AIDA: A Real-Time Global Ionosphere/Plasmasphere Data Assimilation Model

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Abstract

The Advanced Ionospheric Data Assimilation (AIDA) is a real-time data assimilation model of global 3D ionosphere and plasmasphere electron density. Changes in the local space environment can occur on very short timescales, particularly during disturbed geomagnetic conditions. This space weather has an impact on many modern systems including Global Navigation Satellite System (GNSS) signals and High Frequency radio communications. To provide an ionospheric specification in real-time, AIDA ingests data streams from over 2000 GNSS receivers, using observations from both the Global Positioning System (GPS) and Galileo constellations, along with ionosonde-derived characteristics from the Global Ionosphere Radio Observatory (GIRO). These measurements are assimilated using a particle filter into the empirical NeQuick ionosphere model and Neustrelitz Plasmasphere Model (NPSM). The GNSS receiver Differential Code Biases (DCBs) are solved self-consistently using Rao-Blackwellized particle filtering. AIDA produces output at three latencies, the real-time Ultra Rapid product, the near-real-time Rapid product which operates at a 90-minute delay, and the Final product with a one day lag. The Ultra Rapid and Rapid products also include forecast products out to 6 hours ahead of real time.

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SERENE SPACE ENVIRONMENT

Abstract

The Advanced Ionospheric Data Assimilation (AIDA) is a real-time data assimilation model of global 3D ionosphere and plasmasphere electron density. Changes in the local space environment can occur on very short timescales, particularly during disturbed geomagnetic conditions. This space weather has an impact on many modern systems including Global Navigation Satellite System (GNSS) signals and High Frequency radio communications. To provide an ionospheric specification in real-time, AIDA ingests data streams from over 2000 GNSS receivers, using observations from both the Global Positioning System (GPS) and Galileo constellations, along with ionosonde-derived characteristics from the Global Ionosphere Radio Observatory (GIRO). These measurements are assimilated using a particle filter into the empirical NeQuick ionosphere model and Neustrelitz Plasmasphere Model (NPSM). The GNSS receiver Differential Code Biases (DCBs) are solved self-consistently using Rao-Blackwellized particle filtering. AIDA produces output at three latencies, the real-time Ultra Rapid product, the near-real-time Rapid product which operates at a 90-minute delay, and the Final product with a one day lag. The Ultra Rapid and Rapid products also include forecast products out to 6 hours ahead of real time.

