Precise Orbit Determination of the Spire Satellite Constellation for Geodetic, Geophysical, and Ionospheric Applications
–
Project Overview and First Orbit Determination Results

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ION GNSS+ 2022

19–23 September 2022

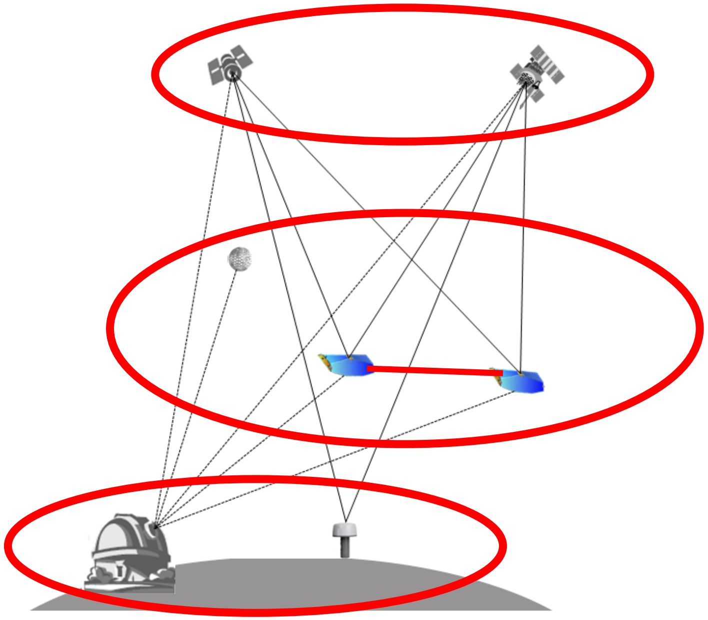
ERC Project SPACE TIE

European Research Council
Established by the European Commission

Data Basis

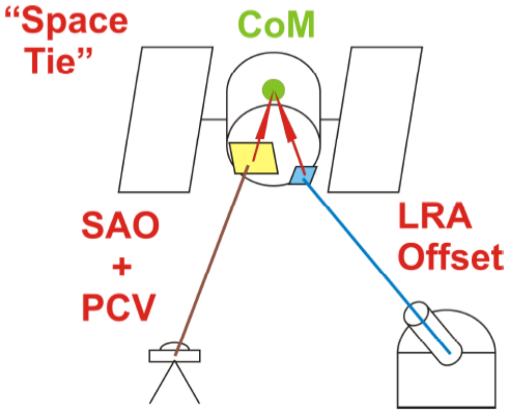
- ~ 80 GNSS satellites
- ~ 20 scientific LEO satellites (**gravity** and **altimetry**)
- GNSS and SLR ground networks

=> A more rigorous joint adjustment is envisaged



Main Idea (in a nutshell)

- Use of the Earth's gravity field to act as an additional global tie via satellite orbits
- Exploitation of space co-locations (space ties) on both **GNSS** and **LEO** satellites

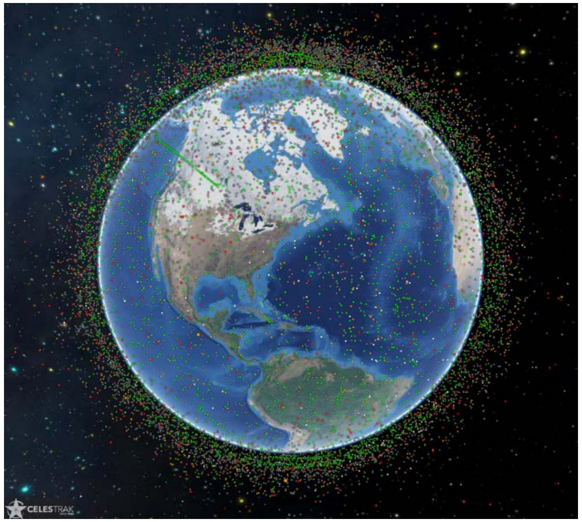


ESA Data AO Project

Data Basis

- ~ A multitude of CubeSats exist
- ~ 100 Spire satellites in different orbits (offering dual-frequency GPS POD data)
- Other constellations are at the horizon

=> What is the potential of these GPS / GNSS data for scientific applications?



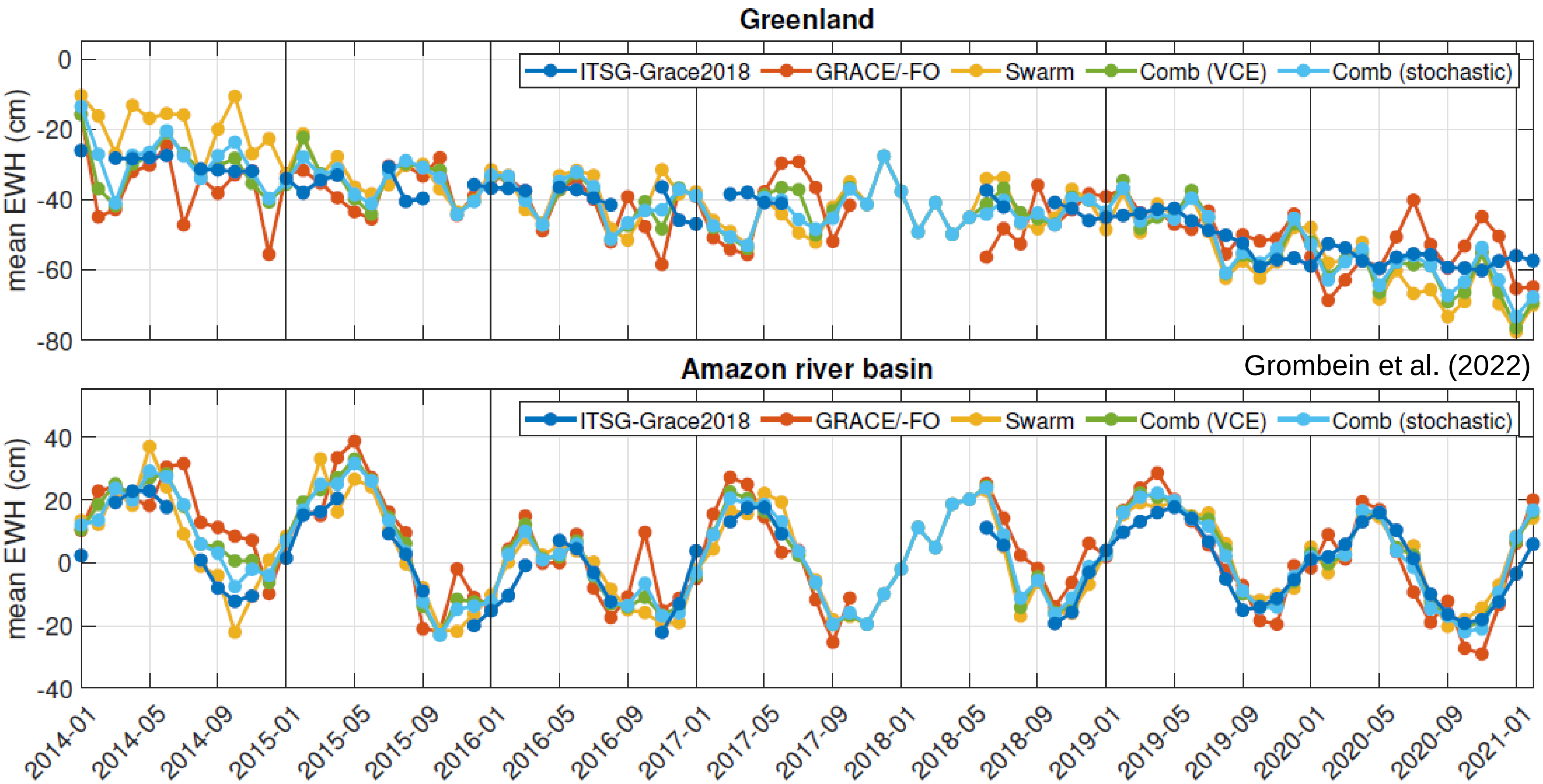
Main Idea (in a nutshell)

- Use dual-frequency Spire GPS POD data of a selected time period to check their impact on
  - Time-variable gravity field recovery
  - Reference frame applications
  - Ionosphere applications

of the ERC project.

