Impact of incorporating SPIRE CubeSat GPS observations in a global GPS network solution

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Introduction

Typically, precise orbit determination (POD) of low earth orbiters (LEOs) and computation of network solutions for the Global Positioning System (GPS) are separate processes. The orbits and clocks of GPS satellites, which were previously determined as part of a network solution, are usually fixed in a LEO POD. Various studies have shown that GPS observations of LEOs can contribute to a global solution, particularly in terms of determining geodetic parameters, such as the Earth's center-of-mass coordinates (Haines et al. 2015, Männel and Rothacher 2017). Since recently, scientifically designed experiments can be carried out using GPS data that was collected by cubesats operated by Spire Global, which are equipped with dual-frequency GPS receivers. The aim of the present study is to determine how incorporating GPS observation data from specific SPIRE satellites affects the computation of a global network solution. A combined GPS-LEO solution is obtained by processing the code and phase observations received by GPS receivers aboard selected SPIRE cubeSats with those from IGS ground stations together. Using this approach, SPIRE satellite orbits are determined jointly with GPS orbit parameters and geodetic parameters, such as station coordinates, Earth rotation parameters, and the Earth's center-of-mass. The procedure is carried out exemplary for the time period 1st May 2020 - 13th July 2020.

Ground station selection

Today, the IGS network consists of more than 500 stations. Due to geographical conditions, however, there are regions that are poorly covered, e.g., over the oceans. In this study, a subset from all available ground stations is selected. Only GPS observations from stations that contributed to the CODE (Center for Orbit Determination in Europe) repro3 product series (Selmke et al. 2020) are made use of. A reduced ground station network drastically reduces the computation time and in turn, also increases the effect of including LEO data in the processing. In the present study, a subset with 240 ground stations is used, as indicated in Fig. 1. In the analyzed time span, on average 231 stations provided data to a one day (24h) solution.

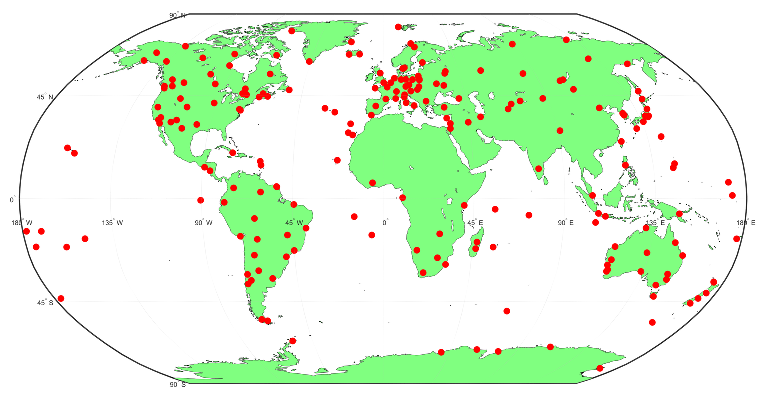

Figure 1: Selected ground stations

Low Earth Orbiters

Apart from the GPS data received aboard specific SPIRE satellites (FM) also GPS observations from scientific LEO missions are included. Orbit characteristics of these satellites are provided in Table 1.

Name	Launch	Altitude	Inclination
FM 099 JohanLoran	01/04/2019	505 km	97.36°
FM 101 Elham	01/04/2019	505 km	97.36°
FM 102 Victor-Andrew	01/04/2019	505 km	97.35°
FM 103 Wanli	05/07/2019	530 km	97.64°
FM 104 LillyJo	05/07/2019	530 km	97.64°
FM 106 Ejatta	05/07/2019	530 km	97.63°
FM 107 Morag	05/07/2019	530 km	97.64°
FM 108 GregRobinson	05/07/2019	530 km	97.63°
FM 115 JpgSquared	11/12/2019	550 km	36.92°
Sentinel-3A	16/02/2016	800 km	98.60°
Sentinel-3B	25/04/2018	800 km	98.60°
Grace Follow-On 1	22/05/2018	500 km	89.00°
Grace Follow-On 2	22/05/2018	500 km	89.00°
SWARM-A	22/11/2013	446 km	87.30°
SWARM-B	22/11/2013	511 km	87.80°
SWARM-C	22/11/2013	446 km	87.30°
Jason-3	17/01/2016	1343 km	66.04°

Table 1: Processed Low Earth Orbiters

Integrated processing parametrization

The integrated processing method utilized in this study necessitates the estimation of a large number of parameters, including geodetic and orbit parameters for both GPS and LEO satellites, as well as necessary clock corrections and ground station coordinates. Table 2 provides comprehensive details on the parametrization of the determined solutions in terms of the total number of parameters and corresponding constraints.

