EGU2018-7023
European Geosciences Union
General Assembly 2018
07 April - 13 April 2018, Vienna, Austria

Imaging the topside ionosphere and plasmasphere using Swarm GPS observations

L. Schreiter[1], D. Arnold[1], V. Sterken[1], A. Jäggi[1], C. Stolle[2]
[1]: Astronomical Institute, University of Bern, Bern, Switzerland
[2]: GFZ Potsdam, Section 2.3 Geomagnetism, Germany

RECONSTRUCTION METHOD

Observables

Only **phase measurements** were considered and the data was **screened for cycle slips**. We are using the geometry free linear combination of the two phase observables L_1 and L_2,

$$L_{gf} = L_1 - L_2 \approx \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \cdot 40.3 \int_{LEO}^{GPS} N_e dl + C_{ARC}. \quad [1]$$

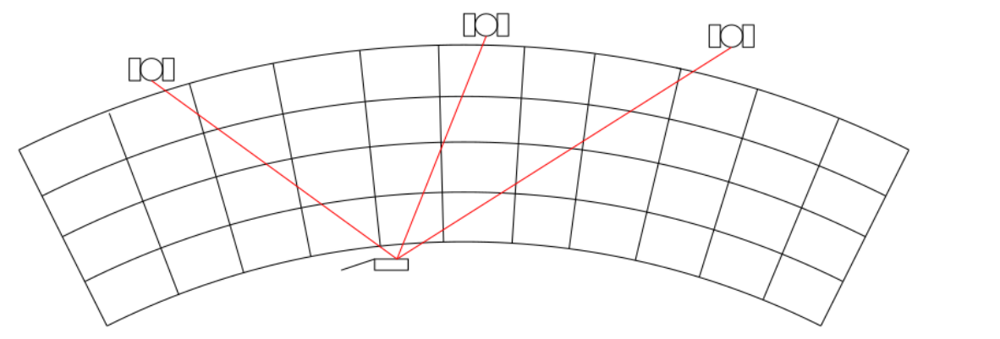
The **linear combination L_{gf}** is in first order propotional to

the integrated **electron density N_e** along the line of sight from the LEO-receiver to the GPS-satellite

plus an **unknown offset**, which contains the ambiguities and unknown biases. This offset is be assumed to be constant as long as there is no loss of lock.

Reconstruction Technique

The reconstruction relies on **discretization**. We divide the two-dimensional plane into N grid cells.



$$L_{gf} \approx \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \cdot 40.3 \sum_{i=0}^{N} l_i(N_e)_i + C_{ARC}. \quad [2]$$

After computing the length of the **line of sight L_i** in each cell, we can approximate integral [1].

In each cell we assume the plasma density $(N_e)_i$ to be constant.

We selected the settings:

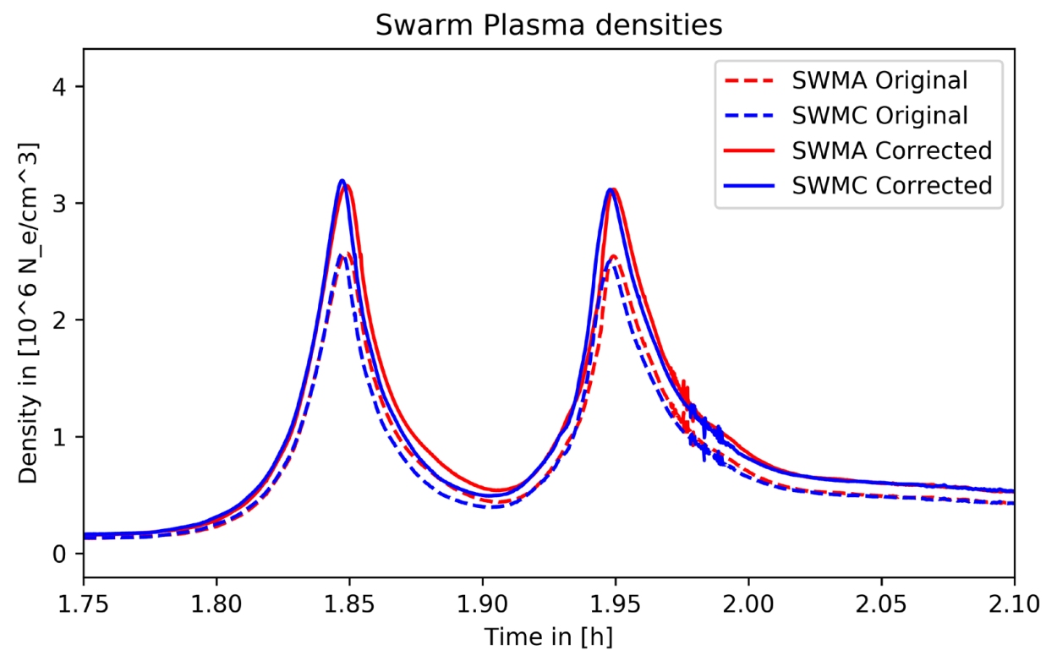
- 0.5 ° resolution in latitude
- 180 boxes in altitude from LEO altitude to GPS altitude
- altitudinal bins exponentionally increasing (20km – 700km)
- rays were mapped in the 2D-plane, length were computed 3D
- offsets estimated in least square solution

