SUPPORTING THE COPERNICUS POD SERVICE

Heike Peter (1), **Tim Springer** (1), **Michiel Otten** (1), **Jaime Fernández** (2), **Diego Escobar** (2), **Pierre Féménias** (3)

(1) *PosiTim UG, In den Löser 15, 64342 Seeheim-Jugenheim, Germany, Email:heike.peter@positim.com*
(2) *GMV AD., Isaac Newton 11, 28760 Tres Cantos, Spain, Email:jfernandez@gmv.com*
(3) *ESA/ESRIN, Via Galileo Galilei, I-00044 Frascati, Italy, Email:pierre.femenias@esa.int*

ABSTRACT

The Copernicus POD (Precise Orbit Determination) Service is part of the Copernicus PDGS (Payload Data Ground Segment) of the Sentinel missions. A GMV-led consortium is operating the Copernicus POD Service being in charge of generating precise orbital products and auxiliary data files for their use as part of the processing chains of the respective Sentinel PDGS. As part of the consortium PosiTim is responsible for implementing and testing software and model updates thoroughly before integrating them in the operational chain of the Copernicus POD Service.

The NAPEOS (Navigation Package for Earth Observation Satellites) software is used for the generation of the orbit products within the Copernicus POD Service.

The test procedures and results obtained for a recent software and model update to IERS 2010 Conventions are presented. It has been tested as well that the arc length of 72 hours for the non-time critical (NTC) orbit solutions might be shorten to 48 hours without losing accuracy. Orbit comparisons to external solutions help to validate the different orbit solutions.

GPS antenna phase centre variations (PCVs) are one of the largest systematic error sources in POD. Since the satellite body may cause signal multipath a ground calibration of the GPS antenna without taking into account the satellite body might not be sufficient to quantify the PCVs. The PCVs are therefore obtained by an in-flight calibration.

A first map for the PCVs determined from a limited amount of data at the beginning of the mission has shown significant multipath signals in parts of the antenna for code and carrier phase measurements. Since the satellite has moving parts it has been checked carefully if these multipath regions are moving as well or if they are antenna-fixed.

Normally the correction maps are only applied for the carrier phase measurements. Since significant multipath has been spotted for the code measurements as well investigations are performed to study the impact of additionally applying code correction maps in the POD process.

1. INTRODUCTION

The European Copernicus programme aims to establish European capacity for Earth Observation. The Sentinel satellite missions are part of this programme. The first satellite of the programme, Sentinel-1A, has been launched on 3 April 2014. Sentinel-1 is a SAR (Synthetic Aperture Radar) mission. The first satellite of the optical mission, Sentinel-2A, will follow in June 2015. Sentinel-3A, the first satellite of the altimeter mission, is planned to be launched end of the year 2015. The B-satellites for all three missions are planned for 2016/2017.

All three Sentinel missions are equipped with an 8-channel GPS (Global Positioning Service) receiver for precise orbit determination. The satellites of Sentinel-3 are additionally equipped with a DORIS (Doppler Orbitography and Radio Positioning by Satellite) receiver and a laser retro-reflector array for SLR (Satellite Laser Ranging) measurements.

The Copernicus POD Service (CPODS) is providing precise orbital products and auxiliary data files to the Copernicus customers and the processing chains of the Sentinel PDGSs (Payload Data Ground Segment). At the moment the service is running operationally for Sentinel-1A only but will be running for all Sentinel-1, -2, and -3 satellites as soon as they are launched and operational.

The CPODS is a consortium consisting of the following members:

- GMV, Tres Cantos, Spain (project lead)
- PosiTim UG, Seeheim-Jugenheim, Germany
- Deutsches Zentrum für Luft-und Raumfahrt (DLR), Oberpfaffenhofen, Germany
- Technische Universität München (TUM), Munich, Germany
- Veripos, Aberdeen, United Kingdom
- Astronomical Institute, University of Bern (AIUB), Bern, Switzerland
- Technical University of Delft (TUD), Delft, The Netherlands

The different responsibilities of the individual members within the CPODS are described in [1].