Courtesy: Spire

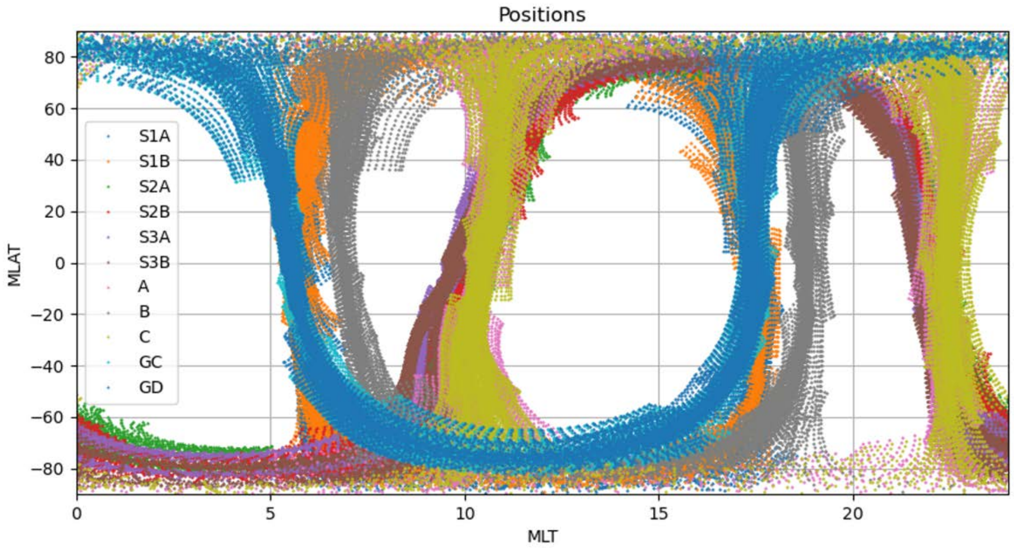
Time-Variable Gravity Field Recovery

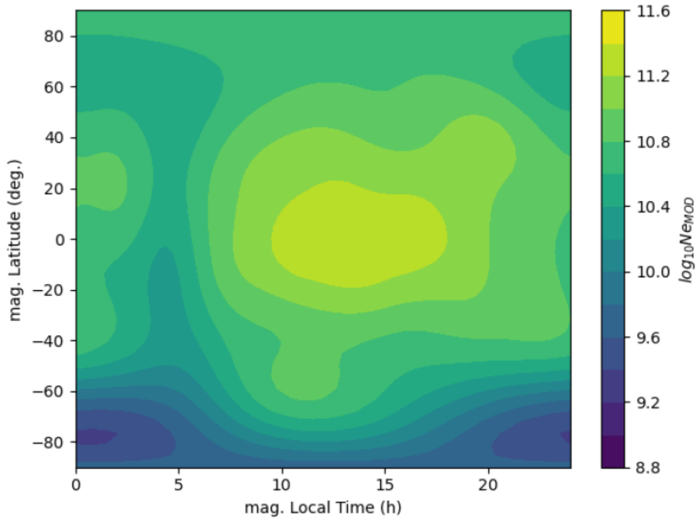


GPS hl-SST data of **non-dedicated gravity missions** allow to recover the long wavelength part of the Earth's time-variable gravity field surprisingly well.

How much can be gained by adding GPS hl-SST data from **existing CubeSats**?

Iono- and Plasmasphere Modeling





Schreiter (2021)

GPS hl-SST data of a fleet of LEO satellites with zenith-looking antennas allows it to recover a few hours 3D-model snapshots of the iono- and plasmasphere. Limiting factors are the **limited coverage of local times** by scientific LEO missions and the **limited coverage of orbital altitudes**.

How much can the spatial and temporal resolution be improved by adding the GPS hl-SST data of the **existing Spire satellites**?

Assessment of Spire GPS Data

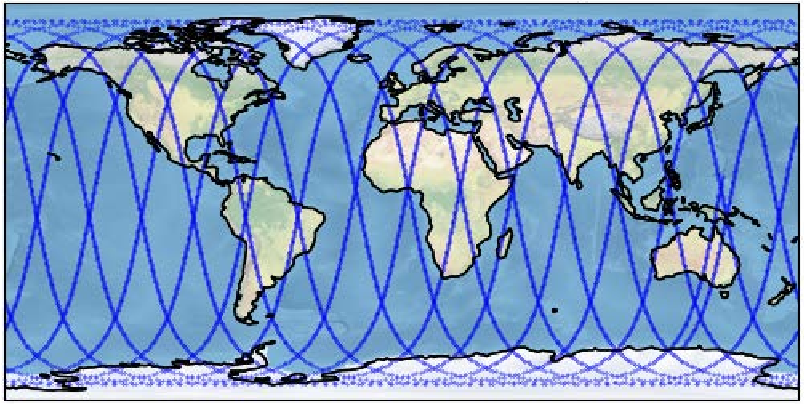
Courtesy: Spire

- **FM099** (JohanLoran)
  - Orbit: 484.8 km x 501.6 km
  - Inclination: 97.4°
- **FM103** (Wanli)
  - Orbit: 513.3 km x 546.5 km
  - Inclination 97.6°
- **FM115** (JpgSquared)
  - Orbit: 570.5 km x 578.0 km
  - Inclination: 37.0°

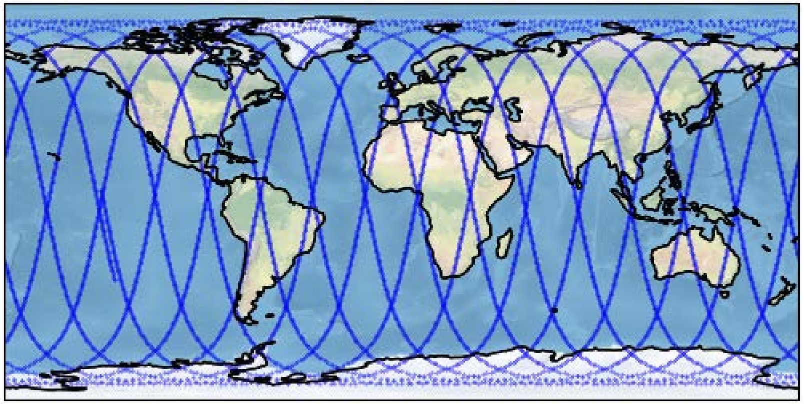
- GPS data from POD antenna: 1 Hz dual-frequency data, 10 s sampling used for the period **May – October, 2020**.
- Ionosphere-free linear combination of code and carrier-phase measurements used for POD, 0° elevation cut-off angle. No ambiguity fixing yet.
- Attitude quaternions used for attitude modelling.
- Fixed final GPS orbits and high-rate clock corrections from CODE.

Ground Tracks of Spire Satellites

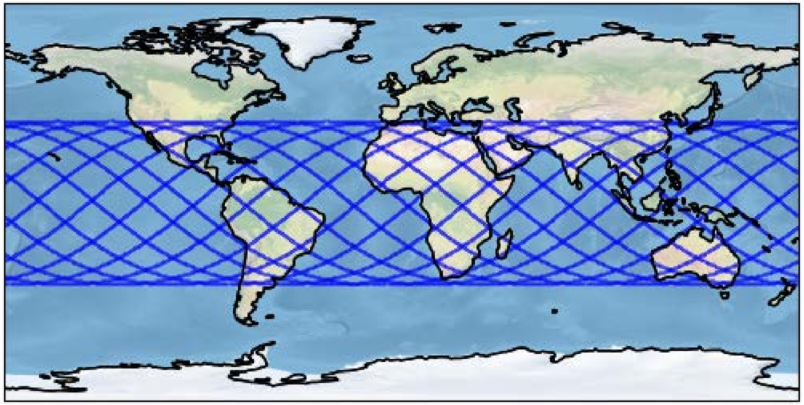
Ground track of FM099 for 12 May 2020



Ground track of FM103 for 12 May 2020



Ground track of FM115 for 12 May 2020



- **FM099** (JohanLoran)
  - Orbit: 484.8 km x 501.6 km
  - LTAN: 21.6 h
- **FM103** (Wanli)
  - Orbit: 513.3 km x 546.5 km
  - LTAN: 15.0 h
- **FM115** (JpgSquared)
  - Orbit: 570.5 km x 578.0 km

GPS Data Processing

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

Reduced-dynamic orbits:
"AIUB solution"

NAPEOS – POD settings

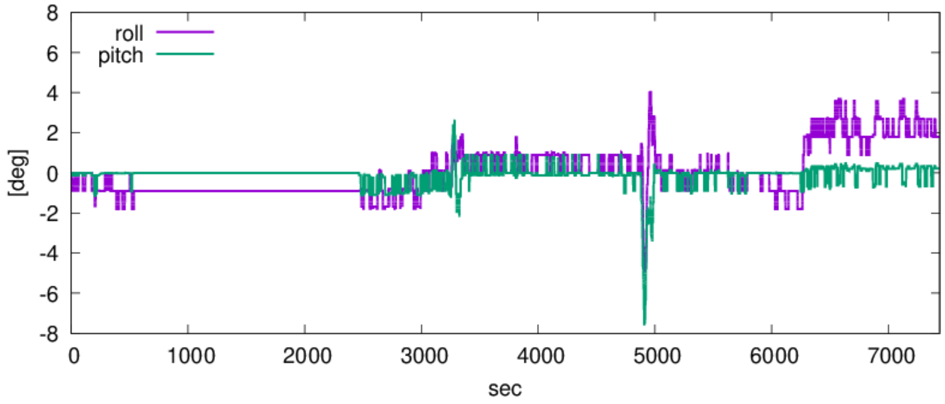
Force modelling of reduced-dynamic orbits:

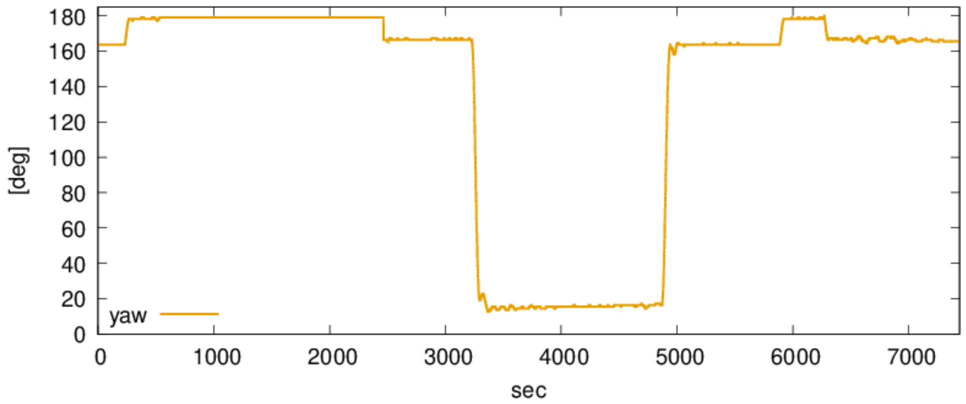
- Radiation pressure and atmospheric drag modelling with constant area of 0.12 m^2, scale factors fixed to 1.0
- 2 h constant, sine and cosine acceleration parameters in along-track and cross-track directions

More dynamic orbits:
"PosiTim solution"

The **two software packages allow for inter-comparisons**, a role model that is e.g. inherited from the work of the POD Quality Working Group of the Copernicus POD Service. It enables an independent quality and integrity assessment of the Spire inputs and products.

Attitude of Spire Satellites

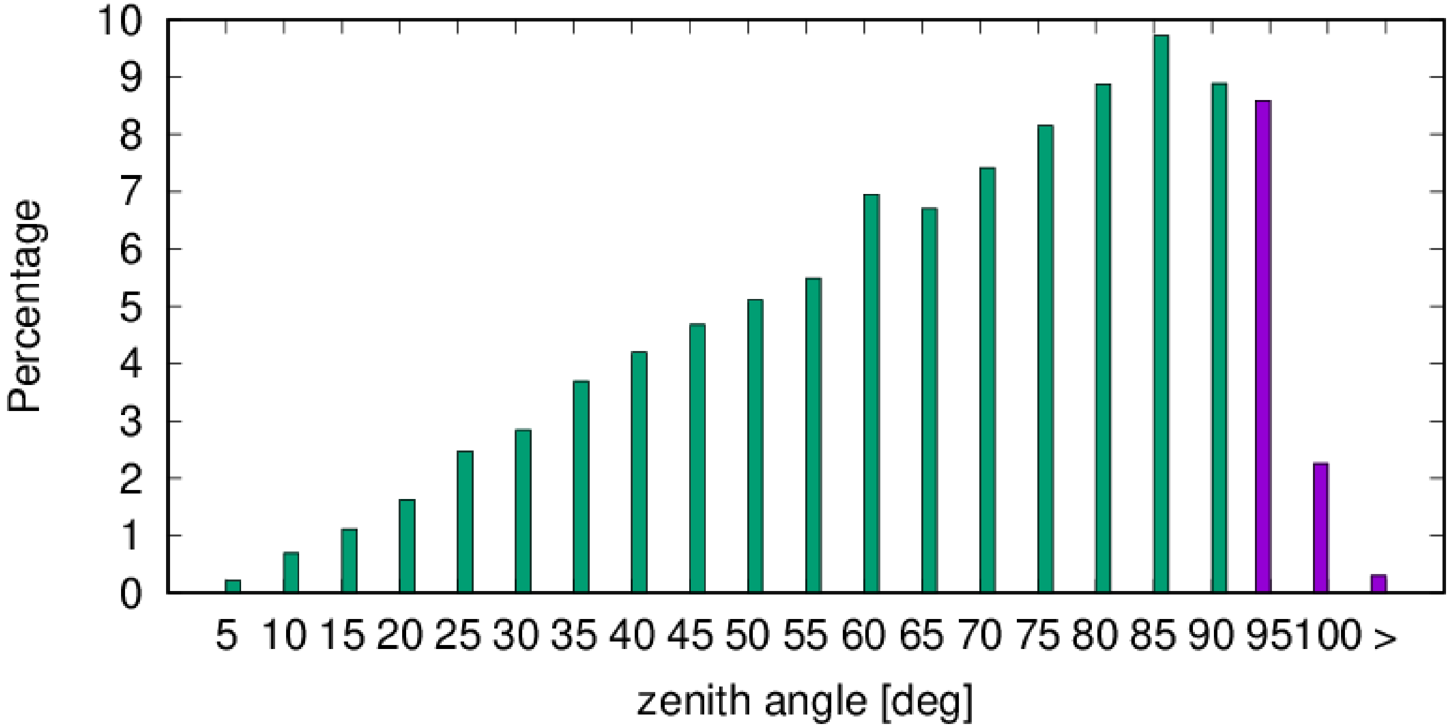




Example for attitude behavior of the Spire satellites (roll, pitch, yaw angle).

Several yaw flips per day are performed. Attitude quaternions provide the rotation of the **satellite reference frame** to **the local orbital frame**, which is not common practice and needs to be implemented accordingly.

