SINGLE-RECEIVER AMBIGUITY RESOLUTION FOR COPERNICUS SENTINEL SATELLITES
COPERNICUS POD SERVICE

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Photography encouraged

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ABSTRACT

Single-receiver GPS ambiguity resolution methods are started to be deployed for precise orbit determination (POD) of the Copernicus Sentinel satellites. Previous analyses from other groups showed the improvement of the orbit results of Sentinel-3A when applying ambiguity-fixing (Montenbruck et al. 2017 , Otten et al. 2018, Mercier et al. 2018, Simons et al. 2018). Prerequisite for these methods are the GPS wide-lane bias product together with the corresponding orbit and clock products. Currently, these necessary inputs are and will be made available from different analysis centres of the International GNSS Service. The Copernicus Sentinel-1, -2, and -3 orbit products delivered by the Copernicus POD Service to the PDGSs (Payload Data Ground Segment) of the individual missions are not yet based on fixed carrier phase ambiguities. Effort is taken to develop and implement corresponding interfaces and ambiguity fixing strategies. Aim is to be able to deliver ambiguity-fixed Sentinel orbits in the operational environment of the Copernicus POD Service in the near future.

The impact of the ambiguity-fixed carrier phases on the resulting Copernicus Sentinel orbit products is analysed. Due to the different latencies of the orbital products it has to be carefully investigated for which product lines dedicated bias products are available in time. Backup procedures for the case that the necessary information is missing have to be developed as well. Additionally, Sentinel-1 and -2 do not provide observations at multiples of 10 seconds. This might complicate the applicability on those missions.

This study will give an overview of the work done at the Copernicus POD Service to follow up recent developments in the frame of single-receiver ambiguity resolution for POD of the Copernicus Sentinel satellites. It also includes the assessment of current and potential future sources of the clock and biases needed.

OVERVIEW OF THE COPERNICUS POD SERVICE

Copernicus program facts:
- A joint initiative of the European Commission implemented in partnership with the ESA and EUMETSAT, among others
- Monitoring, recording and analysing environmental data and events around the globe
- Different families of satellites (Sentinel-1 to -6)
- The first three families the subject of the Copernicus POD Service

Copernicus POD accuracy and timeliness requirements:

Mission	Category	Orbit Accuracy (RMS)	Latency
S-1	NRT	10 cm (2D)	180 min.
	NTC	5 cm (3D)	20 days
S-2	NRT (predicted)	3 m (2D)	90 min. before ANX
	NRT	1 m (3D)	30 min.
S-3	NRT (S3PODDPF)	10 cm radial (target of 8 cm)	30 min.
	STC	4 cm radial (target of 3 cm)	1.5 days
	NTC	3 cm radial (target of 2 cm)	25 days

Copernicus POD Service facts:
- Part of the **PDGS Ground Segment** of the Sentinel missions
- In charge of the generation of **precise orbital products** and auxiliary data files
- **Developed** and operated by a **GMV-led consortium**
- **Location**: Operated on **GMV premises** (Tres Cantos, Spain)
- **S-3 POD IPF**, an Instrument Processing Facility developed by GMV, integrated in
- S-3 PDGS to generate **NRT orbits** and platform for the Sentinel-3 mission

Because of timeliness of GPS biases, orbits and clocks used, ambiguity-fixing algorithms can only be applied for the NTC products

Operational ambiguity-fixing facts:
- The CPOD Service requires new inputs to perform ambiguity-fixing based on single-differences: the so-called **wide-lane satellite biases (WSBs)** and consistent orbit and clock products
- CNES/CLS provides these inputs (referred to as GRG) with a timeliness of 5-12 days
- Due to the latency of the different operational solutions and the timeliness of the GRG inputs, **ambiguity-fixing algorithms are only applicable for the NTC products**
- CODE produces signal-specific phase bias products which can be used to fix ambiguities in undifferenced ambiguity-fixing applications. This approach is still to be explored by the CPOD Service
- If applicable, other bias products becoming available for single-receiver ambiguity-fixing will be explored as well

COPERNICUS SENTINEL MISSIONS			
	Sentinel-1	**Sentinel-2**	**Sentinel-3**
Altitude	639 km	786 km	814.5 km
Inclination	98.18 deg.	98.58 deg.	98.65 deg.
GPS	2 GPS receivers	2 GPS receivers	2 GPS receivers
LRR	None	None	1 LRR
DORIS	None	None	1 DORIS
Launch date	3rd April, 2014 (SEN-1A) 25th April, 2016 (SEN-1B)	23rd June, 2015 (SEN-2A) 7th March, 2017 (SEN-2B)	16th February, 2016 (SEN-3A) 25th April, 2018 (SEN-3B)