This paper concentrates on the tasks under the responsibility of PosiTim. PosiTim is among others responsible for implementing and testing software and model updates in detail before they are integrated in the operational chain of the CPODS and are set active for the generation of the orbit products.

The NAPEOS (NAvigation Package for Earth Observation Satellites, [2]) software is used for the orbit generation of the Sentinel satellites. There is a long history in using NAPEOS for the precise orbit determination of low Earth orbiting (LEO) satellites (e.g., [3]). In particular the state-of-the-art dynamical modelling used in the software and the short computing times makes it a unique tool for the different demands in terms of orbital accuracy and latency of the products from the different Sentinel missions.

In order to stay state-of-the-art during the entire mission times updates and changes in the program settings have to be done from time to time. The IERS (International Earth Rotation Service) Conventions [4] are for instance updated regularly and it is of course necessary to follow these updates in due time. Since it is an operational environment it has to be assured, however, that the integration of such updates and changes does not interrupt or harm the CPODS. Therefore, the updates and changes have to be thoroughly tested.

Section 2 briefly describes the CPODS and its data flow. Section 3 summarises the current orbit modelling set up for Sentinel-1A and in Section 4 the tests done for validating the update to the IERS Conventions 2010 are described. In Section 5 the results of orbit comparisons of orbit solutions with different orbit parametrization and arc lengths are explained and Section 6 deals with the antenna phase centre variations (PCVs). The currently used PCVs are shown as well as the result from a calibration from a longer time series. Investigations to the usage of code PCVs are done as well. Section 7 summarises and concludes this article.

2. COPERNICUS POD SERVICE (CPODS)

The CPODS is and will be responsible for the POD products of all satellites of the Sentinel-1, -2, and -3 missions. Fig. 1 shows the schematic view of the data flow for the Service. CNES (Centre National d´Études Spatiales) will also deliver a NTC (non-time critical) orbit product for the Sentinel-3 satellites. The S-3 POD IPF (Internal Processing Facility) will be run at S-3 PDGS, which is located in two places: EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites), responsible for the Marine Centre and on Svalbard (the Core Ground Station), which is responsible for the Land Centre. The IPF will deliver NRT (near real-time) orbit products for the Sentinel-3 satellites.

More details on the structure of the CPODS may be found in [1].

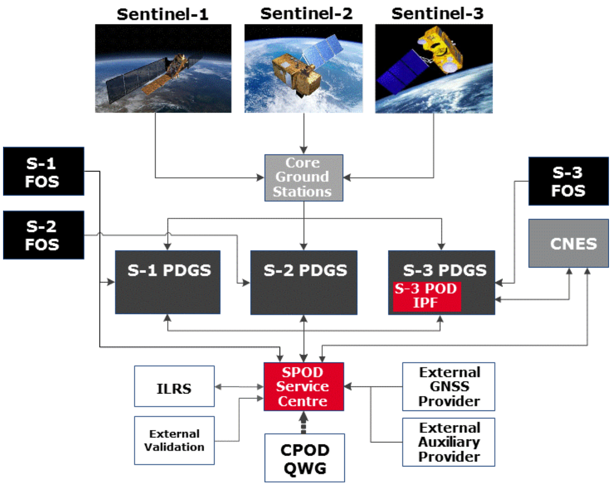


Figure 1 Schematic view of the data flow for the Copernicus POD Service

The Copernicus POD QWG (Quality Working Group) supports the CPODS. POD experts from different institutions and universities build the core of the QWG. Additionally, responsible ESA managers from each Sentinel-mission as well as experts from the application side (e.g., altimetry) are members of the QWG. The function of the group is at first to support the CPODS in terms of providing independent orbit solutions for comparison and validation. Secondly, the QWG may recommend updates of models and/or settings in the orbit parametrization.

