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Quantifying the plasmaspheric electron content in Swarm GPS TEC using Sentinel GPS TEC

Introduction

The topside ionosphere, usually defined as the part of the ionospheric F layer which is located above the peak density, is difficult to monitor using ground-based observations. LEO missions like Swarm, GOCE, GRACE, and the Sentinels 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 ionospheric plasma irregularities may be detected using the GPS phase observables and how large the electron content of the plasmasphere may become in Swarm Slant TEC. Eventually, we will show an example for ionospheric tomography and how the observation specific weights from the orbit determination are used to improve ionospheric tomography

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:

$$L_{gf} = L_1 - L_2$$

$$sTEC \approx \frac{1}{40.3} \cdot \left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \right) (L_2 - L_1)$$

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.

$$ROTI = \sqrt{\frac{\langle \Delta TEC^2 \rangle - \langle \Delta TEC \rangle^2}{\Delta t}}$$

$$\sigma^2_{ROTI} = max(1, 60 \cdot ROTI)$$

$$\sigma^2_{d2} = \begin{cases} 1, & \text{if } d^2/dt^2 L_{gf} < 0.025 cm/s^2 \\ 21, & \text{if } d^2/dt^2 L_{gf} \geq 0.025 cm/s^2 \end{cases}$$

$$\sigma^2 = max(\sigma^2_{ROTI}, \sigma^2_{d2})$$

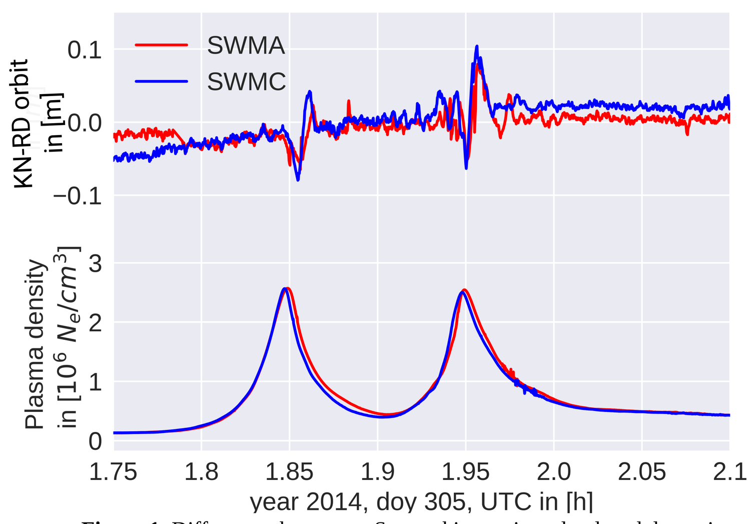

Figure 1: Differences between a Swarm kinematic and reduced dynamic orbit compared to plasma density obtained by Swarm Langmuir probes.

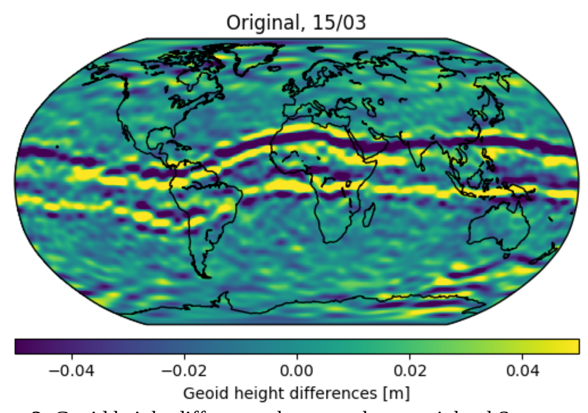

Figure 2: Geoid height differences between the unweighted Swarm GPS only gravity field solution and the JPL GRACE solution

