Effective ion mass from electron density reconstruction based on LEO GNSS observations and ion density from Swarm Langmuir probes

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Swarm 10 Year Anniversary & Science Conference 2024

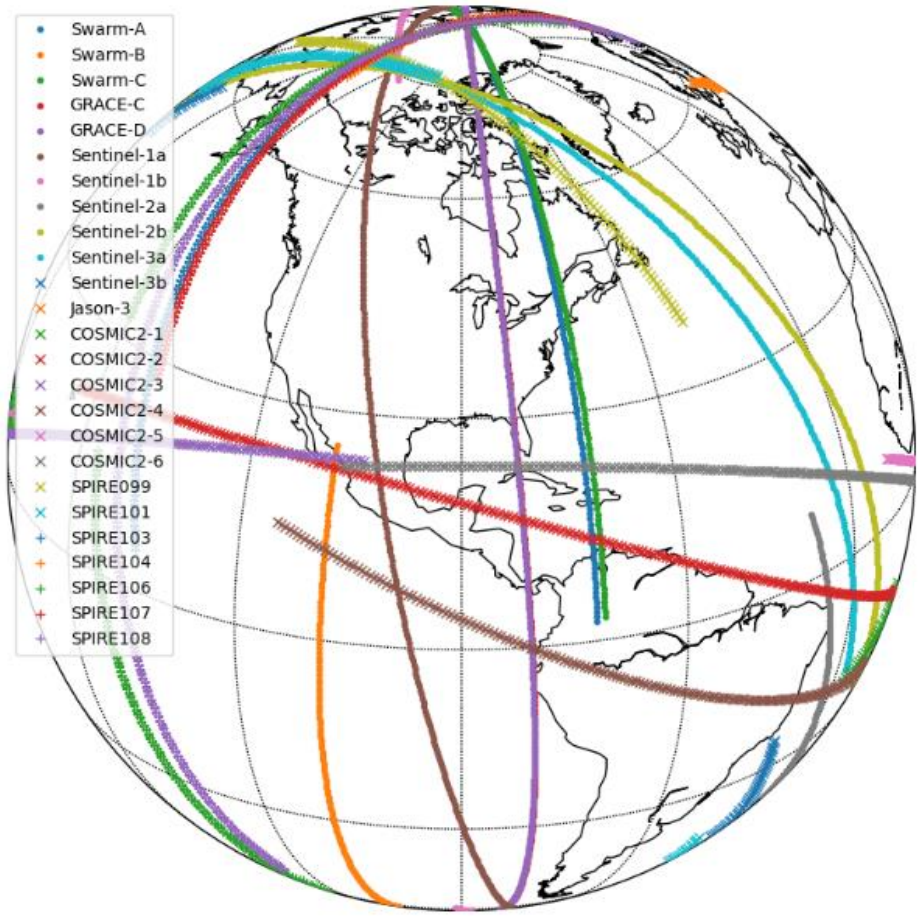
Motivation:

- A systematic difference between COSMIC (radio occultation) and Swarm electron density (Langmuir) is observed. This is most prominent during nighttime when more light ions are present (e.g., Smirnov, 2021).
- This issue was successfully addressed in the **Swarm Langmuir probe ion drift, density and effective mass (SLIDEM)** project (Pakhotin, 2022), however many gaps are present.