SINGLE-RECEIVER AMBIGUITY FIXING IN PRECISE ORBIT

Precise orbit determination processing:
- Measurements filtering and ionosphere-free linear combination between GPS codes L1 P(Y) and L2 P(Y) and GPS phases L1 and L2
- Generation of an initial orbit by applying the Bancroft algorithm over the code measurements
- Orbit determination based on phase ambiguities estimated as floating numbers. It relies on the proper modelling of the orbital dynamics at which the measurements are fitted in a least-squares sense
- Application of **single-receiver ambiguity-fixing algorithms** to fix the phase ambiguities as integer numbers and generate consistent ionosphere-free ambiguities
- Orbit determination once the ionosphere-free ambiguities are fixed

Main configuration of the POD processing during the ambiguity-fixing validation campaign:

Parameter:	Configuration
Software	NAPEOS
Generated products	Daily orbits for every mission from September 23rd, 2018 to January 20th, 2019
Arc length	32 h (day-1 19:00 - day+1 03:00)
Radiation Pressure Model	Box-wing model with instantaneous re-radiation
Earth Radiation Model	Albedo and Infra-red applied
Atmospheric Density Model	Msise90 (Hedin 1991)
Estimated Radiation Pressure Coefficients	One per arc
Estimated Drag Coefficients	15 per arc
Empirical Accelerations	Three sets per arc (along-+cross-track, sine+cosine)
Receiver clocks	Per observation epoch, every ten seconds
Carrier phase ambiguities	Estimated as integer: single-differences + GRG WSBs (Laurichesse et al. 2009)
Observations used	Ionosphere-free linear combination of phase and pseudo-range GPS measurements
Sampling	10 s
Elevation cut-off angle	7 deg
GPS orbits	GRG finals
GPS clocks	GRG finals

Percentage of fixed ambiguities		
	Mean [%]	**StD [%]**
SEN-1A	98.65	0.72
SEN-1B	98.06	0.79
SEN-2A	98.16	0.92
SEN-2B	98.75	0.91
SEN-3A	98.08	0.90
SEN-3B	98.13	0.93

Single-receiver ambiguity-fixing algorithm:
- GRG orbit, clock and wide-lane satellite bias (WSB) products routinely generated by CNES/CLS are prepared to be used in undifferenced/single-differences ambiguity-fixing applications
- Averaging pass by pass the single-differentiated (i.e., differences between two GPS satellites and a single receiver) Melbourne-Wuebbena combinations, $\Delta\widetilde{MW}$, before adding the corresponding WSBs, $\Delta\hat{b}$, allows to fix the single-differentiated wide-lane ambiguities , $\Delta\widetilde{N}_{wl}$, to the nearest integer value as (being λ_{wl} the wide-lane wavelength)

$$\Delta\widetilde{N}_{wl} = \left[\frac{\Delta\widetilde{MW}}{\lambda_{wl}} + \Delta\hat{b}\right]_{roundoff}$$

provided that the fixing probability lies above a given threshold (probability g.t. 0.94 for the POD processing)
- Using $\Delta\widetilde{N}_{wl}$ together with the pass-averaged single-differentiated ionosphere-free floating ambiguities, $\Delta\widetilde{B}$, the integer narrow-lane ambiguities, $\Delta\widetilde{N}_{nl}$, can be rounded from (being λ_{nl} and λ_2 the narrow-lane and L2 signal wavelengths, respectively)

$$\Delta\widetilde{N}_{l} = \left[\frac{1}{\lambda_{nl}}\Delta\widetilde{B} - \frac{\lambda_{wl}}{\lambda_2}\Delta\widetilde{N}_{wl}\right]_{roundoff}$$

as long as the fixing probability is above a given threshold (probability g.t. 0.94 for the POD processing)
- From the fixed $\Delta\widetilde{N}_{wl}$ and $\Delta\widetilde{N}_{l}$, a set of pass-specific constraints over the single-differentiated ionosphere-free ambiguities of the form

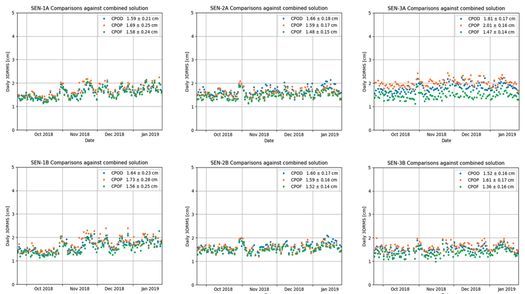
$$\Delta\tilde{B} = \lambda_{nl}\left(\Delta\widetilde{N}_{l_L} + \frac{\lambda_{wl}}{\lambda_2}\Delta\widetilde{N}_{wl_L}\right)$$

is applied in a subsequent iteration of the POD processing. After two iterations, the number of fixed ambiguities gets steady around ~98% with a narrow dispersion