Data Sources

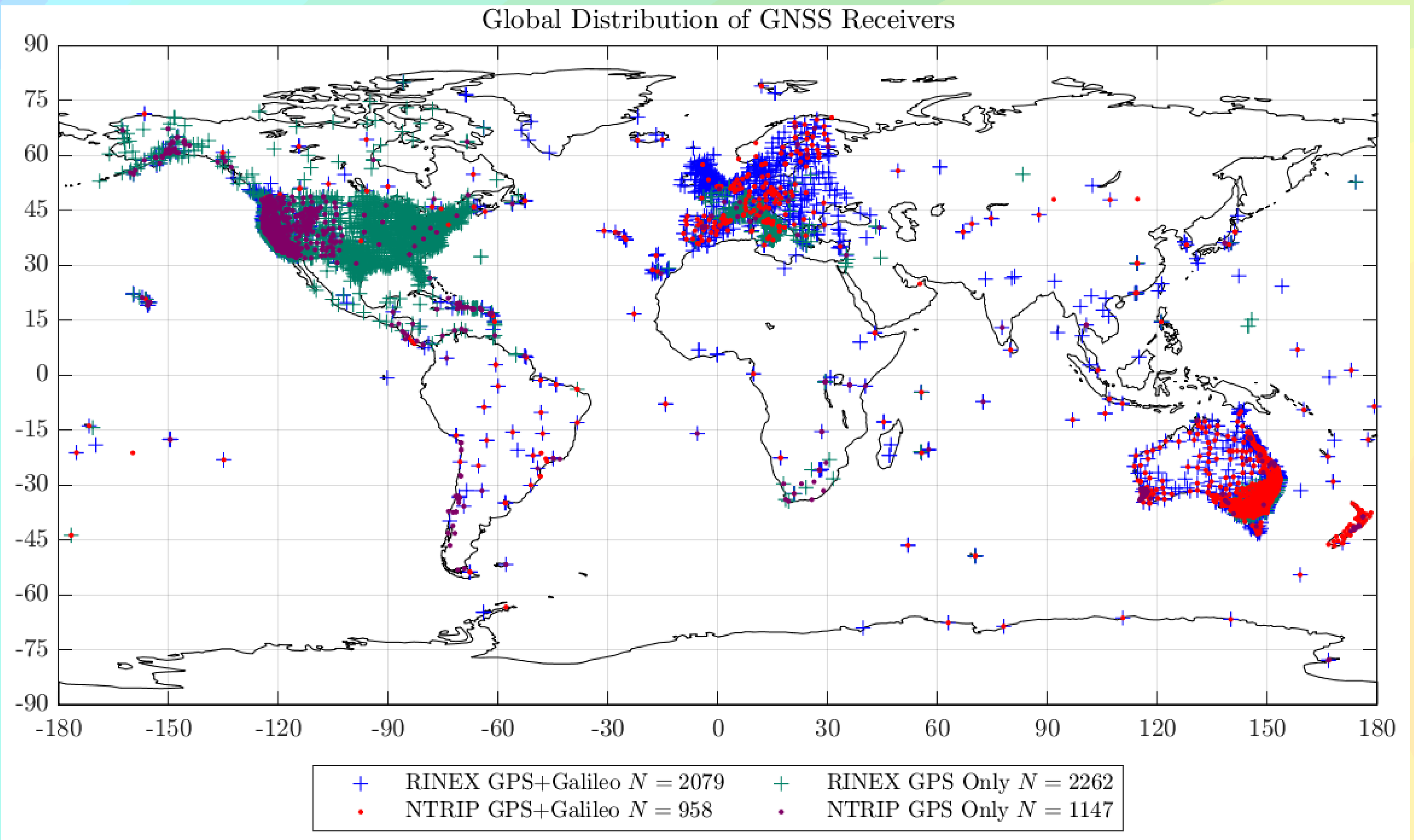

Figure 1: GNSS stations included in AIDA. Stations marked with dots provide data in real time through the NTRIP protocol. Stations marked with crosses provide RINEX data within 3 hours of the end of day for the Final model.

Table 1: GNSS Pseudorange observable combinations used by AIDA.

RINEX Version	GNSS Constellation	Pseudorange Combination
RINEX V2	GPS	C1-P2
RINEX V3	GPS	C1C-C2S C1C-C2W C1C-C5Q C1C-C5X C1W-C2L C1W-C2S C1W-C2W C1W-C2X C1W-C5Q C1W-C5X
RINEX V3	Galileo	C1C-C5Q C1C-C6C C1C-C7Q C1C-C8Q C1X-C5X C1X-C7X C1X-C8X C5Q-C6C

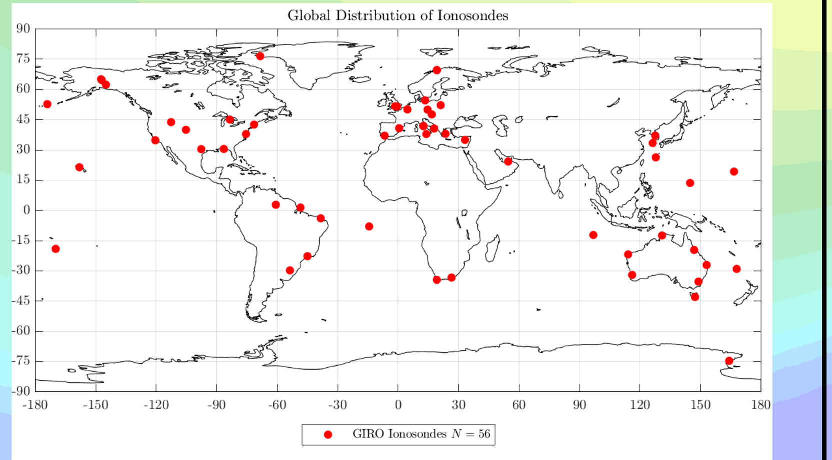

Figure 2: GIRO ionosondes reporting data during 2023. Typically 30 to 60 ionograms are available during a 5-minute assimilation window for the Rapid model. foF2, hmF2, foF1, and hmF1 are all assimilated.