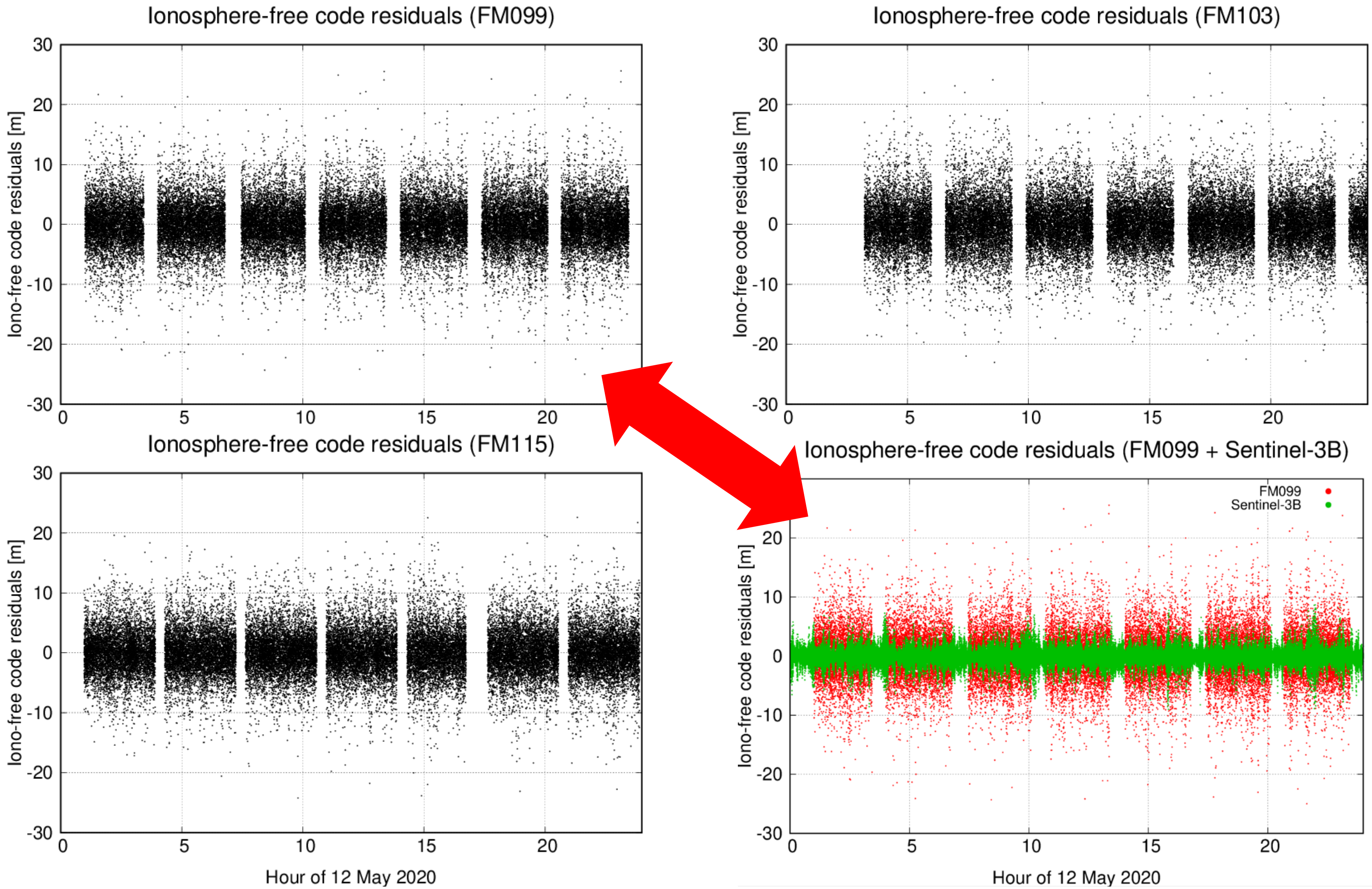
GPS Satellite Tracking



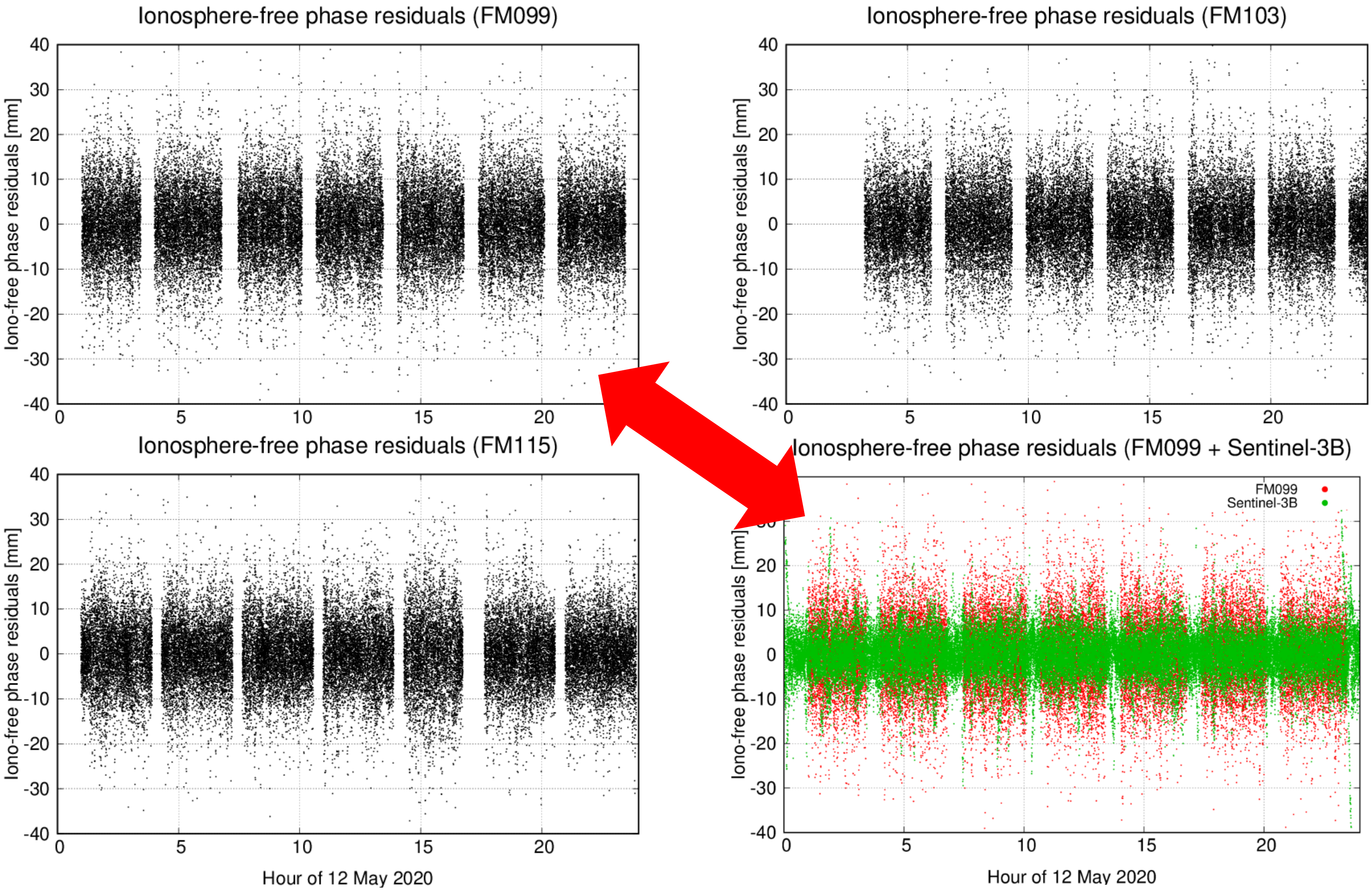
The number of tracked GPS satellites per epoch is very good with most epochs having between 6 and 11 observed satellites (example of FM099).

The histogram of the observation distribution in 5-deg bins shows that more than **10% of the observations** are collected **below the local horizon** of the antenna. Currently these observations are discarded from the POD processing.

Code Residuals



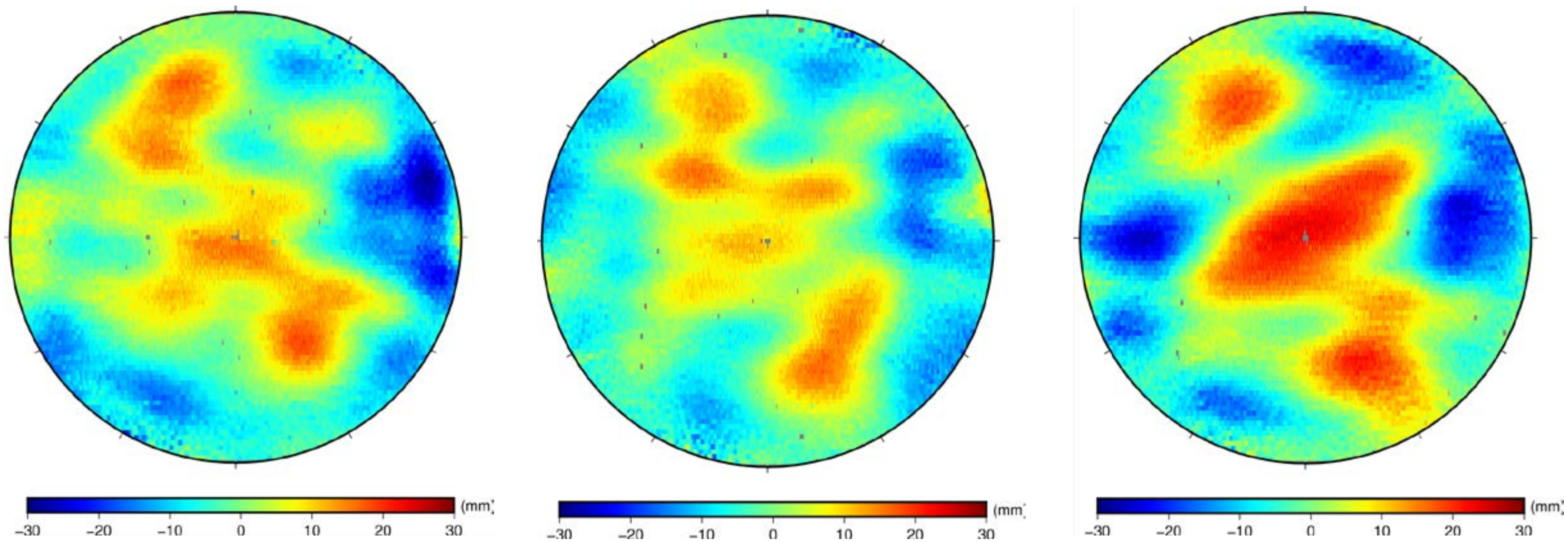
Carrier Phase Residuals



Estimated PCV Maps

FM 099 | FM 103 | FM 115

NAPEOS



Flight Direction

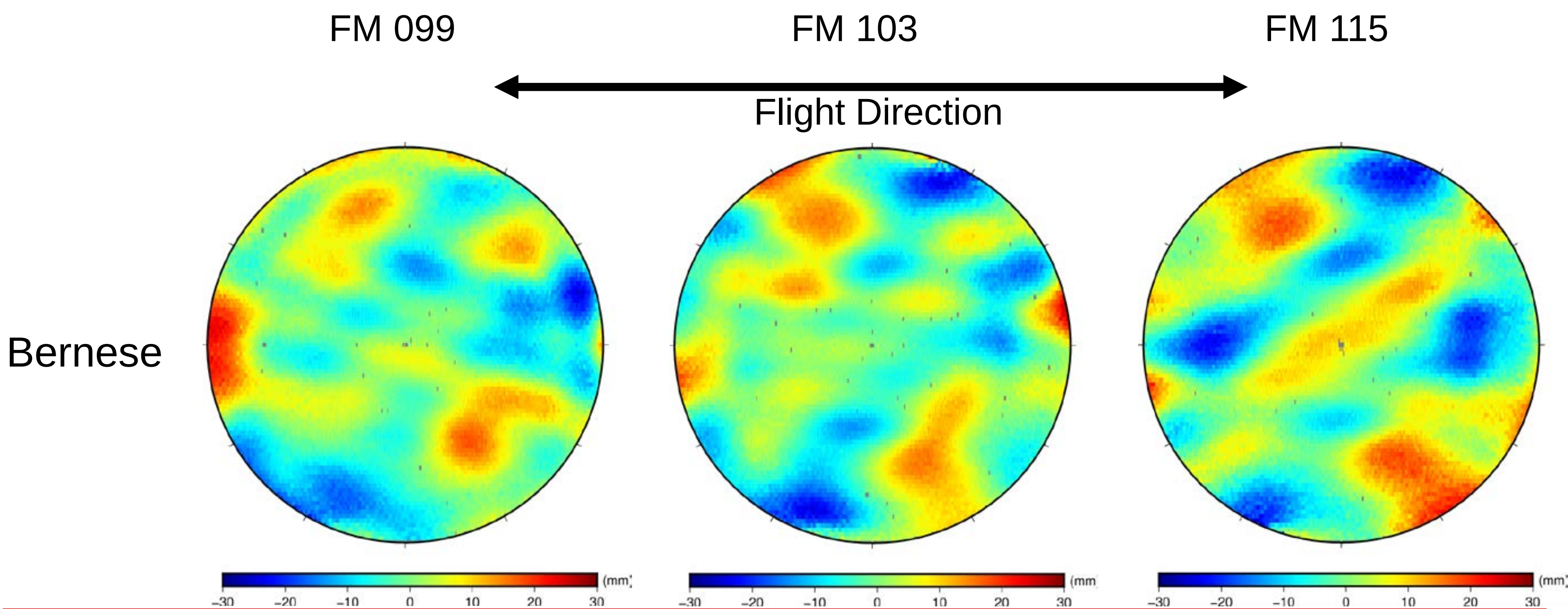
PCV maps are derived using the residual stacking approach (Jäggi et al., 2009).

