Imaging Ionospheric Electric Fields and Conductances at Small-Scales Globally: Advancing Research on Cross-Scale Coupling in the M-I-T System

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Cross-scale coupling has emerged as a key theme in the Decadal Survey discussions for achieving breakthroughs in all Heliophysics disciplines, including both magnetospheric, and ionosphere-thermosphere-mesosphere (ITM) science. Understanding how the neutrals and plasmas interact to produce multiscale structures was listed in the previous Decadal Survey as one of its primary science goals under Atmosphere-Ionosphere-Magnetosphere Interactions (8.4.4 AIMI Science Goal 4) and it continues to be a significant Heliophysics research thrust. Increasingly it is recognized that the magnetosphere-ionosphere-thermosphere (M-I-T) system exhibits structure in key parameters such as electric field and conductance over a vast range of spatial and temporal scales and that critical processes are mediated by cross-scale coupling [see a review by Nishimura et al., 2021]. The significance of structure and variability in the electric fields for Joule heating and magnetosphere-ionosphere (MI) coupling has long been recognized but is far from resolved. Satellite observations of field-aligned currents (FACs) have indicated the existence of significant structure at ten km scale lengths [e.g., McGranahan et al. 2017] that must be associated with analogous structure in electric fields and conductivity. Self-consistency among the parameters, however, is often not considered because not all three parameters are observed at relevant scales. Statistical models are widely used to specify the parameters on global scales but they lack spatial resolution and inconsistency between the models creates artificial structures. Progress in understanding the relationships between the critical parameters and resolving the physics of cross-scale coupling in the M-I-T system requires that we make observations at higher resolution than has heretofore been routinely available. Examples of research for which high-resolution observations play a critical role include the electrodynamics of highly structured auroral features such as discrete arcs and auroral streamers [Lyons et al., 2021a, 2012b] and subauroral phenomena such as sub-auroral ion drift (SAID) [Anderson et al., 2001; Oksavik et al., 2006] and Strong Thermal Emission Velocity Enhancement (STEVE) [MacDonald et al., 2018; Gallardo-Lacourt et al., 2018]. Polar cap convection can also be structured yielding flow channels on open field lines that interact with nightside aurora [Nishimura et al., 2014; Lyons et al., 2018]. There are connections between structure and variability in ionospheric electric fields and the occurrence of ionospheric irregularities that result in space weather impacts such as scintillations on GNSS signals [Moen et al., 2013].

The ionospheric electric field is a critical parameter in the electrodynamics of the M-I-T system. Impressive statistical models of the large-scale pattern of electric field have been derived that show remarkable consistency across the various measurement techniques [Weimer, 1995; Ruohoniemi and Greenwald, 1996; Cousins and Shepherd, 2010; Thomas and Shepherd, 2018; Bristow et al., 2022a]. However, these models lack the realism at meso- and small-scales to be useful for studying cross-scale coupling. The existence of variability on small scales has been demonstrated statistically in a number of studies and its significance amply demonstrated [Codrescu et al., 1995; Matsuo and Richmond, 2008; Cousins and Shepherd, 2012a; 2012b; Liuzzo et al., 2015]. Instrumentation on satellites observe structure in the electric field on the order of kilometers [McFadden et al., 1999]. Ground-based incoherent and coherent scatter radar systems are capable of more widespread observations but have been limited to coarser resolution by instrumental factors. In order to address the issues in understanding coupling on all scales between field-aligned currents, conductivity, and electric fields, we need higher resolution observations of ionospheric electric field from radars that are spatially distributed. It is also important to build a capability that these measurements could be obtained continuously so as to capture all manner of M-I-T activity including extreme events that are relatively rare but highly impactful for space weather.