Montenbruck O., Hackel S., Jäggi A., 2017. Precise orbit determination of the Sentinel-3A altimetry satellite using ambiguity-fixed GPS carrier phase observations
Otten M., Flohrer C., Springer T., Enderle W., 2018. 2018 Ocean Surface Topography Science Team Meeting. Integer Ambiguity Resolved Orbits for Sentinel-3A and Sentinel-3B
Mercier F., Masson C., Houry S., Ait-Lakbir H., Couhert A., Jalabert E., Moyard J., 2018. 2018 Ocean Surface Topography Science Team Meeting. Fixed GPS Ambiguity Orbit Solutions
Simons W., Visser P., Naeije M., Copernicus POD QWG team, 2018. 25 Years of Progress in Radar Altimetry Programme. Precise Orbit Determination of the Sentinel Satellites with Gipsy-Oasis
Fernández J., Peter H., Calero E.J., Berzosa J., Gallardo L.J., Féménias P., 2019. Sentinel-3A – Validation of Orbit Products at the Copernicus POD Service
Laurichesse D., Mercier F., Berthias J.P., Broca P., Cerri L., 2009. Integer ambiguity resolution on undifferenced GPS phase measurements and its application to PPP and satellite precise orbit determination

VALIDATION OF THE RESULTS

- The CPOD Service is supported by a number of associated entities: **AIUB, DLR, ESOC, TU Delft, TUM, CLS, CNES, EUMETSAT** (latter three for S-3 only)
- A **combined orbit** is generated from the solutions provided by the external entities (Fernández et Al., 2019)
- Three in-house solutions have been considered:
  - **CPOD** is based on IGS final products + floating ambiguities (operational configuration)
  - **CPOP** is based on GRG final products + floating ambiguities (prior to fix ambiguities)
  - **CPOF** is based on GRG final products + integer ambiguities (fixed ambiguities configuration)
- Daily comparisons against the combined orbit conclude:
  - The best agreement is related to the CPOF solution. The overall improvement with respect to the operational solution (i.e., CPOD) range from 0.1 mm in the worst scenario (SEN-1A) to 3.5 mm in the best one (SEN-3A)
  - Comparing CPOF against CPOP, it is observed that fixing the ambiguities always results in an improvement of accuracy → the implemented algorithm is consistent with the GRG processing



SLR residuals for Sentinel-3			
	CPOD	**CPOP**	**CPOF**
SEN-3A	0.44 ± 1.15 cm	0.41 ± 1.24 cm	0.43 ± 1.04 cm
SEN-3B	0.41 ± 1.14 cm	0.37 ± 1.11 cm	0.39 ± 1.05 cm

Sentinel-3 satellites are equipped with a LRR instrument → external validation based on SLR observations

The SLR residuals show lower levels of dispersion for the CPOF solution than for the others

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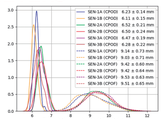
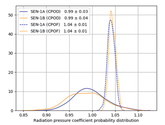
OTHER POD METRICS AND PARAMETERS

Phase residuals of the POD processing are larger for the CPOF solution than for the CPOD solution → biases related to the phase ambiguities are no longer absorbed by the estimated orbit

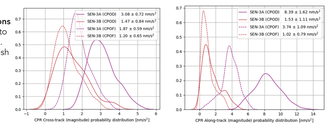
Larger dispersion for the CPOF phase residuals than for the CPOD ones → the CPOF solution absorbs lower levels of noise



Due to the **SAR** instrument and the widely-deployed **solar panels**, the dynamics of Sentinel-1 is strongly influenced by the radiation pressure. The estimation of its related coefficient during the POD processing is much more stable for the CPOF solution than for the CPOD one



During the POD processing, **empirical accelerations** in along- and cross-track directions are estimated to absorb the uncertainties of the physical modelling. It is clearly observed that both components diminish in the case of Sentinel-3



CONCLUSIONS

- Ambiguity fixing capabilities have been implemented into the operational tools of the CPOD Service
- A description of the single-receiver ambiguity fixing algorithm has been introduced, showing its high performance in fixing ambiguities for the Copernicus Sentinel missions
- The validation of the results has been proven by comparing the resulting solutions against a baseline solution generated from the combination of the orbits provided by the CPOD QWG
- Direct comparisons between the estimated parameters of the operational solution and the ones estimated after fixing the ambiguities have revealed interesting characteristics of the physical problem which lies beneath
- Further ambiguity-fixing methodologies are still to be explored by the CPOD Service

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