The orbit accuracy requirement for the NTC orbit solutions of Sentinel-1 is very demanding with 5 cm in 3D. The independent orbit solutions from the QWG POD expert groups are at the moment the only source for validating the orbit products for Sentinel-1A from the CPOD System. The independent orbit solutions are therefore of very great help. This is in particular true for the Sentinel-1 and -2 missions because no independent space geodetic technique is available for orbit validation of these two missions.

3. SENTINEL-1A ORBIT MODELLING

The current orbit modelling set up in the CPOD System and used for the Sentinel-1A satellite is listed in Tab. 1. This setup is used since January 7th, 2015 for the operational NRT and NTC orbit products. Before this date the IERS Conventions 2003 were applied and an older gravity field (EIGEN-4C) and ocean tide model (FES2004) have been used for the processing. The time varying gravity field terms were also not applied in the previous version. First comparisons of the operational software settings with other software packages from members of the QWG in September 2014 revealed that an update to the IERS Conventions 2010 deemed to be necessary to be state-of-the-art with the CPODS (see also Section 4).

Table 1 Sentinel-1A orbit models and parameter setup in NAPEOS

Arc cut	
Arc lengths	3.0 days
Handling of Manoeuvers	Manoeuvres are calibrated in the POD process
Reference System	
Polar motion and UT1	IERS C04 08
Pole model	IERS 2010 Conventions
Precession/Nutation	IERS 2010 Conventions
Gravity	
Gravity field (static)	EIGEN-6S2.5ext (120x120)
Gravity field (time varying)	drift/annual/semi-annual piece wise linear terms up to degree/order 50
Solid Earth tides	applied (IERS 2010)
Ocean tides	EOT11a (50x50, 106 tidal constituents)
Atmospheric gravity	
Atmospheric tides	
Earth pole tide	IERS 2010
Ocean pole tide	IERS 2010
Third bodies	Sun, Moon, Planets DE405
Surface forces and empiricals	
Radiation Pressure model	Box-wing model
Earth radiation	Albedo and Infra-red applied
Atmospheric density model	msise90
Radiation pressure coefficient	1 per arc (loosely constrained to 1.0)
Drag coefficients	18 coefficients per arc (loosely constrained to 1.0)
1/rev empiricals	6 sets per arc: in along-track and cross-track direction (with sin/cos signals)

4. VALIDATION OF UPDATES IN THE CPOD SYSTEM

The Copernicus POD Service is supported by the Copernicus POD QWG. Contributions from the following institutions are available and they are used to validate the recent CPOD System update:

- European Space Operation Centre (ESOC), Darmstadt, Germany using NAPEOS
- PosiTim (PTIM), Germany using NAPEOS
- Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany using GHOST (GPS High Precision Orbit Determination Software Tools, [5])
- Astronomical Institute, University of Bern (AIUB), Bern, Switzerland using Bernese GNSS Software [6]

The time periods for comparison are from 1 to 28 May 2014. Many manoeuvres have, however, taken place in May 2014 and the days with manoeuvres have to be excluded from the comparisons because not all institutions provided orbit solutions for these days.

Tab. 2 lists the mean RMS values of the orbit differences between the orbits of the old CPOD System and the available independent orbit solutions. Tab. 3 lists the corresponding mean offsets of the orbit differences. Two significant mean offsets of more than 3 cm may be observed for the radial component in the comparison to the AIUB orbits and for the out-of-plane component in the comparison to the DLR orbits.
Only the comparison to ESOC and PTIM are close to the 5 cm 3D limit (see 3-D column in Tab. 2). In order to improve the CPOD orbit solutions for Sentinel-1A and to fulfil the orbit accuracy requirements the update to the IERS Conventions 2010 was necessary.