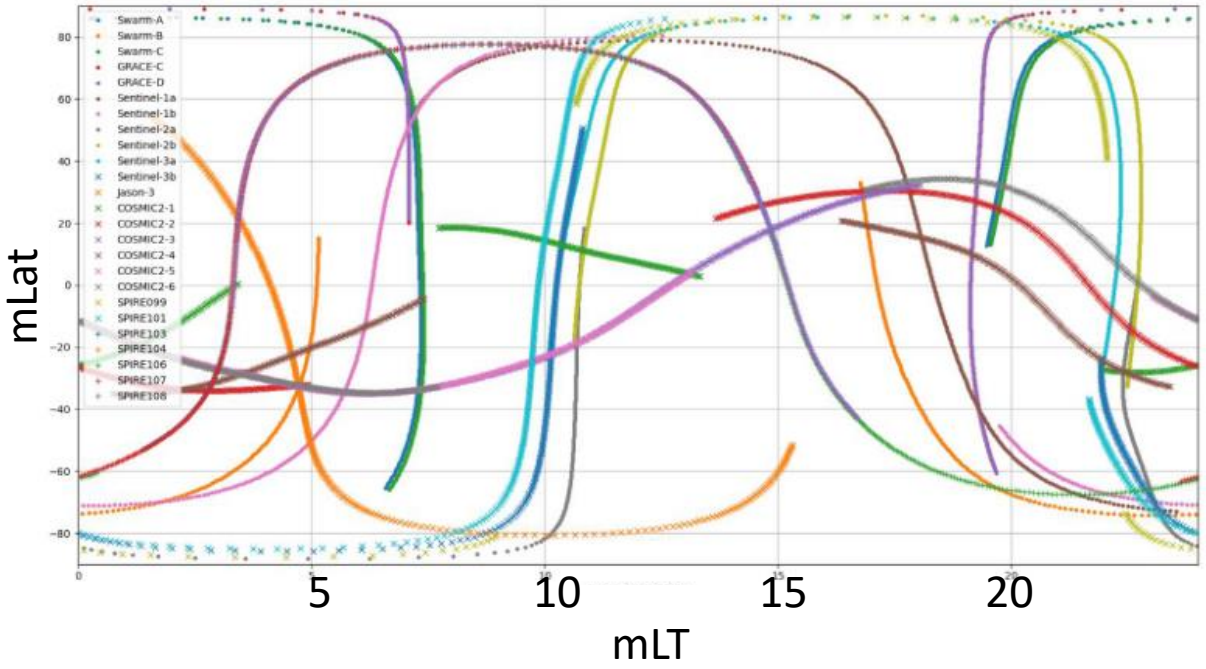
In this work:

- We construct a three-dimensional electron density model based on GPS **slant Total Electron Content** (sTEC) from **multiple LEO** satellites
- We validate the model using electron density from Swarm, DMSP, and GRACE-FO
- By comparing the electron density form Swarm Langmuir probes and the model, we derive effective ion mass.

Satellites used in this study:
Swarm, GRACE-FO, Jason-3, Sentinel 1/2/3, COSMIC-2, Spire



Positions of the LEO satellites between 00:00 UTC and 01:00 UTC
(May, 2, 2020)