Lower boundary condition

We use relative measurements, which makes it necessary to specify **reference values**. Swarm satellites are equipped with **Langmuir probes**, which allow an in-situ measurement of the ambient plasma density.

Comparison of GPS, ionosonds and radar measurments by Lomidze et. al (2018) showed, that Langmuir probes **tend to underestimate Plasma density**.

We calibrated the Langmuir probe measurements using values given by Lomidze et. al (2018) and assigned the **average value** in each latitudinal bin to lower boundary.



Regularisation

The ray geometry is very weak. In order to obtain **stable** solutions, regularization is important.
We use a **Tikhonov regularization**:

$$\underbrace{\|Ax - y\|}_{\text{least square solution following (2)}} + \lambda \underbrace{\|Bx\|}_{\text{regularization term}} \to min. \quad [3]$$

The regularization matrix *B* is defined: the regularization term **vanishes**, if the **value** in one box **matches weighted average** of the surrounding ones:

$$(Bx)_i = \sum_{j}^{N} ((N_e)_i - (N_e)_j) \cdot l_{ij}, \quad [4]$$

l_{ij} is the length of the edge between box_i and box_j.

The physical interpretation implies, that the **inflow should match the outflow** and that the solution should be **locally divergence free**.
This can be justified by the conductivity along the magnetic field lines.

IN A NUTSHELL

GPS for Ionosphere:

The benefit of dual frequency GPS to gather ionospheric information is well understood and used for TEC Maps or ROTI products. There exist applications on ionospheric tomography too [1].
The major difficulty is that it is an **ill posed inverse problem** due to ray geometry. To overcome these difficulties most of the present models heavily contrain to background models, use long time averaging or big arrays of ground receivers - Minkwitz et al. (2015), Norberg et al. (2015).

Problematic Swarm Data:

Commonly the Swarm GPS receivers had **schematic errors** in the data **during high ionospheric activity**. This is clearly visible in the gravity field solutions, even though for the precise orbit determination the ionosphere-free linear combination was used[2].

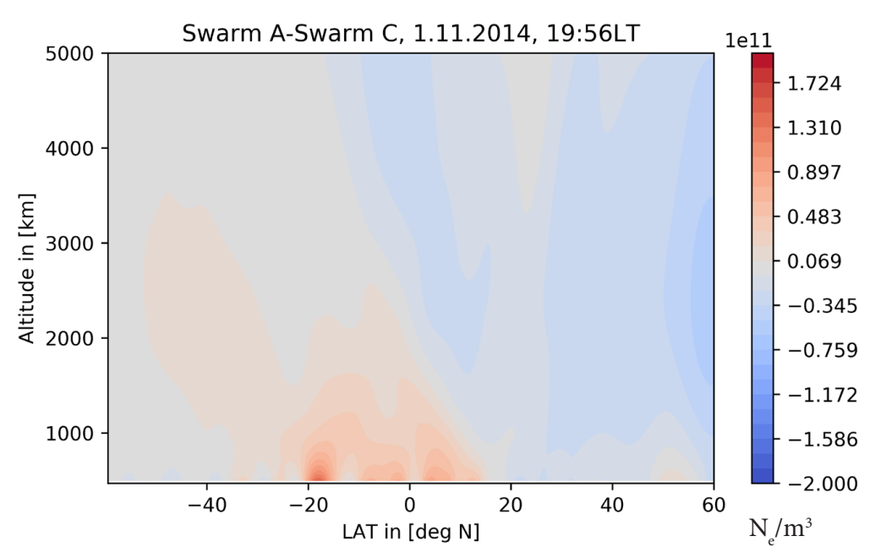
Weighting and screening strategies were developed by TU Graz and AIUB to remove those errors. Since Mai 2015 Swarm tracking loops were updated, which again improved the data quality.