Table 2 Mean RMS values (cm) of orbit differences w.r.t. old CPOD solution (IERS2003); May 2014

	radial	**along-track**	**out-of-plane**	**3-D**
DLR	1.99	4.84	4.63	**7.04**
ESOC	1.60	3.54	3.09	**4.98**
AIUB	3.68	3.93	3.00	**6.17**
PTIM	1.25	3.60	3.24	**5.01**

Table 3 Mean offsets (cm) in differences between orbits from old CPOD System and corresponding orbits; May 2014

	radial	**along-track**	**out-of-plane**
DLR	0.28	0.82	3.95
ESOC	-0.43	0.32	-0.48
AIUB	-3.26	-0.05	-0.03
PTIM	-0.08	0.19	-0.67

After upgrading NAPEOS to the IERS Conventions 2010 the same orbit comparisons are performed with a new set of orbit solutions from the updated CPOD system.

In Tab. 4 the mean RMS values of the orbit differences w.r.t. the orbits of the updated CPOD system are listed. Tab. 5 lists the corresponding mean offsets. The significant offsets for DLR (out-of-plane) and AIUB (radial) are still present and other offsets increased compared to the first comparison. The 3D RMS values, however, decreased well below the 5 cm 3D limit for all comparisons except DLR. The large out-of-plane offset is mainly responsible for the large 3D RMS values for DLR. The systematic orbit differences for DLR and AIUB will be further investigated in future to find the cause of it.

Table 4 Mean RMS values (cm) of orbit differences w.r.t. updated CPOD solution (IERS2010); May 2014

	radial	along-track	out-of-plane	3-D
DLR	1.85	4.14	3.52	**5.83**
ESOC	0.94	1.70	1.49	**2.52**
AIUB	3.32	2.10	1.35	**4.17**
PTIM	0.63	1.60	1.56	**2.37**

Table 5 Mean offsets (cm) in differences between orbits from updated CPOD System and corresponding orbits; May 2014

	radial	along-track	out-of-plane
DLR	0.44	-0.78	3.28
ESOC	-0.32	-0.55	-1.11
AIUB	-3.16	-0.92	-0.67
PTIM	0.03	-0.68	-1.31

5. IMPACT OF MODIFICATIONS IN ORBIT PARAMETRIZATION AND OF ARC LENGTH

The orbit parametrization used for Sentinel-1A has been set up before real data of the satellite has been available. In preparation of the other Sentinel missions, in particular Sentinel-3, different orbit parametrization is tested to find the most ideal settings for the satellite(s). The current arc length of the NTC orbit is 72 hours though only the central 24 hours plus at maximum one revolution at the beginning and at the end of the arc are used as final NTC orbit product. It is tested whether a shorter arc length and thus a shorter processing time may be used without losing accuracy. In addition, the orbit parametrization is adopted in the way that a more dynamical modelling is envisaged. The following three solutions are done for these tests (only the differences to the settings in Tab. 1 are mentioned):

1. Fix solar radiation coefficient to 1.0; estimate constant CPR in along-track and out-of-plane.
2. Fix solar radiation coefficient to 1.0; estimate constant CPR in along-track and out-of-plane; arc length of 48 h (± 12 h of the central 24 h)
3. Original parametrization; arc length of 48 h (± 12 h of the central 24 h)

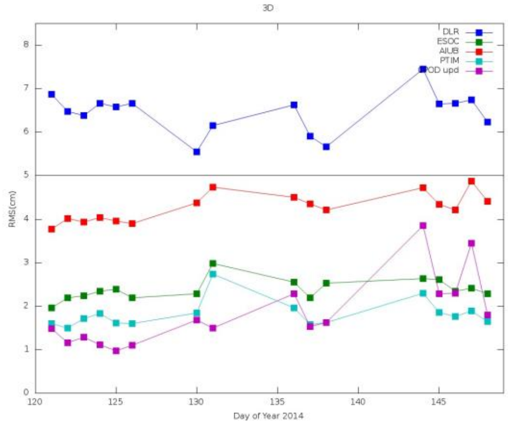


Figure 2 3D-RMS values (cm) of differences of Solution 1 w.r.t. the corresponding orbits

