Precise Orbit Determination of the Spire Satellite Constellation for Geodetic, Geophysical, and Ionospheric Applications

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Project Overview and First Orbit Determination Results

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Introduction

The main objective of the project "Precise Orbit Determination of the Spire Satellite Constellation for Geodetic, Geophysical, and Ionospheric Applications" (ID no. 66978), which was approved on 7 September 2021 in the frame of an ESA Announcement of Opportunity (AO), is to generate and validate precise reference orbits for selected Spire satellites and, based on this, to ingest and assess the requested Spire GPS data into three scientific applications, namely gravity field determination, reference frame computations, and ionosphere modelling to study the added value of the Spire GPS data. Due to the fact that the Spire constellation populates for the first time the Low Earth Orbit (LEO) layer at different inclinations with a large number of satellites, which are all equipped with high-quality dual-frequency GPS receivers, it opens the door to significantly strengthen all of the three above mentioned scientific applications.

In the initial phase of the project the focus will be on the precise orbit determination (POD) of selected Spire satellites. Two independent, state-of-the art software packages, namely the Bernese GNSS Software (BSW) and ESA's NAPEOS software, will be used for this purpose. This will allow for inter-comparisons, a role model that is inherited from the work of the POD Quality Working Group of the Copernicus POD Service. It will enable an independent quality and integrity assessment of the Spire inputs and products.
We will analyse the quality of the Spire GPS code and carrier phase date and validate antenna phase centre calibrations. Based on this we will determine reduced-dynamic and kinematic orbits for selected Spire satellites. Eventually we will evaluate the quality of the reconstructed orbits by means of orbit overlap analyses, cross-comparisons of kinematic and reduced-dynamic orbits computed within one and the same software, and cross-comparisons of the orbits derived with the Bernese GNSS Software and ESA's NAPEOS software, as well as comparisons to the orbits provided by Spire.

Lemur-2 (2nd gen.) Image credits: Spire

Satellite used in the processing:
- FM099, Johan Loran
- Satellite bus: Lemur-2_3.4
- Mass: 5.1 kg
- Launch date: April 1, 2019
- Semi major axis: 6844 km
- Inclination: 97.3°, sun-synchronous orbit
- Data: 1 May – 31 October 2020

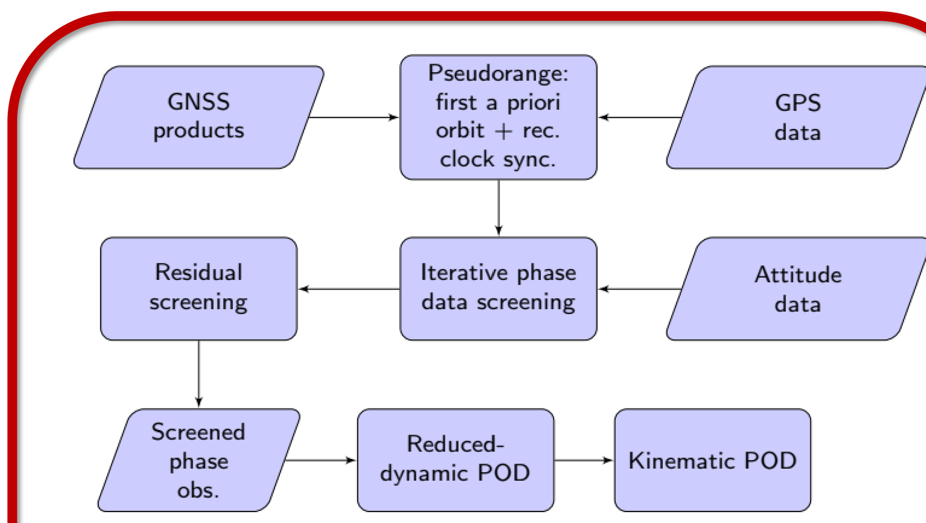
- GPS data from POD antenna; 1 Hz dual-frequency data, 10 s sampling used
- Ionospheric-free linear combination of code (only NAPEOS) and carrier-phase measurements used for POD, 0° elevation cut-off angle
- Attitude quaternions used for attitude modelling
- Fixed final GPS orbits and clocks from CODE analysis centre (GNSS products)

Bernese GNSS Software – POD settings

Force modelling of reduced-dynamic orbits:
- Constant accelerations in radial, along-track, cross-track directions
- Sine and cosine acceleration parameters in all directions
- 6-min piece-wise constant accelerations in all directions

