Swarm SCARF Equatorial Electric Field Inversion Chain

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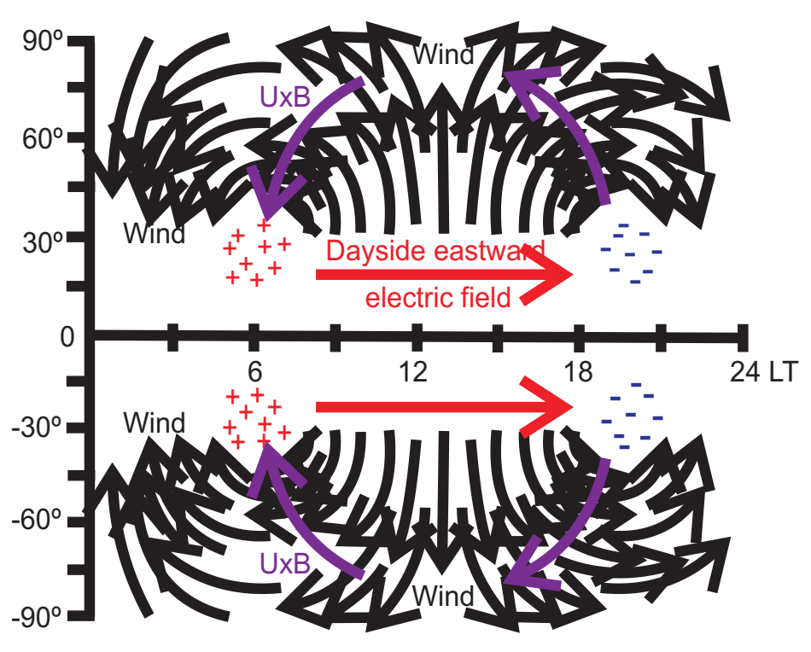
Abstract

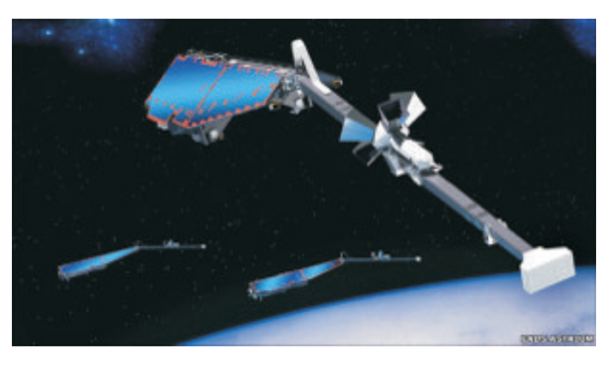
The day-time eastward equatorial electric field (EEF) in the ionospheric E-region plays a crucial role in equatorial ionospheric dynamics. It is responsible for driving the equatorial electrojet (EEJ) current system, equatorial vertical ion drifts, and the equatorial ionization anomaly (EIA). Due to its importance, there is much interest in accurately measuring and modeling the EEF for both climatological and near real-time studies. The Swarm satellite mission offers a unique opportunity to estimate the equatorial electric field from measurements of the geomagnetic field. Due to the near-polar orbits of each satellite, the on-board magnetometers record a full profile in latitude of the ionospheric current signatures at satellite altitude. These latitudinal magnetic profiles are then modeled using a first principles approach with empirical climatological inputs specifying the state of the ionosphere. Since the EEF is the primary driver of the low-latitude ionospheric current system, the observed magnetic measurements can then be inverted for the EEF. This paper details the algorithm for recovering the EEF from Swarm geomagnetic field measurements. The equatorial electric field estimates are an official Swarm level-2 product developed within the Swarm SCARF (Satellite Constellation Application Research Facility). They will be made freely available by ESA after the commissioning phase.