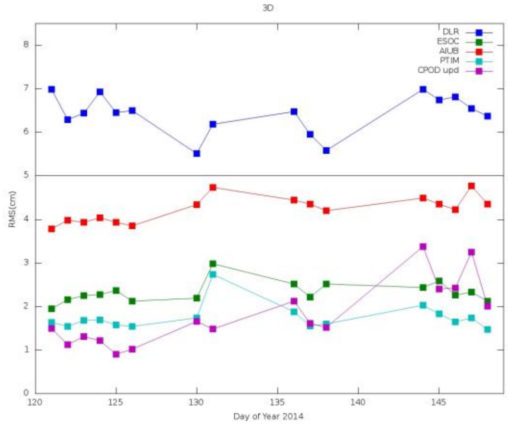


Figure 3 3D-RMS values (cm) of differences of Solution 2 w.r.t. the corresponding orbits

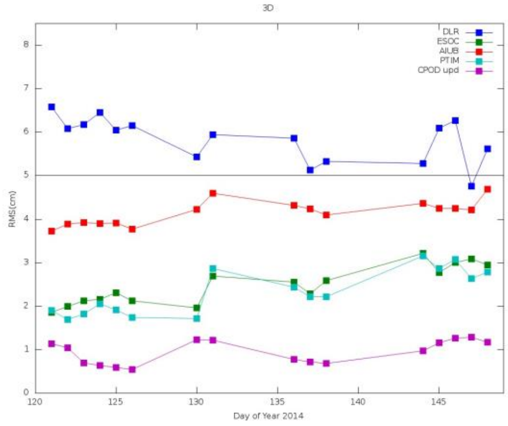


Figure 4 3D-RMS values (cm) of differences of Solution 3 w.r.t. the corresponding orbits

The 3D-RMS values of the orbit differences w.r.t. the independent orbit solutions (Fig.2 for Solution 1; Fig.3 for Solution 2; Fig.4 for Solution 3) show that all three solutions deliver comparable solutions. Tabs. 6 - 8 list the mean RMS values for all directions and these numbers confirm that the orbit differences are on the same level for all test solutions. The systematic orbit differences already seen in the comparisons of Section 4 are present in these comparisons as well. The overall conclusion of these tests is that all three solutions would be feasible as official solutions for Sentinel-1A. In particular the shortening of the arc length to 48 h (Solution 2 and 3) has no negative impact on the orbit accuracy. The option to fix the solar radiation coefficient to 1.0 (Solution 1 and 2) is also feasible. However, the value of 1.0 implies the perfect knowledge of the satellite model and its characteristics, a perfect knowledge of the attitude and a perfect knowledge of the movement of the solar panels. This is not the case and therefore it is recommended to wait until a longer data set (at least one year) is available and a realistic solar radiation coefficient can be estimated from this longer data set.

The estimated solar radiation coefficient may then be used for a reprocessing where the coefficient will be fixed. The setup of the empirical parameters has to be adapted as well. By fixing the solar radiation coefficient a more dynamical orbit modelling may be realised, which is in particular important for the altimeter mission Sentinel-3. In the case of Sentinel-3 the procedure will then be the same as soon as real data are available for the satellite.

Table 6 Mean RMS values (cm) of orbit differences w.r.t. Solution 1; May 2014

	radial	**along-track**	**out-of-plane**	**3-D**
DLR	1.87	4.05	4.61	**6.46**
ESOC	1.30	1.76	0.93	**2.39**
AIUB	3.45	2.09	1.36	**4.28**
PTIM	0.46	1.49	0.91	**1.82**

Table 7 Mean RMS values (cm) of orbit differences w.r.t. Solution 2; May 2014

	radial	**along-track**	**out-of-plane**	**3-D**
DLR	1.86	4.04	4.59	**6.43**
ESOC	1.29	1.72	0.87	**2.33**
AIUB	3.44	2.07	1.30	**4.24**
PTIM	0.44	1.46	0.83	**1.75**