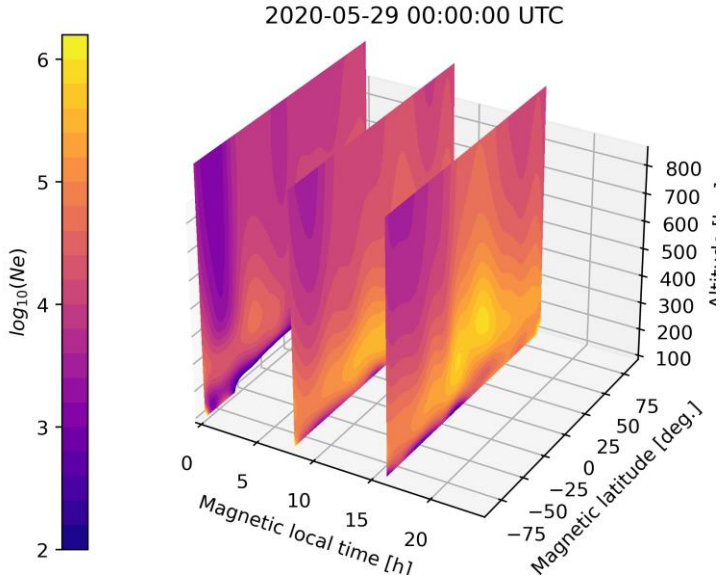


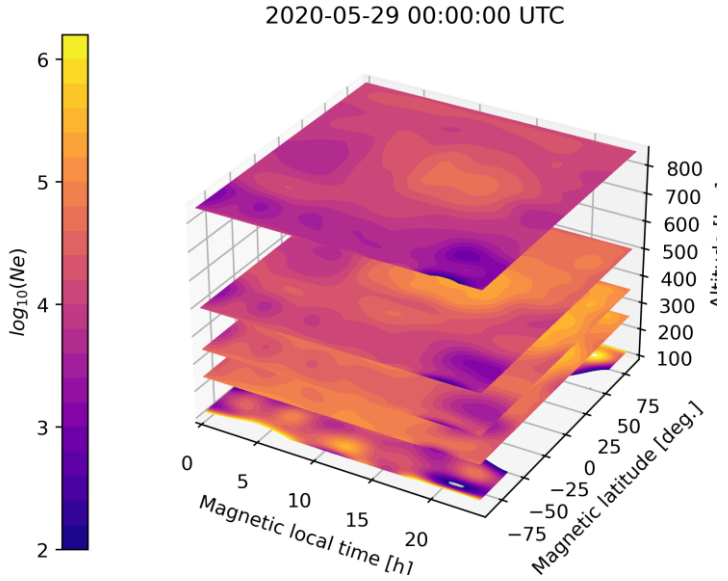
In total 25 satellites provide a good global coverage within just 1 hour.

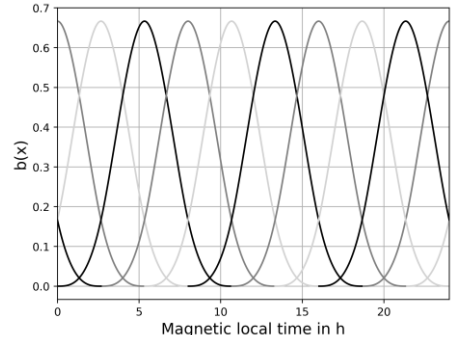
- The model utilizes cubic B-splines in mag. Latitude, local time, and altitude to model logarithmic electron density:

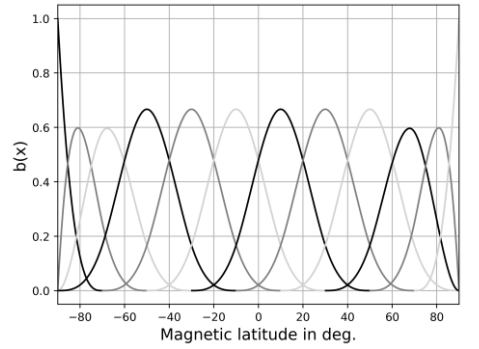
$$\log\left(N_e(lat_m, lt_m, h)\right) = \sum_{i,j,k} c_{ijk} \cdot B_i(lat_m) \cdot B_j(lt_m) \cdot B_k(h)$$

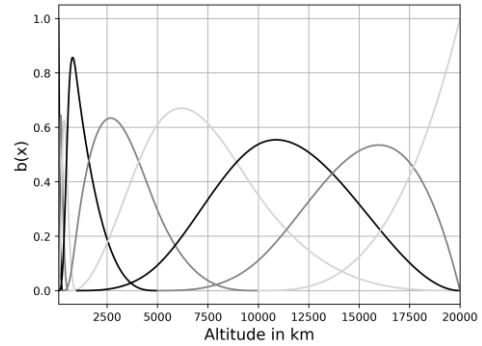
- Coefficients are estimated using a Kalman filter approach.
- Relative sTEC observations are assimilated using integration along the line of sight.











Example of cubic basis splines

Model Adjustment by **extended** Kalman-Filter,
relative slant TEC observations are assimilated:

Integration along the ray-path:

$$sTEC = \int_{rec}^{GNSS} Ne(s)ds + b \approx \sum_{i=1}^{n_{int}} w_i \cdot Ne(s_i) + b$$

w_i are the weights and s_i are the support points we used **Gauss-Legendre** quadrature.

