The Electromagnetic Ionosphere

Research Seminar on Sun-Earth Connections

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Outline

- Average ionospheric current pattern
  - electrojets
  - R1 and R2 field-aligned currents
- Determining ionospheric currents
  - magnetic field measurements
  - a method determining ionospheric currents from magnetic field data
  - examples

Plasma Convection 1/3

- When solar wind with a velocity $\mathbf{V}$ and a southward IMF component interacts with the geomagnetic field $\mathbf{B}$, an electric field, pointing from dawn to dusk, is imposed according to the ideal MHD relation

$$\mathbf{E}_{pc} = -\mathbf{V} \times \mathbf{B}. \tag{1}$$

- $\mathbf{E}_{pc}$ maps down to the ionosphere along the highly conducting geomagnetic field lines causing the plasma in the polar cap to drift antisunward with the velocity

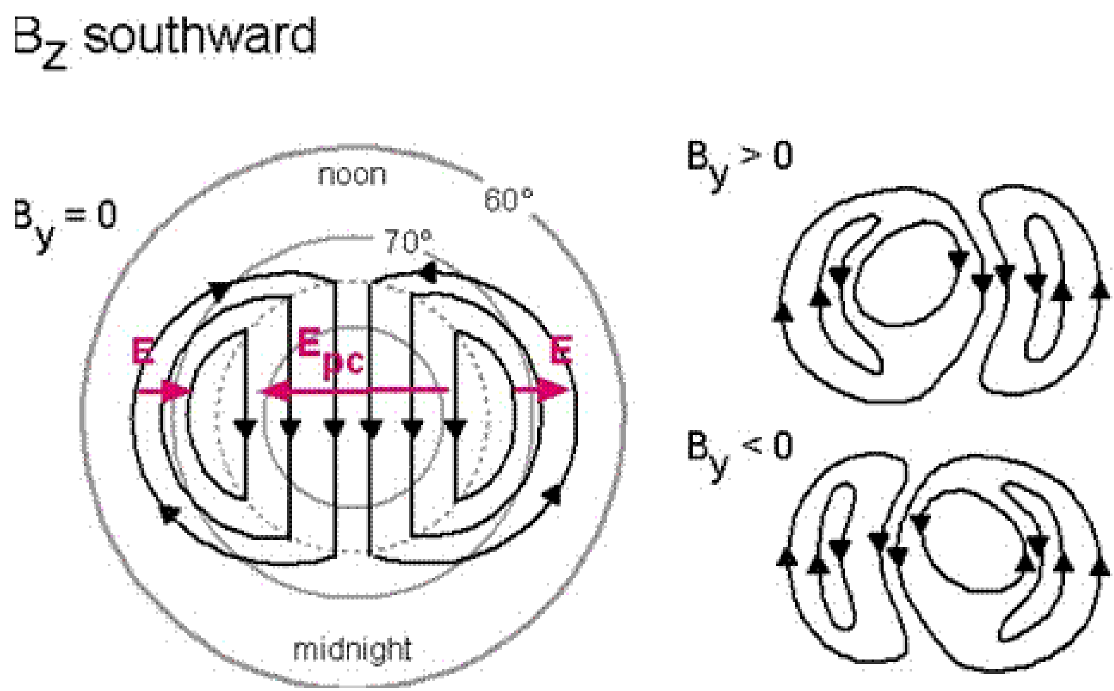
$$\mathbf{v} = \frac{\mathbf{E}_{pc} \times \mathbf{B}}{B^2}. \tag{2}$$

Plasma Convection 2/3

- The electric field across the polar cap implies the existence of charge separation on the surface between the open and closed field lines.
- The charge is positive on the dawnside and negative on the duskside, and therefore causes on the nearby closed field lines electric fields that are oppositely directed to that of the polar cap.
- These electric field also map down to the ionosphere, and cause plasma to drift sunward.

Plasma Convection 3/3

- Thus when the IMF is southward, the ionospheric plasma flows across the polar cap from the dayside to the nightside, where the flow is split in two, and returns to the dayside in the dawn- and duskside auroral ovals.