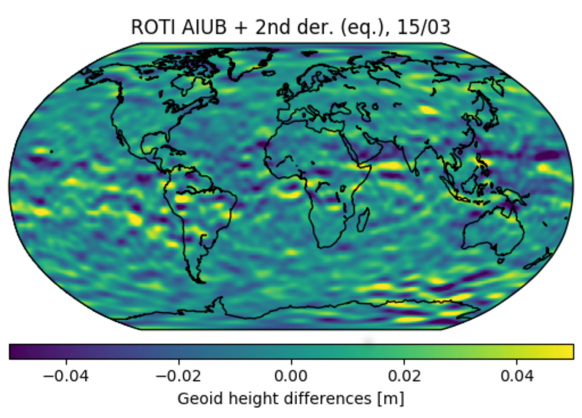

Figure 3: Geoid height differences between the weighted Swarm GPS only gravity field solution and the JPL GRACE solution

Electron density from sTEC

For estimating the electron density from sTEC measurements we assume an exponential decay with two scale-heights, H_1 for lower (h<2000 km) and H_2 for higher altitudes (h>2000 km). The reference electron density N_{1000} is set at 1000 km.

$$\mathrm{N}_e(h, mlat, mLT) = \begin{cases} N_{1000} \cdot e^{\frac{-(h-hm)}{H_1}}), & h < 2000km \\ N_{1000} \cdot e^{\frac{-(2000km-hm)}{H_1} - \frac{(h-2000km)}{H_2}}, & h \geq 2000km \end{cases}$$

The key parameters N_{1000}, H_1, and H_2 are expressed by the exponential of a spherical harmonics expansion using magnetic latitude and local time (LT) as reference. For N_{1000} degree and order 5 is used, for H_1 and H_2 degree and order 4:

$$N_{1000}(mlat, mLT) = \exp\left\{ \sum_{i=0}^{5} \sum_{j=-i}^{i} c_{ij} f_{ij}(mlat, mLT) \right\}$$

$$H_1(mlat, mLT) = \exp\left\{ \sum_{i=0}^{4} \sum_{j=-i}^{i} d_{ij} f_{ij}(mlat, mLT) \right\}$$

$$H_2(mlat, mLT) = \exp\left\{ \sum_{i=0}^{4} \sum_{j=-i}^{i} e_{ij} f_{ij}(mlat, mLT) \right\}$$

where f_{ij} are the spherical harmonic base functions (degree i, order j) and c_{ij}, d_{ij}, e_{ij} are the corresponding coefficients. For deriving sTEC from the model a Gauss-Legendre quadrature is used with the line of sight sampled at each 10 nodes below and above 2000 km. This implies that the integration may be expressed by a linear operator L. Therefore we can use the equation:

$$sTEC = L \cdot D(x) + bias$$

To avoid leveling errors propagate into the solution, the P1-P2 bias is set up 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 values is shown in Fig. 5 and the estimated P1-P2 biases are shown in Fig. 6.