Real-Time Operation

1 Hz data is streamed from over 2000 worldwide NTRIP-capable GNSS receivers, which is saved to disk at 5-minute intervals in RINEX v3 format. As soon as it is available, this new data is ingested by AIDA and all phase-levelling is re-calculated. The sTEC from the previous 5 minutes is assimilated by the AIDA Ultra Rapid model until a new set of NTRIP data becomes available, at which point the current ionospheric state is finalized and published online. The AIDA Rapid model operates concurrently to share data processing overhead. The sTEC from 90 minutes in the past is assimilated, along with automatically processed ionosonde measurements from GIRO [1]. Receiver DCBs for both models are fixed in the Rapid model using Rao-Blackwellized particle filtering [2]. Once the outputs of both models are finalized, each is forecast up to 6 hours into the future, and made available within 5 minutes.

The AIDA Final model uses RINEX GNSS data, which allows many more stations to contribute measurements, along with the GIRO ionosondes. In the future this model will also include other data sources which are able to operate in near-real-time, including the SENTINEL altimeter vTEC and the near-real-time SWARM data products.

A New Ionosphere-Plasmasphere Parameterization

AIDA uses a particle filter data assimilation technique similar to that used in A-CHAIM [3]. AIDA uses the NeQuick ionosphere model [4] and the Neustrelitz Plasmasphere Model [5] as empirical background models. A new ionosphere-plasmasphere electron density parameterization was developed to combine the two models consistently. The AIDA ionospheric electron density has the same parameterization as NeQuick:

$$\mathrm{Ne}_{iono} = \begin{cases} \mathrm{NmF2}\cdot\mathrm{sech}^2\left(\frac{h-\mathrm{hmF2}}{2\cdot H}\right) & h \geq \mathrm{hmF2} \\ \mathrm{NmF2}\cdot\mathrm{sech}^2\left(\frac{h-\mathrm{hmF2}}{2\cdot \mathrm{B2_{bot}}}\right) + \mathrm{NmF1}^*\cdot\mathrm{sech}^2\left(\frac{h-\mathrm{hmF1}}{2\cdot \mathrm{B1}}\right) + \mathrm{NmE}^*\cdot\mathrm{sech}^2\left(\frac{h-\mathrm{hmE}}{2\cdot \mathrm{BE}}\right) & h < \mathrm{hmF2} \end{cases}$$

where:

$$\mathrm{B1} = \begin{cases} \mathrm{B1_{bot}} & h < \mathrm{hmF1} \\ \mathrm{B1_{top}} & h \geq \mathrm{hmF1} \end{cases} \quad \mathrm{BE} = \begin{cases} \mathrm{Be_{bot}} & h < \mathrm{hmE} \\ \mathrm{Be_{top}} & h \geq \mathrm{hmE} \end{cases} \quad H = \mathrm{B2_{top}}\cdot\left(1 + \frac{rg(h-\mathrm{hmF2})}{r\mathrm{B2_{top}} + g(h-\mathrm{hmF2})}\right)$$

In NeQuick the parameters $r = 100$ and $g = 0.125$ have fixed values. In AIDA they are defined to ensure the ionosphere profile merges seamlessly with the plasmasphere electron density. AIDA uses the same plasmapause model as the NPSM:

$$\mathrm{Ne}_{pp} = F_{pp}\cdot\mathrm{Nmpt}\cdot\exp\left(\frac{R_E\cdot(1-L)}{\mathrm{Hpt}}\right) + 1\times10^7 \quad \text{where} \quad F_{pp} = \frac{1}{\pi}\,\mathrm{atan}\left(\frac{(L_{pp}\cos^2\mathrm{mlat} - 1)R_E - h}{500\ \mathrm{km}}\right) + \frac{1}{2}$$

The NPSM also includes a lower plasmasphere component, and in AIDA r and g are fixed to replace this lower plasmasphere.

$$\mathrm{Ne_{NPSM}} = \mathrm{Nmpl}\cdot\exp\left(\frac{-h}{\mathrm{H_{pl}}}\right) + \mathrm{Ne}_{pp}$$