Our Approach

It relies on a **single spacebourne GPS receiver** onboard a Swarm Satelite, uses only **20 min. of GPS carrier phase observations,** and is **independent of model assumptions** (like IRI, PIM or IGRF Models).
It **produces a two dimensional slice** showing the Plasma density distribution in latitude and altitude. We investigate the stability of the reconstruction by applying different weighting strategies and perform validation by comparing the results from Swarm A to nearby satellite Swarm C.

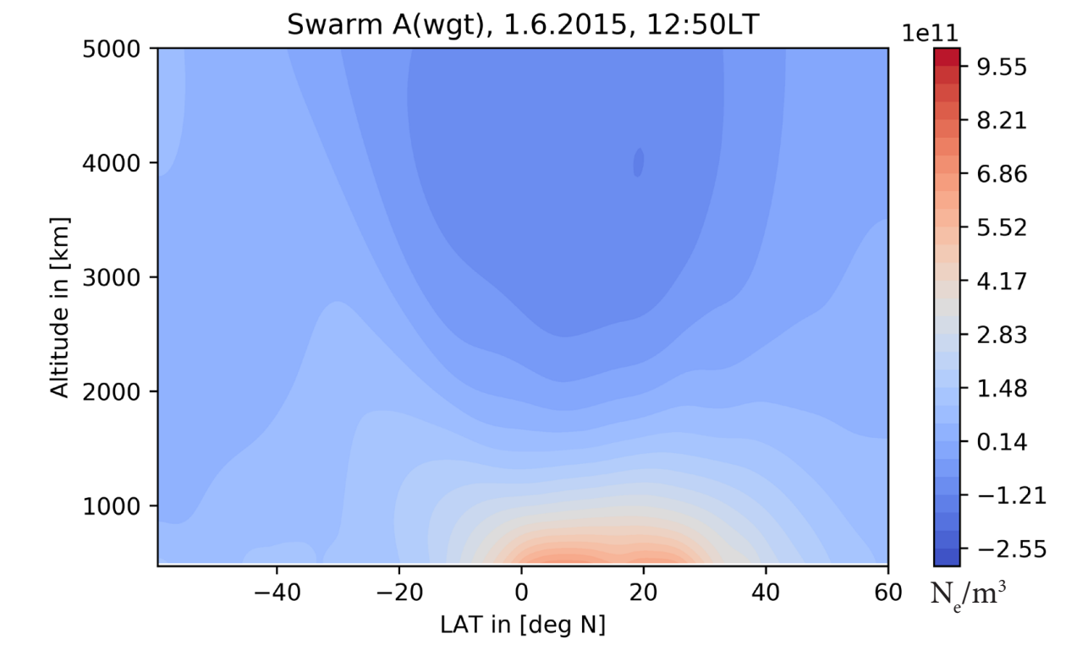
Validation

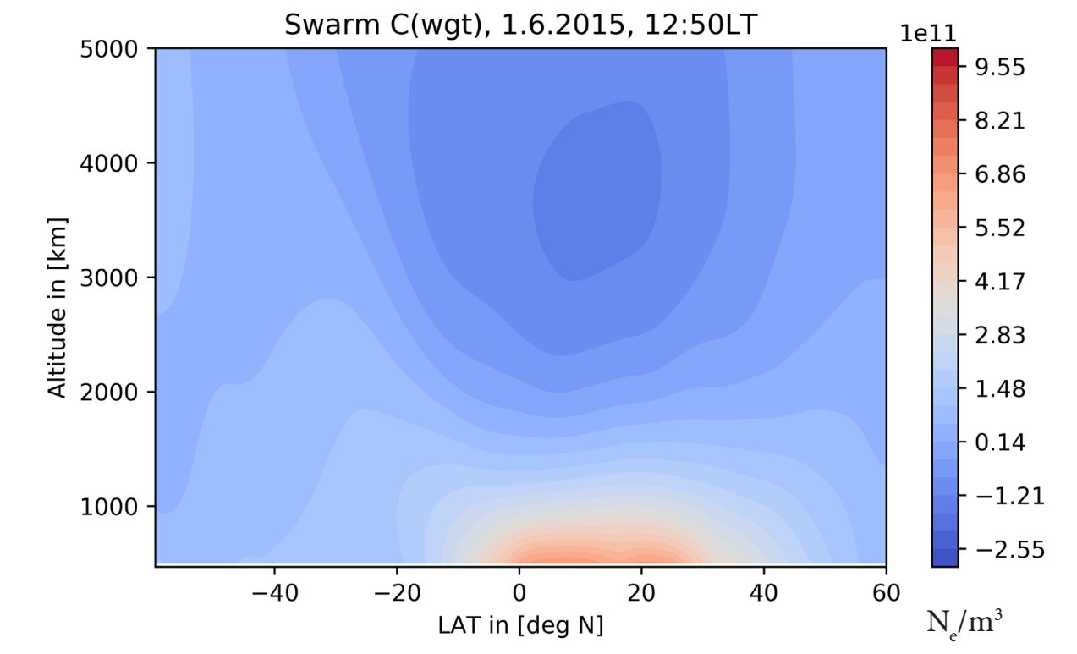
The Swarm mission offers an **unique option** to validate the reconstruction. Swarm A and C are **separated by only 6° in longitude** at equatorial regions. If the reconstruction algorithm is stable, results from A and C should be similar.