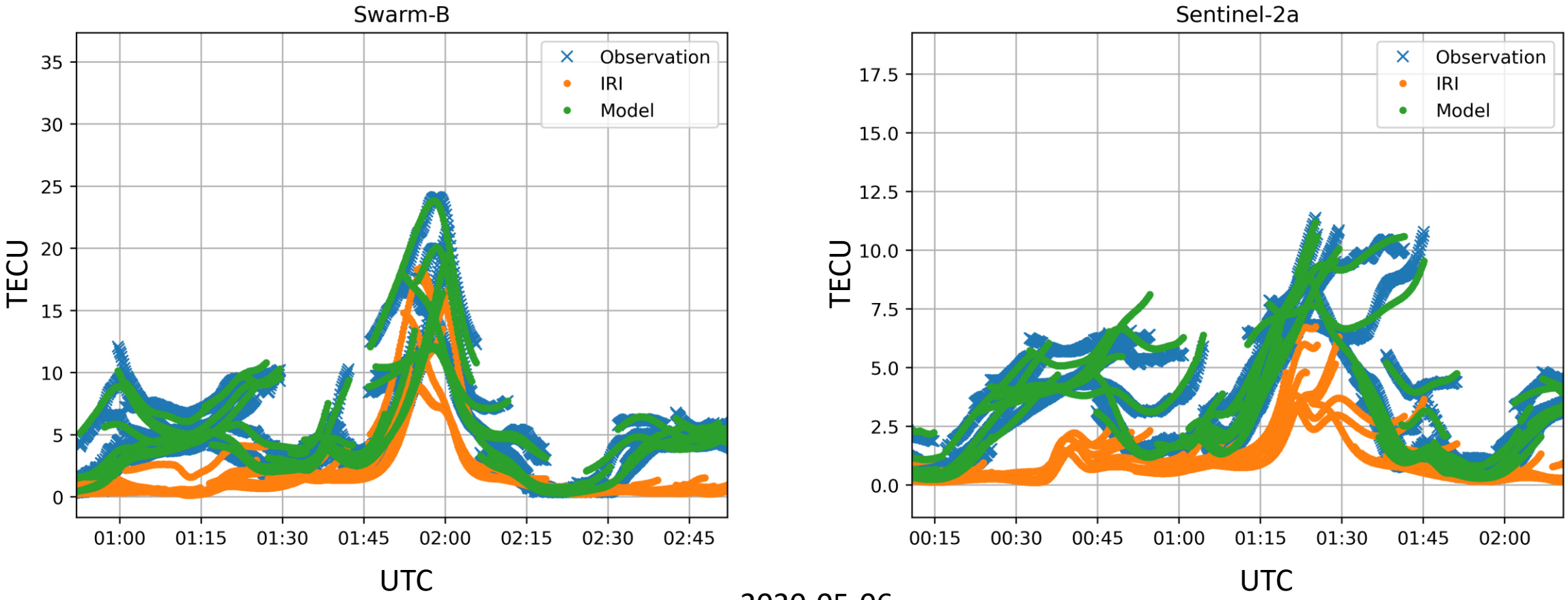
For Assimilating sTEC observations, this is rewritten as:

$$\boldsymbol{sTEC} = \underbrace{\boldsymbol{W} \cdot \exp(\boldsymbol{D} \cdot \boldsymbol{x})}_{H(x)} + \boldsymbol{b}$$