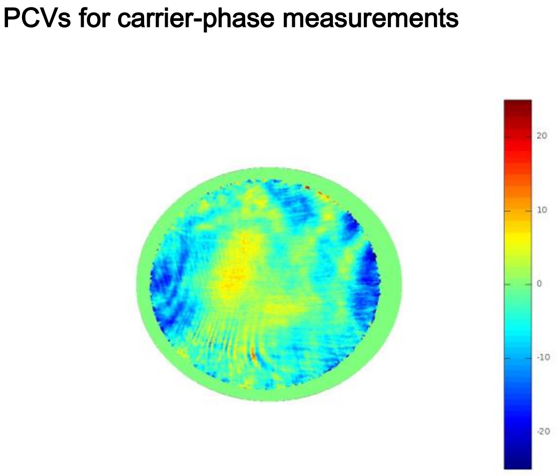
Table 8 Mean RMS values (cm) of orbit differences w.r.t. Solution 3; May 2014

	radial	**along-track**	**out-of-plane**	**3-D**
DLR	1.84	4.12	3.55	**5.83**
ESOC	0.94	1.69	1.45	**2.48**
AIUB	3.32	2.09	1.31	**4.15**
PTIM	0.61	1.59	1.51	**2.32**

6. ANTENNA PHASE CENTRE VARIATIONS

Antenna phase centre variations (PCVs) are one of the largest error sources in LEO POD procedures. If PCVs are not applied to the carrier phase measurements high-precision orbit determination is not possible.

Since the satellite body may cause signal multipath a ground calibration of the GPS antenna without taking into account the satellite body might not be sufficient to quantify the PCVs. The PCVs are therefore obtained by an in-flight calibration based on the carrier-phase residuals.



PCVs for carrier-phase measurements

Figure 5 Antenna PCVs (mm) in an antenna-fixed azimuth-elevation diagram from May 2014. Azimuth of 90 degree points approximately into flight direction when nominal attitude law is assumed.

A first map for the PCVs (Fig. 5) determined from a limited amount of data (May 2014) at the beginning of the mission has shown significant multipath signals (stripes) in parts of the antenna. Since the satellite has moving parts (solar panels) it has to be checked carefully if these multipath regions are moving as well or if they are antenna-fixed or not.

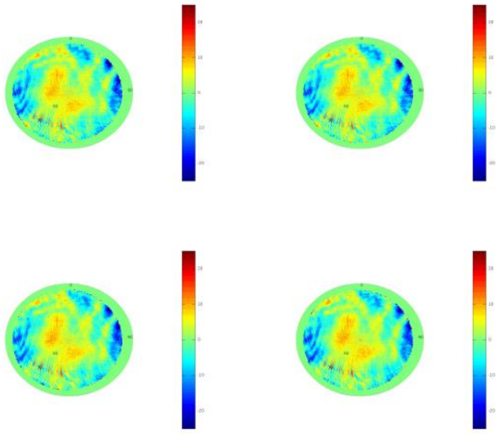


Figure 6 Antenna PCVs (mm) for September (top left), October (top right), November (bottom left), and December (bottom right) 2014.

Monthly maps are generated for September, October, November, and December 2014 (Fig.6). The PCV maps are very similar and no change of the systematic stripes is visible. To confirm that the stripes are antenna-fixed several orbit solutions are generated for 15 days in January 2015. For each of the solution a different PCV map is applied.

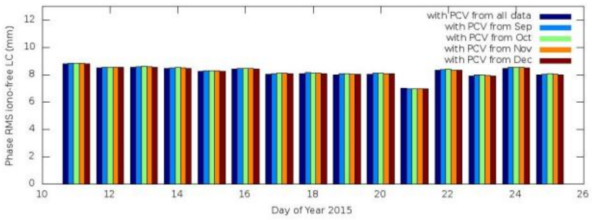


Figure 7 Carrier-phase RMS values for the ionosphere-free linear combination (mm) for orbit solutions applying different PCV maps.