Introduction

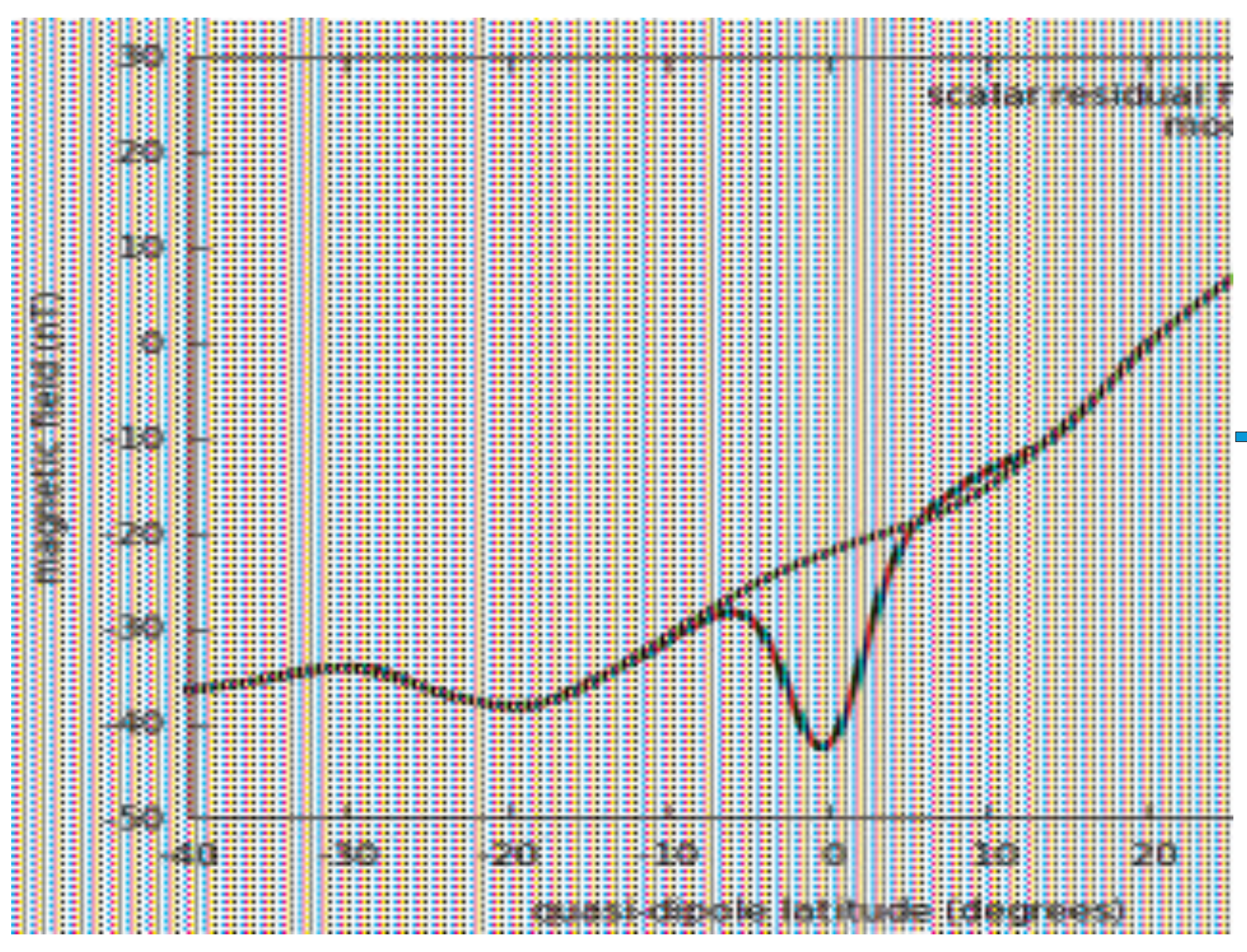


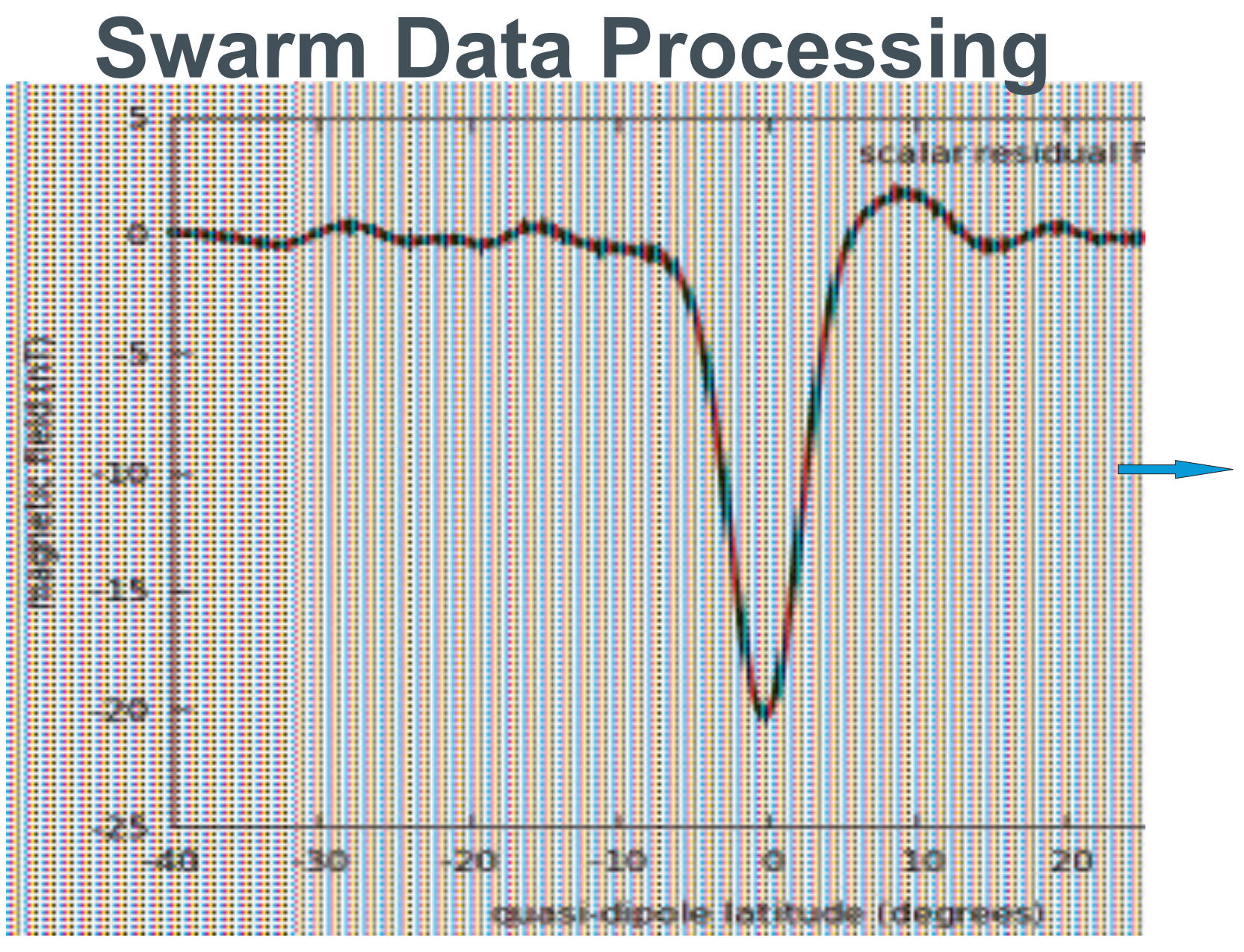
The dayside equatorial electric field (EEF) is generated by the motion of neutral winds in the ionosphere. As the sun ionizes the dayside, neutral winds push the ions causing large scale currents, with positive ions tending toward the dawn terminator and negative ions toward dusk. This causes an electric field across the dayside in the equatorial region, typically eastward. This electric field is responsible for driving the equatorial electrojet current system, vertical ion drift and the equatorial ionization anomaly.