In NeQuick-style topsides r determines the asymptote of the topside scale height, which is chosen to be the lower plasmasphere scale height from NPSM:

$$r = \frac{\mathrm{H_{pl}} - \mathrm{B2_{top}}}{\mathrm{B2_{top}}}$$

g is fixed by forcing the ionospheric topside to converge with the lower NPSM plasmasphere at a fixed height h_g, where the scale height must be H_g:

$$H_g = \frac{h_g - \mathrm{hmF2}}{2\cdot Ag}$$

$$A_g = \mathrm{asech}\left(\sqrt{\frac{\mathrm{Nmpl}}{\mathrm{NmF2}}\exp\left(\frac{-h_g}{\mathrm{H_{pl}}}\right)}\right)$$

$$g = \frac{r\mathrm{B2_{top}}(H_g - \mathrm{B2_{top}})}{(h_g - \mathrm{hmF2})(r\mathrm{B2_{top}} - H_g + \mathrm{B2_{top}})}$$

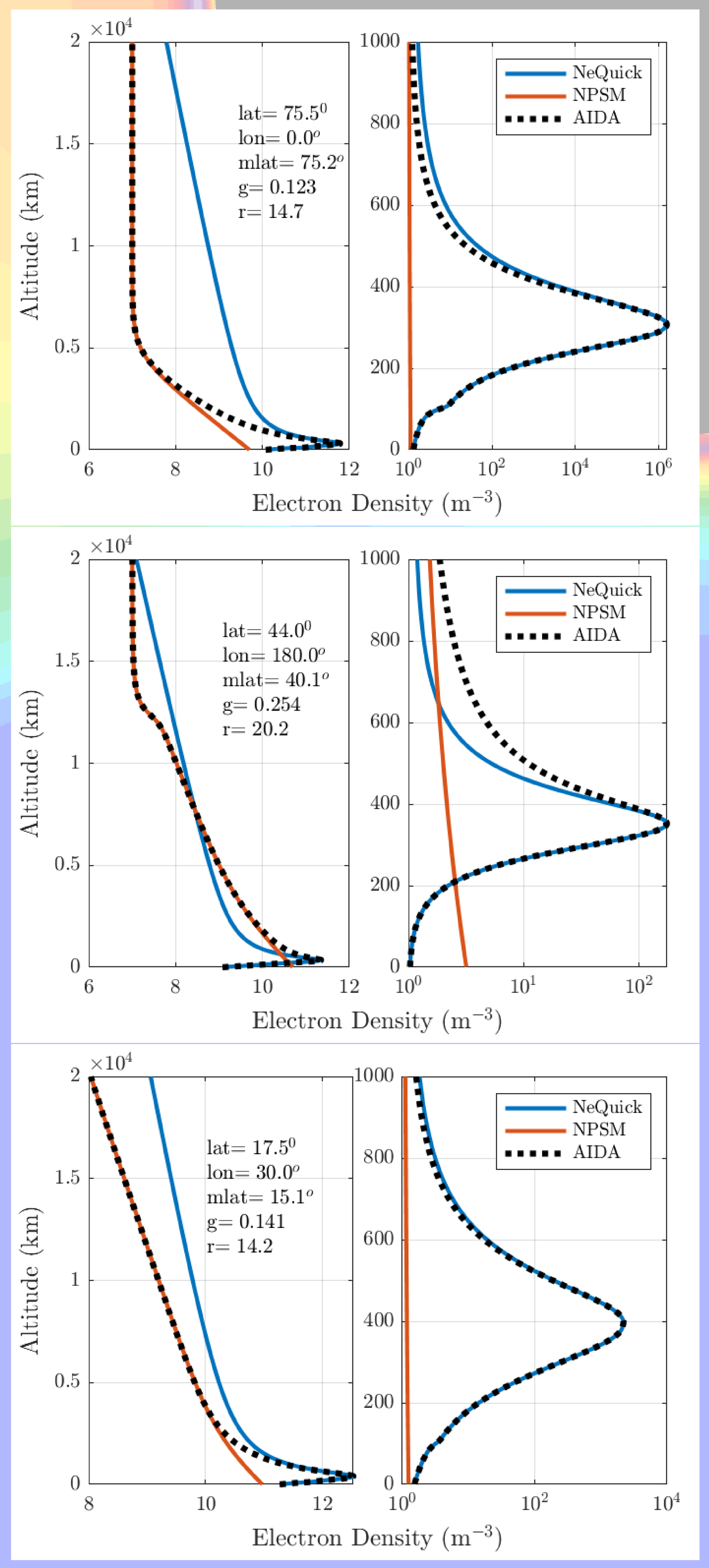

Figure 3: High-, mid-, and equatorial latitude vertical electron density profiles for NeQuick, NPSM, and AIDA.

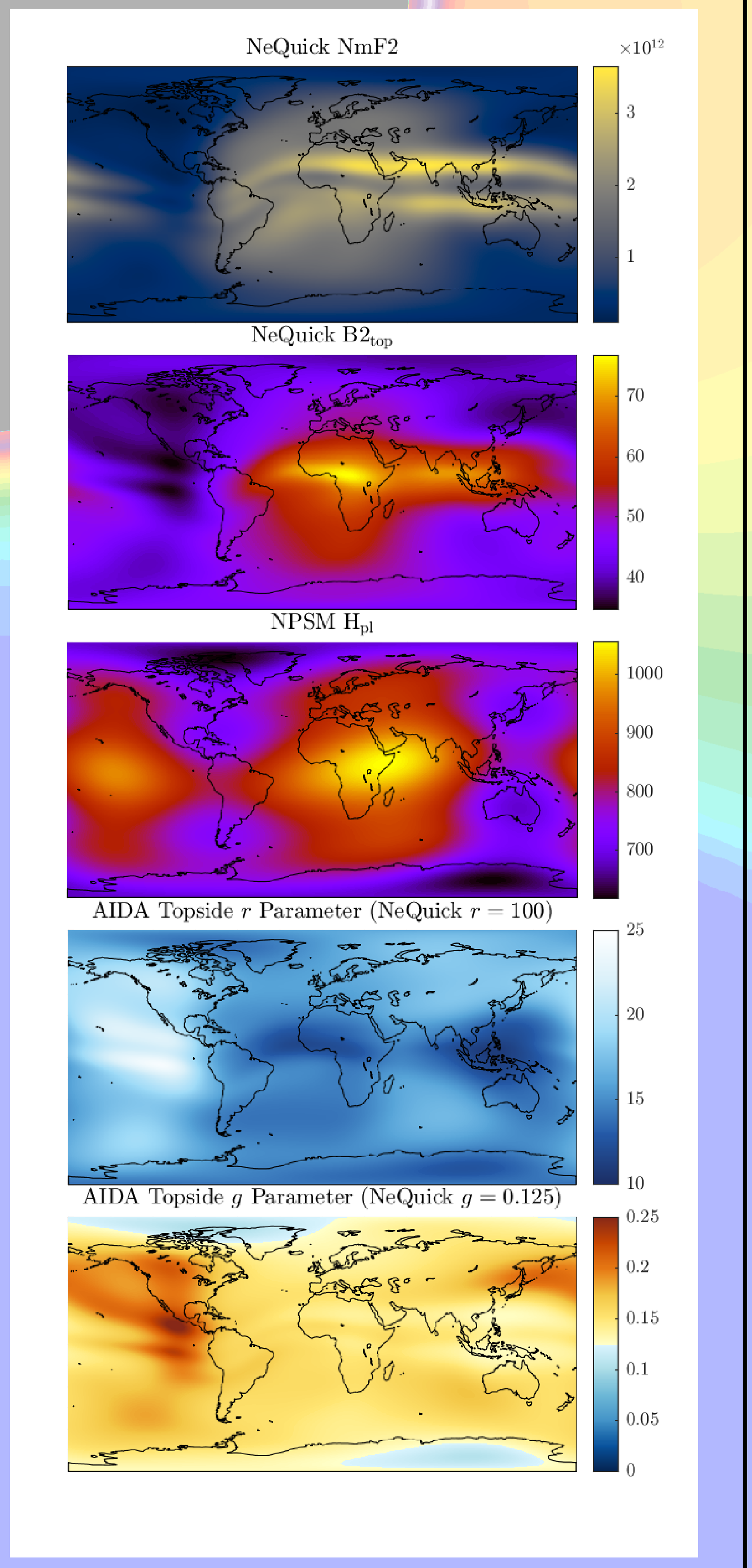

Figure 4: NeQuick topside and NPSM plasmasphere scale heights, and the resulting r and g values used in AIDA.

