Convection mapping with Swarm satellite and SuperDARN radar data

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In 2012 the European Space Agency will launch the Swarm mission to provide the best ever survey of the geomagnetic field (Frisch-Christensen et al., 2006, 2008). The Swarm satellites will make continuous observations of the plasma drift, making it an ideal instrument for mapping the ionospheric convection pattern. The spherical harmonic analysis (SCHA) technique developed for mapping the magnetic field based on observations covering a cap-like region of the spherical Earth (Haines 1985; 1988; 2007) has been adapted for mapping convection based on ion drift measurements from the Canadian Electric Field Instrument (EFI) onboard the Swarm satellites. Previous, convection maps were generated based solely on simulated Swarm measurements. The region of the map constrained by data was limited to a narrow track surrounding the footprints of the satellite trajectory. To increase the mapping region, measurements from the SuperDARN radar array are added to the Swarm data set. It is shown that the combination of the Swarm and SuperDARN data sets increases both the region of constraint by convection measurements, and the accuracy of the resultant convection maps that could be generated based on data from either instrument alone.

Convection mapping with the Swarm satellites

• The Swarm mission consists of three satellites flying in near-polar circular orbits. The lower satellite pair, Swarm A and B, will fly in a near-parallel orbit having a spatial separation of ~1° of longitude measured at the equator.
• Each satellite will take ~ 20 minutes to cross the high-latitude region (~50° MLAT) at a frequency of ~15 passes per day.
• The B-field measured by magnetometers and the ion drift measured by the EFI can be combined to find the ionospheric E-field in the plane perpendicular to the B-field.

• The Swarm satellites will make continuous observations of the ionospheric plasma drift, making it an ideal instrument for mapping the ionospheric plasma flow. Previous work has examined mapping convection based solely on Swarm data. Convection was successfully mapped based on data from 2-3 satellites, but was only constrained over a narrow region surrounding the ionospheric footprints of the satellites. The best results occurred when all 3 satellites overlapped in such periods are infrequent. The potential for mapping ionospheric convection based on Swarm observations is better met by developing methods to constrain the convection estimates by means of a spacecraft trajectory. To increase the footprint of the satellite trajectory. To increase the mapping region, measurements from the SuperDARN radar array are added to the Swarm data set. It is shown that the combination of the Swarm and SuperDARN data sets increases both the region of constraint by convection measurements, and the accuracy of the resultant convection maps that could be generated based on data from either instrument alone.

SCHA approach to convection mapping

• SCH has been previously developed for mapping the ionospheric convection pattern based on Swarm 1-s velocity measurements (Fiori et al., 2009).
• For a set of observations roughly confined to a spherical cap of angular radius (or cap-size) \( \theta_c \), the electrostatic potential is represented by series expansion

\[
\phi(\theta, \phi) = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} \phi_n^m \cos \phi \cos n \theta.
\]

where \( \phi_n^m \) is the associated Legendre Polynomial of order \( m \) and degree \( n \), and \( \phi(\theta, \phi) \) is the electrostatic potential.

• The fitting coefficients \( g_n^m \) and \( b_n^m \) are determined by minimizing the difference between the velocity determined by the Swarm EFI and the velocity represented above.

• For accurate portrayal of the ionospheric plasma flow, convection should only be plotted when adequately constrained by measurements. A masking algorithm has been developed.

• The minimum wavelength \( \Delta \theta \) of structures that may be mapped for a given data set is given by (Haines, 1988)

\[
\Delta \theta = \frac{4}{p} = \frac{4}{K}.
\]

where \( \Delta \theta \) is the angular spacing between observations, and \( p \) is the number of observations that must be present on a given wavelength. For uniformly distributed data, \( p=2 \). For a real data set, a \( p=2 \) is required to ensure an accurate map. In practice, a value of \( p=4 \) is required for Swarm convection maps.

• For each point of measurement, convection is adequately constrained within a circle radius of \( \Delta \theta \) provided there are at least \( p \) data points inside the circle, see Figure 2.

