Open Call for Ideas for

New data products, tools and services for Swarm

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In order to facilitate 'cross pollination' between ideas and research groups, the Proposer(s) declare in submitting this idea, that the Swarm DISC may publish the name(s) of the proposer(s) and the title of the idea. Please indicate below (select Yes or No) whether DISC can also publish the entire content of the submitted idea:

Publish the entire content *Yes*

Title: Multi-Scale Irregularities Product (m-SIP): a data product utilizing the high-resolution Swarm plasma density data for space weather applications

Product Description

- **Description of current state of the art and level of maturity of proposed algorithm**

It is nowadays crucial to monitor and forecast space weather conditions, and in particular variations in the near-Earth space environment which are induced by the Solar Wind-Magnetosphere-Ionosphere-Thermosphere interactions. They can affect critical infrastructure and services that include communications and navigation systems, as well as satellite operations. Such technologies are increasingly important to our modern society. For example, today there are more than 6 billion Global Navigational Satellite System (GNSS) devices in use worldwide, and this number is continuously growing with the development of autonomous systems that rely on GNSS. Thus, GNSS disruptions due to the space weather effects can have global societal consequences, both in terms of economic impact, and in the context of security and safety of operations. However, as for now there is no space weather product that can monitor and predict the global space weather impact on the GNSS users. In this regard, the Swarm mission can contribute by its high-resolution faceplate (FP) plasma density measurements.

We propose the Swarm multi-scale irregularities product (m-SIP). m-SIP will be a Swarm-based data product that can characterize small-scale irregularities (< 10 km) and at different scales down to near the Fresnel's scale (~400 m), which is particularly useful for the GNSS users. m-SIP will use the high-resolution (16 Hz) plasma density data of Swarm.

The new data product m-SIP consists of two parts: 1) The derived plasma density parameters at small spatial scales, e.g., the rate of change of density in the 1-second window (RODI1s), density gradients at 5 km and at 10 km, and the spectral slope of power spectral density; 2) The modelled S4 index based on the WAM model (Wernik et al., 2007, Alfonsi et al., 2017). An algorithm similar to that in the first part has been used in the level 2 IPIR data product (IPDxIRR_2F, Jin et al., 2022). In the proposed new m-SIP dataset, we will work with a new dataset, i.e., the high-resolution FP plasma density data, and we will focus on the small-scale irregularities, which are the ones that mainly affect the performance of the GNSS services. The second part is based on Rino's theory for weak scattering regime for calculating the amplitude scintillation index (Rino, 1979). The amplitude scintillation index S_4 of a trans-ionospheric signal having wavelength λ can be modelled by using the formula (31) of Rino (1979):

$$S_4^2 = (r_e\lambda)^2 L \sec\theta \, C_s Z^{\frac{2\nu-1}{2}} \frac{\Gamma\left(\frac{2.5-\nu}{2}\right)}{2\sqrt{\pi}\frac{(\nu+0.5)}{2}\,\Gamma\left(\frac{2\nu+1}{2}\right)} F, \qquad (1)$$

where r_e is the classical electron radius, θ is zenith angle of the signal path, L is the thickness of the irregularity layer, C_s is the strength of turbulence, ν is the spectral slope of irregularities, F is the geometry-dependent Fresnel's filter factor, and Z is the Fresnel's zone parameter (Imam et al., 2023). The NeQuick2 model (Nava et al., 2008) is utilized to reconstruct the irregularity layer parameters, the GPS L1 wavelength is considered and the overhead propagation ($\theta = 0°$) to represent a virtual GNSS receiver located below the considered Swarm satellite. Both algorithms are very mature and have been proven to be useful for addressing the space weather impact on ionospheric plasma conditions, including plasma irregularities. This ensures the feasibility of development of the proposed m-SIP product.