Among the most significant impacts of properly characterizing structure in the electric field and in the conductance is the estimation of energy and momentum coupling between the ions and the neutral atmosphere [e.g Zhu et al., 2018]. Enhanced density and conductivity by precipitation shorten the ion drag time scale and accelerate the neutrals by electric field more efficiently [Nishimura et al., 2020a]. Accurate specification of the multi-scale geomagnetic forcing is critical to modeling and predicting variability in the the upper atmosphere under different conditions. Currently however, general circulation models (GCMs) are usually driven by empirical models, which provide statistically averaged patterns of high-latitude electric potential and auroral particle precipitation and primarily represent large-scale (>500 km) structures. The difference between electric field observations and the statistical averages is called "electric field variability". Studies [Coderescu et al, 1995; Matsuo and Richmond, 2008; Deng et al, 2009] have shown that electric field variability can be comparable to the average electric field and significantly contributes to Joule heating [Deng at al, 2021; Zhu et al, 2018]. However, the approaches in those works are mainly climatological in nature and the electric field variability is typically parameterized as the standard variation referred to the average large-scale electric field.

Recent technical developments now enable the derivation of high-resolution regional ion convection and particle precipitation patterns from the Super Dual Auroral Radar Network (SuperDARN) and Time History of Events and Macroscale Interactions during Substorms (THEMIS) All-Sky Imager (ASI) observations, respectively. The improvements make it possible to directly resolve the multi-scale structure of electric fields and particle precipitation for event studies. In *Sheng et al.* [2022], a global ionosphere-thermosphere model (GITM) is driven by high-resolution patterns derived from those new observational capabilities to simulate the I-T response to multi-scale geomagnetic forcing during the March 26th, 2014 event. It is found that the magnitude of the meso-scale electric field is comparable to the large-scale value, which increases the regional Joule heating by ~30% on average. Both meso-scale convection and precipitation forcing are found to enhance meso-scale structuring in thermospheric disturbances with magnitudes of a few tens of meters per second in the horizontal neutral winds at 270 km and a few percent in the neutral density at 400 km.

Another topic that requires observational capabilities to resolve mesoscale structure is medium scale traveling ionospheric disturbances (MSTIDs) at middle and subauroral latitudes during geospace storms. These zonally propagating MSTIDs were develop near the base of storm enhanced density (SED) plumes on the duskside. Recent studies suggest a physical connection between subauroral electrodynamic processes (including SAPS and the disturbance dynamo) and the development of ionospheric instabilities (e.g., Zhang et al., 2022). Midlatitude SuperDARN radars, along with other ground-based instruments (i.e., ISRs and GNSS), can provide critically needed measurements to characterize these MSTIDs and subauroral electric fields and so facilitate improved understanding of the newly uncovered meso-scale structuring and processes.

The Super Dual Auroral Radar Network (SuperDARN) of high-frequency (HF) radars is well known for providing measurements of ionospheric electric field on the basis of coherent backscattering from ionospheric irregularities in the plasma density [Greenwald et al., 1995; Chisham et al., 2007; Nishitani et al., 2018]. Figure 1 shows the radar fields-of-view in the northern and southern hemispheres, indicating the broad regions of ionosphere over which measurements of the ionospheric electric field are made.

These measurements have been used extensively over decades to derive best-fit, high-time resolution maps of the global pattern of electric fields [Ruohoniemi and Baker, 1995; Shepherd and Ruohoniemi, 2000; Bristow et al., 2022b]. The data have also been useful for study of electrodynamics on meso and somewhat smaller scales. The resolution that is available routinely is one minute in time and tens of kilometers in space. In certain specialized operations temporal resolution of less than one second and spatial resolution of 6 km have been achieved.