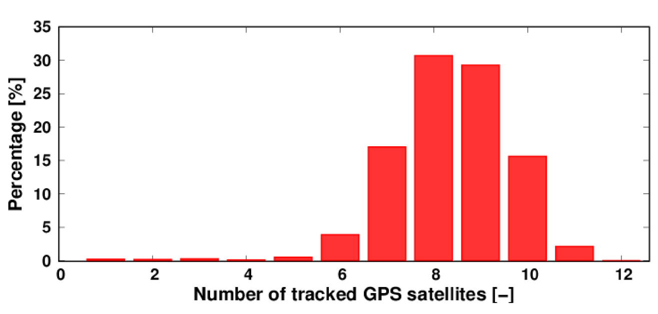
NAPEOS – POD settings

Force modelling of reduced-dynamic orbits:
- Radiation pressure and atmospheric drag modelling with constant area of 0.12 m², scale factors fixed to 1.0
- 2 h constant, sine and cosine acceleration parameters in along-track and cross-track directions

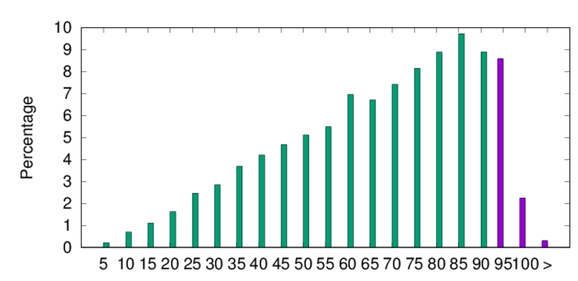


BSW flow diagram for LEO POD. NAPEOS processing is similar but without kinematic POD.

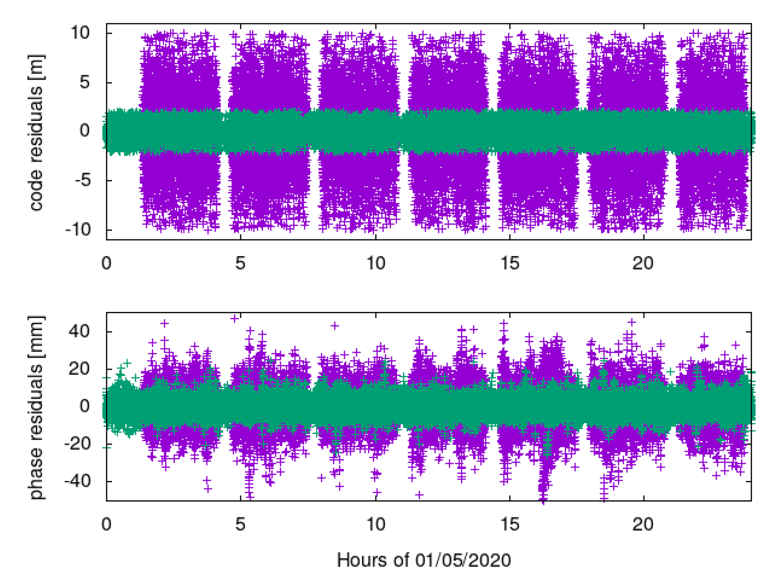
GPS data quantity and quality



Number of tracked GPS satellites per epoch is very good with most epochs between 6 and 12 satellites. At least five observations are needed to determine a reliable kinematic position of the LEO.