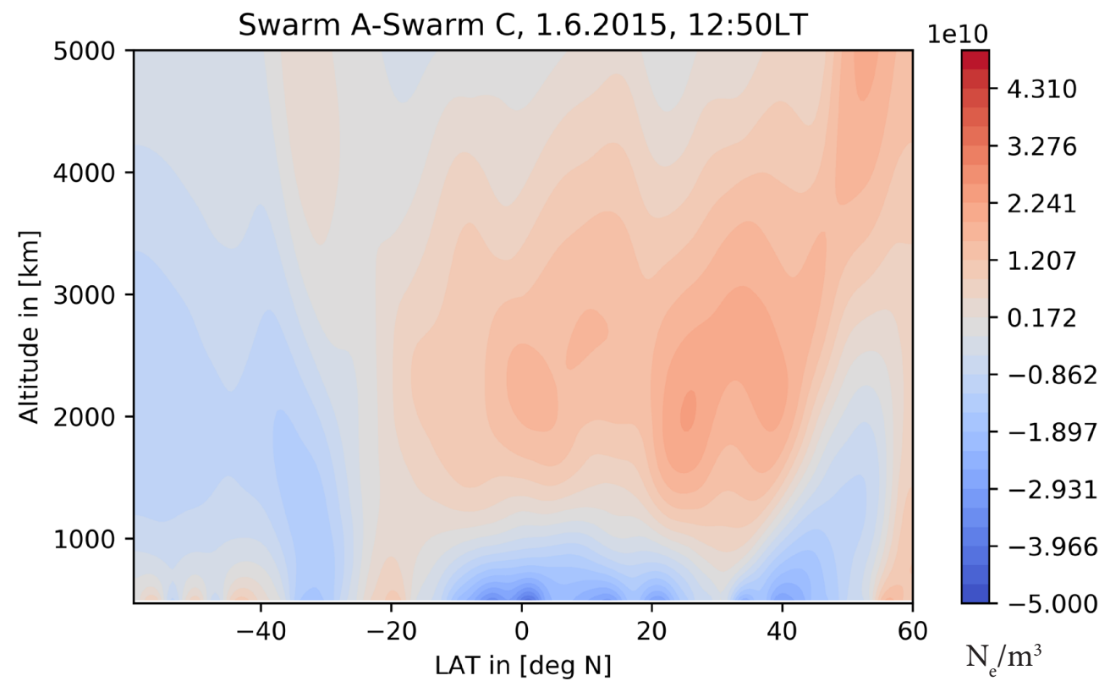


Tracking Loop

For June 2015 the Tracking Loop settings of Swarm A and C had been **updated**. It allows to crosscheck the **impact** of the tracking loop update **on the reconstruction**.
The differences (as illustrated in the third image) are very small.







SWARM SPECIFIC ISSUES

Weighting

To **overcome possible data problems**, different weightings have been developed for precise orbit determination and subsequent gravity field recovery. We use these weightings to derive *a* covariance matrix *P* which we apply on [3] s.t.

$$\|P(Ax - y)\| + \lambda \|Bx\| \to min. \quad [5]$$

ROTI (Rate of TEC index)

ROTI is defined via the **quadratic variance of the slant TEC** and computed from the **RINEX** observation file:

$$ROTI = \sqrt{\frac{\langle \Delta TEC^2 \rangle - \langle \Delta TEC \rangle^2}{\Delta t^2}} \quad [6]$$

As in Zehentner et al. (2015) ROTI was applied in a 31*s* sliding window manner and scaled.