Parameter	Number	Constraint
Station coordinates	3/station (X/Y/Z)	No-Net-Translation
(Datum definition)		No-Net-Rotation
Station clocks	288/station	zero-mean
Zenith path delay	12/station	relative: 1m
Horizontal gradient	1 set (N/E)/station	-
Earth rotation	2 sets/day (X&Y-pole,dT)	dT1:10^{-4}ms
Earth's center-of-mass	3	-
GPS orbital elements	13/satellite	-
GPS stoch.param.(Pulses)	3/satellite	R:10^{-6},A:10^{-5},C:10^{-8}m/s
GPS satellite clocks	288/satellite	-
LEO orbital elements	9/satellite	-
LEO stoch. param. (PCA)	3·240/satellite	(R/A/C):$5 \cdot 10^{-9}$m/s
LEO satellite clocks	288/satellite	-
Ambiguities	~9000	-

Table 2: Parametrization of computed solutions of a one day (24h) arc

It is evident in Table 2 that for many of the estimated parameters no constraints are applied. For each GPS satellite a set of velocity pulses (in Radial/Along-track/Cross-track) is set up at orbit midnight. For details about the parametrization for the GPS orbit solutions see Selmke et al. 2020. To compensate for modelling errors in the LEO POD, in particular neglecting non-gravitational force modelling like solar radiation pressure and air drag, piece-wise constant accelerations (PCA) are estimated together with six Keplerian elements plus constant accelerations over one arc in radial (R), along-track (A) and cross-track (C) directions. A data sampling of 5 min has been utilized, whereby all observations from stations and LEOs have equal weights.

Low Earth Orbiter Precise Orbit Determination

In order to ascertain the potential utility of GPS observations obtained from GPS receivers onboard of LEOs in determining a global GPS network solution, it is first necessary to evaluate the quality the observations. To achieve this, a classical LEO-only POD is conducted and the resulting daily phase RMS is analyzed. The data quality of GPS observations from SPIRE satellites is evaluated by comparing the phase RMS to the results obtained from the POD of scientific LEOs (from Table 1).