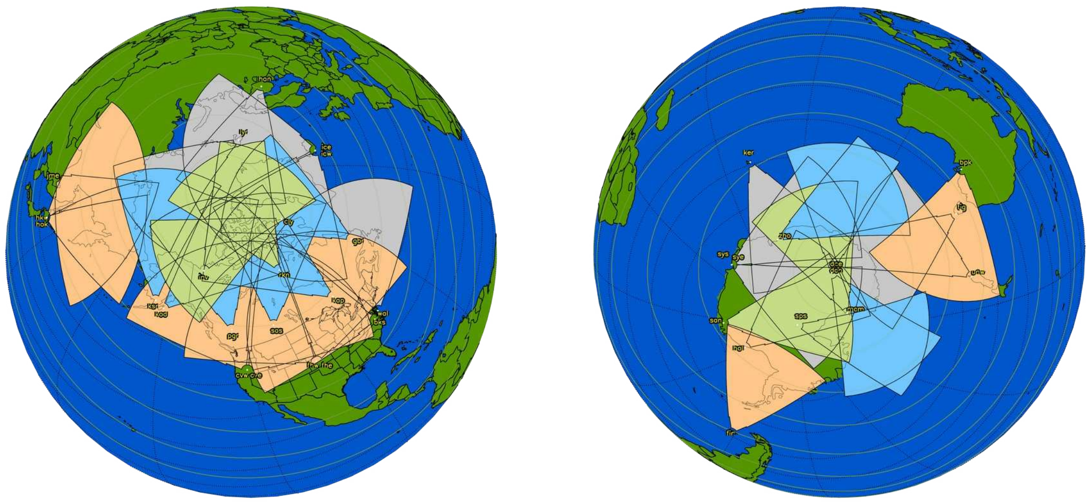

Figure 1. SuperDARN fields-of-view (FOVs) in the northern and southern hemispheres. FOVs are color-coded according to their nominal region of coverage with orange, blue and green representing mid-, high and polar latitudes. Gray indicates radars that are being refurbished in 2022.

Progress in understanding the coupled M-I-T system has been made possible largely through measurements from distributed instrument networks, such as GPS TEC receivers, all-sky imagers (ASIs), ground- and space-based magnetometers (SuperMAG and AMPERE) and ground-based radars (SuperDARN). Together with more localized ground-based measurements, such as those from ISRs, and in-situ space-based measurements a more complete picture of the dynamics of the M-I-T system is emerging. Further progress in these areas, however, requires comprehensive measurements at smaller spatial scales, while maintaining the temporal resolution and large area coverage of the observations.

Recent advances in instrumentation have created the possibility for performing imaging with the SuperDARN HF radars, i.e., collecting measurements over wide areas with heightened spatial resolution simultaneously. In the radar imaging paradigm, receivers are installed at each of the elements of the multi-element antenna array. Signals from each element can then be combined and processed using software to resolve returns from all directions simultaneously. The benefits of this approach for resolving structure and variability have been demonstrated with observations from two of the SuperDARN radars located at Kodiak, Alaska and McMurdo, Antarctica [Kiene et al., 2018, 2019; Bristow, 2019]. Figure 2 shows an example of the increased spatial resolution that is available with these advancements. Structures that were smeared out previously are now resolved and can be used to study cross-scale coupling.

Figure 3 shows an example of localized measurements from the Poker Flat ISR (PFISR) combined with those from the THEMIS ASI and SuperDARN networks, giving a clearer picture of the two-dimensional flows during a substorm onset [Lyons et al., 2021a]. Figure 4 shows another example in a similar format, illustrating the connection of auroral streamers and flow channels with large-scale traveling ionospheric disturbances (LSTIDs) [Lyons et al., 2021b]. These examples highlight the importance of electric field measurements at finer spatial scales in order to resolve details commensurate with the auroral features observed at tens of km in scale. Other examples include resolving sub-auroral features with spatial scales of tens of km such as SAID and STEVE [Nishimura et al., 2020b]. Furthermore, efforts to model the thermosphere system have demonstrated the need for higher spatial resolution electric field measurements as boundary conditions for the global models [c.f., Liuzzo et al., 2015].