- **Description of proposed product**

The proposed product will include a series of output variables, i.e., Timestamp, Latitude, Longitude, Height, Ne, Grad_Ne@5km, Grad_Ne@10km, Grad_Ne@20km, Grad_Ne@50km, Grad_Ne@100km, ROD, RODI1s, RODI5s, RODI10s, RODI20s, spectral slope, S_4, turbulence strength log10(Cs), and quality_flag. The table of variables describing the detailed variables with explanation can be found in Annex (*cdf variables.pdf*).

- **Data input needs**

For this data product, we use the Swarm FP 16 Hz plasma density data (SW_EXTD_EFIx_LP_FP), the Swarm IPIR dataset (SW_OPER_IPDxIRR_2F), and the NeQuick2 model. The 16 Hz FP data is the key dataset for m-SIP. Figure 1 shows daily average of plasma density and RODI1s. It can be seen that availability is very good between 2015 and late 2019. More importantly, the availability of the FP data is increasing during the recent years. This is very useful for monitoring the increasing ionospheric variability during increasing solar activity. In addition, two other Swarm satellites can complement the availability of the FP data from Swarm A.

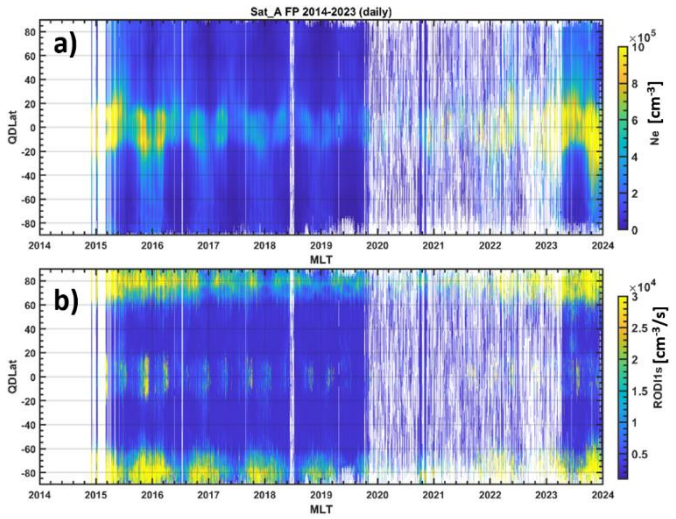


Figure 1. The daily average of plasma density (top) and RODI1s (bottom) calculated (and collected in the new data product) from the FP data onboard Swarm A along the quasi-dipole latitude

- **Expected output**

The output will be a dataset provided in daily *cdf* files. Each *cdf* file will include a series of variables (see Annex: *cdf variables.pdf*). The data will be provided as soon as the FP data is available, and it will also be provided from the start of the Swarm mission.

- **Scientific/application benefits**

The new data product will be useful for monitoring the space weather impact for the GNSS users. Due to its long availability around the globe at all latitudes, it would ease the development of specific models to characterise small-scale irregularities in the ionospheric plasma density and their impact on the GNSS services. In addition, the data product will be useful for improving the fundamental understanding of ionospheric processes and formation of plasma irregularities. It will contain parameters necessary for characterizing plasma irregularities at multiple scales and the energy cascading across different spatial scales (including the spectral slope) down to near the Fresnel's scale of GNSS signals. It can be used to study the turbulent ionosphere at both high and low latitudes. It will also expand the VirES portfolio with additional parameters that will allow a quick assessment of the space weather conditions in the ionosphere.

It is worth noting that the product is distinct from the existing IPIR L2 dataset. The new data product m-SIP utilizes the 16Hz FP dataset, and all parameters are calculated based on this dataset which captures small scales in the plasma density that are relevant for the GNSS users. It also employs a novel model that allows calculating expected scintillations on the GNSS signals. IPIR can be considered as complementary to m-SIP and will be used for cross-validation of m-SIP at large spatial scales.

