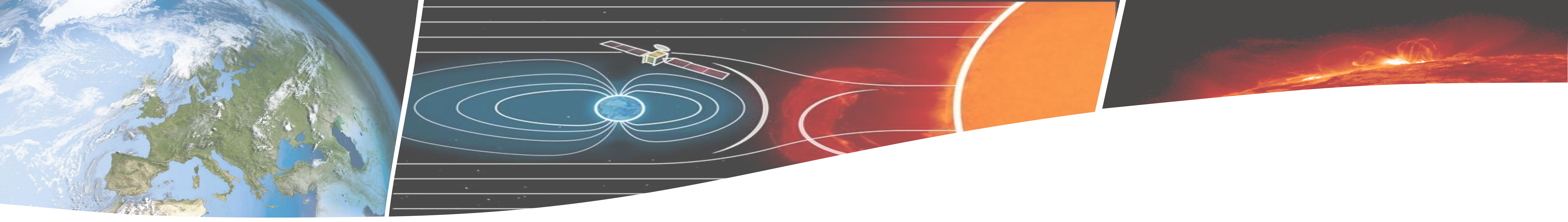

Quantifying uncertainty in thermospheric mass density from satellite measurements via data assimilation with CTIPe model

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Introduction

This study proposes a **new method for estimating the uncertainty of thermospheric mass density (TMD) derived from satellites**. Neutral density is a crucial parameter that characterizes the upper atmosphere. The accuracy of satellite trajectory calculations is heavily influenced by the accuracy of this parameter, and **uncertainty in neutral density** can lead to significant errors in such calculations, particularly in situations that require collision avoidance measures [Hejduk, 2018]. The proposed method **combines measurements of thermospheric neutral density** with the physics-based Coupled Thermosphere Ionosphere Plasmasphere with electrodynamics (**CTIPe**) **model** through **data assimilation**. We analyze data from two different satellites missions, CHAMP and Swarm, during a period of **quiet geomagnetic conditions**. By analyzing the effects of **different uncertainties** on the assimilation results of the forecast and analysis estimates (fig. 1) , we can approximate a range of the uncertainty in the neutral density measurements. The results show an **uncertainty of 13% for CHAMP** and **22% for Swarm** during quiet geomagnetic conditions.

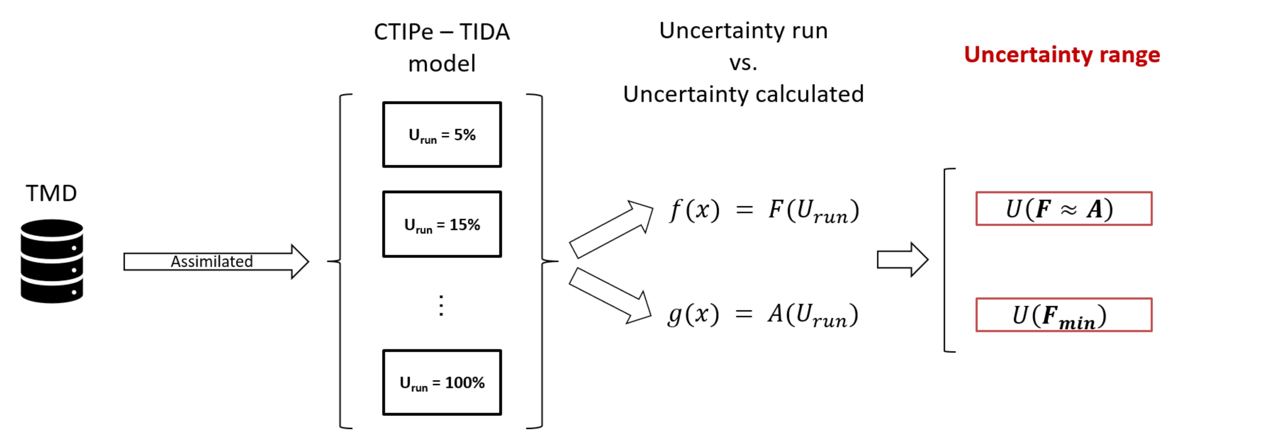

Figure 1. Schematic view of the procedure to approximate uncertainties of satellite derived thermospheric mass density with data assimilation into a physics-based model varying the uncertainty input (U_{run}). The results for both forecast and analysis estimates define the range of uncertainty of the neutral density.

Method

- **TMD observations** derived from **CHAMP** and **Swarm** satellite are assimilated into the Coupled Thermosphere Ionosphere Plasmasphere with electrodynamics (**CTIPe**) physics – based model during **quiet geomagnetic conditions**.
- An implementation of an **ensemble Kalman filter** is used to assimilate neutral density into the CTIPe model. The state vector updates the forcing parameters and the necessary quantities to calculate neutral density every 10 minutes.
- TMD along the orbit of the satellite **observations** (Fig. 2) are compared to the CTIPe free run with no assimilation (**reference**), the prior state (**forecast**) and the assimilation run (**analysis**).
- Different runs are performed assimilating the same data with **different uncertainty runs** in a range between **1% and 100%** depending on the mission.
- The **quiet time period** selected for CHAMP is 3-8 March 2007 and for Swarm 1-5 August 2015.

