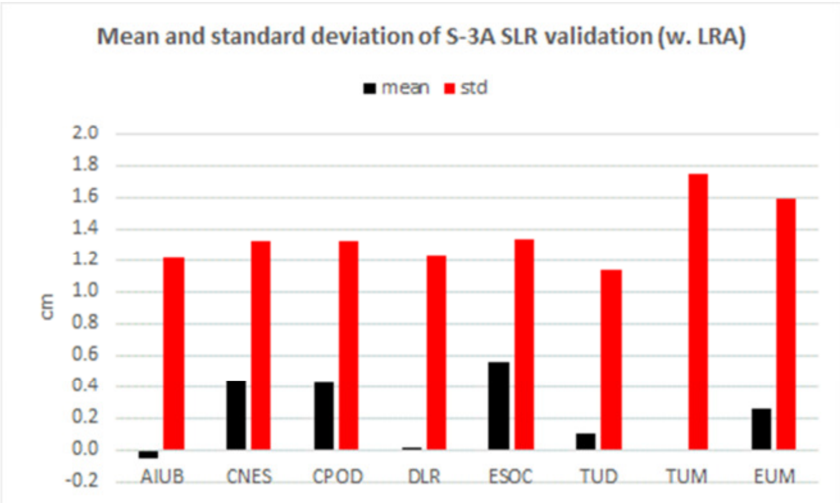

Figure 6 Mean and standard deviation for S-3A SLR validation of Copernicus POD QWG orbits from 1April 2016-31 May 2017, selected nine stations (see Table 1) are used

Figure 6 shows the mean and standard deviation from a Sentinel-3A SLR validation of the Copernicus POD QWG orbits from 1 April 2016-31 May 2017 based on the observations of the nine selected stations. No elevation cut-off angle but LRR corrections have been applied for the analysis. The results confirm an excellent orbit accuracy between 1.13 cm (TUD) and 1.75 cm (TUM) for Sentinel-3A. The mean offsets range between -0.05 cm (AIUB) and 0.56 cm (ESOC). Remaining small differences between the orbit solutions are under investigations.

4. Laser retro-reflector (LRR) position estimation with SLR observations

The LRR position has been estimated by fixing the Sentinel-3A orbits coming from all the QWG centres and minimising the SLR observations residuals. The positions are estimated on monthly basis. The computational timespan starts on 01 June 2016 and ends on 01 June 2017. The monthly delta estimates to the current position are displayed in Figure 7 for the three satellite body-fixed directions X, Y, and Z. The mean estimated LRR position offsets are listed in Table 2. The values range between -5.18 mm and 14.10 mm. The results are different for the QWG centres, which may be attributed to different modelling aspects of the software packages. Further investigations have to follow to analyse in particular the estimated z-offsets, because they are related to the radial orbit direction. The radial orbit accuracy is most important for the altimeter Sentinel-3A mission.

Figure 7 Monthly delta estimates of LRR position for orbits of different QWG centres

Table 2 Mean of estimates of delta LRR positions (mm) per QWG centre

	CPOD	AIUB	CNES	ESOC	DLR	TUM	TUDF	AVERAGE
LRR X offset (mm)	5.02	3.14	8.59	3.73	3.52	14.10	2.11	**5.74**
LRR Y offset (mm)	9.97	5.65	10.10	-0.29	2.53	-1.05	6.17	**4.73**
LRR Z offset (mm)	-3.49	3.57	-4.16	-5.18	2.14	2.34	1.14	**-0.52**

5. Analysis of accuracy of CPF files

The Consolidated Prediction Format (CPF) files delivered to the ILRS Community are based on an orbit propagation from the STC (short-time critical) product for 5 days into the future. The accuracy of the CPF files is assessed by comparison to the STC product with the coverage of the first predicted day of the CPF. Results in Figure 8 show that the CPFs accuracy is typically below 20 m 3D RMS.

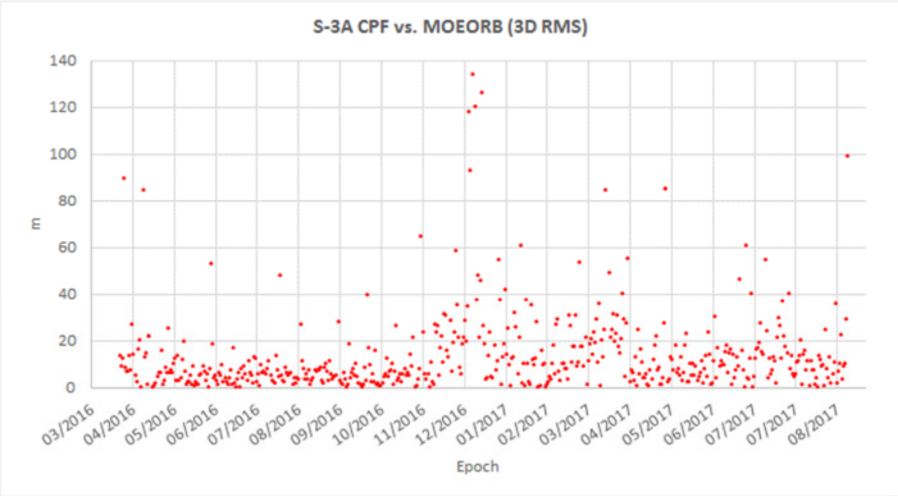

Figure 8 Comparison of S-3A CPF files vs. STC orbits

6. CONCLUSIONS

1. The Copernicus POD Service is responsible for the generation of Precise Orbit products for the Sentinel-3 mission with very demanding accuracy requirements due to the altimetry processing.
2. The Copernicus POD Service serves as the interface with the ILRS Community, and is in charge of the generation of the CPF orbit files with the adequate latency and accuracy requirements. Moreover, it is responsible for the routinely use of the SLR measurements from all stations to validate the generated orbital products to ensure that there are no unexpected biases which might have a negative impact on the altimeter results.
3. Sentinel-3B will fly in tandem formation with Sentinel-3A during its commissioning phase to calibrate several instruments. An interleaved tracking in long passes will be much appreciated during this phase to estimate relative biases.
4. A common list of SLR stations for the Copernicus QWG has been developed based on the number of observations, the quality of the SLR analysis, the PSD correction results and the statistics of ILRS analysis centres (e.g. the range biases of Lageos2 and residuals mean of Jason-2 SLR).

7. ACKNOWLEDGEMENT

The Copernicus POD Service is financed under ESA contract no. 4000108273/13/1-NB
The work performed in the frame of this contract is carried out with funding by the European Union. The views expressed herein can in no way be taken to reflect the official opinion of either the European Union or the European Space Agency.