Results

All results are from the operational AIDA model. Output is available in real-time at `https://spaceweather.bham.ac.uk/output/`. Results from NeQuick were produced using a python implementation of the NeQuickG model, and not from the official Fortran source.

Ionosondes

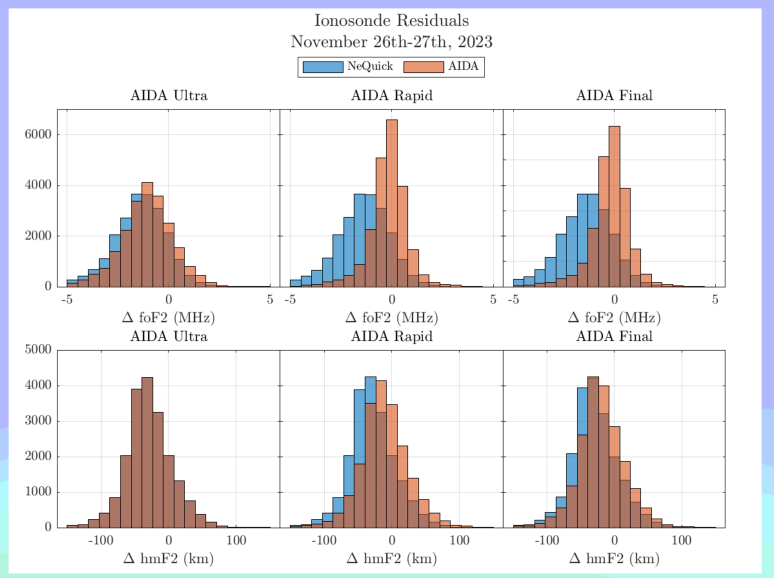

Figure 5: Residual foF2 and hmF2 from the ionosondes assimilated by AIDA. The AIDA Ultra model does not assimilate ionosonde data, and has hmF2 fixed to the background model. The AIDA background model and NeQuick are identical in the bottomside.