PCV maps show similarities, but also **pronounced differences**. Especially the PCV map of FM 115, i.e., the satellite in the inclined orbit, is notably different.

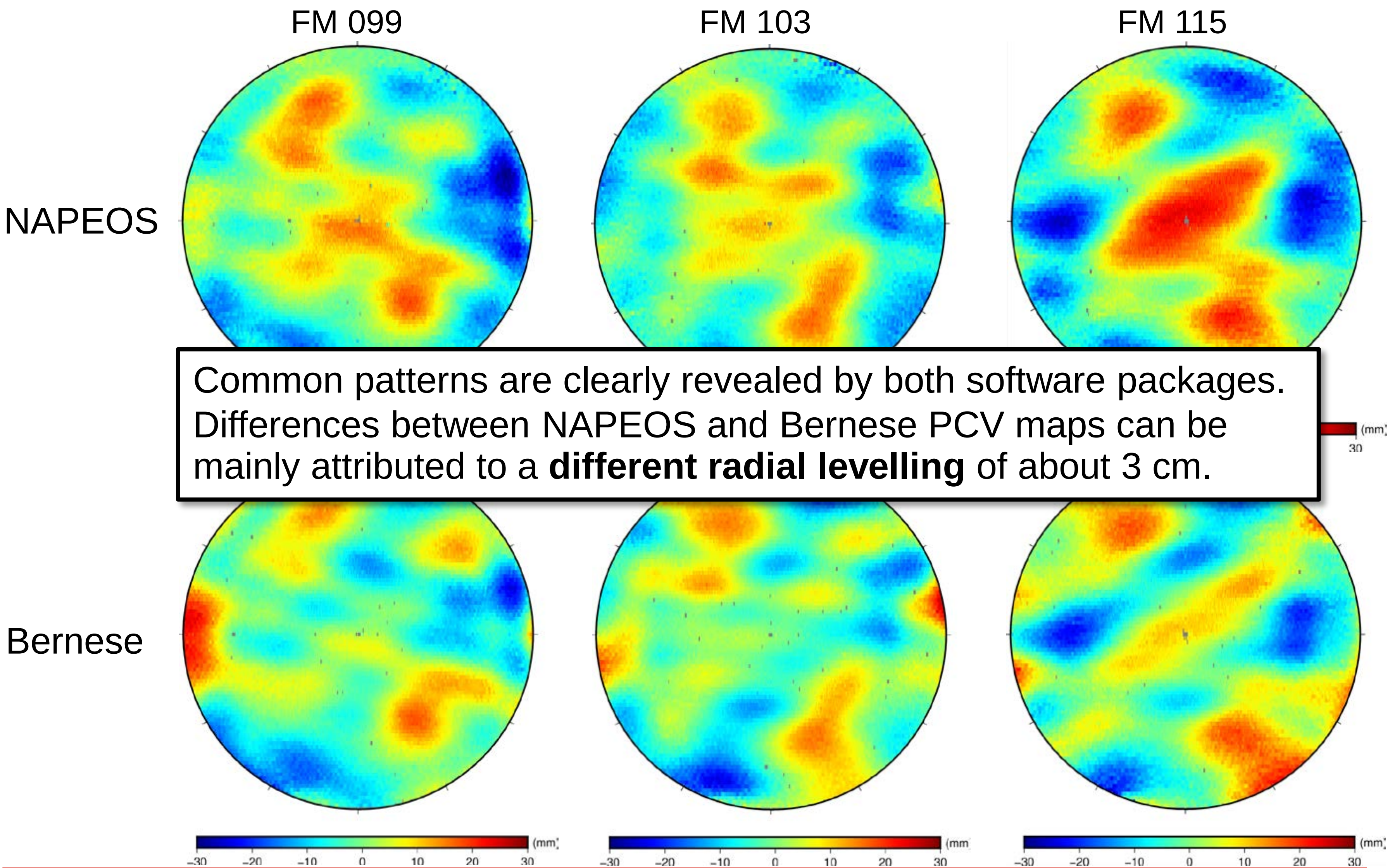
The scale is quite large with variations of **± 3 cm**. An elevation cut-off of 0° is used.

Estimated PCV Maps

PCV maps derived by Bernese tend to be “flatter” due to the reduced-dynamic approach. Similar to Napeos, the PCV maps show similarities between different satellites, but also pronounced differences. Again, the PCV map of FM 115 shows the largest differences.

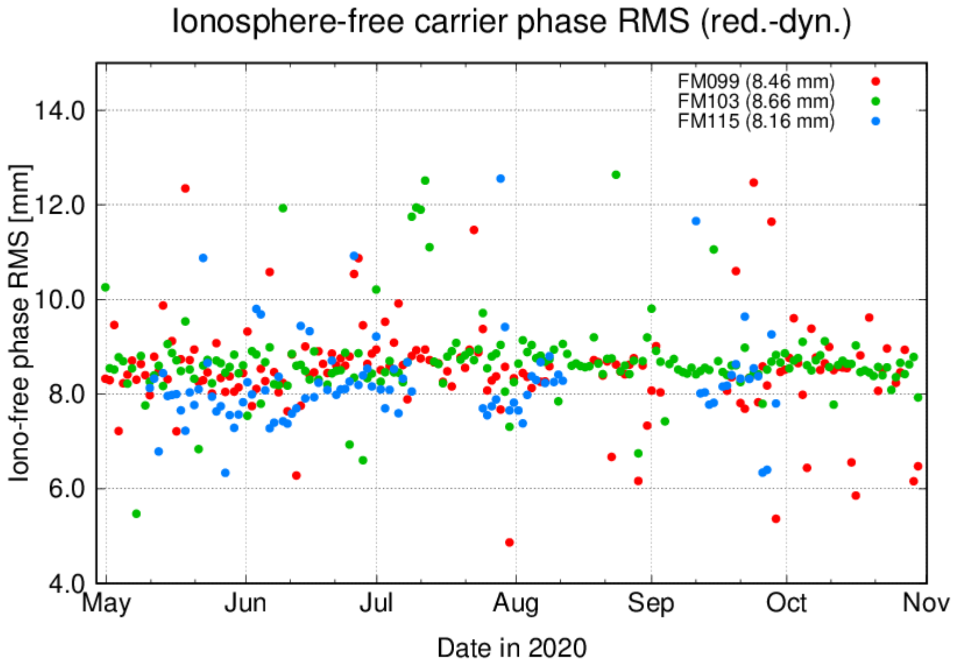


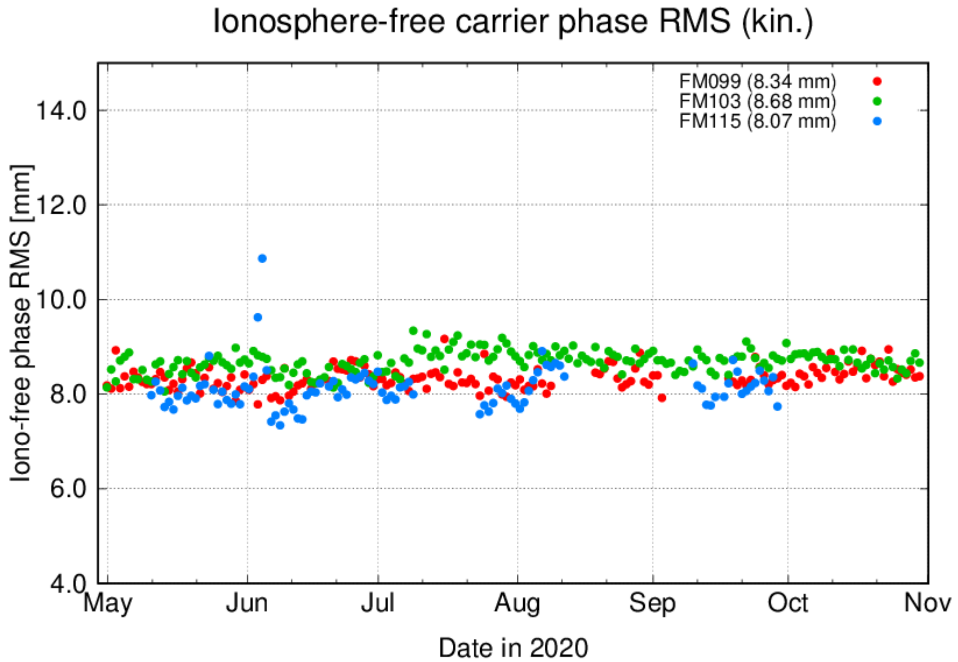
Estimated PCV Maps



Common patterns are clearly revealed by both software packages. Differences between NAPEOS and Bernese PCV maps can be mainly attributed to a **different radial levelling** of about 3 cm.