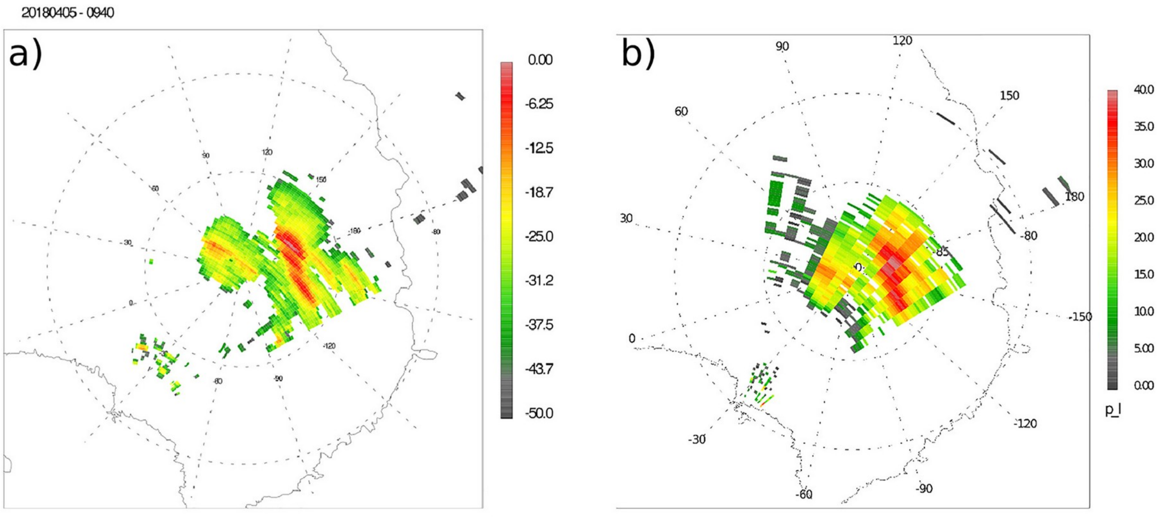

Figure 2. (a) High spatial resolution imaging of ionospheric irregularities with SuperDARN and (b) standard SuperDARN beam forming resolution, after Bristow, (2019).

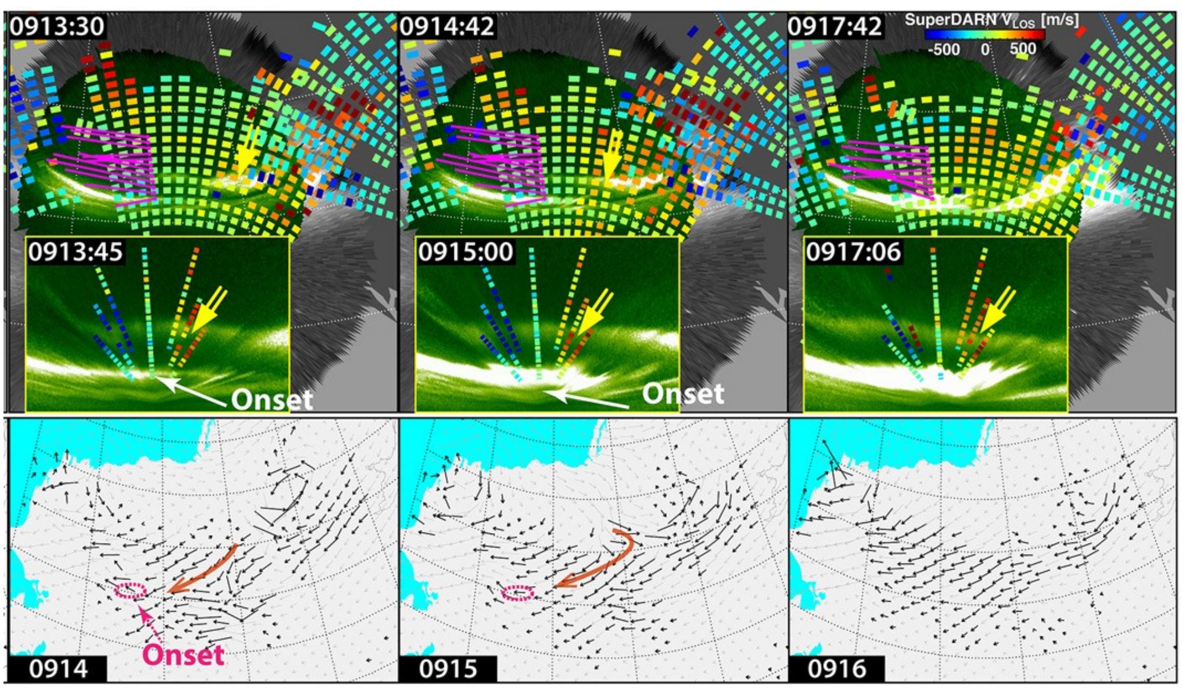

Figure 3. Composite images over Poker Flat, Alaska during a substorm onset, including 557.7 nm images from Poker Flat, with THEMIS ASI image mosaics for the region surrounding the Poker image. Flow vectors derived from PFISR measurements are shown in magenta. SuperDARN line-of-sight (LOS) shown in color according to the scale. After Lyons et al., [2021a].