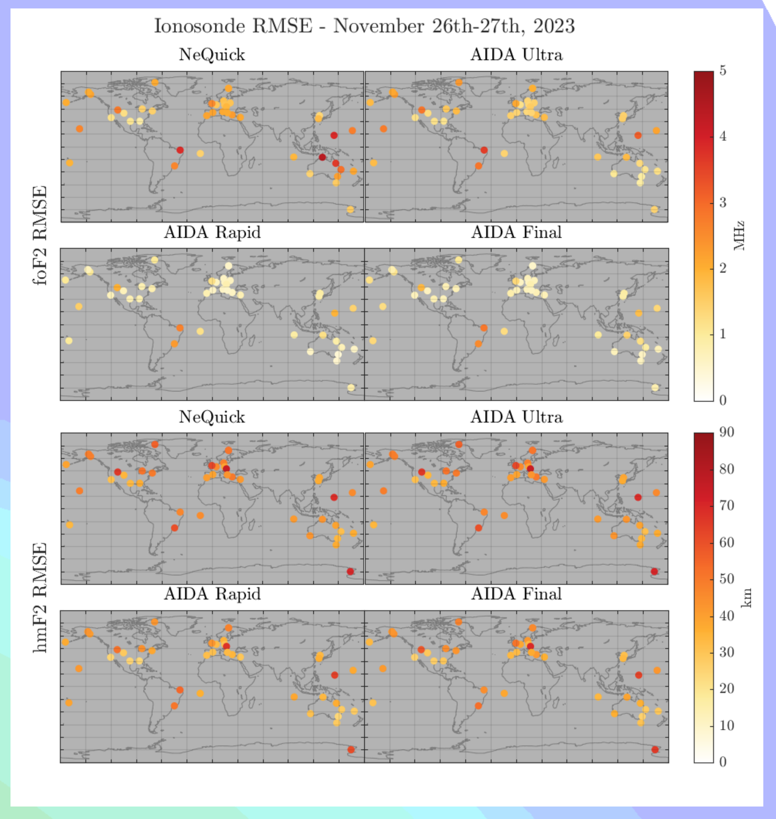

Figure 6: Change in RMSE for each model compared to NeQuick

In-Situ

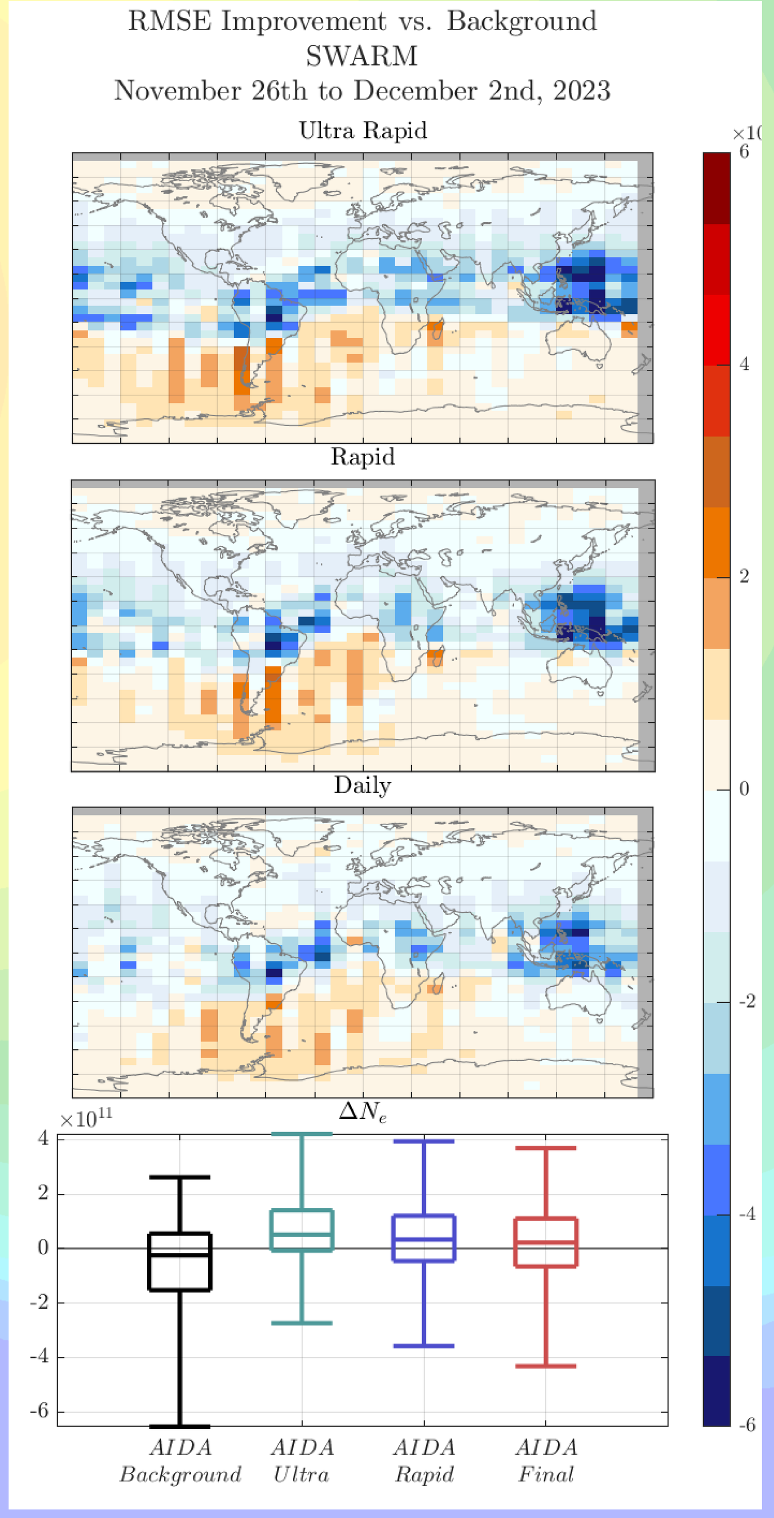

Figure 7: In-situ measurements from the SWARM A, SWARM B and SWARM C fast level 1B data products.

