Helio2050: Ionosphere-thermosphere system science and the use of distributed heterogeneous data arrays: vector fields, volumetric densities, auroral imagery

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We focus on tools and techniques for the use of heterogenous distributed data sets for ionosphere system science, including *distributed vector data*, *volumetric plasma density data*, and *invertible filtered auroral imagery*. We will specifically focus on (a) aligning, combining, and assimilating data from multiple sources into combined model-driving input, and (b) understanding how to derive distributed vector field maps from multisensor observations, which differentiates this effort from the existing body of work of aggregating and assimilating scalar data (e.g. TEC). Deriving vector fields is an outstanding and critical topic for comprehensively understanding 3-D electrodynamics in the ionosphere-thermosphere. Moving to vector fields such as bulk plasma flow fields (ionospheric electric fields) and current density fields (magnetometry) adds new complications, but also brings rich new information and beauty. Rigorous representation of these distributed I-T vector fields in the context of information provided by ionosphere electron density tomography and auroral imagery is fundamental to a system-level understanding. Tools for simply assessing the differences and similarities between two different maps of vector quantities, such as, "is this simulated flow field a good interpretation of this set of distributed flow measurements?" or "how does this resolution affect my interpretation of this shear?" are surprisingly complicated. Additionally, tools for visualizing, quantifying, and comparing related vector fields in a quantifiable fashion are interesting and high-dimensional. Work is needed in our field to pull together best practices for interpretation and manipulation of distributed vector field data, for use as part of combined input for data-driven ionospheric system science models.

Learning how the Earth's ionosphere works as a coupled, driven, active system is critical to understanding of terrestrial and planetary systems. Ionosphere/Thermosphere (I-T) system science benefits now from (a) the advent of distributed and heterogeneous sensor platform arrays, together with (b) newly capable three-dimensional time-dependent computational models which bypass standard idealizations. Constraining I-T system science requires distributed and heterogeneous observations. Existing observational arrays such as AMPERE, SuperDARN, SuperMAG, and the THEMIS-GBO are soon to be expanded by, first, EISCAT3D (beginning in 2021) and second, arrays of low-Earth-orbit cubesats and other distributed small spacecraft resources that are rapidly becoming available. Figure 1(left) illustrates one potential measurement array, newly feasible in the present smallsat environment, allowing truly multipoint, in situ observations of ionospheric fields. Optimal use of these distributed data arrays includes computational tools for managing, aggregating, and analyzing distributed vector field data. One such use of data from such a distributed array is illustrated

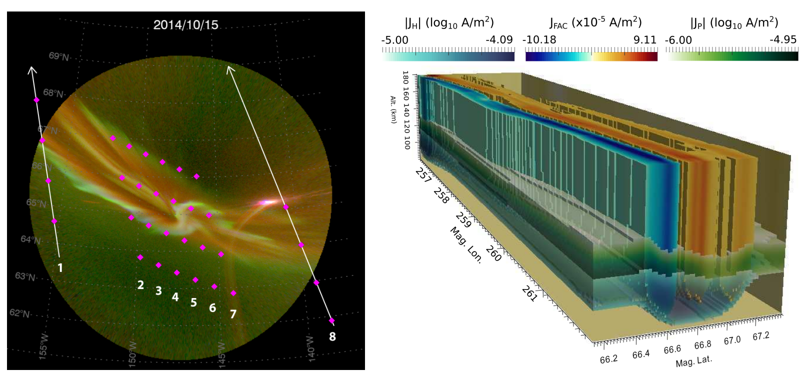

FIGURE 1: (left) Proposed arrays of low-Earth-orbit cubesats enable multipoint in situ distributed observations of fields. New tools are needed to make best use of these observations. *Cubesat and imagery array concept courtesy of K. Lynch & D. Hampton.* (right) A 3-d volume representation of the current structures in an auroral arc. *GEMINI model output visualization courtesy of M. Burleigh.*

in Figure 1(right), showing a representation of the 3D volumetric current closure structure of an auroral arc as modelled by the GEMINI ionospheric data-driven physics-based model (*Zettergren et al.*, 2014).

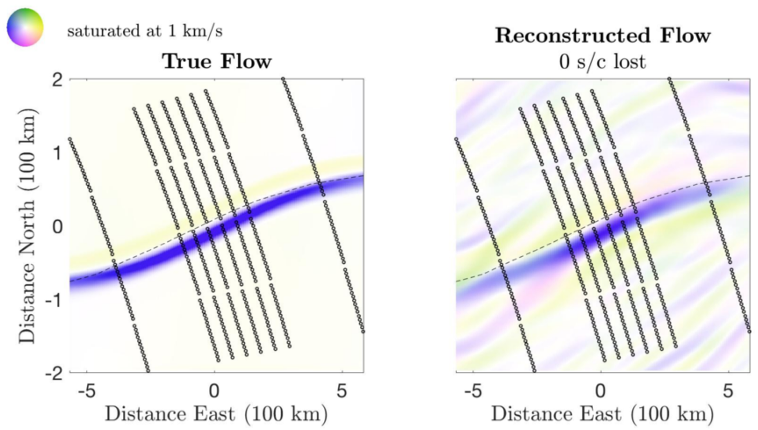

FIGURE 2: *(left)* A swarm of cubesats make distributed vector measurements across a simulated auroral arc ionospheric signature. *Concept study, courtesy K Lynch, B Anderson, T Evans.*