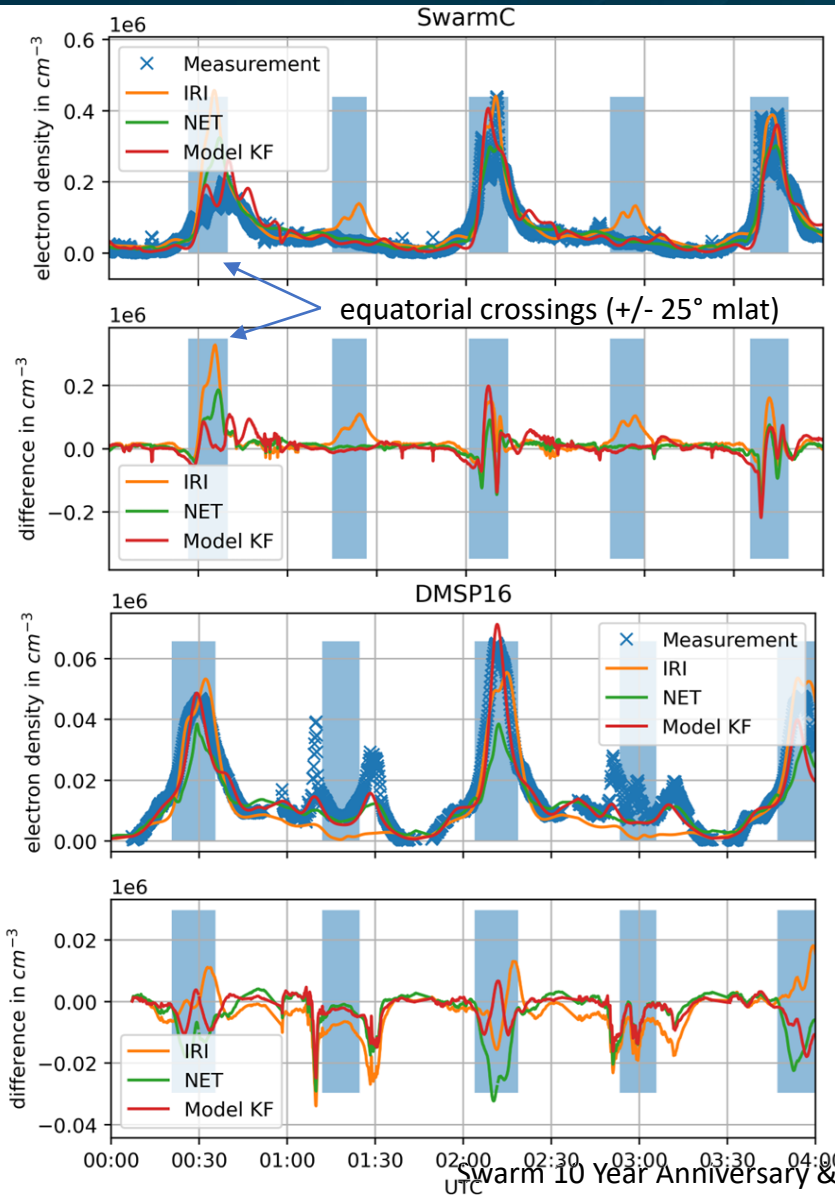
Non-linear observation operator

$\boldsymbol{W}$ is a matrix containing the weights, and $\boldsymbol{D}$ evaluates the logarithmic electron density at the support points. $\boldsymbol{b}$ contains arc-specific biases, such as ambiguities (eliminated by differencing).