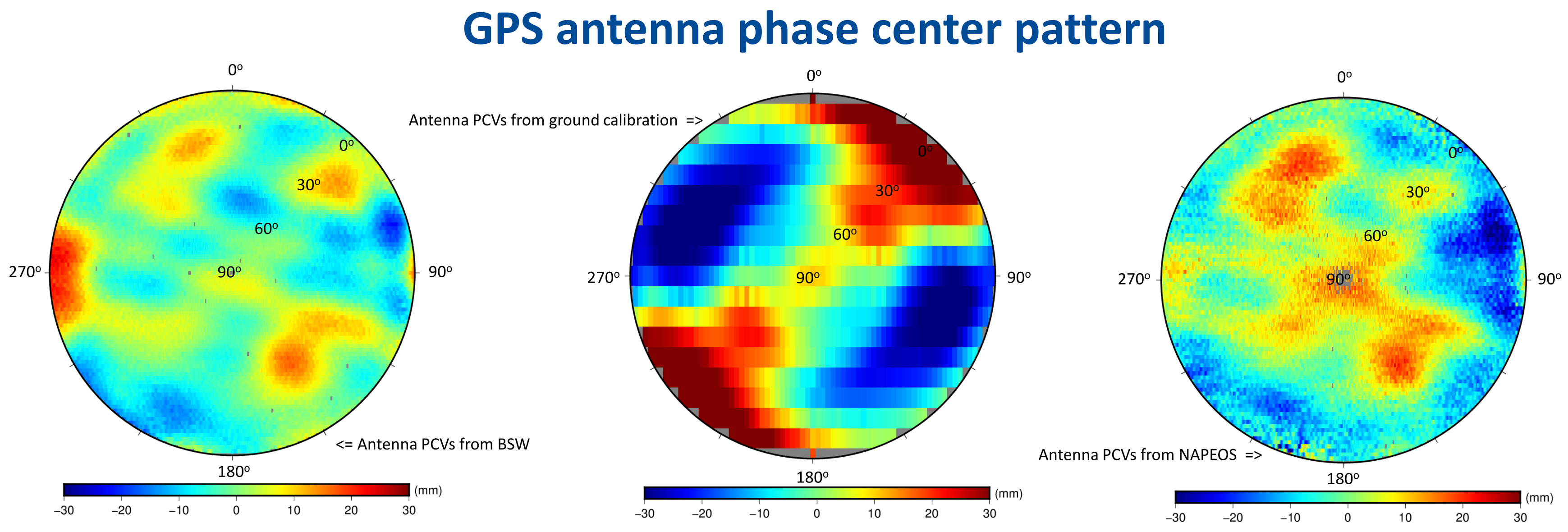


Histogram of observation distribution in 5-deg bins. More than 10 % of the observations are gathered **below** the local horizon of the antenna. Currently these observations are discarded from the POD processing. It has to be investigated, if they can be of use.



Code (**top**) and carrier phase (**bottom**) residuals from NAPEOS processing for one example day. Residuals from both observation types are significantly larger than for other scientific Earth observation satellites; **SPIRE FM099**, **Sentinel-3B.** Code residuals are "cut" due to screening options.
SPIRE satellites data have regular gaps due to duty cycles of less than 100%. Larger data gaps may lead to degraded orbit results for the reduced-dynamic orbit results. Kinematic orbits have gaps when no data is available.
Further investigations will follow to study the impact of these data gaps on the planned scientific applications of the SPIRE data.