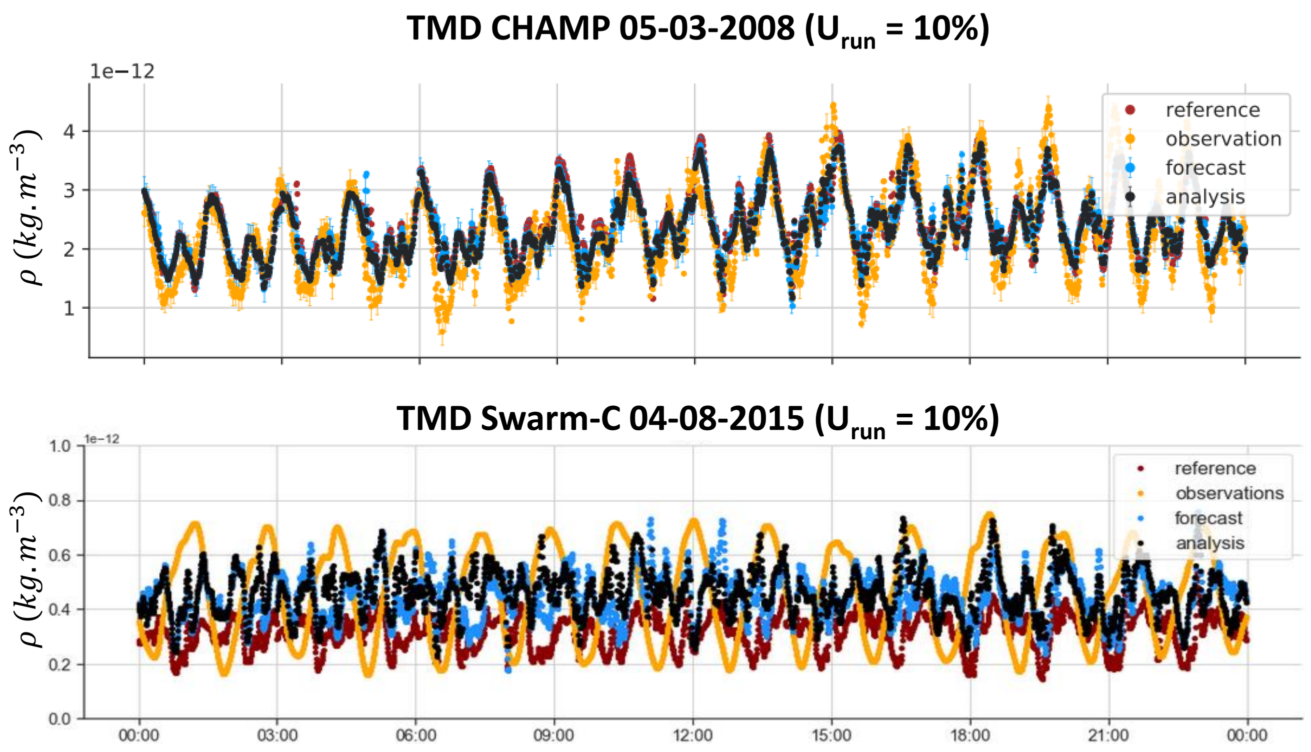

Figure 2. Example of one day data assimilation run for along the orbit TMD for CHAMP (upper panel) and Swarm (lower panel) considering an uncertainty run of 10%. Represented are the observations (yellow), the CTIPe free run reference with no assimilation (red), forecast (blue) and analysis (red) estimates.

- The uncertainty is calculated based on **error** (ε) between observation and model results, **standard deviation** (σ) and **relative** (to de mean) **standard deviation** percentage (RSD). The RSD is considered the measure of **uncertainty calculated** ($U_{cal}(\%)$).

$$\bar{\varepsilon} = \langle y_{obs} - y_{mod} \rangle \qquad \sigma = \sqrt{\frac{\sum(\varepsilon_i - \bar{\varepsilon})^2}{(n-1)}} \qquad RSD(\%) = \frac{\sigma}{\langle y_{obs} \rangle} \cdot 100$$

TMD Uncertainty

- The representation of the **uncertainty run vs the uncertainty calculated** (U_{cal}) for the forecast and the analysis, allow us to estimate the uncertainty range.
- The **uncertainty range** is defined between the minimum uncertainty calculated given by the forecast (**F_{min}**), and the value where the analysis and the forecast are equal (**F=A**).
- The results for **CHAMP** show variation of the uncertainty calculated between the **10% and 13%** depending on the day of the run and in agreement with the literature [Sutton, 2007]. Fig. 3 represent the 5 March 2008 where we can see the evolution of the forecast and the analysis for different values of uncertainty run (x axis) and its calculated value (y axis).