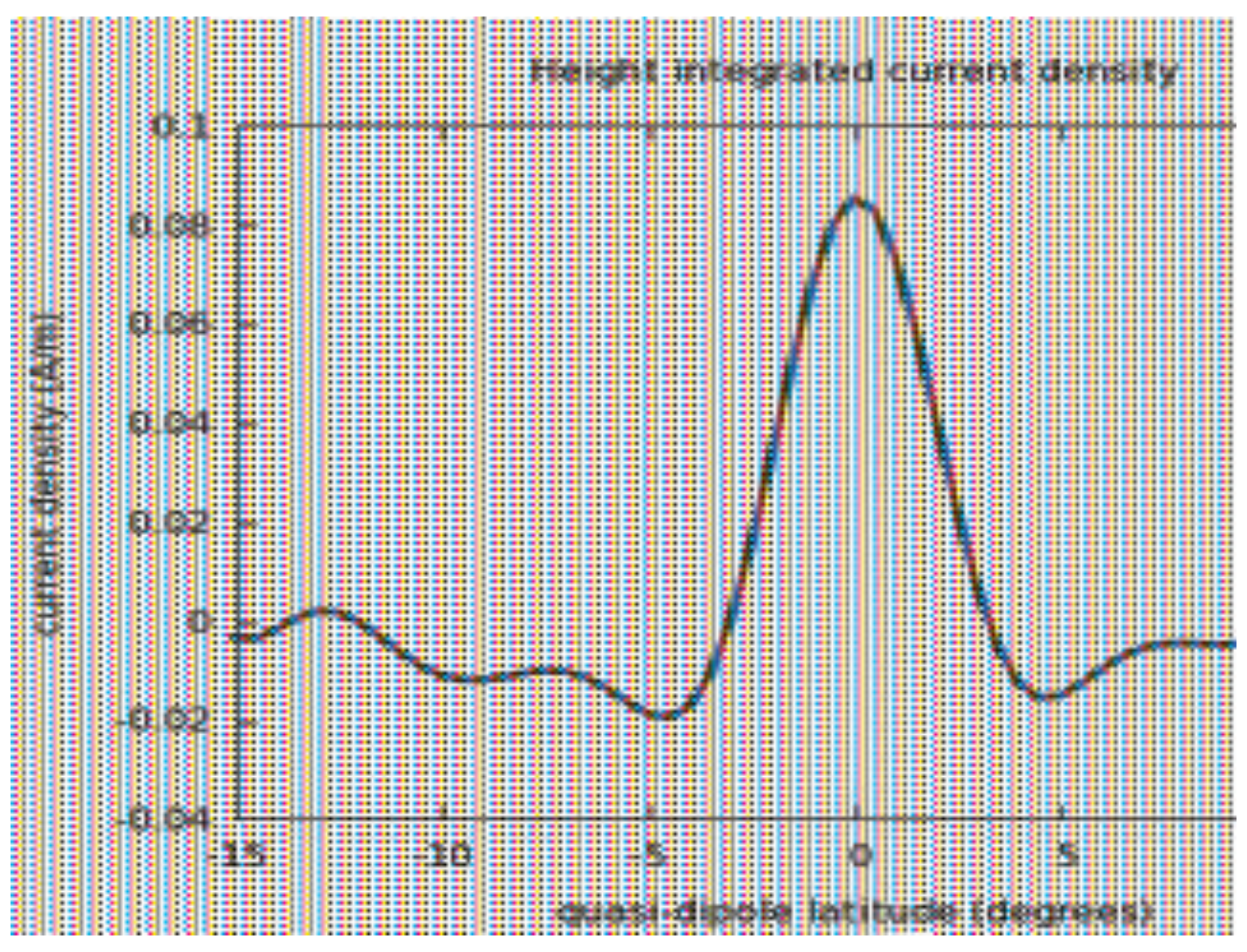
Direct measurements of the EEF have historically proven difficult, and are available only from a small number of ground-based radars (ie: Jicamarca) and a few satellite missions such as C/NOFS. In this Swarm SCARF Level-2 operational product, we demonstrate a method of indirectly estimating the EEF from high-quality measurements of the geomagnetic field for each orbit from Swarm.



Swarm Data Processing







Step 1

First we use scalar magnetic field values from the ASM instrument onboard Swarm and subtract main, crustal, and external field contributions using field models. These residuals are denoted by $F^{(1)}$ (shown in red above):

$$F^{(1)} = F_{swarm} - |\mathbf{B}_{core} + \mathbf{B}_{crust} + \mathbf{B}_{ext}|$$

The $F^{(1)}$ residuals are primarily a combination of magnetic signatures from the EEJ and Sq current systems, as well as other external fields not well represented by the field models. To eliminate Sq and external fields, we fit a simple spherical harmonic expansion to the $F^{(1)}$ residuals, shown in green above in order to reduce these effects and recover the EEJ signal. The EEJ is of main interest for us since it is directly generated by the equatorial electric field we are trying to estimate.