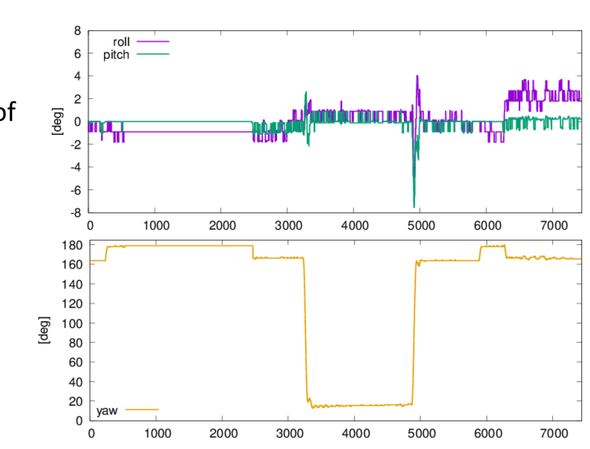
GPS antenna phase center pattern

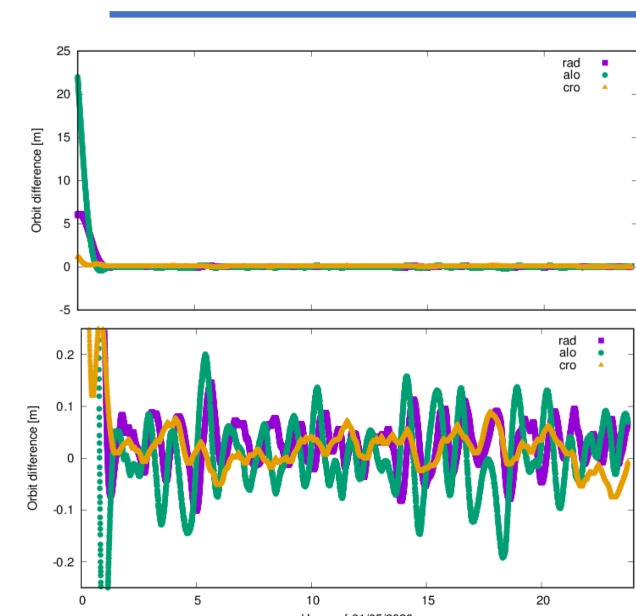


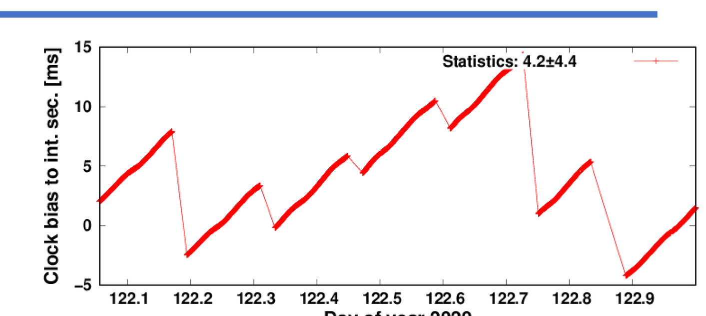
Azimuth-elevation dependent antenna phase center corrections either estimated in-flight with BSW (left, 6 months data) or NAPEOS (right, 1 month data). Middle plot shows values from ground calibration. Estimated values agree regarding the large structures. Magnitudes vary due to different POD processing setups. Differences to ground calibration has to be further investigated.

Attitude information

Right: Example for attitude (**roll**, **pitch**, **yaw** angle). Several yaw flips per day are performed for the satellite. Attitude quaternions provide the rotation of satellite reference frame to the local orbit frame, which is not common practice and has to be implemented accordingly.
Due to the yaw flips it is indispensable to consider the attitude quaternions for the processing. In particular for the estimation of the antenna phase center patterns **(see left)**.



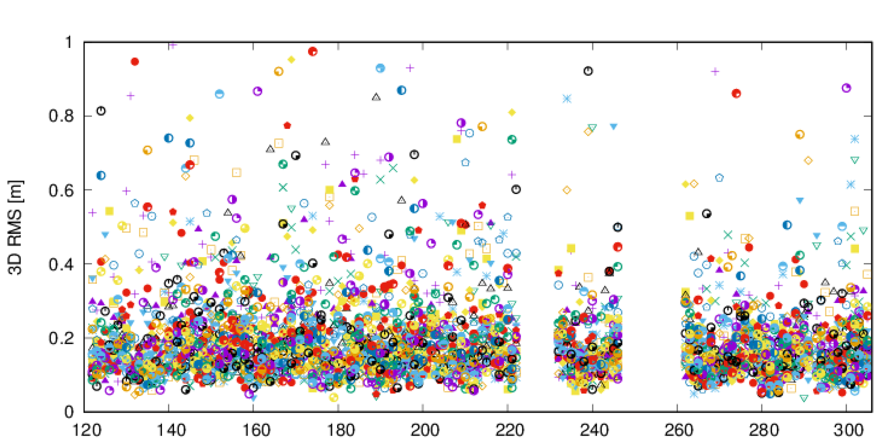


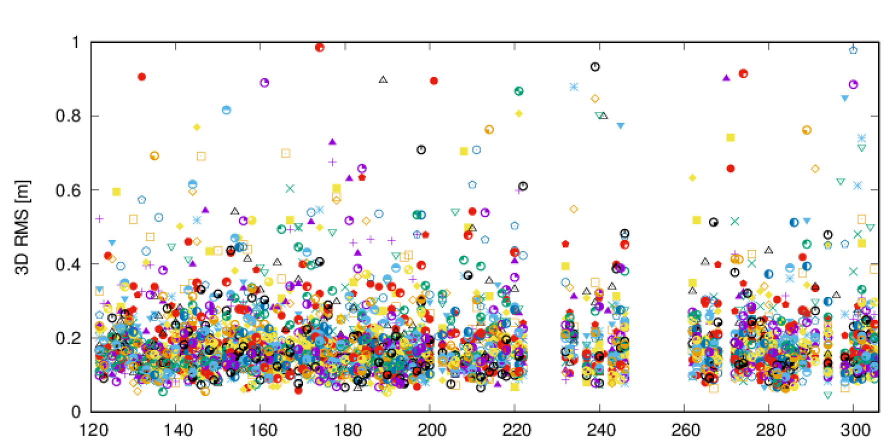


Top: Receiver clock bias show large drift and regular jumps of up to 15 ms.