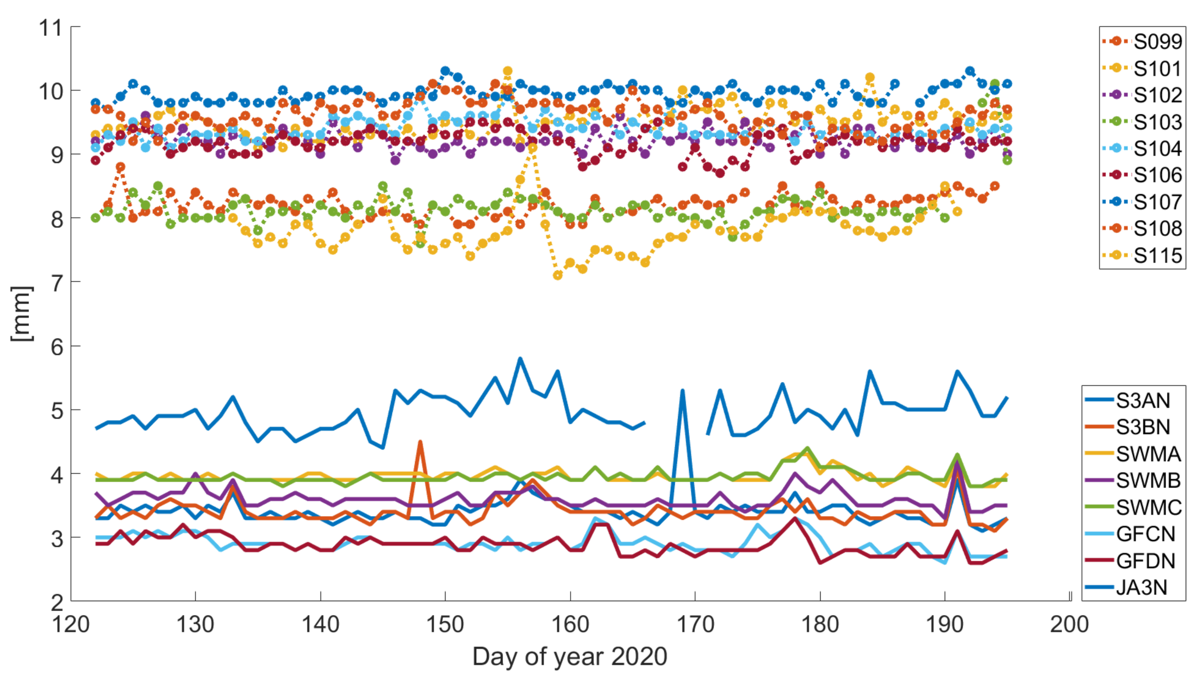

Figure 2: Phase RMS of processed LEOs

As Fig. 2 illustrates, the phase RMS indicate that the POD of LEOs with scientific mission objectives is of superior performance compared to that of the SPIRE satellites. For the SPIRE satellites FM099, FM103 and FM115 a phase center variation map was used in the processing explaining the better performance of the three satellites. Given the varied quality of PODs, it is worth to investigate how different scientific and SPIRE LEOs impact the resulting solution. In all the present plots, the solution including all SPIRE satellites from Table 1 is indicated with "SPIR". "SLEO" describes the solution including all LEOs from Table 1 with scientific mission goals, and "ALEO" includes all LEOs.

Earth's center-of-mass coordinates

The estimated Earth's center-of-mass coordinates are compared to reference values computed by the Jet Propulsion Laboratory JPL (Sun et al. 2016). It is of interest to determine whether the proposed solution via LEO integrated processing allows for an improvement. Based on the mean and standard deviation of the differences shown in Fig. 3, it is apparent that the estimated Z-coordinate of the Earth's center-of-mass coordinates is notably more robust, in terms of standard deviation of differences to the reference solution, when GPS-LEO observations are incorporated.

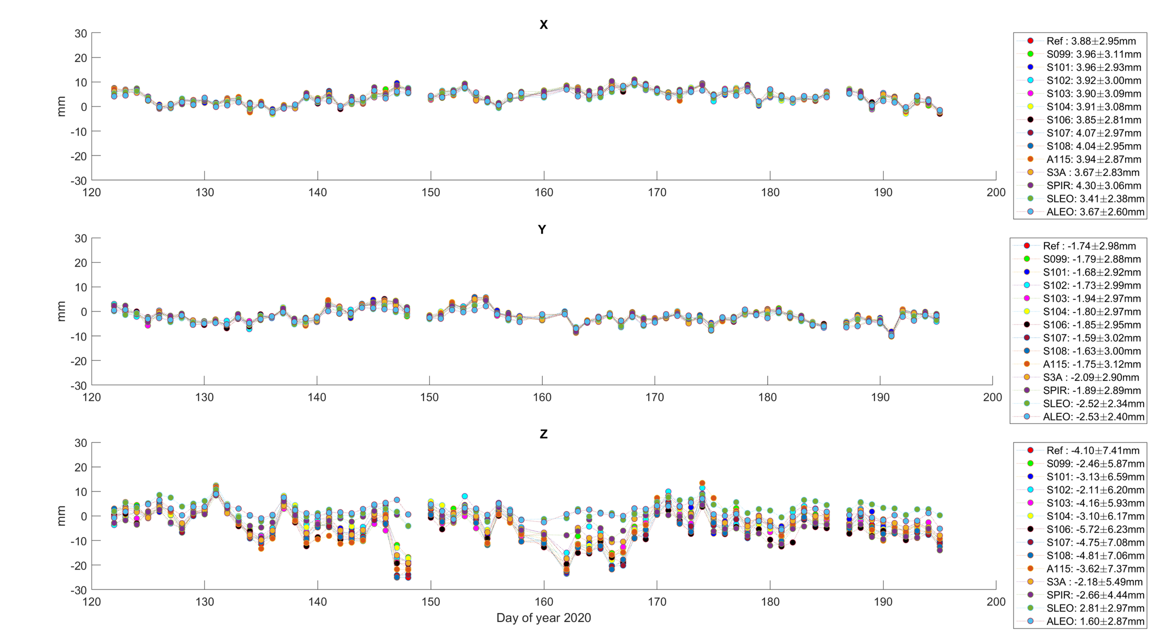

Figure 3: Earth's center-of-mass estimates (differences to JPL solution)