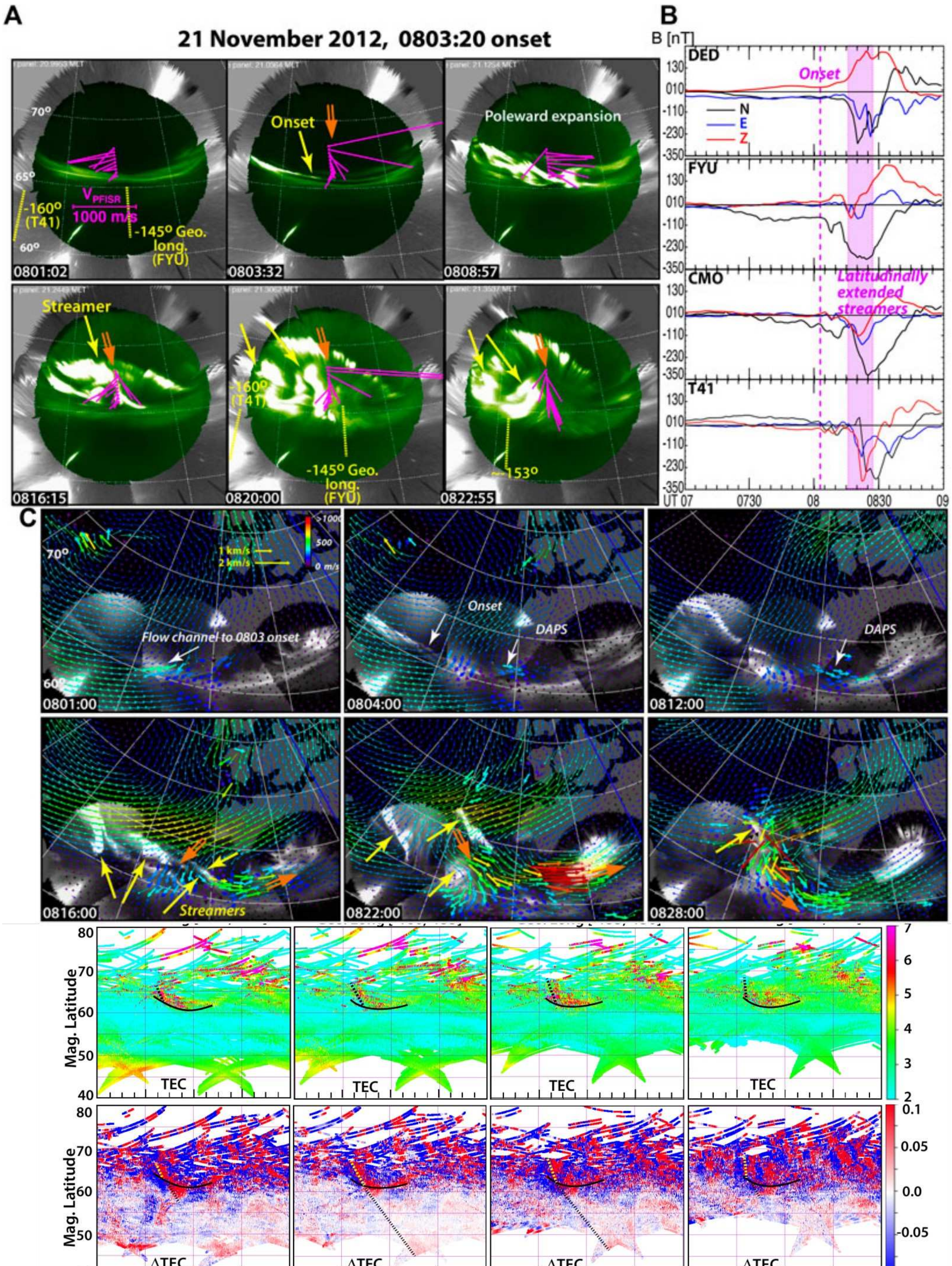

Figure 4. Composite images over Poker Flat, Alaska, highlighting the connection between auroral streamers and flow channels, and large-scale traveling ionospheric disturbances (LSTIDs). Images are from Poker Flat, with THEMIS ASI image mosaics for the region surrounding the Poker image. Flow vectors derived from PFISR measurements are shown in magenta. SuperDARN derived velocities are shown in color. After Lyons et al. [2021b].