Convection mapping with Swarm and SuperDARN data

• Convection maps were generated based on Swarm measurements alone, SuperDARN measurements alone, and Swarm and SuperDARN measurements together for a spherical cap centered over the magnetic pole with \( \theta=40^\circ \) and these variables:

- \( \theta_c \) – magnetic co-latitude, longitude
- \( p \) – integer degree index, order of fit
- \( K \) – maximum degree index/ order of fit
- \( n(m) \) is determined by confining the Associated Legendre Polynomial at the boundary of the spherical cap using

\[
dP_
^m(\cos \theta) = 0 \text{ m even}
\]

\[
P_
^m(\cos \theta) = 0 \text{ m odd}
\]

- \( \Phi_0 \) is related to velocity by the magnetic field through

\[
\mathbf{v} = \frac{\Phi_0}{\mu_0 B} \mathbf{B}.
\]

- The fitting coefficients \( g_n^m \) and \( b_n^m \) are determined by minimizing the difference between the velocity determined by the Swarm EFI and the velocity represented above.

- In Figure 4, 5, and 6, contours of the electrostatic potential are plotted over the region of constraint with a 68% spacing. Velocity vectors are uniformly distributed across the region of constraint at a spacing of 2°.

- Histograms indicate the difference between the north/south and east/west components of the velocity determined from the statistical model (prior to the addition of noise) and the convection velocity.

- Due to the narrow track of observations, the maximum fitting order that could be supported by the Swarm-only convection maps was \( K=2 \), and \( p \) had to be increased to 9 to prevent unphysical characteristics in the convection map. The resulting map is significantly smoothed and the residual distribution is wide.

- Addition of Swarm vectors to the SuperDARN data set did not significantly increase the region of constraint (addition of 26 points), but did improve the standard deviation of the residual value between model and output convection (reduced by half).

Simulating observations

• Swarm and SuperDARN measurements were simulated based on the statistical convection for IMF B B, B, and F, B, <12 with a Heppner Maynard Boundary (Ishii and Greenwald, 1996; Shepherd and Ishii, 2000). See Figure 3.

- SuperDARN 1-s velocities were generated at coordinate locations for the two-minute interval starting at 12:00 UT on January 20, 2001. Swarm measurements were determined along sample satellite A, B, and C trajectories for a 20-minute interval at a sampling resolution of 1 minute between measurements (Figure 4).

- Noise was added to the data set by adding a normal distribution of \( \pm 50 \) m/s to the velocity magnitude and \( \pm 10^\circ \) to the velocity azimuth.

In Figure 4, 5, and 6, contours of the electrostatic potential are plotted over the region of constraint with a 68% spacing. Velocity vectors are uniformly distributed across the region of constraint at a spacing of 2°. Histograms indicate the difference between the north/south and east/west components of the velocity determined from the statistical model (prior to the addition of noise) and the convection velocity. Due to the narrow track of observations, the maximum fitting order that could be supported by the Swarm-only convection maps was \( K=2 \), and \( p \) had to be increased to 9 to prevent unphysical characteristics in the convection map. The resulting map is significantly smoothed and the residual distribution is wide. Addition of Swarm vectors to the SuperDARN data set did not significantly increase the region of constraint (addition of 26 points), but did improve the standard deviation of the residual value between model and output convection (reduced by half).

Figure 4: Swarm & SuperDARN magnetic field data measured over the magnetic pole with \( \theta=40^\circ \), and these variables: \( \theta_c \), \( p \), and \( K \).

Conclusions and future work

• Simulated Swarm and SuperDARN data sets were successfully combined to generate maps of the high-latitude convection pattern, where constrained by measurements.
• Addition of the Swarm vectors to a SuperDARN data set increased the accuracy of the resultant convection map over a SuperDARN-only or Swarm-only data set, despite the large number of SuperDARN vectors compared to Swarm vectors.
• Additional data sets having varying degrees of SuperDARN coverage and varying locations of Swarm data sets will be tested.
• Once the Swarm radar becomes operational, a validation study will be performed to ensure Swarm and SuperDARN measurements are consistent, prior to combining the data sets in practice.

References