Step 2

After subtracting the Sq and external field model from the F(1) residuals, we obtain a latitudinal profile similar to that shown above. The center peak represents the magnetic signature of the EEJ. These data were recorded by CHAMP in December 2005. The peak is downward since CHAMP was flying above the EEJ region, where the magnetic signature opposes the main field direction.

This magnetic profile contains a great deal of information about the ionospheric conditions present at the time of the measurements. The ionospheric conductivity, neutral wind structure, and equatorial electric field all contribute significantly to the shape and structure of this profile.

Step 3

While the $F^{(2)}$ residuals contain a lot of useful information, the actual EEJ current density is the more fundamental quantity to consider. This is the physical parameter which enters into the equations governing the equatorial ionosphere, and our approach involves modeling the low-latitude current system in order to recover the EEF. Therefore we invert the residuals $F^{(2)}$ for the eastward current flow in the ionospheric E-region. This is done by assuming simple line currents flowing at 110km altitude spaced equally in latitude and inverting the $F^{(2)}$ residuals for the strength of these currents. This procedure produces a height-integrated current density (shown above), since one satellite pass is not sufficient to determine the full altitude dependence.

Equatorial Electrojet Modeling

$$\nabla \times \mathbf{E} = 0$$
$$\mathbf{J} = \underline{\sigma}(\mathbf{E} + \mathbf{u} \times \mathbf{B})$$

Step 4

To estimate the value of the EEF during the Swarm satellites' crossing of the magnetic equator, we solve the governing electrodynamic equations (above). Climatological models are used to specify the conductivity σ, neutral wind field **u**, and geomagnetic field **B**. The International Reference Ionosphere (IRI) and NRLMSISE-00 model are used to calculate the conductivity tensor σ. The Horizontal Wind Model (HWM07) specifies the horizontal wind velocity field **u**. The geomagnetic field **B** is given by the POMME-6 model.

Our goal is to determine the eastward component of the electric field vector **E** (E_φ). Therefore we use an iterative approach, using an initial guess for E_φ, computing the current density **J**, comparing with the satellite-derived current density in Step 3, and refining the guess for E_φ until the best agreement is reached.

While the IRI, MSIS, and HWM climatological models are unable to capture the high day-to-day variability of the ionosphere, the eastward electric field E_φ tends to dominate the shape of the current density profile near the equator. Therefore we are able to obtain realistic estimates of the EEF by demanding that our modeled profile agree with the satellite-derived profile at the magnetic equator.