Fig. 7 shows the RMS of the ionosphere-free linear combination of the carrier-phase measurements, which is the main observable for the orbit determination. The values are only slightly different when applying different PCV maps, which confirm that the signature in the PCV maps is antenna-fixed.

A PCV map from several months has been estimated (Fig. 8) to fill all bins in the azimuth-elevation diagram and to smooth out possible outliers by using a large amount of data. The PCV map has been generated in an iterative process with five iterations.

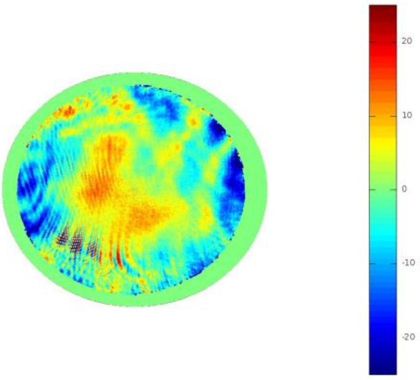


Figure 8 Antenna PCVs (mm) from several months; May and August to December 2014.

PCVs for code measurements

Normally the correction maps are only applied for the carrier phase measurements. Since significant multipath has been spotted for the code measurements as well (Fig. 9) the impact of additionally applying code correction maps in the POD process is studied.

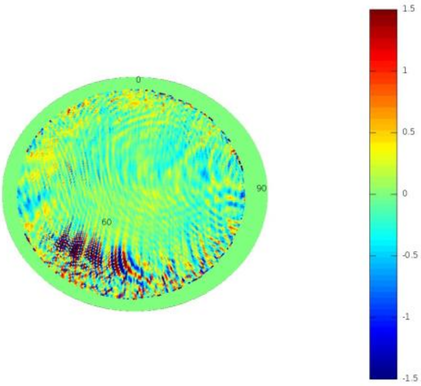


Figure 9 Antenna PCVs (m) for the code measurements.

The code PCV map has been generated from five iterations and the application in the POD process has significant impact on the code RMS (Fig. 10). The code RMS can significantly be reduced from more than 60 cm to less than 50 cm. On some days, however, only a slight improvement may be noticed. These are days with large manoeuvres. The attitude did not follow the nominal attitude law during all the time when large manoeuvres are performed with the satellite. The software is, however, using the nominal attitude law at all the time.

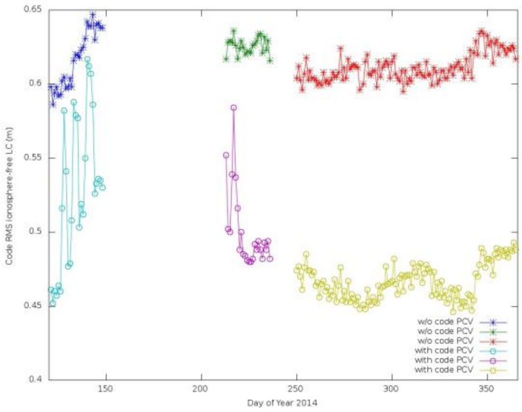


Figure 10 Code RMS (m) for orbit solutions w/o or with applying code PCV map

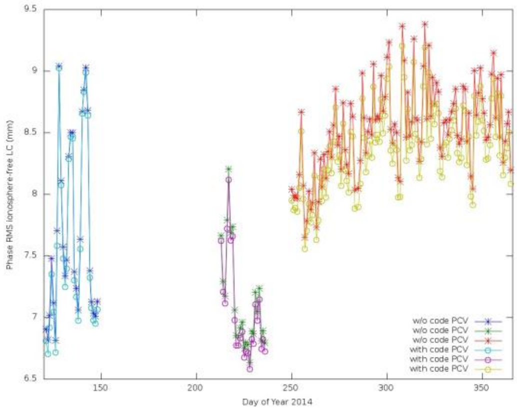


Figure 11 Carrier-phase RMS (mm) for orbit solutions w/o or with applying code PCV map

If the nominal attitude law does not fit the real attitude the wrong corrections from the code PCVs are applied for the code measurements. The code PCVs differ in the range of several metres in the critical regions with the systematic stripes. This has obviously a large impact on the code RMS values.