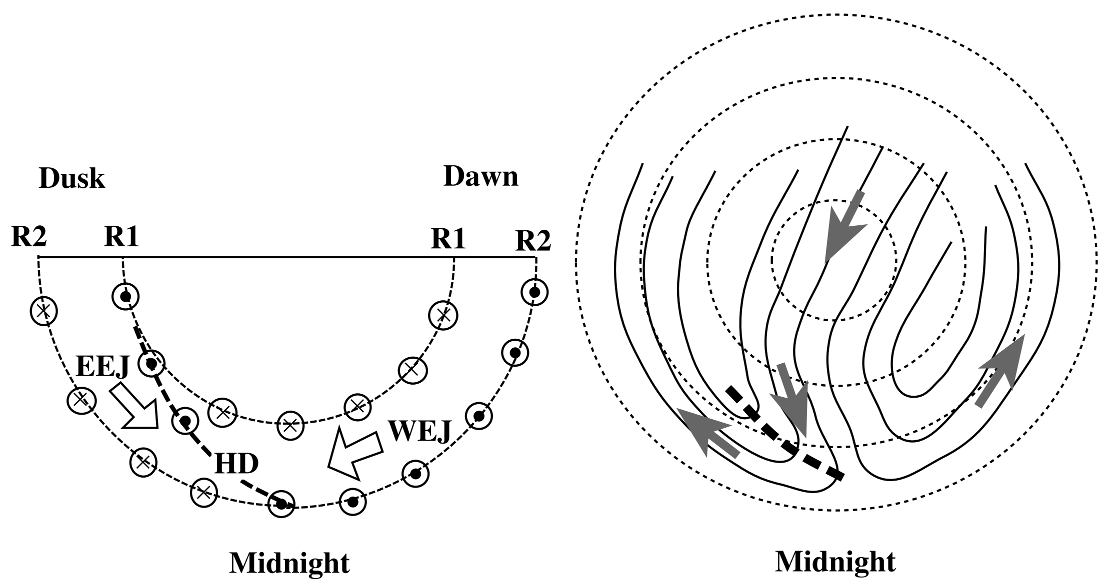


Electrojets 1/2

- Ions in the lower part of the ionosphere are collisional and as such do not follow the drift.
- The flow of the plasma is mostly $\mathbf{E} \times \mathbf{B}$ drift of the electrons, accompanied by an electric current in the opposite direction.
- In the polar cap, the current is generally spred out in a large area, but in the dusk and dawn sector auroral ovals, current densities become significant.
- These electric currents are called the electrojets.
- The average electrojets are observed mainly in a narrow region between 65^o and 70^o of geomagnetic latitude and directed antisunward in both hemispheres.

Electrojets 2/2

- The electric current of the electrojets varies with
  - the intensity of the convection electric field
  - the conductivity of the ionosphere, which is affected by the amount of precipitation, for instance.
- The Harang discontinuity is the region in the nightside auroral oval, where the eastward (EEJ) and westward (WEJ) electrojet meet.

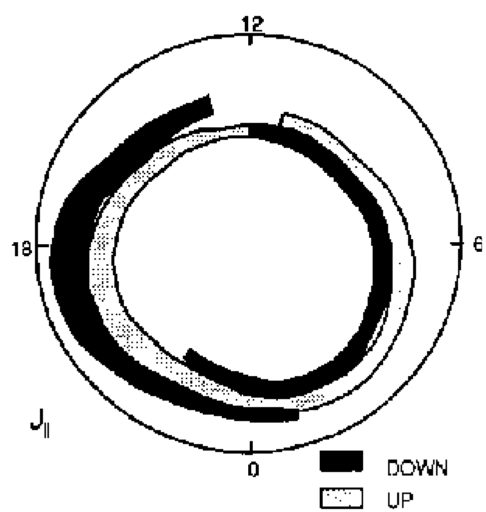


Field-Aligned Currents (FAC) 1/3

- The energetic particle precipitation of the auroral oval
  - ionizes the neutral atmosphere through particle collisions
  - heats up both the ionosphere and the atmosphere
  - causes optical emissions known as the aurorae.
- The nightside precipitation is mostly due to electrons originating from the plasma sheet, and thus reflects the dynamics of the magnetotail.
- The dayside precipitation is directly related to the parameters of the solar wind.

Field-Aligned Currents (FAC) 2/3

- Associated with precipitating electrons, there are electric currents flowing upward along the geomagnetic field lines.
- The return current is provided by upflowing ionospheric electrons.
- For a southward IMF, the field-aligned currents (FAC) are statistically centered upon two regions (R1 and R2) around the magnetic pole.



Field-Aligned Currents (FAC) 3/3

- In general, particle precipitation in the auroral zone is highly structured and time-dependent.
- FACs that flow in and out of the ionosphere are connected via horizontal currents flowing in the lower part of the ionosphere.

Measuring Ionospheric Currents

- Often based on the measuring of the magnetic field (B_r,B_θ,B_ϕ) the currents cause using
  - ground-based magnetometers below the ionosphere
  - magnetometers on-board low-orbit satellites above the ionosphere.
- The measured magnetic field is a superposition of several fields
  - the geomagnetic field
  - the field due to near-space magnetospheric currents (e.g. the ring current)
  - the field due to ionospheric currents
  - the field due to ground-induced currents