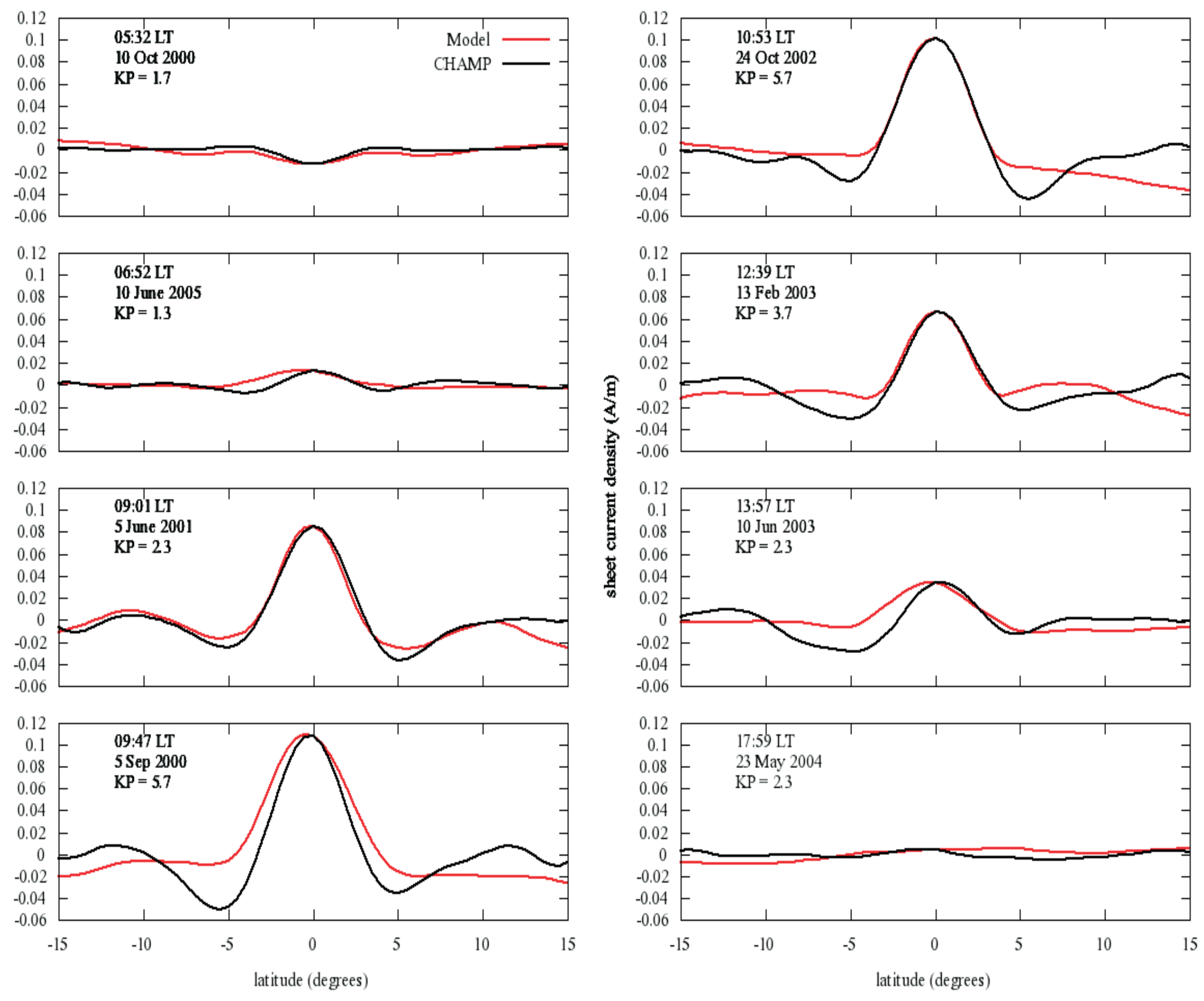
In the figure on the right, we plot a number of satellite-derived current density profiles from CHAMP (black) along with their modeled counterparts in red. A range of different local-times, including quiet and disturbed days were selected.

We see that sometimes the model represents the true current very well, while other times it is unable to adequately model higher latitude behavior. This is primarily due to the high variability in the neutral winds.