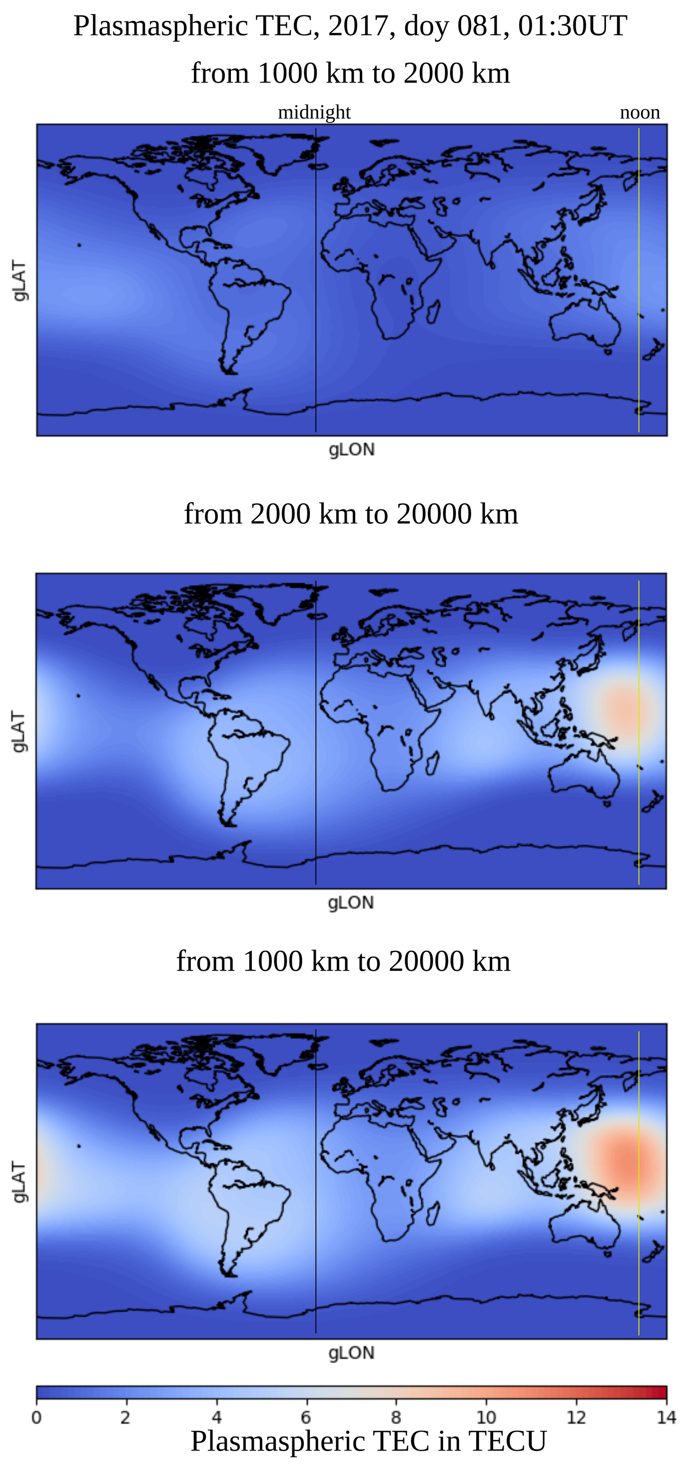

Figure 4: Plasmaspheric TEC, 3/22/2017, 01:30 UT. Parameters estimated based on GPS observations from 00:00 UT to 03:00 UT

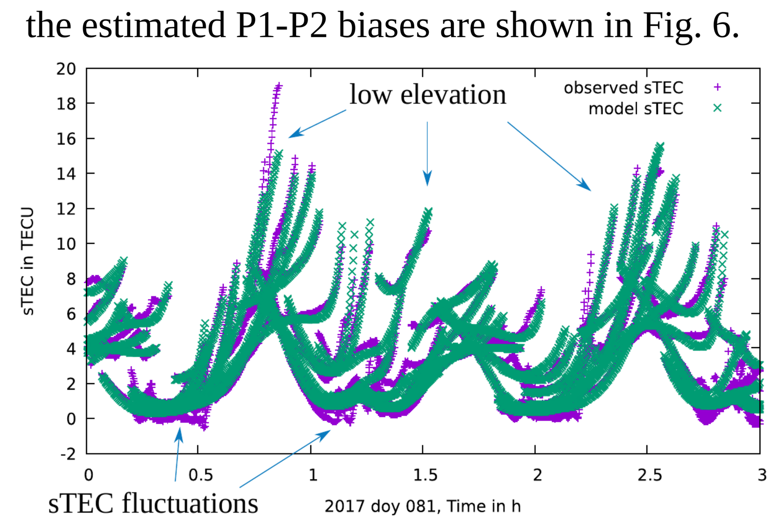

Figure 5: Observed and model slant TEC values for Sentinel 1A. Observed values are shifted by the estimated P1-P2 bias.