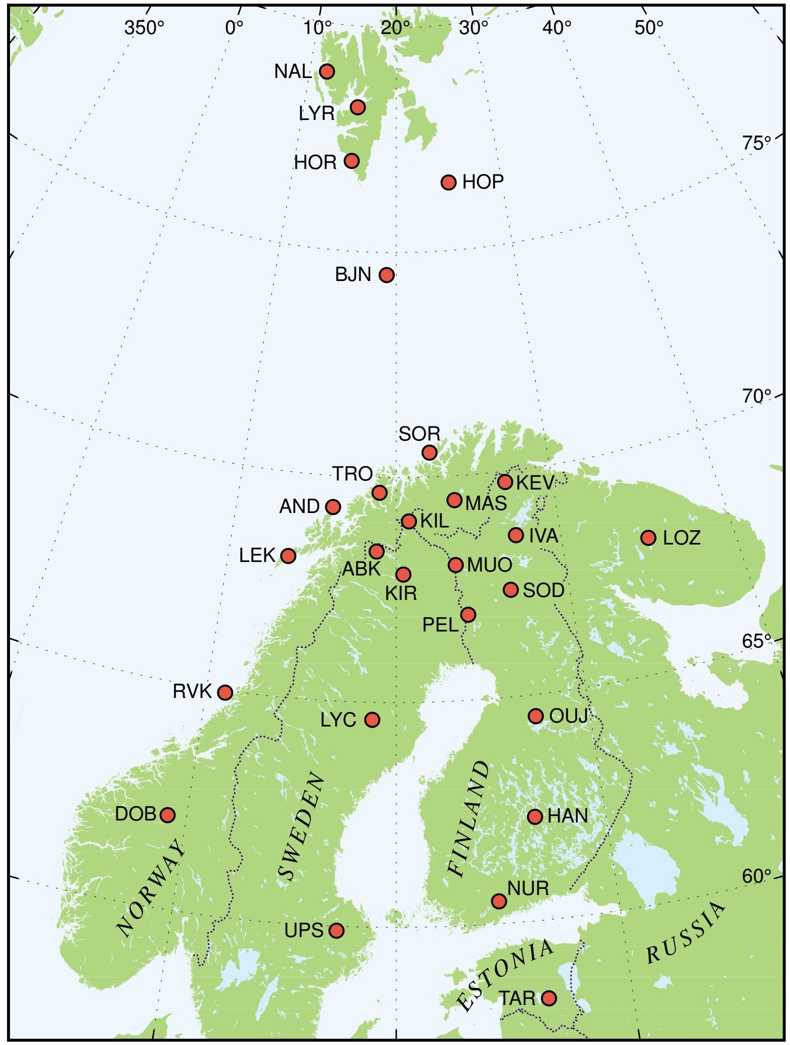
Ground-Based Measurements 1/2

- A unique interpretation of ionospheric currents from ground-based magnetic field measurements is not possible:
  - some of the current systems are not observable from the ground at all, because their magnetic field is confined to the region above the ionosphere
  - a multitude of current densities can generate identical magnetic fields
  - finite number of measurements, noise of the measurement data, etc.

Ground-Based Measurements 2/2

- Equivalent currents are horizontal currents that produce the same magnetic field below the ionosphere as the actual 3D current system
  - a good approximation
  - a basis for a full 3D determination using additional data
  - the data needed for their determination is easily available in dense magnetometer networks over long continuous time sequences.

IMAGE magnetometer network

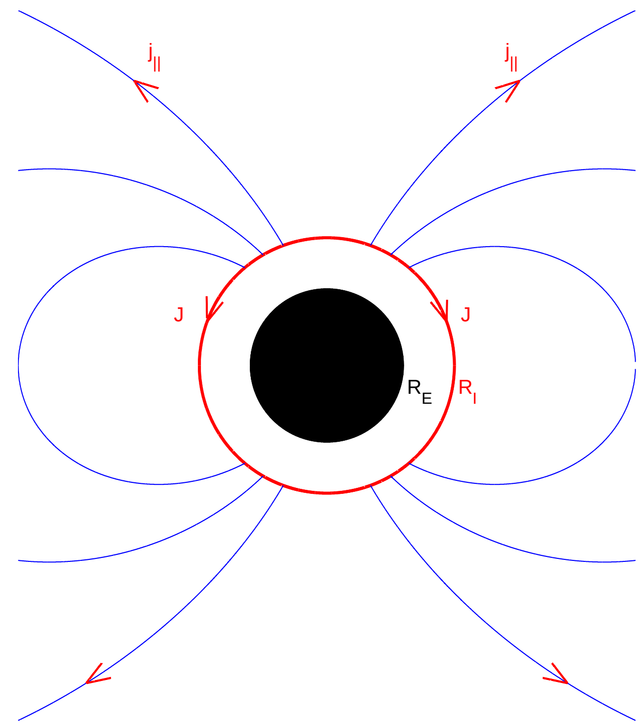


Satellite-Based Measurements

- Theoretically, the full 3D current distribution, including horizontal and field-aligned currents, can be determined.
- One satellite can only measure one-dimensionally.
- Fortunately, 1D assumption is often reasonable (electrojet-dominated cases).
- Uniform spatial coverage of the whole Earth.

Modeling the Ionosphere 1/2

- Because horizontal ionospheric currents are concentrated between about 90–130 km altitude, they are often modeled as
  - a surface current density $\mathbf{J}(\theta, \phi) = \mathbf{J}_{cf}(\theta, \phi) + \mathbf{J}_{df}(\theta, \phi)$ at a constant altitude of $\sim$100 km
  - a field-aligned current density $j_{||}(\theta, \phi) = -\nabla \cdot \mathbf{J}_{cf}$.



Modeling the Ionosphere 2/2

- Ionospheric currents, conductances and electric fields are related via Ohm's law

$$\mathbf{J} = \underbrace{\Sigma_P \mathbf{E}}_{=\mathbf{J}_P} \underbrace{-\Sigma_H \frac{\mathbf{E} \times \mathbf{B}}{B}}_{=\mathbf{J}_H}, \quad (3)$$

  where $\Sigma_P [J_P]$ and $\Sigma_H [J_H]$ are the Pedersen and Hall conductances[currents].

- For uniform Σ_P and Σ_H, $\mathbf{J}_P = \mathbf{J}_{cf}$ and $\mathbf{J}_H = \mathbf{J}_{df}$.

2D SECS Method

- 2D Spherical Elementary Current Systems (SECS) can be used to determine the ionospheric currents from a measured magnetic field.
- The method is based on two sets of basis functions
  - curl-free 2D SECSs
  - divergence-free 2D SECSs
- Any horizontal ionospheric currents distribution can be written as a superposition of these functions.