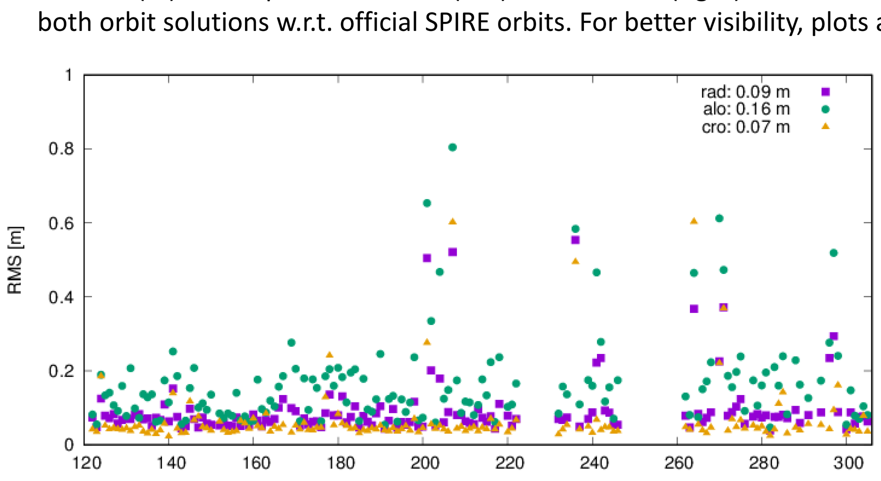
Left: Example of differences between NAPEOS and BSW reduced-dynamic orbit s on 1 May 2020 (**bottom**: zoom in). Data gap at the beginning of the day leads to very large differences. On the rest of the day the orbit solutions are very consistent.

Orbit comparison

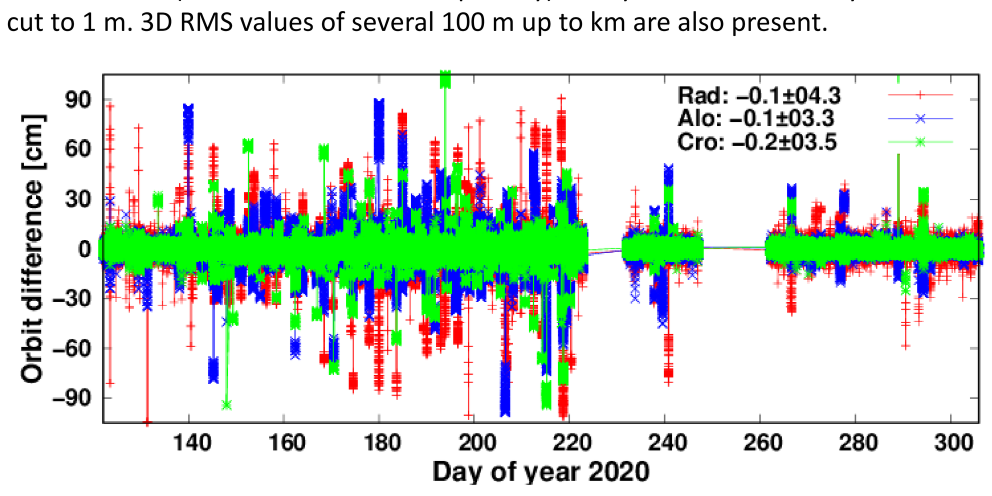




3D RMS (m) of comparison of BSW (left) and NAPEOS (right) orbits to official SPIRE orbits (several short orbit arcs per day) – very similar consistency of both orbit solutions w.r.t. official SPIRE orbits. For better visibility, plots are cut to 1 m. 3D RMS values of several 100 m up to km are also present.



Daily RMS (m) of comparison of NAPEOS and BSW SPIRE FM099 orbits. Differences > 1 m are discarded for the statistics, because data gaps may reduce quality of the orbits. The reduced-dynamic orbits are provided as 24 h arcs (covering also the data gaps). Mainly the along-track component suffers from data gaps at the beginning or at the end of daily arcs. Removing these orbit parts would even further increase the orbit consistency between NAPEOS and BSW orbits.



Orbit differences (cm) between BSW reduced-dynamic and kinematic orbits. Kinematic positions can only be determined if enough observations are available. Orbit differences show good consistency with large improvement towards the end of the time interval. The reason for this is still unknown.

Summary and future work

Dual frequency GPS data from the POD antenna of one (FM099) of the SPIRE satellites has been processed within a project "Precise Orbit Determination of the Spire Satellite Constellation for Geodetic, Geophysical, and Ionospheric Applications" in the frame of ESA AO.
Two different leading LEO POD software packages, namely Bernese GNSS Software and NAPEOS, were used for this purpose and the results are compared to the official available SPIRE products. Although the GPS measurement quality and continuity is not fully comparable to those of other scientific Earth observation satellites, the results are very promising. An orbit consistency on dm level could already be achieved between the two orbit solutions although POD modelling and processing setups are not yet optimally tuned.
Future work includes:
- POD process tuning, e.g., introduce satellite macro model for non-gravitational force modelling
- Carrier phase ambiguity fixing
- POD processing for other SPIRE satellites
- Handling of problematic days, e.g., days with very few data and large data gaps
- Start to use SPIRE data for proposed scientific applications.

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