Internal consistency: Model slant TEC, observed slant TEC and IRI-2020 values



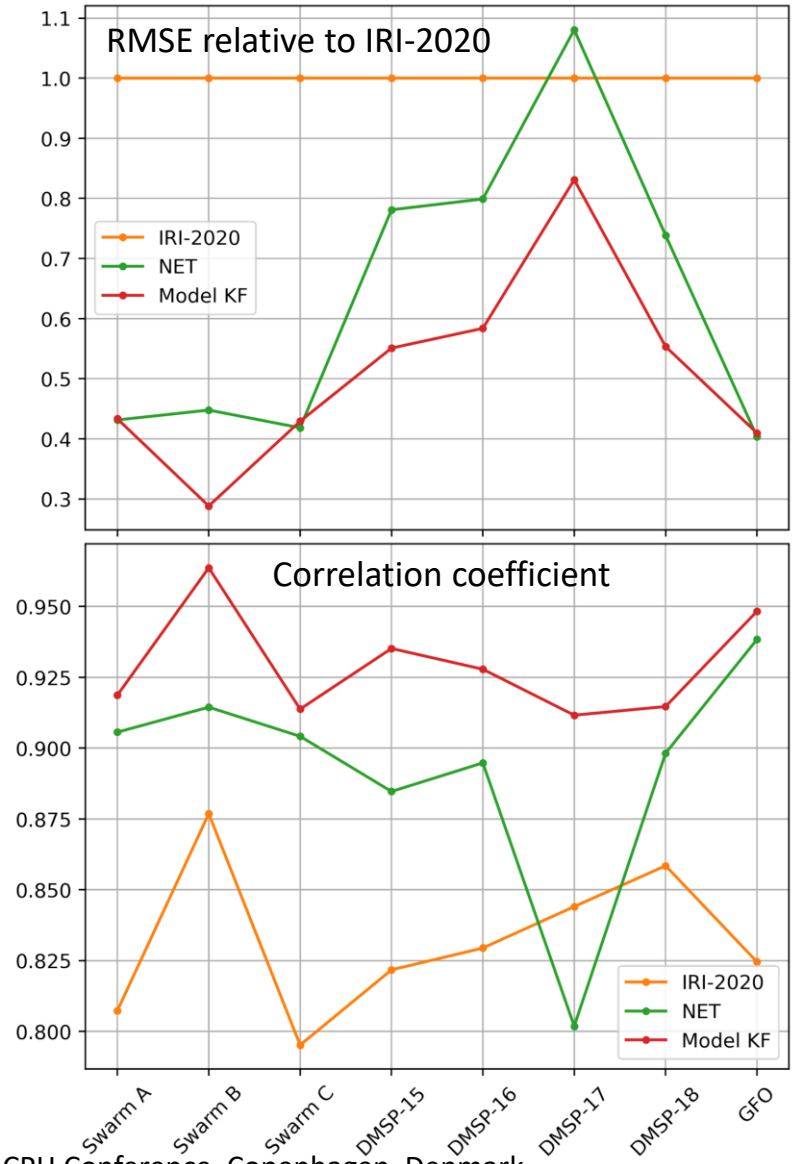
2020-05-06



External validation
2020-05-08

NET model: Neuronal network model by Artem Smirnov

Swarm LP measurements corrected for effective ion-mass using IRI-2020



Assumptions for Swarm. N_e is derived assuming pure oxygen ions (16 AMU, N_i^{16}), and $N_i = N_e$.
If N_i^{16} and N_e are known, m_s can be derived (SLIDEM: from intercomparison with faceplate)