In Figure 2, we show an example of an OSSE (Observing System Simulation Experiment) in which an artificial array of sensors is used to extract data from a modelled field. Tools can be used to reconstruct the underlying field from the extracted synthetic data; constraining reconstruction choices with other information such as imagery can aid in sub-grid information extraction. Here, assumed information about an imaged auroral arc is used to define directions of minimum variance, which can constrain the interpretation and allow sub-grid inferences. Maxwell's equations, and associated diagnostics such as imagery and tomography from heterogeneous arrays, can be used to further constrain possible interpretations of distributed vector data. Given the oncoming onslaught of data from new heterogeneous arrays of sensors, efforts in our community to develop tools for vector field manipulation are timely; and, dovetails with the direction of our ionospheric community toward system science interpretations of the I-T system.

Longstanding interesting questions which we can only begin to address with distributed, high-resolution, vector measurements include many auroral-arc questions. What role does current continuity play in why are there more discrete arcs in the dark ionosphere (*Newell et al.*, 1996; *Borovsky*, 1998)? When is auroral system evolution driven by imposed flows versus by current requirements (*Lysak*, 1985)? When and how does ionospheric reconfiguration play an active versus a passive role in magnetospheric reconfiguration? What quantitative ionospheric electrodynamics can be rigorously inverted from auroral imagery? How important is the role of the (often ignored) neutral wind in the energetics and dynamics of the auroral region? How can it be parameterized? Answering each of these questions will require quantitative manipulation of vector field information, and sensible metrics for comparisons across maps of information. Yet tools for minimizing differences between data and representations, i.e. in a least-squares-minimization search for a parameter, require high-dimensional metrics when applied to distributed vector fields. Even generating a representation of the data, e.g., in the OSSE flow fields illustrated in Figure 2, requires tools for bridging the gaps between the observation points in a manner consistent with Maxwell's equations. These compelling questions concern longstanding non-idealized I-T system behavior; new tools will optimize our use of distributed vector data sets, imagery maps, and tomography volumes as model-driving datasets.

Combining these distributed field maps, with other data sets such as volumetric plasma density volumes from tomography, and high-resolution high-cadence auroral imagery inversion products, requires an additional bank of tools and techniques. System-level ionospheric simulations such as GEMINI and GITM require multi-parameter driving data. Aligning input data from different sources to a common model lattice space and time cadence, and optimizing the use of these combined data sources, is an interesting and complex task. The development of these tools in a community forum will benefit the entire community.

It is only recently that distributed arrays of high-resolution vector data are beginning to become available. Significant advances by large-scale radar systems such as SuperDARN have contributed greatly to our understanding of the ionosphere. However, the cross-scale coupling issues inherent, for example, in auroral studies, require both extended arrays of observations, and fine-scale resolution. Combining both multipoint and high-resolution observations for mesoscale system science is a growing effort. EISCAT3D and localized swarms of cubesats can begin to tackle ionospheric questions. Challenges for using distributed arrays dealing with vector fields include inversion algorithms, metrics for comparisons, and visualization.

The variety of upcoming distributed data sources – arrays of high-resolution radars, arrays of small spacecraft, arrays of imagers, dense-network tomography – reflect increasing interest in the distributed high-resolution constraints needed to cross scales and relate different aspects of the ionosphere and thermosphere to each other at a system level. The CEDAR community has specifically addressed this need, as has the NASA Heliospheric Decadal Survey, both of which advocate for advances in system science and distributed high-resolution observations. While these will be great advances, our community also needs tools to feed the resulting data sets into data-driven models to maximize impact of these new data sources.

Taking as an illustrative example the questions of auroral physics, we can note great advances in the microphysics of auroral processes as illustrated in the ISSI monograph on Auroral Plasma Physics (*Paschmann et al.*, 2003), together with long-term understanding of the larger-scale and statistical behavior of the auroral zone as illustrated by *Newell et al.* (2009) and recent SuperDARN – AMPERE studies of the auroral zone at large scales (*Cousins et al.*, 2015). However, many interesting and open questions stand at the boundary between these: mesoscale, arc-scale questions involving the extended region of an auroral arc system, but quantified by the fine-scale edges and boundaries of these discrete structures. The next large steps in scientific impact will be at these mesoscales. New tools are needed to absorb the necessary distributed vector field observations and their heterogenous counterparts such as auroral imagery and plasma tomography, in order to bypass standard idealizations of the auroral ionosphere.

The tools needed address data sets that we (mostly) do not yet have in hand. At first, we will not be answering many of the interesting questions listed above – we need new data from new missions to do that! In the meantime, we should preemptively gather the tools that can be used, and set up our community to know what is available and how to best proceed once we have the data. For example, we can use the GEMINI and GITM ionospheric models together with an OSSE to generate synthetic data for reconstruction and interpretation with the tools available, including using the OSSE to optimize the design of upcoming arrays.

Relevant upcoming missions in progress include EISCAT3D, NASA's GDC, and ESA's Daedalus. Missions currently in the proposal stage include arrays of smallsats such as the cubeswarm array concepts illustrated in the figures above. The prompting of the CEDAR community and NASA's Decadal Survey toward heterogeneous arrays of observational platforms means that many new efforts will move in this direction. The techniques and best practices developed from these efforts thus will be widely applicable to a range of current, planned, and proposed missions.

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