Ionosphere-Free Carrier Phase RMS

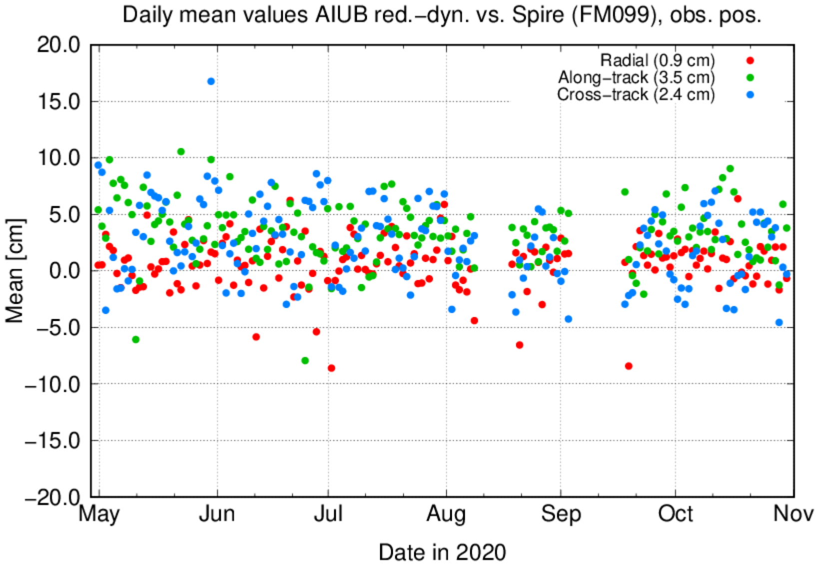




Ionosphere-free carrier phase RMS values are in **the range of 8 – 9 mm** for the AIUB solution This is of course notably increased compared to scientific LEO missions, but still very good considering the simple design of CubeSat missions.

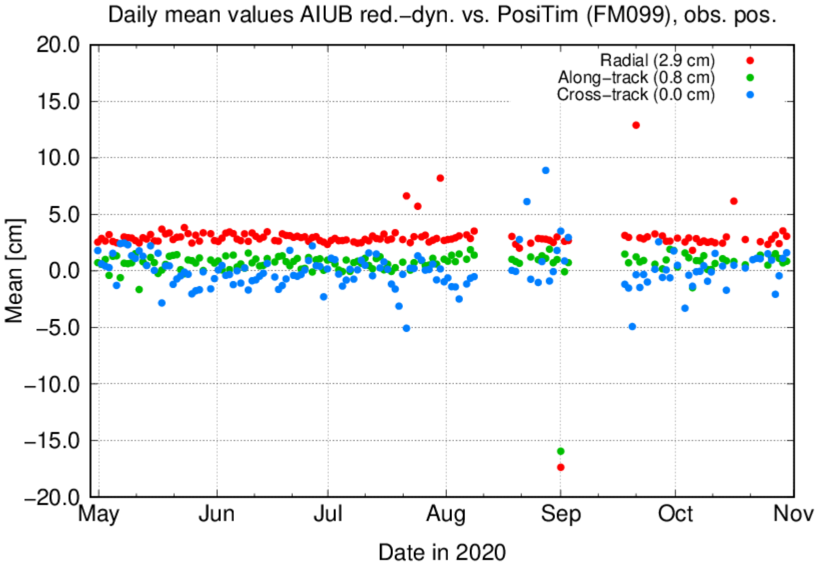
Mean of Orbit Comparisons (FM099)

AIUB – Spire



Median rad. offset: 0.9 cm

AIUB – PosiTim



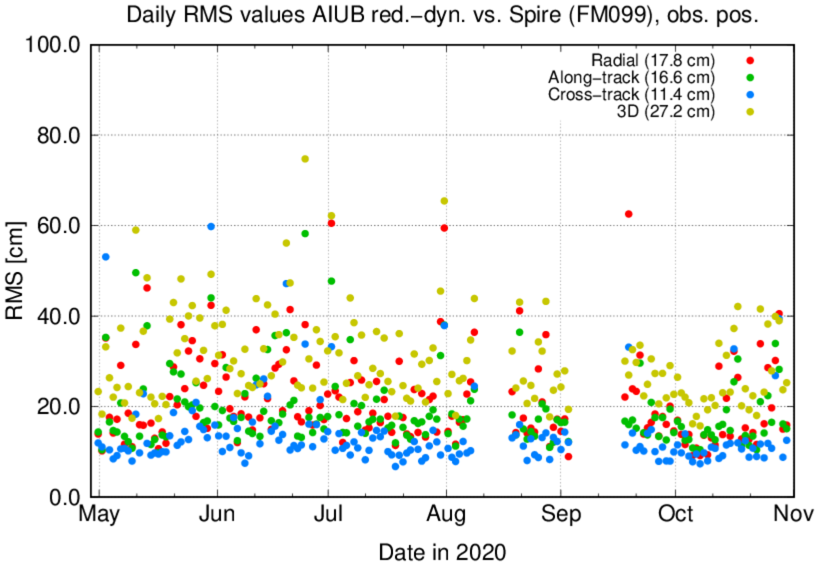
Median rad. offset: 2.9 cm

The orbit differences AIUB – PosiTim reveal a radial offset of several centimeters due to the comparison of **reduced-dynamic vs. dynamic** orbit modeling strategy.

Note that all daily mean values are computed based on epochs only where also Spire orbit data are available.

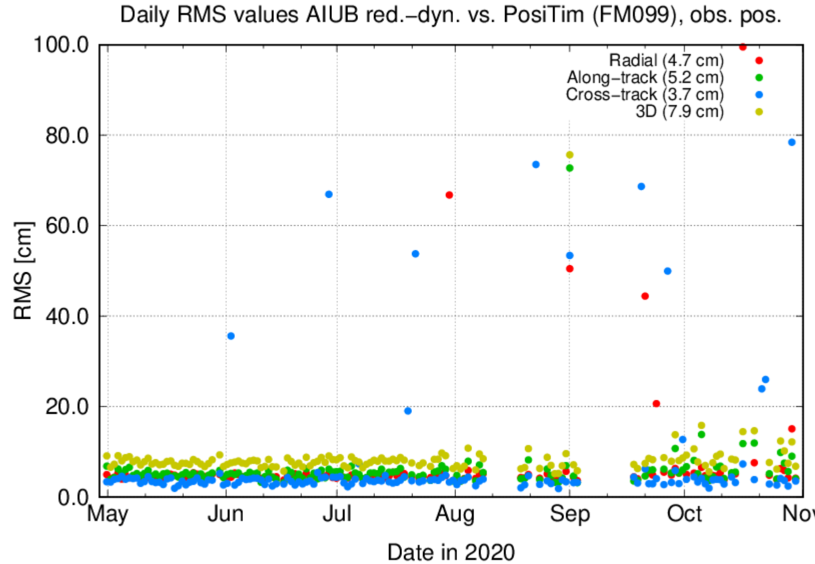
RMS of Orbit Comparisons (FM099)

AIUB – Spire



Median 3D RMS: 27.2 cm

AIUB – PosiTim



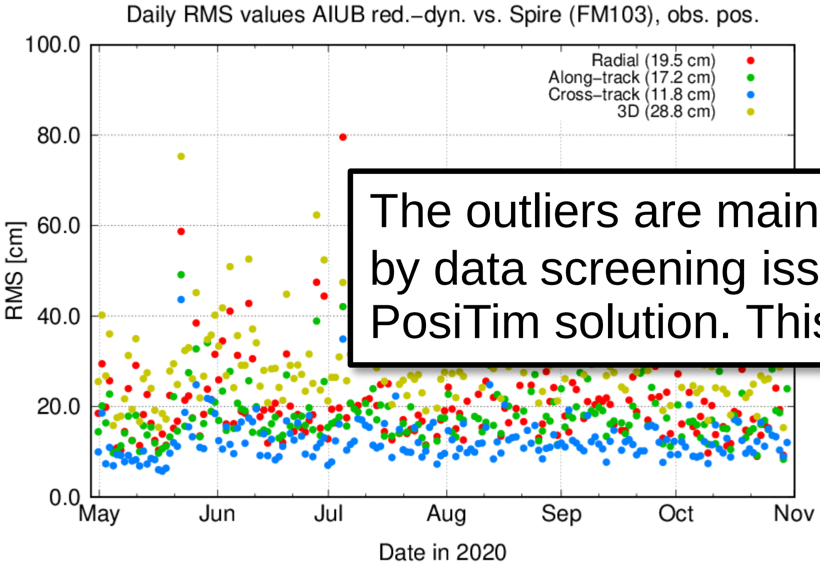
Median 3D RMS: 7.9 cm

The orbit differences AIUB – PosiTim are significantly smaller than the orbit differences AIUB – Spire, which are on a similar level as for PosiTim – Spire.