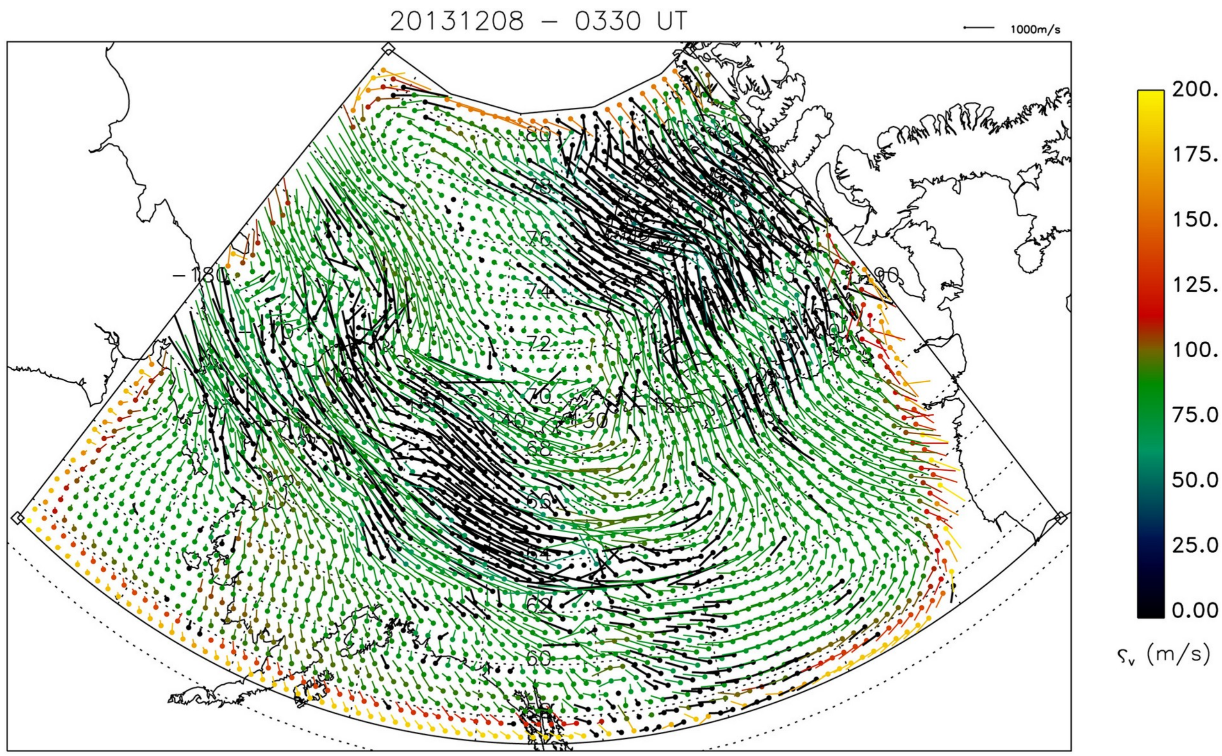

Figure 5. An example snapshot of velocity error estimates from Local Divergence-Free Fitting (LDFF). Black vectors indicate points where SuperDARN directly measured the velocity, while the rest of the points result from the LDFF technique. After Bristow et al., [2016].

Along with advancements in measurement capabilities, recently developments have been made in analysis techniques that benefit directly from the higher spatial resolutions being obtained, providing an increasingly realistic picture of the two-dimension flow of plasma in the ionosphere. Bristow et al., [2016] developed a technique they called Local Divergence-Free Fitting (LDFF) for fitting SuperDARN LOS measurements at tens of km scale over a localized region, resulting in significantly more realistic two-dimensional flow fields than those obtained from global fitting techniques. Figure 5 shows an example of this technique applied to a region extending over much of North America.

Bristow et al., [2022b] extended the LDFF technique, in combination with a statistical model of convection, to obtain a global solution of the velocity field and the electrostatic potential while still maintaining the small-scale features available from localized measurements. Using this technique, combined with higher spatial resolution measurements from SuperDARN, a global specification of the electric potential that maintains the important small-scale features, is possible over much of the polar region.