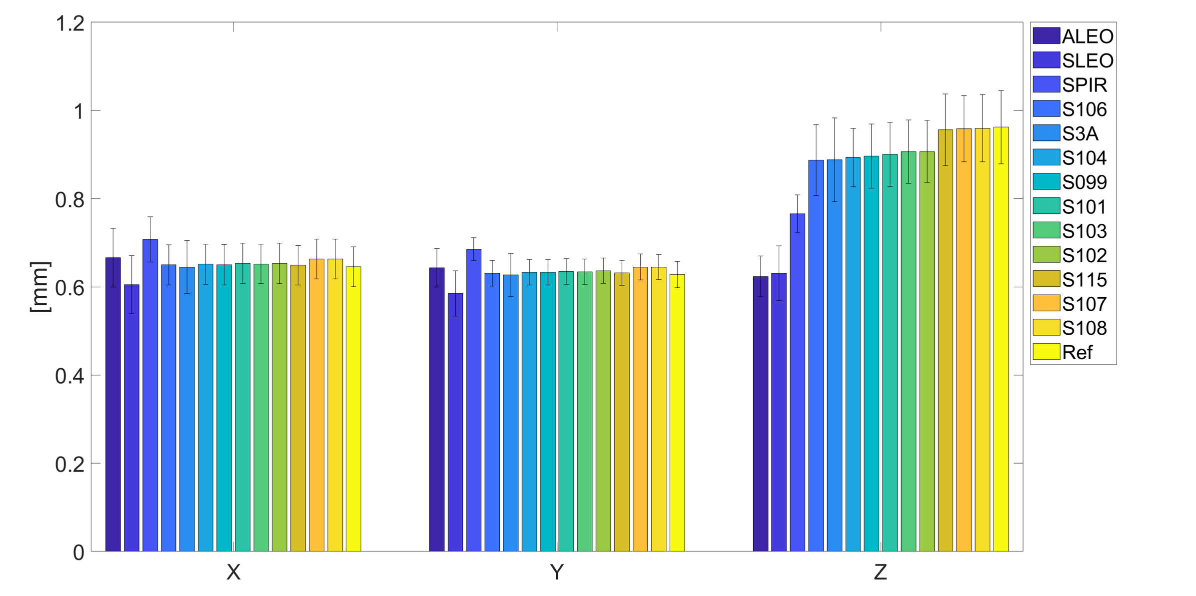

Figure 4: Formal errors Earth's center-of-mass estimates

The "ref" label describes the solution, where no GPS observations from LEOs are integrated. The extent of improvement is dependent on the LEO included, with the influence of GPS observations from scientific LEOs being especially high. The formal errors, shown in Fig. 4, clearly reflect these results. Of particular note is the determination of the Z-coordinate, which exhibits a noticeable improvement. The results do not vary much when exchanging the integrated SPIRE satellite, but show an even better improvement when observations from multiple LEOs are included.

GPS orbit misclosures

In addition to geodetic parameters, it is important to examine the quality of the resulting GPS orbits. For this purpose orbit differences are computed for the overlapping epoch of two consecutive arcs. Figure 5 shows daily mean values over all 32 GPS satellites for radial, along-track and cross-track direction each. The results indicate that incorporating GPS observations from multiple LEOs is advantageous. For the solutions where all SPIRE satellites are included, the mean values for the radial and along-track direction get smaller compared to the reference solution. The results for the cross-track direction show a significantly smaller standard deviation of daily means than the reference solution, whereby the improvement is about 20%.