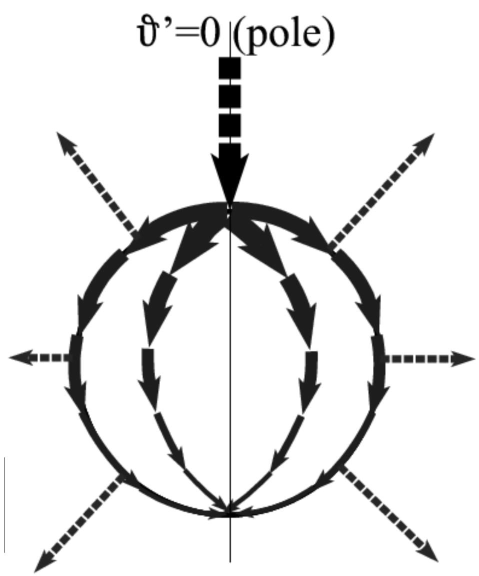
cf 2D SECS and FACs

$$\mathbf{J}_{cf,2D}(\theta',\phi') = \frac{I_{0,cf}}{4\pi R_I}\cot\left(\frac{\theta'}{2}\right)\hat{\mathbf{e}}_{\theta'} \quad (4)$$

$$\mathbf{j}_{||,2D}(r',\theta',\phi') = \begin{cases} \frac{I_{0,cf}}{4\pi r'^2}(1-\frac{2}{\sin\theta'}\delta(\theta'))\hat{\mathbf{e}}_{r'} & , r' \geq R_I \\ 0 & , r' < R_I, \end{cases} \quad (5)$$

$$\mathbf{B} = B_{\phi'}\hat{\mathbf{e}}_{\phi'}, \quad (6)$$

$$B_{\phi'} = \begin{cases} 0 & , r' < R_I \\ -\frac{\mu_0 I_{0,cf}}{4\pi r'}\cot\frac{\theta'}{2} & , r' > R_I \end{cases} \quad (7)$$



Curl-free elementary system
(with associated FACs)

df 2D SECS

$$\mathbf{J}_{df,2D}(\theta', \phi') = \frac{I_{0,df}}{4\pi R_I} \cot\left(\frac{\theta'}{2}\right) \hat{\mathbf{e}}_{\phi'} \tag{8}$$

$$\mathbf{B} = B_{r'} \hat{\mathbf{e}}_{r'} + B_{\theta'} \hat{\mathbf{e}}_{\theta'} \tag{9}$$

$$B_{r'} = \frac{\mu_0 I_{0,df}}{4\pi r'} \begin{cases} \left(\frac{1}{\sqrt{1 - \frac{2r' \cos\theta'}{R_I} + \left(\frac{r'}{R_I}\right)^2}} - 1 \right) & , r' < R_I \\ \frac{R_I}{r'} \left(\frac{1}{\sqrt{1 - \frac{2R_I \cos\theta'}{r'} + \left(\frac{R_I}{r'}\right)}} - 1 \right) & , r' > R_I \end{cases} \tag{10}$$

$$B_{\theta'} = -\frac{\mu_0 I_{0,df}}{4\pi r' \sin\theta'} \begin{cases} \left(\frac{\frac{r'}{R_I} - \cos\theta'}{\sqrt{1 - \frac{2r' \cos\theta'}{R_I} + \left(\frac{r'}{R_I}\right)^2}} + \cos\theta' \right) & , r' < R_I \\ \left(\frac{r' - R_I \cos\theta'}{\sqrt{r'^2 - 2r' R_I \cos\theta' + R_I^2}} - 1 \right) & , r' > R_I \end{cases} \tag{11}$$

1D SECS Method

- 1D = independence of longitude ($\mathbf{J}_{2D}(\theta,\phi) \rightarrow \mathbf{J}_{1D}(\theta)$)
- 1D variant of the 2D SECS method for satellite-based measurements or magnetometer chains.
- The method is based on two sets of basis functions
  - curl-free 1D SECSs
  - divergence-free 1D SECSs

$$\mathbf{J}_{\left\{ {df \atop cf} \right\},1D}(r,\theta,\theta_0) = \int_0^{2\pi} d\phi_0 \mathbf{J}_{\left\{ {df \atop cf} \right\},2D}(r,\theta,\phi,\theta_0,\phi_0), \quad (12)$$

  where (θ_0, ϕ_0) is the pole of a 2D SECS.