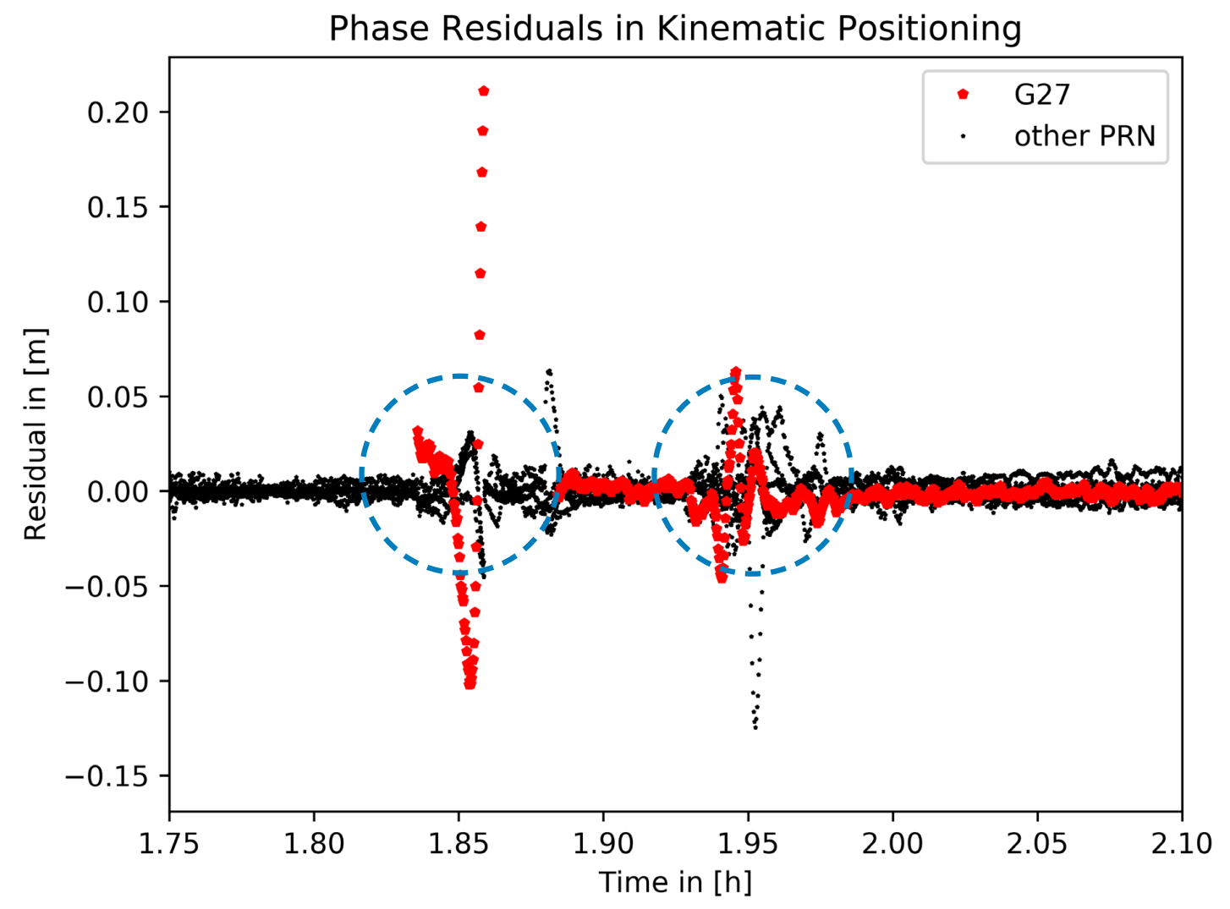
- TU-Graz: $\sigma = exp(20 \cdot ROTI)$
- AIUB: $\sigma = max(1, 60 \cdot ROTI)$