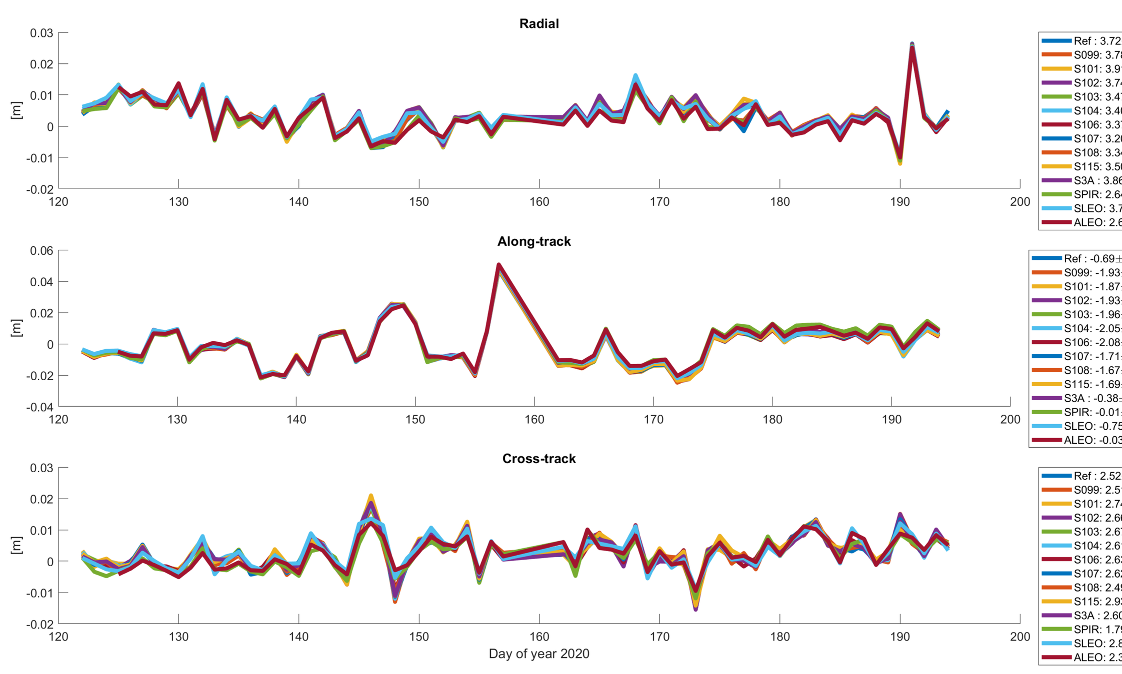

Figure 5: GNSS orbit misclosures

Earth orientation parameters

The resulting Earth rotation parameters (ERPs) were compared to the combined reference solution C04, which is consistent with the International Terrestrial Reference Frame 2014 (ITRF14). The differences between the various solutions are not significant, e.g. for the X-pole estimate an overall maximum difference of 2% in terms of standard deviation results. It appears that including GPS observations from LEOs does not provide any advantage. The formal errors indicate that integrating additional GPS-LEO observations does not improve the determination of Earth Rotation Parameters (ERPs), whereby no significant difference for the integrated LEOs exist.

Ground stations coordinates

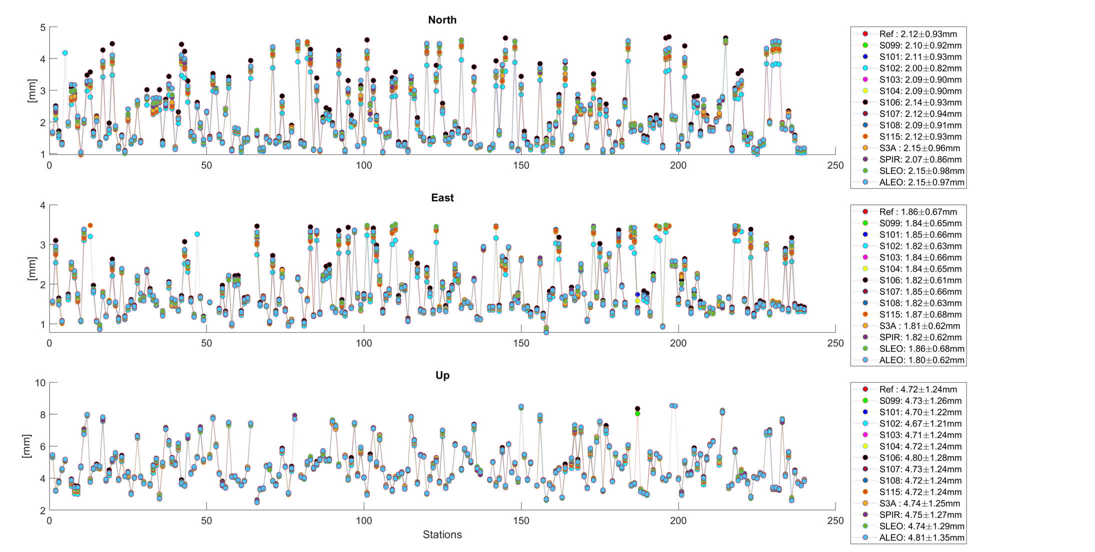

Figure 6: Repeatability of ground station coordinates

The repeatability (given in N/E/U) of the ground stations are shown in Fig. 6. When multiple LEOs are used, it is evident that integrating GPS-LEO observations in a global GPS network solution can be disadvantageous with respect to the repeatability of the station coordinates, which demands for further investigations.

Conclusions

The results of the estimation of Earth's center-of-mass coordinates, as well as their formal errors and the orbit misclosures of the derived GPS orbit trajectories, confirm that including GPS-LEO observations is beneficial when determining a global GPS network solution. The repeatability of the station coordinates shows that the procedure has room for improvement. Especially by explicitly modeling non-gravitational forces in the LEO processing, the results may be improved. When different SPIRE LEOs are included, no significant changes in the resulting solution can be observed. Moreover, it is clearly evident that GPS-LEO observations from scientific LEOs have a more advantageous impact on the solution than those from SPIRE-included solutions. It is evident that including multiple LEOs, as opposed to only one, leads to an improvement in all estimated parameters except station coordinates.

References

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