- **Expected user community**

The user community will be mainly ground-based GNSS users and different groups working on the development of models and services for ionospheric and space weather effects on the GNSS signals. In addition, the scientific communities that are interested in the magnetosphere-ionosphere-thermosphere coupling and near-Earth space environment will also benefit from m-SIP. The new data product can be used in building new global and local models that address the space weather forecasting in ionospheric scintillations. Its global coverage is expected to attract in particular communities focusing on the polar and equatorial regions, where the GNSS scintillation effects can be severe. This product will also lead to the paradigm change in the context of using satellite in-situ measurements for nowcasting ionospheric conditions related to scintillations.

References

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Variable name	Data Type	Description	Unit
Timestamp	CDF_epoch	Milliseconds since Jan 1, 0000, 0 UTC	ms
Latitude	CDF_DOUBLE	Geodetic latitude, WGS84 ellipsoid	deg
Longitude	CDF_DOUBLE	Geodetic longitude, WGS84 ellipsoid	deg
Height	CDF_DOUBLE	Height above reference WGS84 ellipsoid	km
Ne_FP	CDF_DOUBLE	Plasma density derived from the faceplate current	cm^-3
Grad_Ne@5km_FP	CDF_DOUBLE	The plasma density gradient in a running window calculated via linear regression over 11 data points for the 16 Hz plasma density data (Ne_FP)	cm^-3/m
Grad_Ne@10km_FP	CDF_DOUBLE	The plasma density gradient in a running window calculated via linear regression over 21 data points for the 16 Hz plasma density data (Ne_FP)	cm^-3/m
Grad_Ne@20km_FP	CDF_DOUBLE	The plasma density gradient in a running window calculated via linear regression over 43 data points for the 16 Hz plasma density data (Ne_FP)	cm^-3/m
Grad_Ne@50km_FP	CDF_DOUBLE	The plasma density gradient in a running window calculated via linear regression over 107 data points for the 16 Hz plasma density data (Ne_FP)	cm^-3/m
Grad_Ne@100km_FP	CDF_DOUBLE	The plasma density gradient in a running window calculated via linear regression over 213 data points for the 16 Hz plasma density data (Ne_FP)	cm^-3/m
ROD_FP	CDF_DOUBLE	Rate Of change of Density (ROD)	cm^-3/s
RODI1s_FP	CDF_DOUBLE	Rate Of change of Density Index (RODI) is the standard deviation of ROD over 1 seconds (16 data points for the 16 Hz electron data)	cm^-3/s
RODI5s_FP	CDF_DOUBLE	Rate Of change of Density Index (RODI) is the standard deviation of ROD over 5 seconds (80 data points for the 16 Hz electron data)	cm^-3/s
RODI10s_FP	CDF_DOUBLE	Rate Of change of Density Index (RODI) is the standard deviation of ROD over 10 seconds (160 data points for the 16 Hz electron data)	cm^-3/s
RODI20s_FP	CDF_DOUBLE	Rate Of change of Density Index (RODI) is the standard deviation of ROD over 20 seconds (320 data points for the 16 Hz electron data)	cm^-3/s
slope	CDF_DOUBLE	The linear fit of Maybe Fast Fourier Transform (FFT) power spectra in a time window of 10 seconds. The frequency range for the fit is 0.2 – 8.0 Hz.	-
S4	CDF_DOUBLE	Amplitude scintillation index	-
log10(Cs)	CDF_DOUBLE	Logarithm of the turbulence strength rescaled to the peak of the irregularity layer	-
L	CDF_DOUBLE	Irregularity layer thickness	km
z	CDF_DOUBLE	Height of the irregularity layer	km
sigma_dNe2	CDF_DOUBLE	Variance of the plasma density reconstructed at the peak of the irregularity layer	cm^-3/s
sigma_dNe2sat	CDF_DOUBLE	Variance of the plasma density measured at the satellite altitude	cm^-3/s
Quality_flag	Integer	Quality flag	-