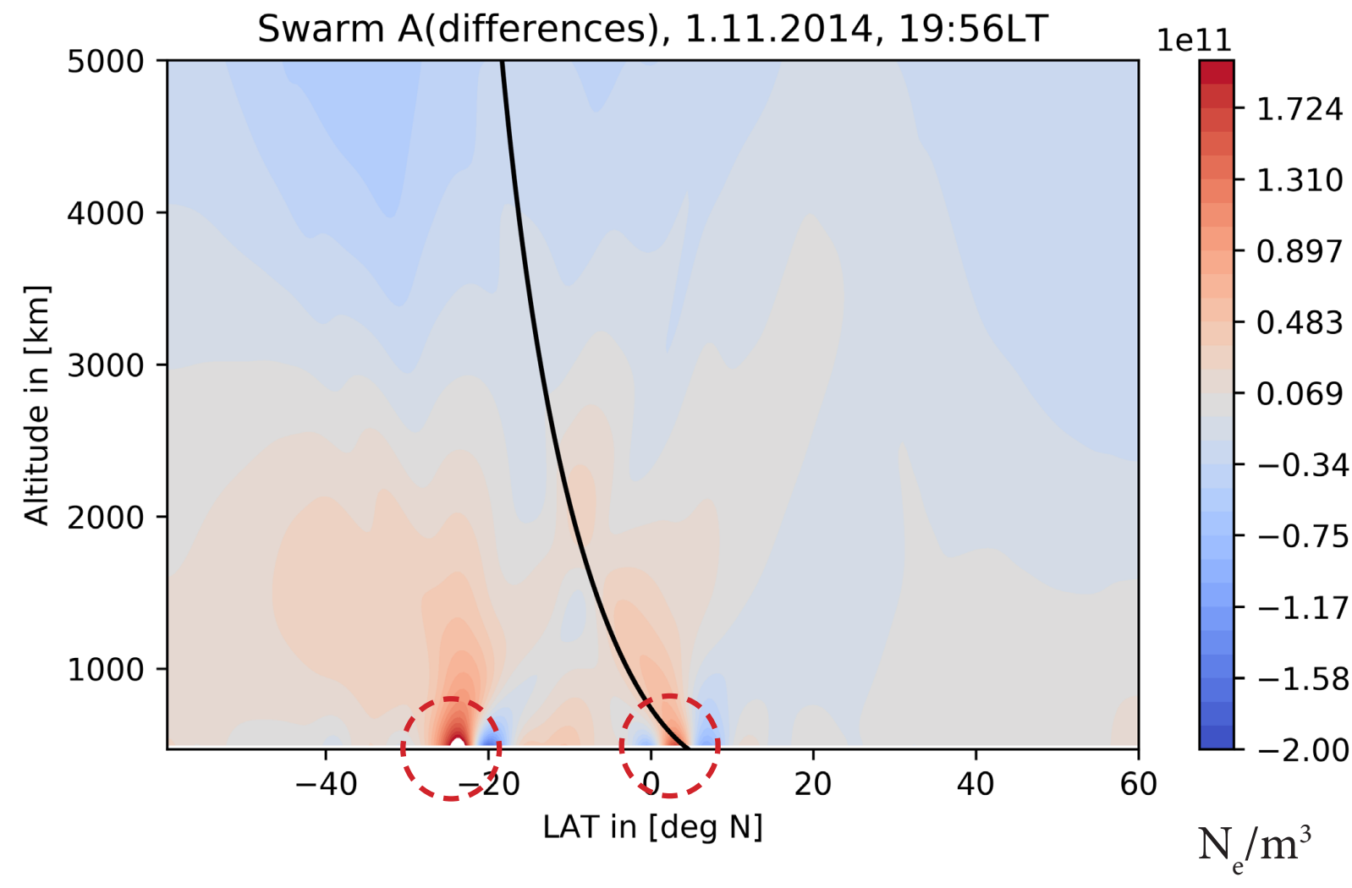
Derivative based

Values with a high second numerical derivative (> $0.025 cm/s^s$) get a σ of 21, other observations stay unaffected (σ = 1). This proved efficient in reducing equatorial artefacts in gravity field recovery[3].