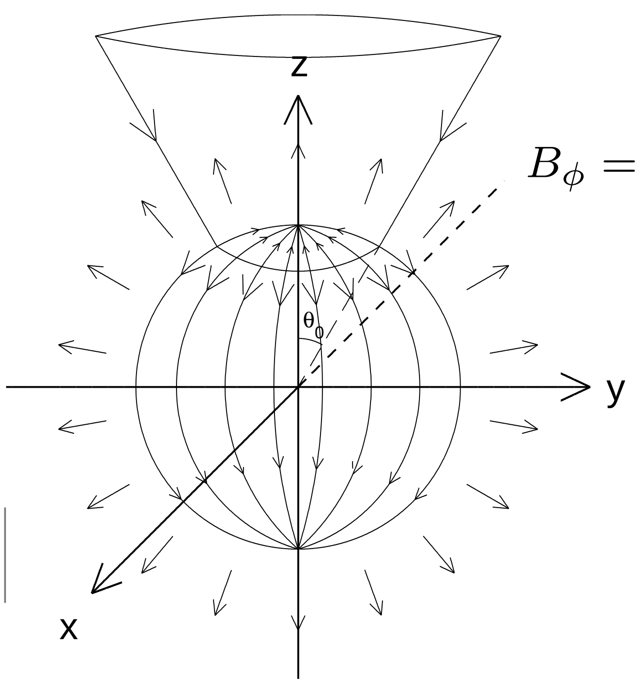
- Any ionospheric current system, which is independent of longitude, can be written as a superposition of these basis functions.

cf 1D SECS and FACs

$$\mathbf{J}_{cf,1D}(\theta,\theta_0) = \frac{I_{0,cf}}{2R_I}\hat{\mathbf{e}}_\theta \begin{cases} -\tan\left(\frac{\theta}{2}\right) & ,\theta < \theta_0 \\ \cot\left(\frac{\theta}{2}\right) & ,\theta > \theta_0 \end{cases} \tag{13}$$

$$\mathbf{j}_{||,1D}(r,\theta,\phi) = \begin{cases} (\frac{I_{0,cf}}{2r^2} - \frac{I_{0,cf}}{r^2\sin\theta_0}\delta(\theta-\theta_0))\hat{\mathbf{e}}_r & ,r \geq R_I \\ 0 & ,r < R_I \end{cases} \tag{14}$$

$$\mathbf{B} = B_\phi \hat{\mathbf{e}}_\phi \tag{15}$$



$$B_\phi = \begin{cases} 0 & ,r < R_I \\ \frac{\mu_0 I_{0,cf}}{2r}\tan\left(\frac{\theta}{2}\right) & ,r > R_I, \theta < \theta_0 \\ -\frac{\mu_0 I_{0,cf}}{2r}\cot\left(\frac{\theta}{2}\right) & ,r > R_I, \theta > \theta_0 \end{cases} \tag{16}$$

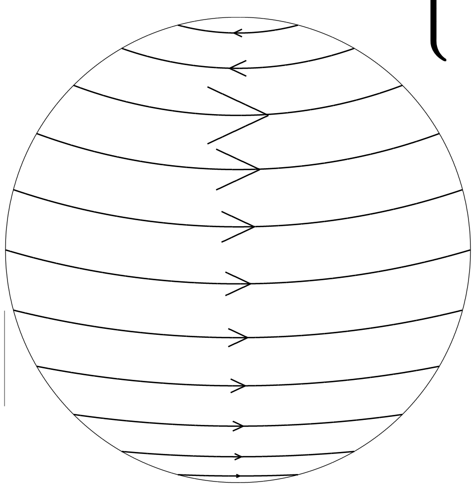
df 1D SECS

$$\mathbf{J}_{df,1D}(\theta,\theta_0) = \frac{I_{0,df}}{2R_I}\hat{\mathbf{e}}_\phi \begin{cases} -\tan\left(\frac{\theta}{2}\right) & ,\theta < \theta_0 \\ \cot\left(\frac{\theta}{2}\right) & ,\theta > \theta_0 \end{cases} \tag{17}$$

$$\mathbf{B} = B_r\hat{\mathbf{e}}_r + B_\theta\hat{\mathbf{e}}_\theta \tag{18}$$

$$B_r = \begin{cases} \frac{\mu_0 I_{0,df}}{2r}\sum_{l=1}^{\infty}\left(\frac{r}{R_I}\right)^l P_l(\cos\theta_0)P_l(\cos\theta) & ,r < R_I \\ \frac{\mu_0 I_{0,df}}{2r}\sum_{l=1}^{\infty}\left(\frac{R_I}{r}\right)^{l+1} P_l(\cos\theta_0)P_l(\cos\theta) & ,r > R_I \end{cases} \tag{19}$$

$$B_\theta = \begin{cases} \frac{\mu_0 I_{0,df}}{2r}\sum_{l=1}^{\infty}\left(\frac{r}{R_I}\right)^l \frac{1}{l}P_l(\cos\theta_0)P_l^1(\cos\theta) & ,r < R_I \\ -\frac{\mu_0 I_{0,df}}{2r}\sum_{l=1}^{\infty}\left(\frac{R_I}{r}\right)^{l+1} \frac{1}{l+1}P_l(\cos\theta_0)P_l^1(\cos\theta) & ,r > R_I \end{cases} \tag{20}$$



Currents Using 1D SECSs

- Ionospheric currents are determined by
  - placing several 1D SECSs at different colatitudes (θ_0)
  - determining their amplitudes ($I_{0,df}$, $I_{0,cf}$) in such a way that their combined magnetic field as closely as possible fits the one measured by the satellite

$$\mathbf{I}_{0,df}(\theta_0) = \overline{\overline{M}}_{df}^{-1}(r,\theta,\theta_0) \cdot \mathbf{B}_{r,\theta}(r,\theta) \quad (21)$$

$$\mathbf{I}_{0,cf}(\theta_0) = \overline{\overline{M}}_{cf}^{-1}(r,\theta,\theta_0) \cdot \mathbf{B}_{\phi}(r,\theta) \quad (22)$$