$$N_i = \frac{d_s\, v_s\, m_s}{2e^2\, \pi\, r_p^2},$$

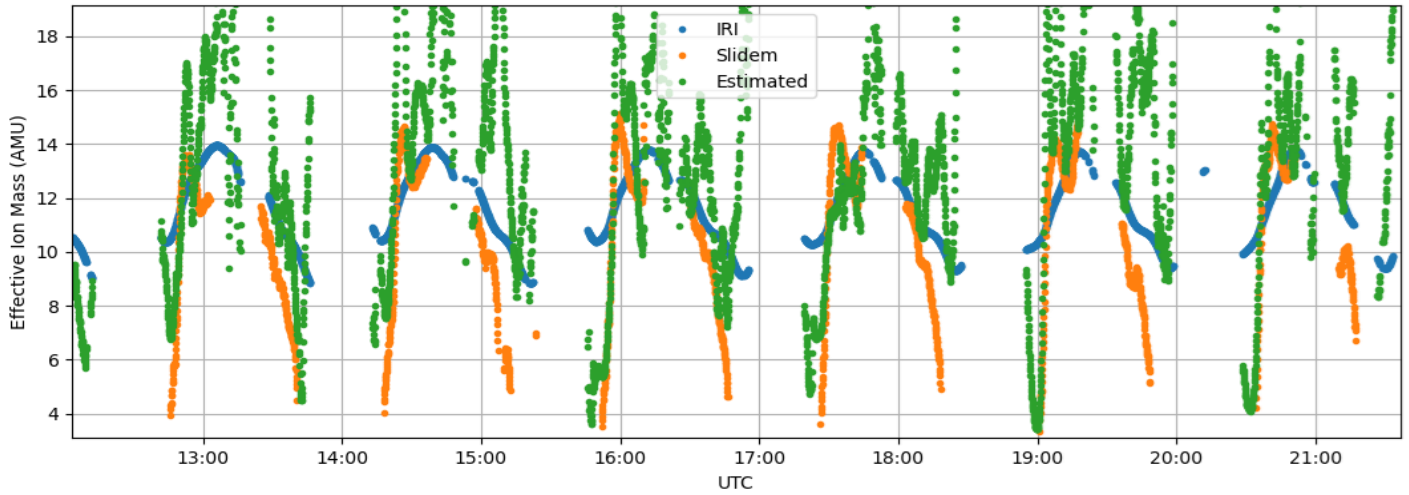
From Model → N_e

From Langmuir Probe → N_i^{16}

$$\frac{N_e}{N_i^{16}} \approx \frac{N_i}{N_i^{16}} = m_s/16$$

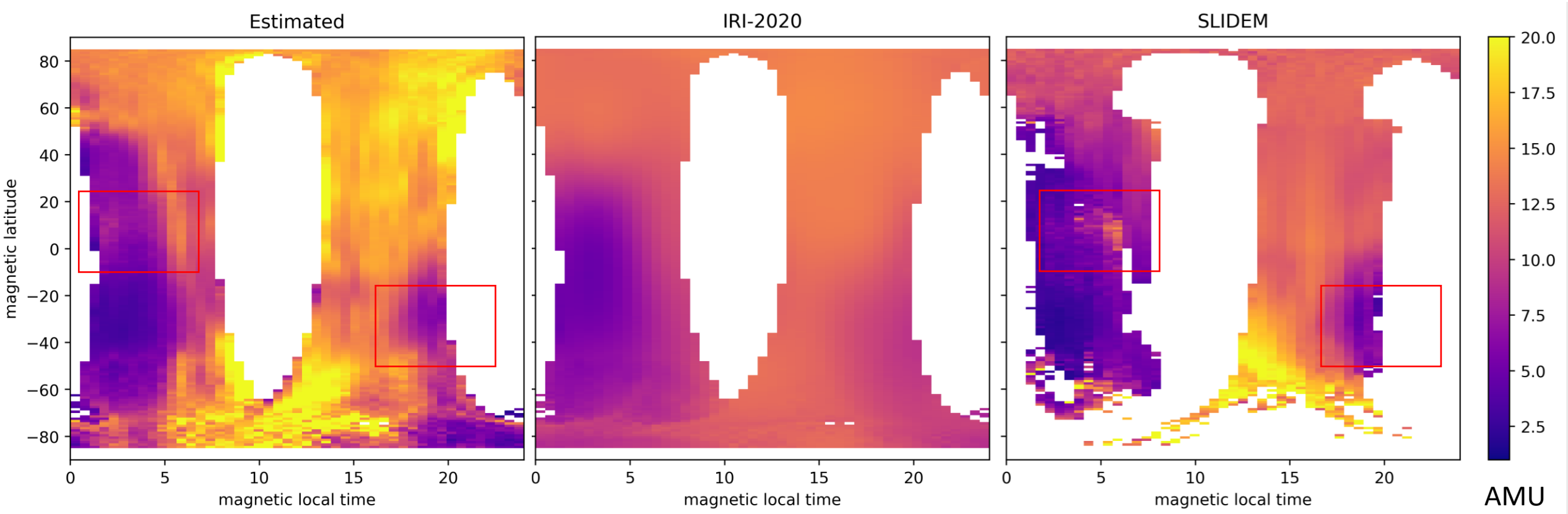
where N_i is the ion density, d_s is the ion admittance, v_s is the plasma ram speed, m_s is the effective ion mass, e is the elementary charge, and r_p is the probe spherical radius.