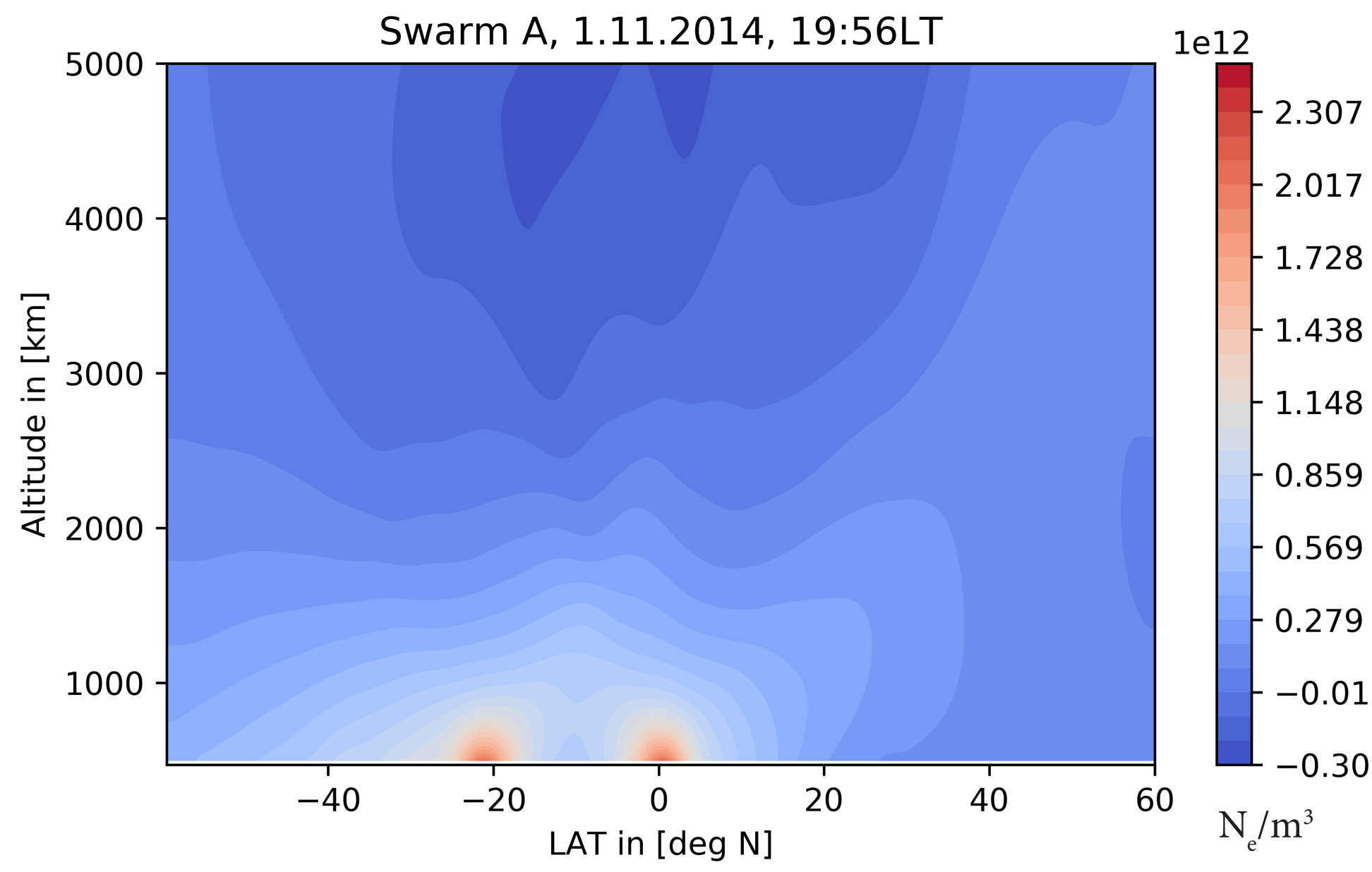
Combined

For gravity field determination a combined approach ($\sigma = max(\sigma_{ROTI}, \sigma_{deriv})$) turned out to be the **most efficient**