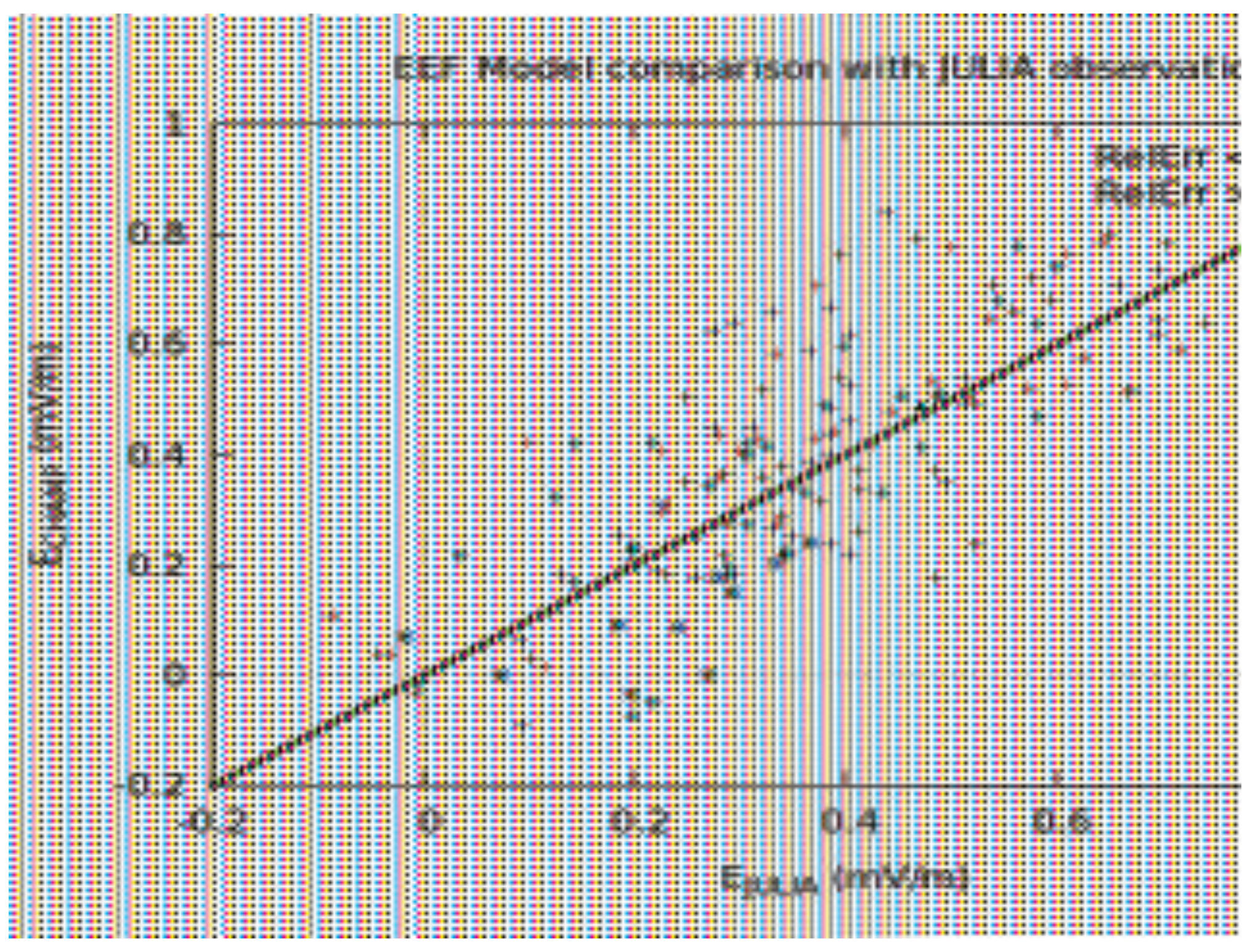
Generally, the model does well in capturing the main EEJ peak. In order to estimate the error in a given EEF estimate, we define the quantity

$$RelErr = \frac{\left|\left|\mathbf{J}_\phi^{MODEL} - \mathbf{J}_\phi^{SAT}\right|\right|}{\left|\left|\mathbf{J}_\phi^{SAT}\right|\right|}$$

where J_φ^{MODEL} is the modeled profile (shown in red) and J_φ^{SAT} is the satellite-derived profile (shown in black). This quantity gives an indication how well the model represents the true current.



Eastward Electric Field Validation



To validate the EEF estimates, we compare with independent measurements made by the JULIA radar at Jicamarca, near Lima, Peru. JULIA measures the velocities of vertically drifting plasma at 150km altitude near the magnetic equator. These vertical drift velocities are directly proportional to the eastward electric field. We took simultaneous measurements from CHAMP and JULIA and plotted them above.

Time period: May 2001 to June 2007
Number of data pairs: 162
Correlation: 0.80
Best fit line: $E_{CHAMP} = 1.04\, E_{JULIA} + 0.01$ mV/m

Conclusions

- Using the scalar ASM instrument on Swarm, we have developed a means of estimating the equatorial electric field for every dayside orbit
- Main steps of the algorithm include
  (1) Subtracting main, crustal, and external field models from scalar data
  (2) Fitting a low-degree spherical harmonic model to residuals to remove Sq effects
  (3) Inverting magnetic signature of EEJ for E-region current density
  (4) Solve the governing electrodynamic equations with climatological inputs to reproduce EEJ current flow, and estimate the EEF value which gives the best agreement with satellite-derived current.
- The EEF estimates have been validated against the JULIA radar with a correlation coefficient of 0.80.

References

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