Effective Ion mass for Swarm C 2020-05-06



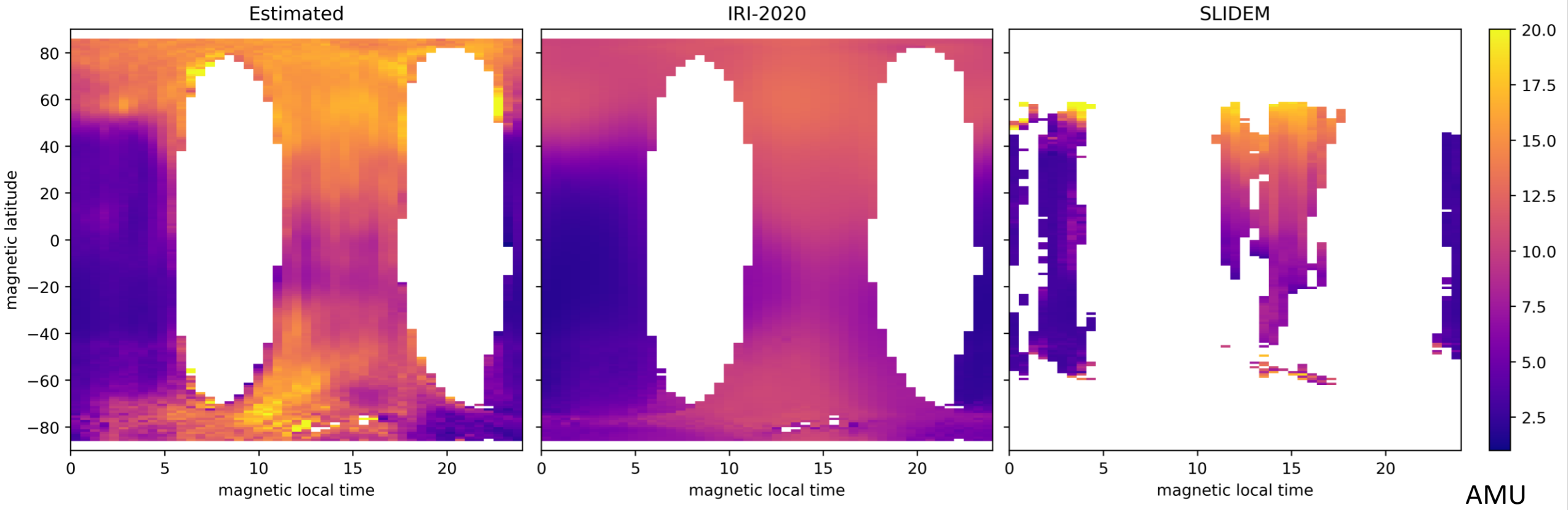
Swarm C, June-July 2020

Comparison of effective ion-mass in magnetic coordinates



Swarm B, June-July 2020

Comparison of effective ion-mass in magnetic coordinates



- We developed a **Kalman-filter model** to provide **3D** electron density
- Model adjustment is performed using **LEO GPS data**
- Validation with insitu data (Swarm, DMSP, GRACE-FO) shows good agreement

- Derived electron density is used as input to **derive effective ion-mass**
- **Similar features** as in the **SLIDEM** data set could be observed
- **Extending the database**, especially for Swarm A and Swarm B
- **Good agreement with SLIDEM**, especially for pre-sunrise features in effective ion mass. Significant differences to IRI, especially on the nightside.

Thank you for your Attention!