In additional to the above, it will be important in coming years to combine ground and space-based observations in order to cover the range of scales significant for energy and momentum transfer between the magnetosphere and ionosphere, which extends to scales smaller than those that can be fully resolved by ground-based radars alone. Figure 6 shows a comparison of cross-track velocities from two Swarm satellites [Knudsen et al., 2017], with flow vectors measured by SuperDARN (in high-resolution mode) projected into the same direction, from an example during which Swarm detected a highly localized flow channel (~0.5 deg in latitude) with a peak velocity of ~2.4 km/s. The SuperDARN signature of this same event was spread over several degrees of latitude, with a peak velocity of just ~700 m/s. While this is an extreme example, a statistical study comparing Swarm and SuperDARN by Koustov et al. [2019] shows that SuperDARN velocities tend to be approximately 33% smaller (or less) on average than those observed by Swarm. Such an underestimation of the velocity could be overcome through radar imaging as discussed in Bristow 2019. In terms of energy transfer as measured by Poynting flux measured by Swarm alone, Billet et al. [2022] show that spatial scales of less than 10 km carry 15% of the total.

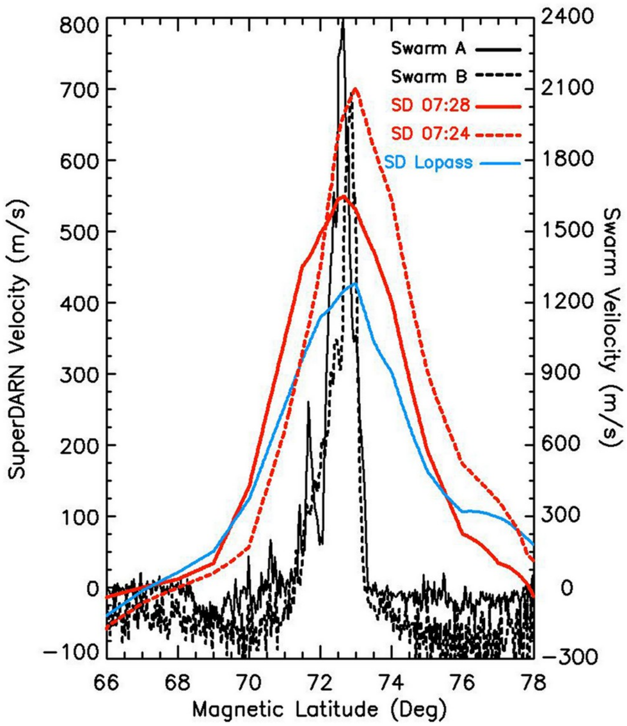

Figure 6. Cross-track velocities measured by Swarm A and B (solid and dashed black lines) compared with the cross-track projection of the SuperDARN HiRes total velocities interpolated along the Swarm trajectory (solid and dashed red lines) at two phases of a field-line resonance on December 19, 2013. See Fenrich et al. [2021] for details.

The planned NASA GDC mission will be an unprecedented IT constellation dedicated to advancing our knowledge about how the IT system responds to solar wind and magnetospheric forcing and how it redistributes mass, momentum and energy. To maximize the GDC science return, we need to bring system sciences mindset into the GDC mission, including incorporating complementary ground- and space-based data sets, which can monitor the momentum and energy input from the solar wind and magnetosphere, as well as provide the necessary context for characterizing the state of the global ionosphere. Large-scale high-resolution 2D SuperDARN datasets are essential for providing large scale convection context for GDC and assisting the interpretation of GDC's in situ plasma drift data.

Realizing the full potential of GDC and further development of our understanding of the roles of various scales in the MIT system requires continued development of our ability to characterize the electric field and conductances. There should be continued development of techniques for analysis and continued development of the numerical simulations that can assimilate the observations. The assimilation algorithms should be able to ingest ground-based and space-based LOS velocities and full vector observations. Further, there should be continued development of the instrumentation to obtain observations. To enable this, it should be a priority to expand the coverage of high-resolution observations of the electric field. Specifically, the capability described in Bristow [2019] should be extended to all US operated SuperDARN radars. The US network of ground-based instrumentation as a whole should be examined and coverage over critical regions like central North America should be improved through strategic placement of new radars, all-sky imagers, and wind imagers. Observations of the auroral luminosity with multi-color cameras should be extended to the widest possible area.

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