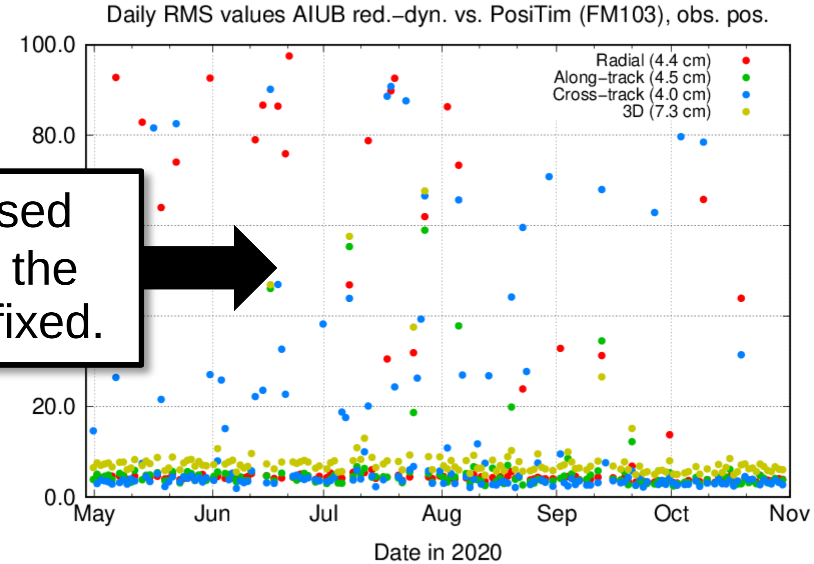
Note that all daily RMS values are computed based only on epochs where also Spire orbit data are available.

RMS of Orbit Comparisons (FM103)

AIUB – Spire



AIUB – PosiTim



The outliers are mainly caused by data screening issues in the PosiTim solution. This can fixed.

Median 3D RMS: 28.8 cm

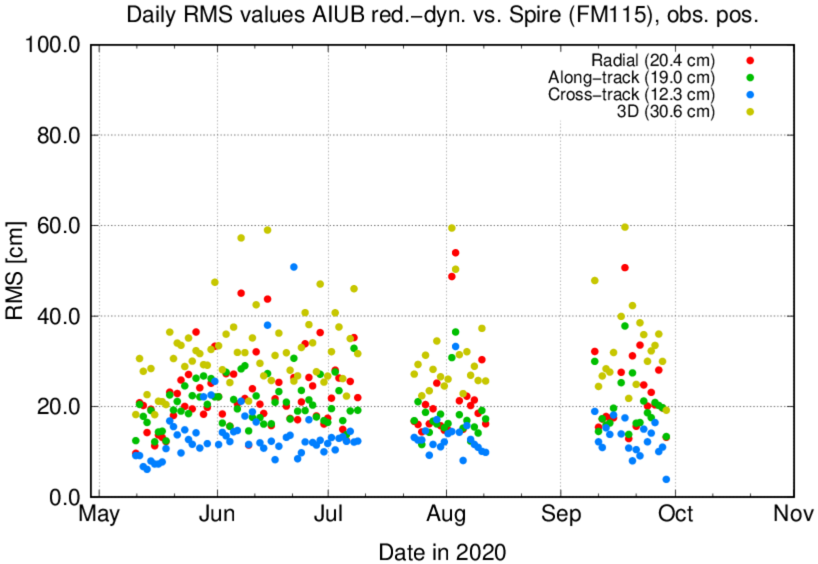
Median 3D RMS: 7.3 cm

The orbit differences AIUB – PosiTim are significantly smaller than the orbit differences AIUB – Spire, which are on a similar level as for PosiTim – Spire.

The slightly better agreement AIUB – PosiTim compared to FM099 might be related to the slightly higher orbital altitude.

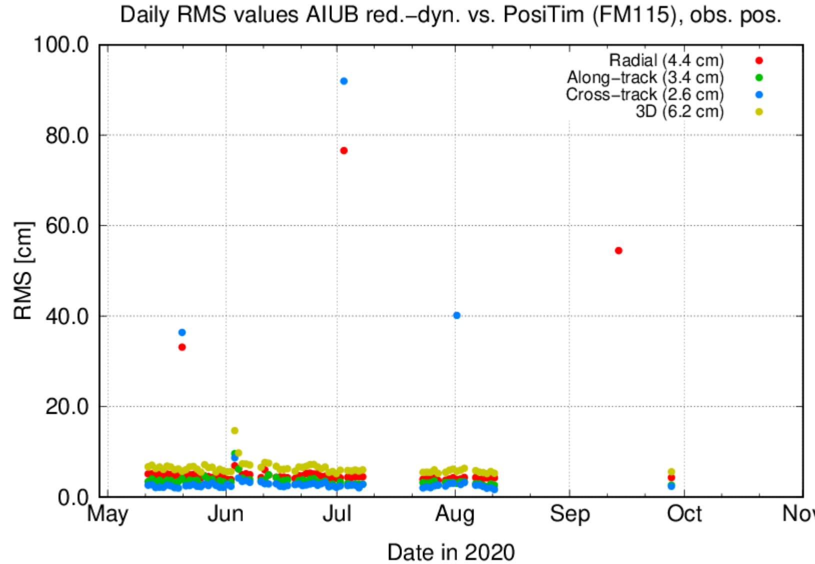
RMS of Orbit Comparisons (FM 115)

AIUB – Spire



Median 3D RMS: 30.6 cm

AIUB – PosiTim

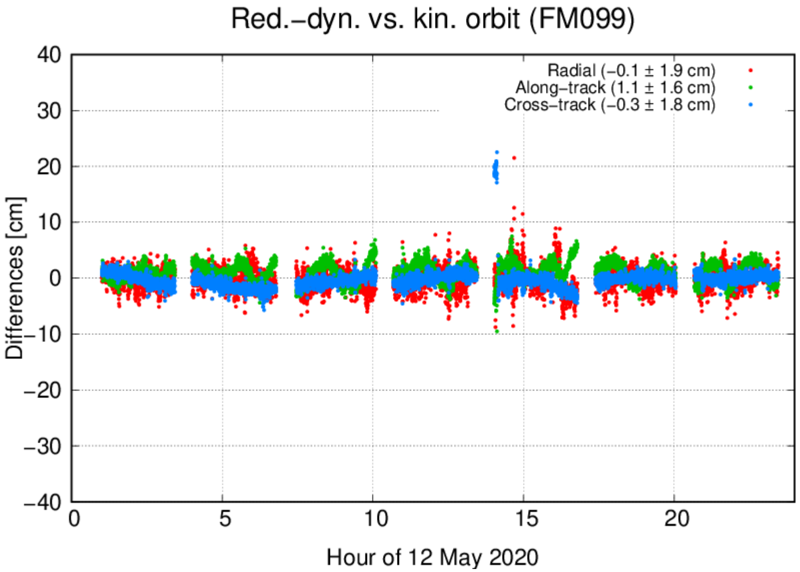


Median 3D RMS: 6.2 cm

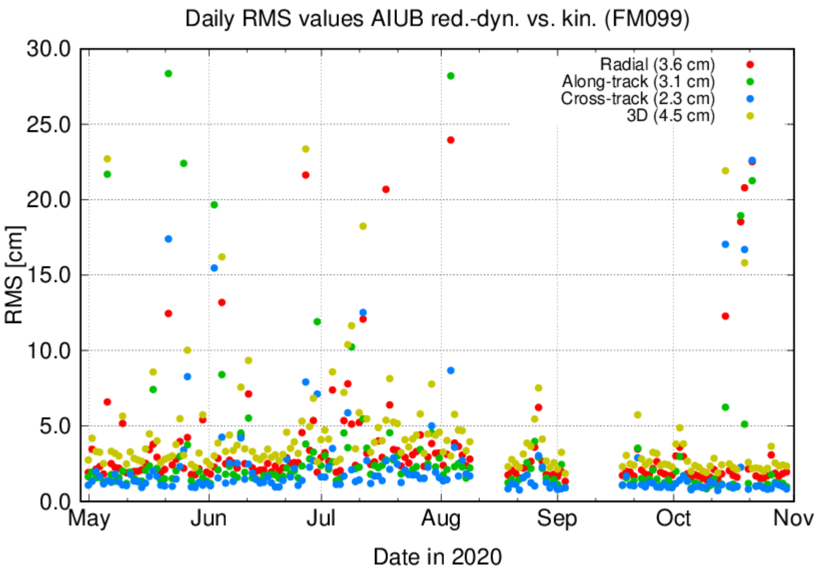
The orbit differences AIUB – PosiTim are significantly smaller than the orbit differences AIUB – Spire, which are on a similar level as for PosiTim – Spire.