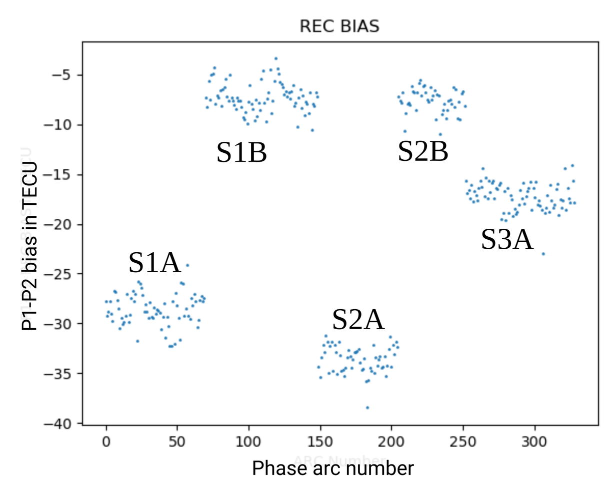

Figure 6: Arc-wise estimated P1-P2 receiver bias for each GPS phase arc between 00:00 UT and 03:00 UT, 3/22/2017.

Ionospheric Tomography Using Weighting

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 and above 2000 km, all respresented by a spherical harmonics expansion.

For this example a day is choosen, where the local times of Swarm are close to the local times of Sentinel. For doy 130, year 2017 the local times of Swarm are 9/21 LT, whereas the local times of Sentinel are 6/18 LT and 10/22 LT. The plasmaspheric electron content in Swarm sTEC is then removed by evaluating the model using line-of-sight integration form 1000 km to GPS altitude. The difference between the sTEC values is shown in Figure 7.

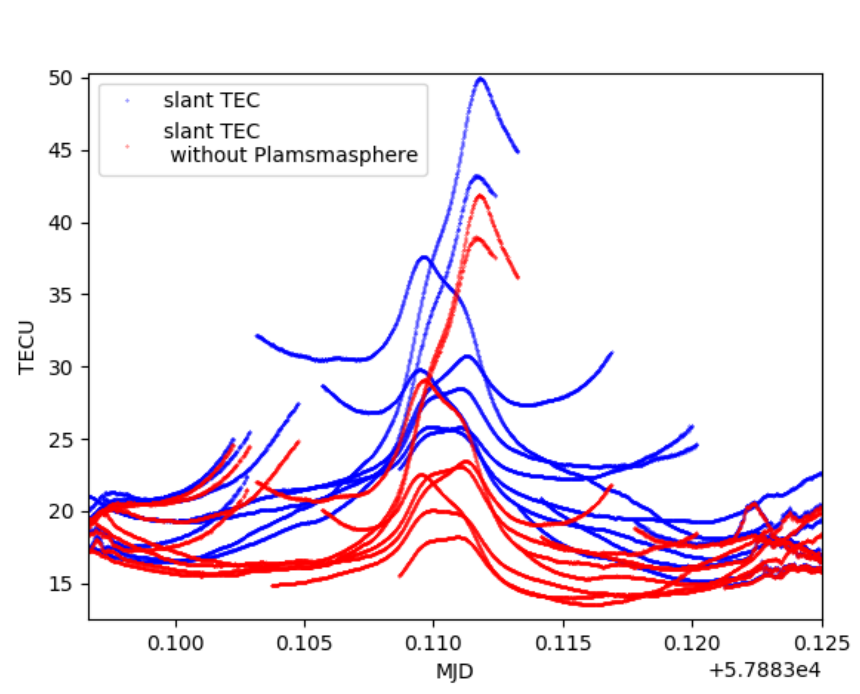

Figure 7: Swarm slant TEC with and without plasmaspheric electron content.

The ionospheric tomography is perfomed 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 aproximated by the weighted sum of the pixel density:

$$sTEC = \int_{LEO}^{GPS} N_e dl + C_{ARC} \approx \sum_{i=0}^{N} l_i (N_e)_i + C_{ARC}.$$

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

$$\|P(Ax - y)\| + \lambda \|Bx\| \rightarrow min.$$

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

$$x_j^{k+1} = x_j^k \cdot \Pi_{i=1}^m \left(\frac{y_i}{(Ax^k)_i} \right)^{\lambda A_{i,j}/\|A_i\|} \Pi_{i=1}^k \left(\frac{(-C^- x^k)_i}{(C^+ x^k)_i} \right)^{\lambda C^+_{i,j}/\|C_i^+\|}$$

The results are shown in Figure 8. When applying the MART algorithm more details become visible and the unrealistically large 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 disapear.