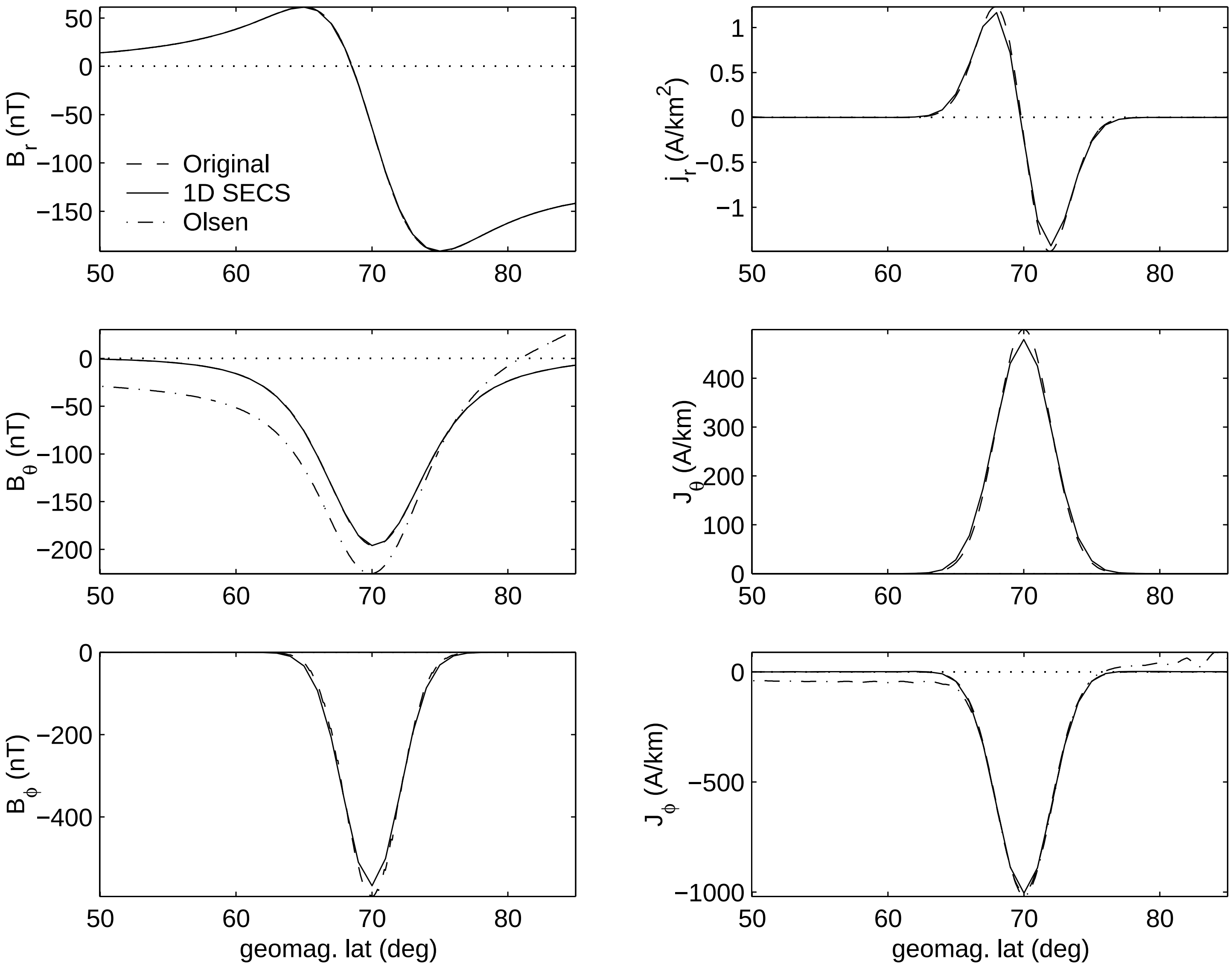
- The current distribution has to be relatively 1D and stationary during the overflight.

1D:ness

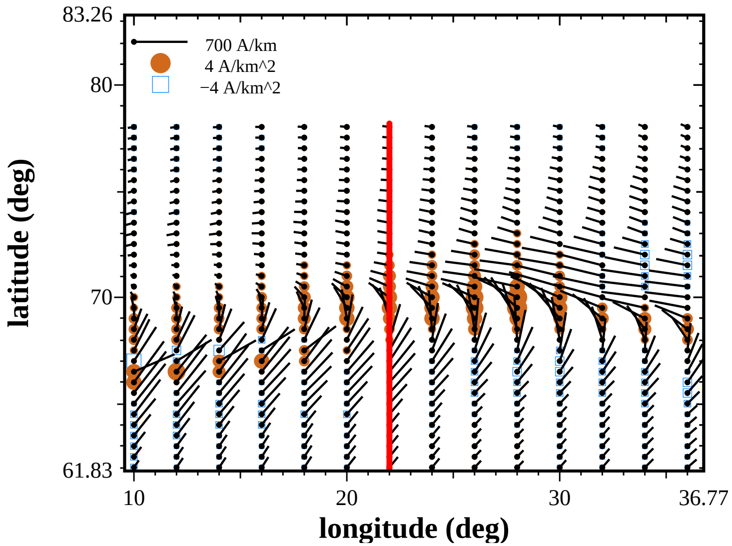
- The 1D SECS method yields most reliable results when the current distribution under analysis is 1D
- A measure for the 1D:ness of the situation can be obtained by
  1. fitting only B_r when determining the divergence-free currents
  2. comparing the 1D SECSs' B_θ with the measured one
     - The more 1D the situation, the closer the two profiles resemble each other
     - The difference of the two profiles can be evaluated as