The slightly better agreement AIUB – PosiTim compared to FM099 and FM103 is probably again related to the higher orbital altitude.

Comparisons to Kinematic Orbits (FM099)



Difference for one day

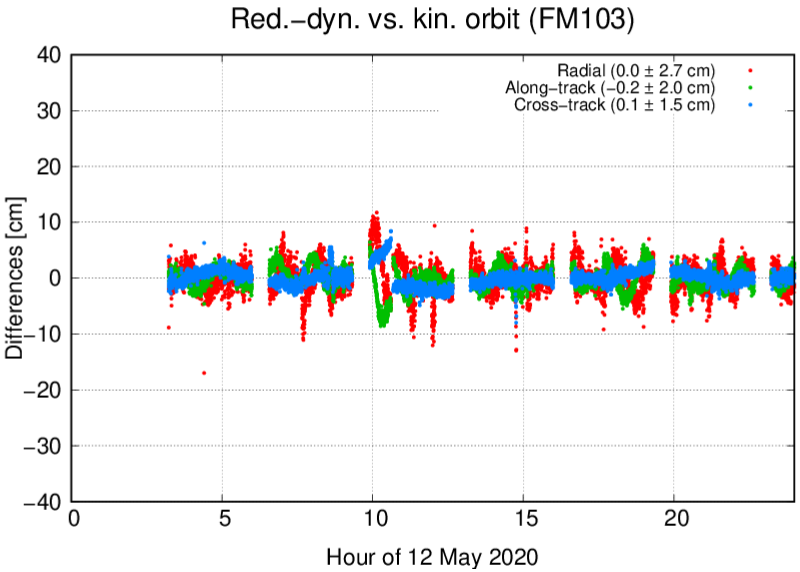


Median 3D RMS: 4.5 cm

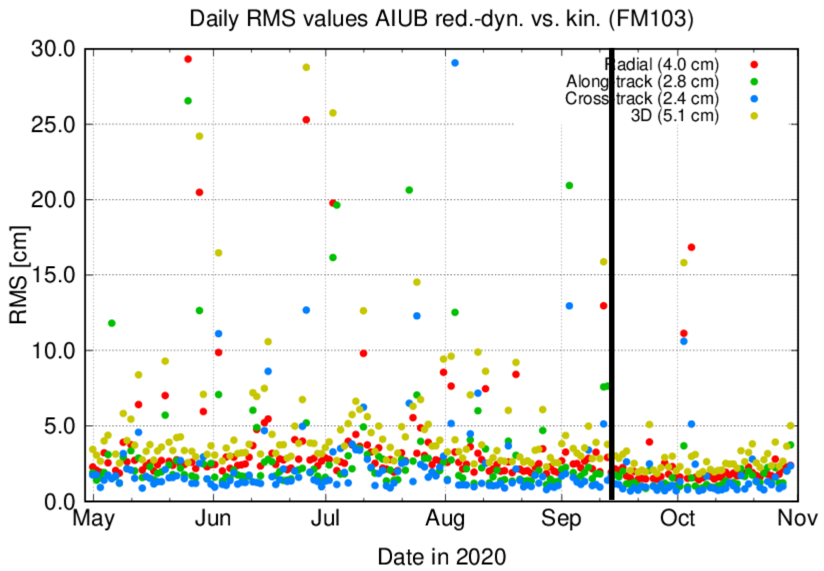
Kinematic positions are fully independent of force models used for dynamic or reduced-dynamic Spire orbit determination.

The differences between kinematic and reduced-dynamic orbits are a measure of the **consistency** between the two orbit-types.

Comparisons to Kinematic Orbits (FM103)



Difference for one day

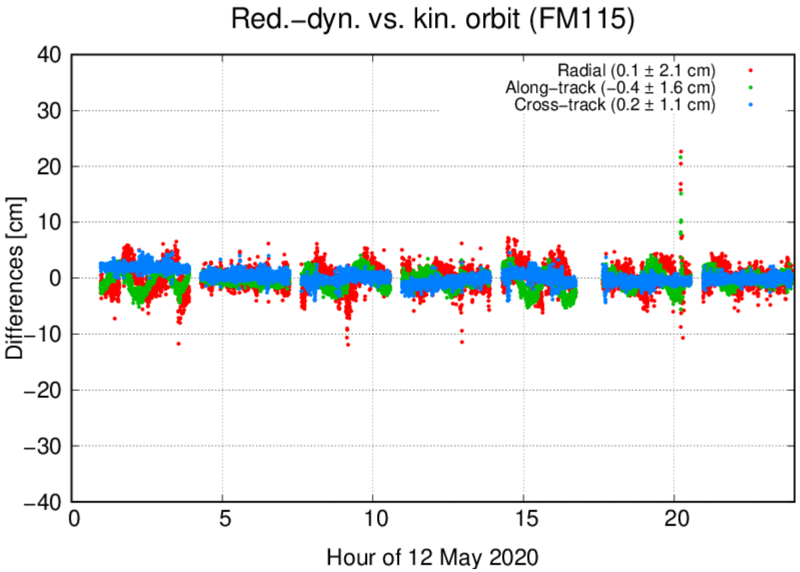


Median 3D RMS: 5.1 cm

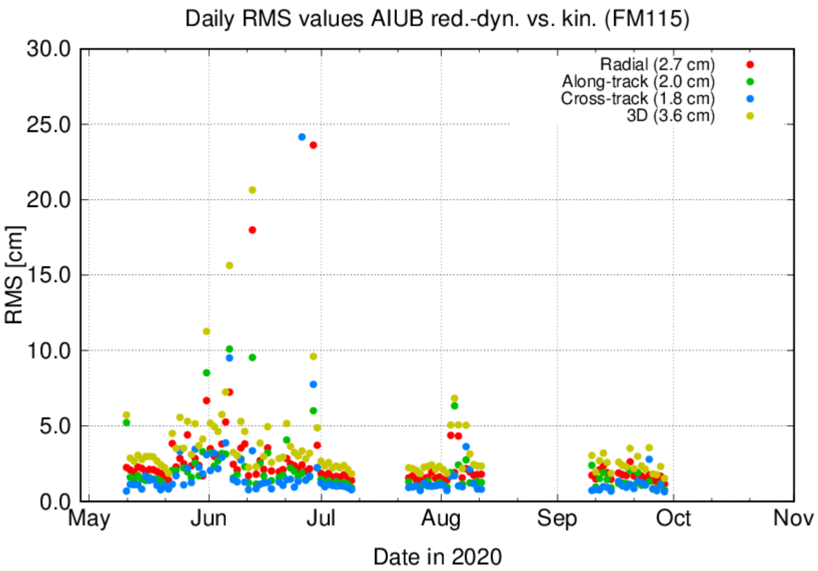
A similar, slightly worse agreement than for FM099 is obtained for FM103.

The improved tracking leads to a slightly better performance of the kinematic orbits from **mid September onwards**.

Comparisons to Kinematic Orbits (FM115)



Difference for one day



Median 3D RMS: 3.6 cm

A slightly better agreement than for FM099 is obtained for FM115.

This is probably related to the higher orbital altitude, leading to less disturbances of the GPS data, e.g., due to the ionosphere.

Summary

- Reduced-dynamic, more dynamic, and kinematic orbits have been computed for three different Spire satellites for a period of six months by using two independent, state-of-the-art software packages.
- An agreement of about **6 - 8 cm** in the sense of a median 3D RMS between AIUB – PosiTim could be demonstrated. Occasional outliers could be attributed to data screening issues in the PosiTim solution. This can be improved.
- The demonstrated agreement is better than the agreement of about **27 - 30 cm** obtained between AIUB – Spire and PosiTim – Spire.
- A systematic radial difference of about **3 cm** has been found between the orbits from AIUB and PosiTim.
- PCV maps of different Spire satellites show notable differences.
- PCV maps from AIUB and PosiTim agree well. Differences between the maps mainly reflect the different radial levelling.

Outlook

- Tuning of the POD process, e.g., introduce satellite macro model for non-gravitational force modelling.
- Investigate possibilities to fix carrier phase ambiguities.
- Improve handling of problematic days, e.g., days with very few data and large data gaps.
- Process Spire data of further satellites.
- Start using Spire data for scientific applications.

We acknowledge the support from Spire Global and the provision of Spire data by ESA.