Though the application of the code PCVs has only little impact on the carrier-phase RMS (Fig. 11) and no impact on the orbit results (not shown here) this experiment has clearly shown that one has to be careful when using manoeuvre days for the estimation of the PCVs. Since the attitude does not follow the nominal attitude law around the manoeuvres the corresponding days have to be excluded from the PCV estimation.

7. SUMMARY AND CONCLUSIONS

The Copernicus POD Service provides state-of-the-art orbital products for the Sentinel-1, -2, and -3 missions. In order to guarantee this a lot of effort has to be taken besides running the operational POD procedures of the Service. For instance updates in the IERS Conventions have to be followed in the NAPEOS software and the implementations have to be thoroughly tested.

It could be shown that the recent update to the IERS Conventions 2010 significantly improved the orbit accuracy of the Sentinel-1A NTC product.

The orbit parametrization, arc length and other settings in the POD procedure have to be reviewed regularly to be able to deliver best possible orbit products for all Sentinel missions. It has been investigated that the arc length might be shortened from 72 h to 48 h without losing orbit accuracy. The shortening of the arc length would shorten the processing time as well.

The orbit parametrization may be adapted individually for the different Sentinel satellites because the satellite characteristics are very different. Mainly in view of the altimeter mission Sentinel-3 the modelling should be as dynamical as possible.

Antenna PCVs for Sentinel-1A have been estimated from several months of data. It could be confirmed that the systematic stripes visible in the PCVs are not caused by moving parts of the satellite but are antenna-fixed. The application of code PCVs reduces the code RMS significantly but has no impact on the orbit results at all. It has to be taken care, however, to exclude manoeuvre days from the PCV generation, because the nominal attitude law is not followed around the manoeuvre and the residuals are because of wrong azimuth-elevation information not usable for the PCV estimation.

8. ACKNOWLEDGEMENTS

The Copernicus POD Service is financed under ESA contract no. 4000108273/13/1-NB which is gratefully acknowledged.

Acknowledgments are due to the companies and institutions being part of the GMV-led consortium as well. Namely:

1) POSITIM
2) DLR
3) TUM
4) AIUB
5) TU Delft
6) VERIPOS

They all provided significant and immeasurable support for the definition of the CPOD Service, for which the authors are extremely grateful.

9. REFERENCES

1. Fernández, J., D. Escobar, F. Ayuga, H. Peter, P. Féménias (2015) *Copernicus POD Service Operations*, ESA-SP 734

2. Springer, T., F. Dilssner, D. Escobar (2011) *NAPEOS: The ESA/ESOC Tool for Space Geodesy*

3. Flohrer, C., M. Otten, T. Springer, J. Dow (2011) *Generating precise and homogeneous orbits for Jason-1 and Jason-2*, Adv Space Res, 48(1), 152-172, doi: 10.1016/j.asr.2011.02.017

4. IERS Conventions (2010). Gérard Petit and Brian Luzum (eds.). (IERS Technical Note ; 36) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2010. 179 pp., ISBN 3-89888-989-6

5. Helleputte, T. Van (2004) *GPS High Precision Orbit Determination Software Tools: User Manual*, Doc. No. FDS-SUM-3110

6. Dach, R., U. Hugentobler, P. Fridez, M. Meindl (Eds) (2007) *Bernese GPS Software Version 5.0***.** User manual, Astronomical Institute, University of Bern.