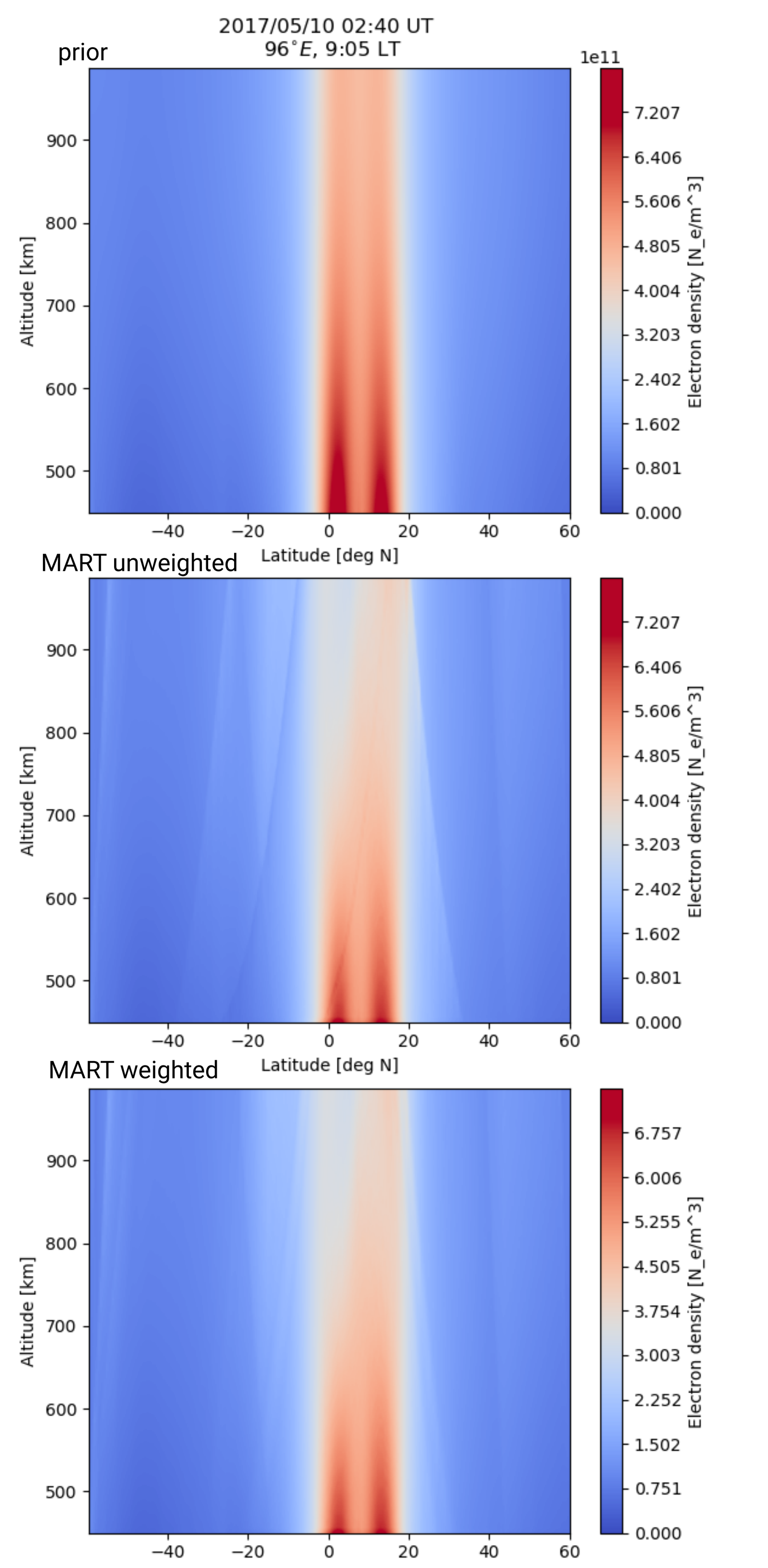

Figure 8: Ionospheric reconstruction, prior (top), MART unweighted (mid) and MART weighted (bottom)

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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