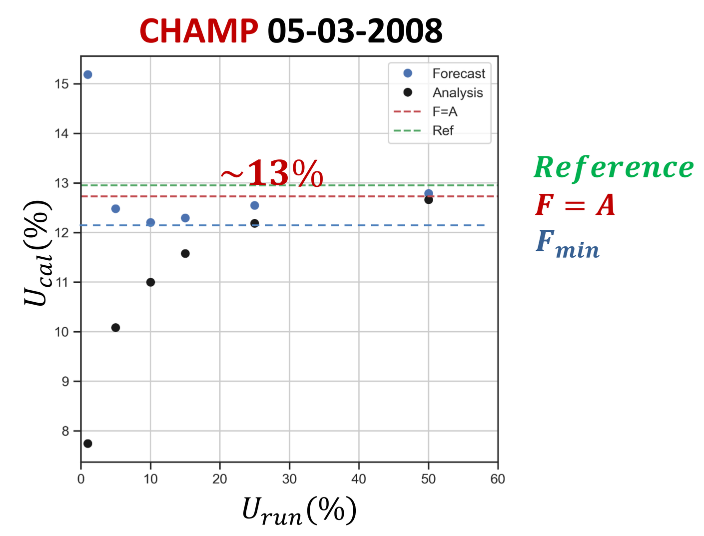

Figure 3. CHAMP Uncertainty run vs. Uncertainty calculated for the 5 March 2008. Forecast (blue) and analysis (black) are represented with the constant value given by the reference (green), the minimum of the forecast and the convergence between forecast and analysis. The reference is very close to the value calculated with data assimilation.

- In the case of Swarm the uncertainty calculated is approximately **20%** for **Swarm – A and C**, and **30%** for **Swarm – B**. The range of values varies a 3% depending on the day. Fig. 4 represent the results for Swarm – C and B (Swarm – A results are similar to C).

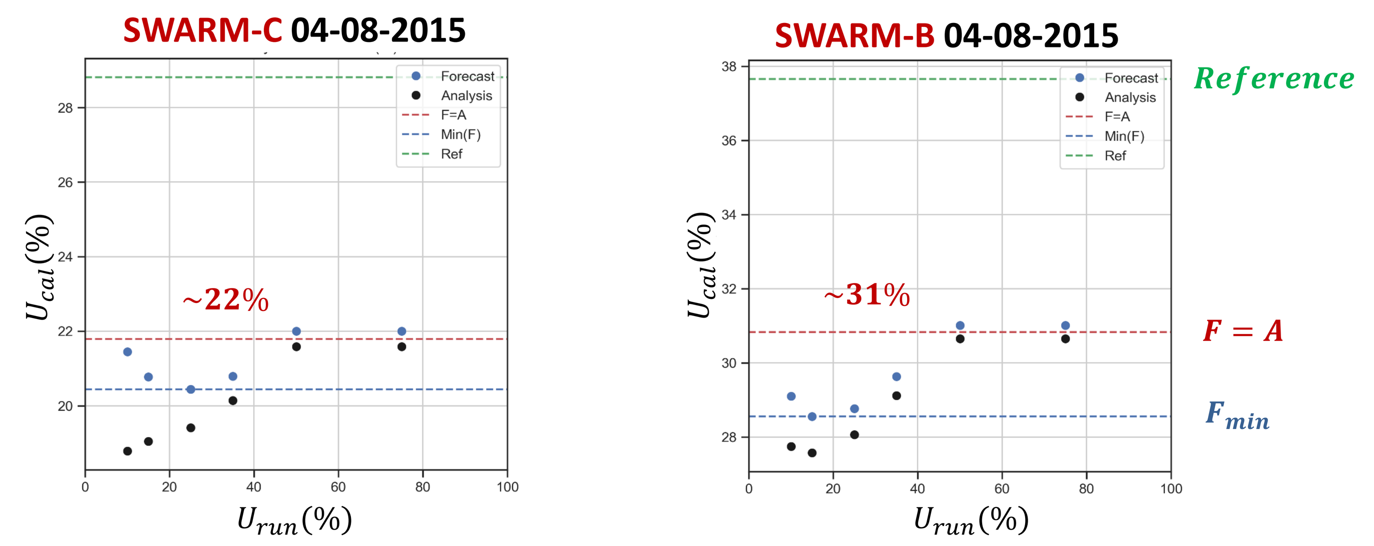

Figure 4. Neutral density uncertainty calculated for Swarm-C (left) and Swarm-B (right). The values are 22% and 31% respectively for the 4 August 2015. The reference run (green dashed line) is approximately a 5% higher that the value calculated with data assimilation.

Summary

- A new method has been developed to **calculate uncertainties associated with neutral density measurements** derived from satellites.
- The uncertainty calculation is **based on data assimilation**, which involves combining neutral density measurements into a physics-based model with different input uncertainty values\
- The method is applied to data of two different missions, **CHAMP** and **Swarm**, with uncertainty results of **13%** and **22%** respectively during **quiet geomagnetic conditions**.

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