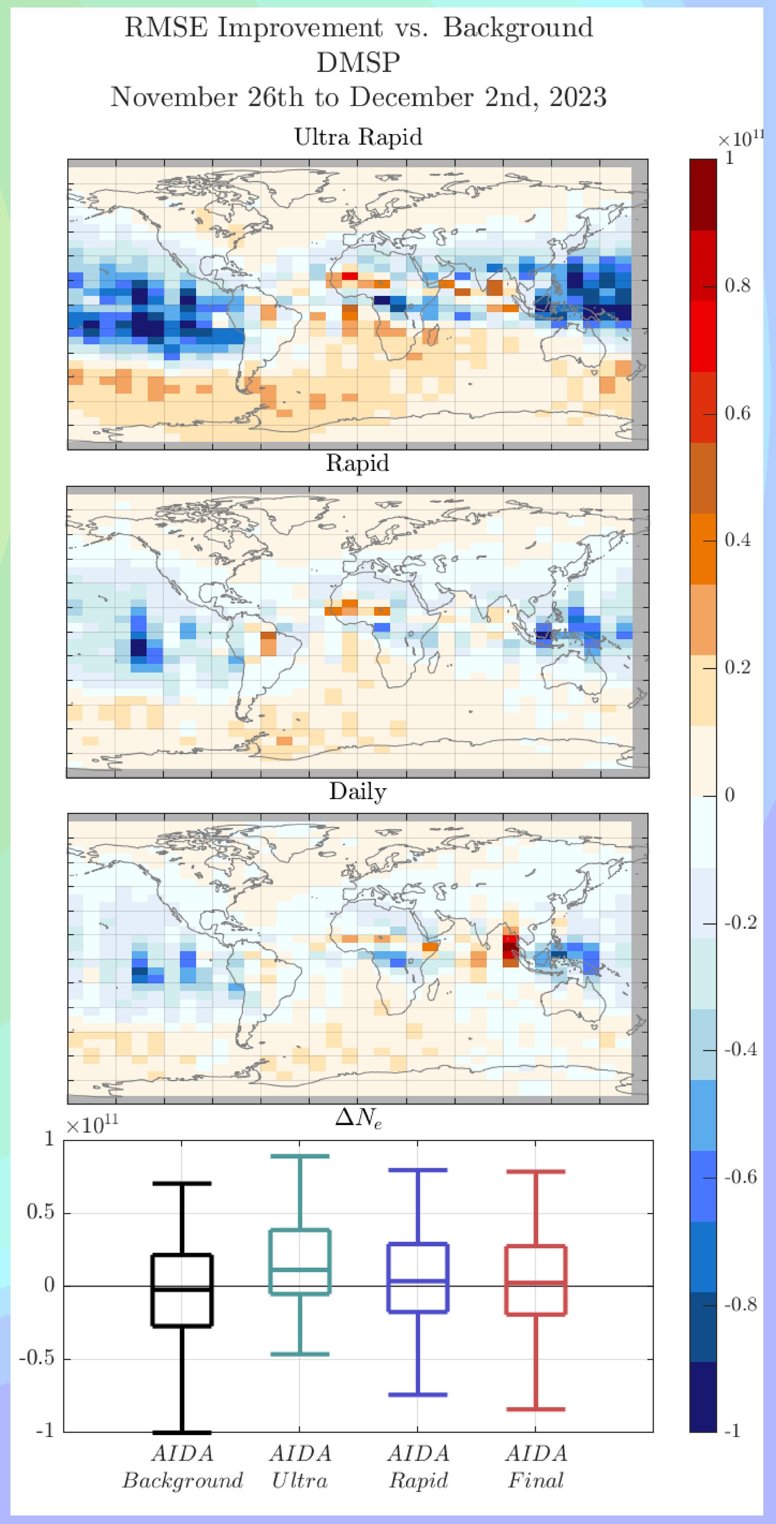

Figure 8: In-situ measurements from DMSP F16, DMSP F17, and DMSP F18.

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