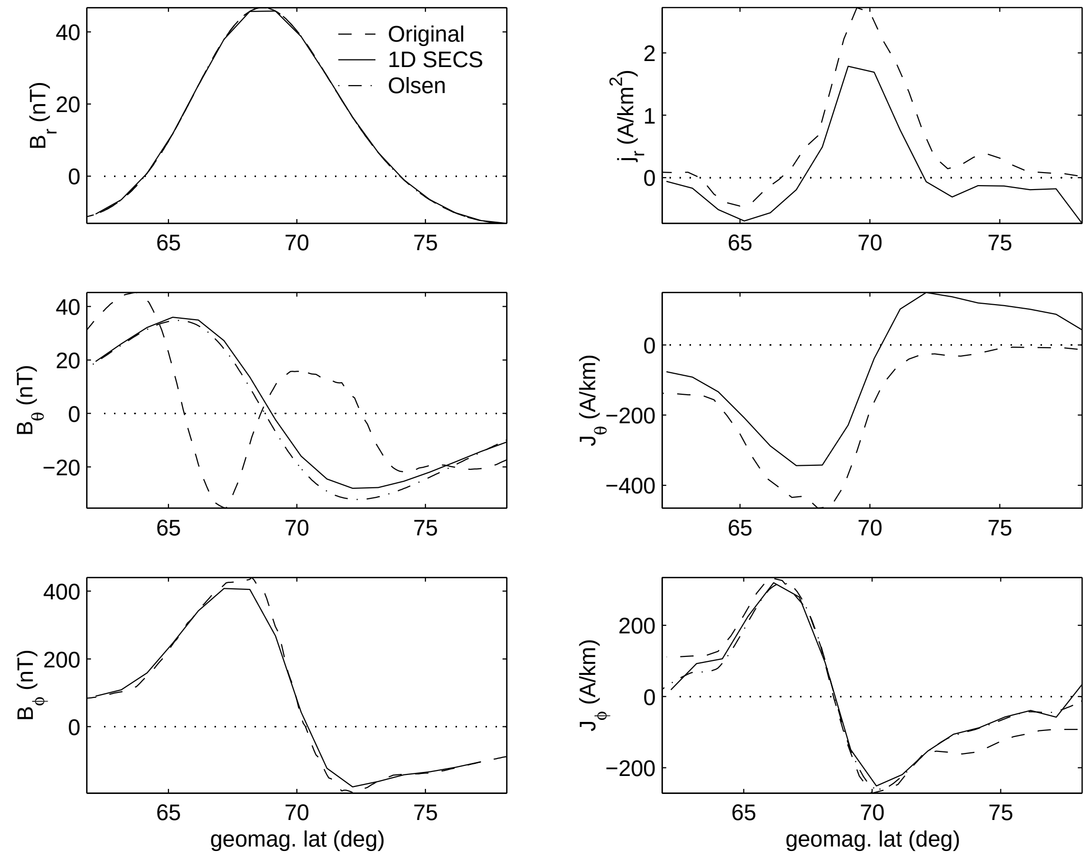
$$error = \frac{\overline{|\mathbf{B_\theta}^{measured} - \mathbf{B_\theta}^{1DSECS}|}}{\overline{|\mathbf{B_\theta}^{measured}|}} \cdot 100\%. \qquad (23)$$

Example: Electrojet (model)