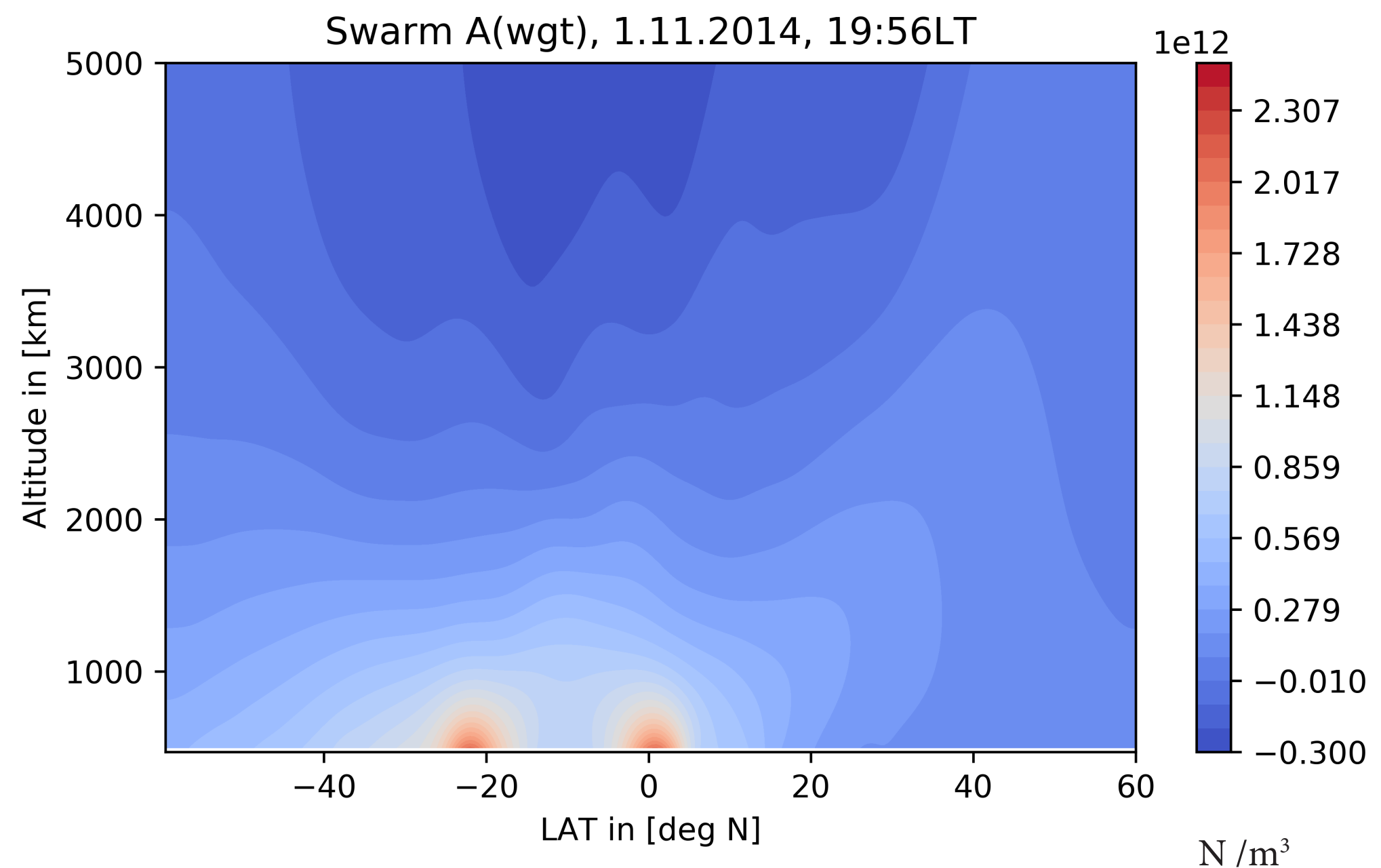




Data problems around the geomagnetic equator affect the reconstruction (black: line-of-sight Swarm A-G27)



Plasma density reconstruction unweighted



Plasma density reconstruction weighted
(2nd derivative)

CONCLUSIONS

- **Two dimensional reconstruction** is possible in short arcs with constraints
- Results are **sensitive to problematic GPS data** known from gravity field recovery
- problematic GPS data may be handled with **Covariance Matrix**
- **Swarm A** and **C** show a good **agreement** (Before/after tracking loop update)
- Reconstruction seems to **benefit from tracking loop update**

References:

1: **Schlüter S., Stolle C., Jakowski N., Jacobi C.** (2003) Monitoring the 3 Dimensional Ionospheric Electron Distribution based on GPS Measurements. In: Reigber C., Lühr H., Schwintzer P. (eds) First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies. Springer, Heidelberg

2: **Dahle, C., D. Arnold, A. Jäggi (2017):** Impact of tracking loop settings of the Swarm GPS receiver on gravity field recovery. Advances in Space Research, 59(12), 2843-2854, doi:10.1016/j.asr.2017.03.003

3: **Jäggi, A** & Meyer, Ulrich & Schreiter, Lucas & Sterken, V & Dahle, C & Arnold, D & Encarnação, João & Visser, Pieter & van den IJssel, Jose & Mao, Xinyuan & Iorfida, Elisabetta & Bezdek, Ales & Sebera, Josef & Mayer-Gurr, T & Zehentner, Norbert & Shum, C.K. & Luck, C & Rietbroek, R & Kusche, Jürgen & Zhang, Yu. (2018). Assessment of individual and combined gravity field solutions from Swarm GPS data and mitigation of systematic errors.

N. Zehentner, T. Mayer-Gürr: Mitigation of ionospheric scintillation effects in kinematic LEO precise orbit determination, EGU General Assembly 2015

Minkwitz, D., van den Boogaart, K. G., Gerzen, T., and Hoque, M.: Tomography of the ionospheric electron density with geostatistical inversion, Ann. Geophys., 33, 1071-1079, https://doi.org/10.5194/ageo-33-1071-2015, 2015.

Norberg, J., Virtanen, I. I., Roininen, L., Vierinen, J., Orispää, M., Kauristie, K., and Lehtinen, M. S.: Bayesian statistical ionospheric tomography improved by incorporating ionosonde measurements, Atmos. Meas. Tech., 9, 1859-1869, https://doi.org/10.5194/amt-9-1859-2016, 2016.

Lomidze, L., Knudsen, D. J., Burchill, J., Kouznetsov, A., Buchert, S. C. (2018). Calibration and validation of Swarm plasma densities and electron temperatures using ground based radar sandsatellite radio occultation measurements. Radio Science, 53, 15,A S.36. https://doi.org/10.1002/2017RS006415

Bassiri, S. and Hajj, G. A.: Higher-order ionospheric effects on the global position- ing system observables and means of modelling them, Manuscr. Geodaet., 18, 280, S.289, 1993.

CONTACT / COPYRIGHT

Lucas Schreiter
Astronomical Institute, University of Bern
Sidlerstrasse 5
3012 Bern (Switzerland)
lucas.schreiter@aiub.unibe.ch