Quantifying the plasmaspheric electron content in Swarm GPS TEC

Introduction

The topside ionosphere, usually defined as the part of the ionospheric F layer which is located above 1000 km, is difficult to monitor using ground-based observations. LEO missions like Swarm, GOCE, GRACE, and the Sentinel give insight into these altitudes. As many LEO missions, they are equipped with dual-frequency GPS receivers, which are used for precise orbit determination (POD), but may also be used for slant TEC computation. In the presented case we will use the Sentinel satellites to estimate the electron content above 1000 km.

We will show how the Swarm GPS receiver is susceptible to strong gradients in electron density, how plasmaspheric plasma density is modeled using the GPS phase observables and how large the electron content of the plasmasphere may become in Swarm Start TEC. Eventually, we will show an example for ionospheric tomography and how the observation specific weights from the tomographic inversion can be used to improve electron density estimates.

Ionosphere in Swarm GPS only gravity fields

In Swarm GPS-only gravity field computation systematic errors have been observed near the geomagnetic equator (Jäggi et al., 2016) (Figure 2). These systematic errors are already visible on orbit level when comparing the Swarm A kinematic orbit to a reduced-dynamic orbit (Figure 1). These errors come from systematic errors in the GPS phase observables. By construction the ionosphere should not be visible in the orbits in this extent, since for POD the ionosphere-free linear combination is used.

To mitigate the impact of these errors, screening and weighting methods have been developed (Schreiter et al., 2019). These methods are based on the geometry-free linear combination, which to first order is proportional to the slant TEC.

\[ L_{\text{sl}} = L_1 - L_2 \]

\[ s\text{TEC} = \frac{1}{40.3} \left( \frac{r_1^2 f_2^2 - f_1^2 r_2^2}{f_1^2 f_2^2} \right) (L_2 - L_1) \]

The most successful approach was a combination of the second time derivative with weighting based on the Rate Of TEC Index (ROTI) using a 31 s window, Figure 3.

\[ \text{ROTI} = \frac{\delta (s\text{TEC})}{\delta t} \]

\[ \sigma_{\text{ROTI}} = \max \left\{ 1, 6 \cdot \text{ROTI} \right\} \]

To simplify the tomographic approach and to reduce the dimension of the grid, we first remove the plasmaspheric electron content (1000 km to 2000 km) from the Swarm sTEC observations. The plasmaspheric electron density is modeled using Sentinel sTEC observations. The model uses the electron density at 1000 km and two scale heights for below 1000, \( H_1 = 1000 \) km, and above 2000 km, \( H_2 > 2000 \) km. The reference electron density is assumed an exponential decay with height. The observed and computed values is shown in Fig. 5 and Fig. 4, a comparison for Sentinel 1A concerning P1-P2 bias is set up for each connected phase arc. To avoid leveling errors propagate into the solution, the P1-P2 bias is set for each connected phase arc. The estimated topside/plasmasphere TEC map is shown in Fig. 4, a comparison for Sentinel 1A concerning observed and computed TEC values is shown in Fig. 5 and the estimated P1-P2 biases are shown in Fig. 6.

Ionospheric Tomography Using Weighting

The ionospheric tomography is performed using a multistep procedure based on approximately 25 minutes of GPS phase data and plasma density measurements. First the area of interest is discretized in altitude (60 steps) and latitude (120 steps (0.5°)). Then the integral equation is approximated by the weighted sum of the pixel density:

\[ s\text{TEC} = \frac{\int_{\text{LEO}} N_{\text{dE}} + C_{\text{ARC}}}{C_{\text{ARC}}} \]

Furthermore, the lower boundary is constrained to the corrected in situ Langmuir probe densities (see Lomidor et al. 2018) and additional constraints are applied, to ensure the smoothness of the reconstruction and to avoid unrealistic values. With the conditions a priori solution is computed in a least squares adjustment with regularization:

\[ P[Ax - y] + \| Bx \| \rightarrow \min \]

Eventually the design matrix and the matrix containing the inner constraints as well as the prior solution is further refined using a modified multiplicative algebraic reconstruction technique (MART) algorithm. The MART algorithm only support positive values of x and positive entries in the matrices. Therefore, the matrix containing the constraints (C-B) needs to be decomposed into a positive (C+) and a negative part (C-).

The results are shown in Figure 8. When applying the MART algorithm more details become visible and the uncalibrated and unrealistic values in higher altitudes become smaller, but also the MART is sensitive to artifacts (mid), which may be seen, when adopting the weight matrix (bottom) and these artifacts virtually disappear.

Conclusions

The Sentinel GPS TEC provides detailed information about the electron content above 1000 km. This information may then be used to simplify tomographic approaches using Swarm GPS TEC. Even if the Swarm POD GPS data has known artifacts tomographic approaches can be applied, when carefully mitigating these artifacts by using weighting matrices.

To improve the plasmaspheric plasma density estimation other Satellites in different local times may be beneficial, like the upcoming COSMIC-2 mission.

References


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