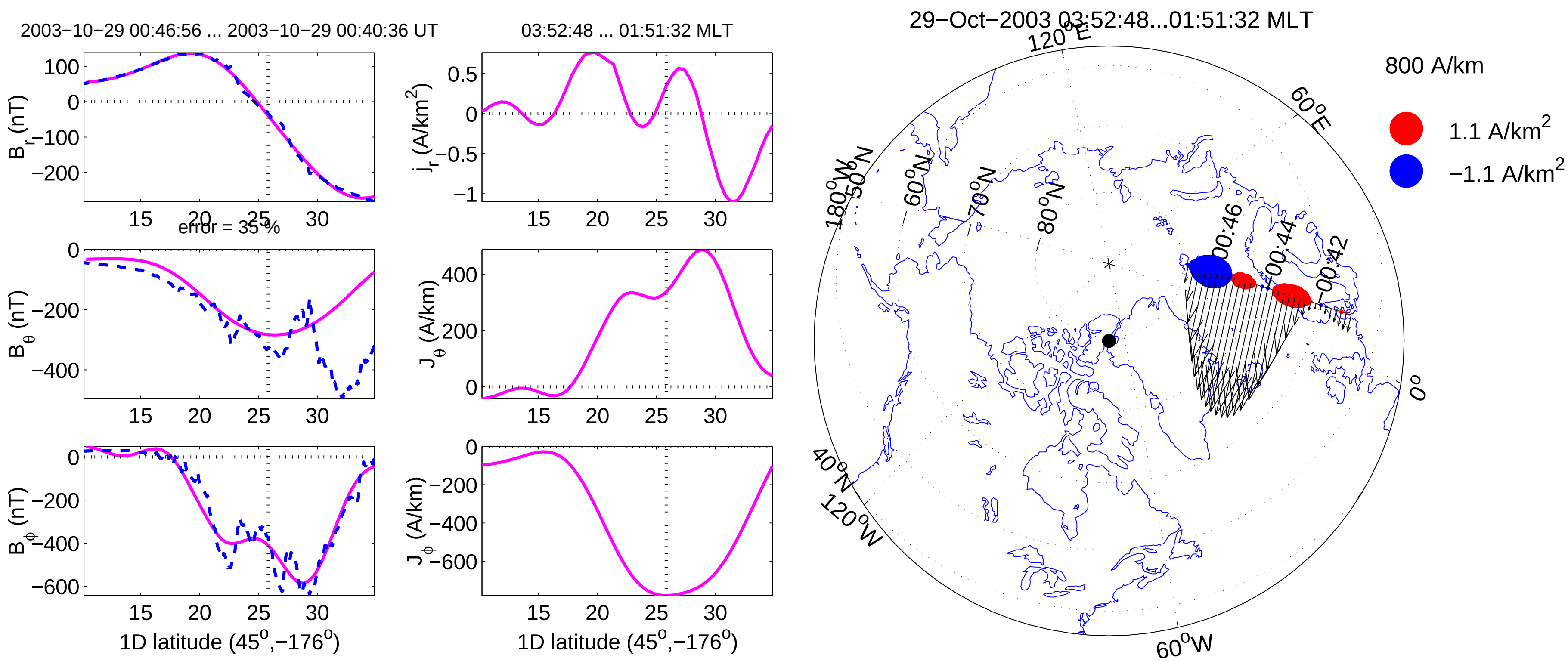


Example: Harang Discontinuity (model)

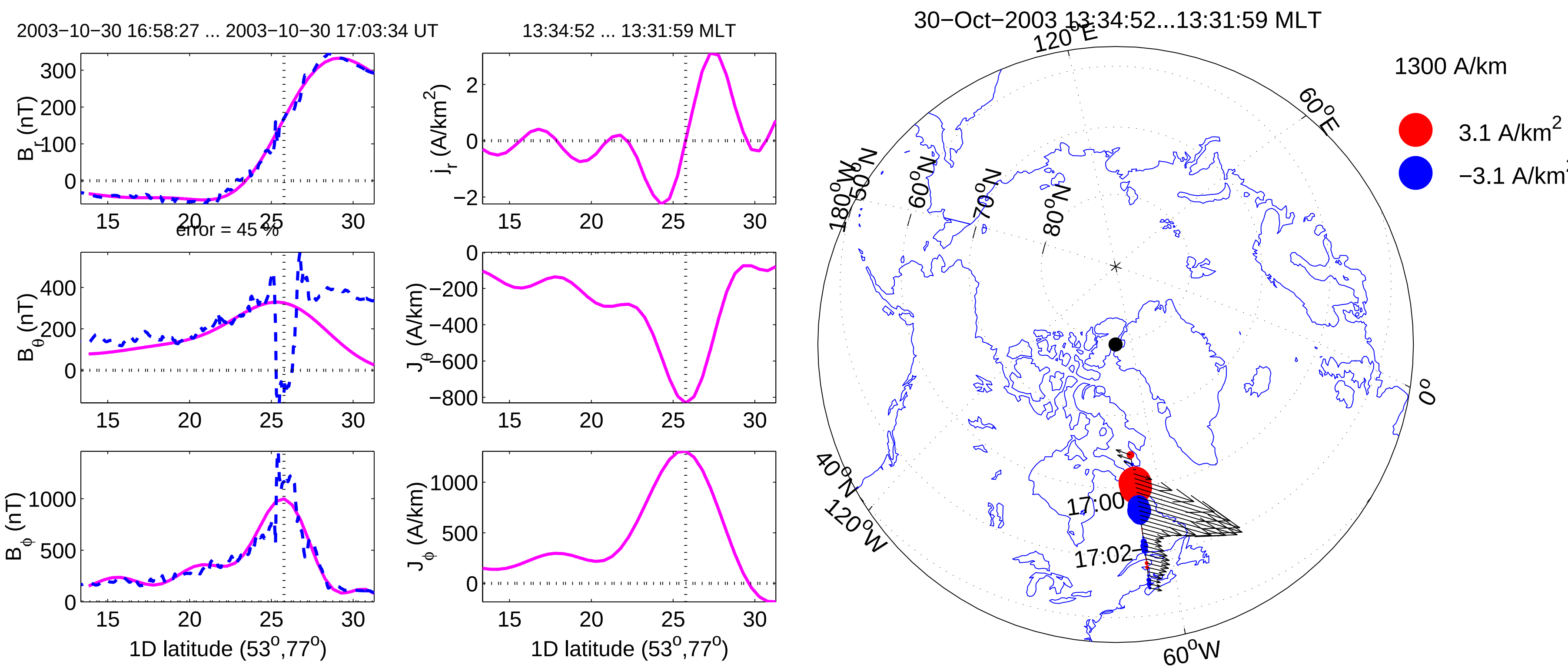




Example: CHAMP 1/2



Example: CHAMP 2/2



CHAMP 2001–2002

0.00 <= $|I_\phi|$ <Inf MA

IMF $B_Z < -3$ nT

1209 overflights