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Space Weather Modeling Capabilities Assessment: Auroral Precipitation and High Latitude Ionospheric Electrodynamics

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Key Points:

- A working team has been established to develop a process for validation of auroral precipitation and electrodynamics models.
- Validation of auroral electrodynamic models against standardized metrics requires generation of ground-truth data sets for selected space weather events.
- Current observations and data assimilation techniques continue to improve the accuracy of global auroral electrodynamic specification.

Abstract

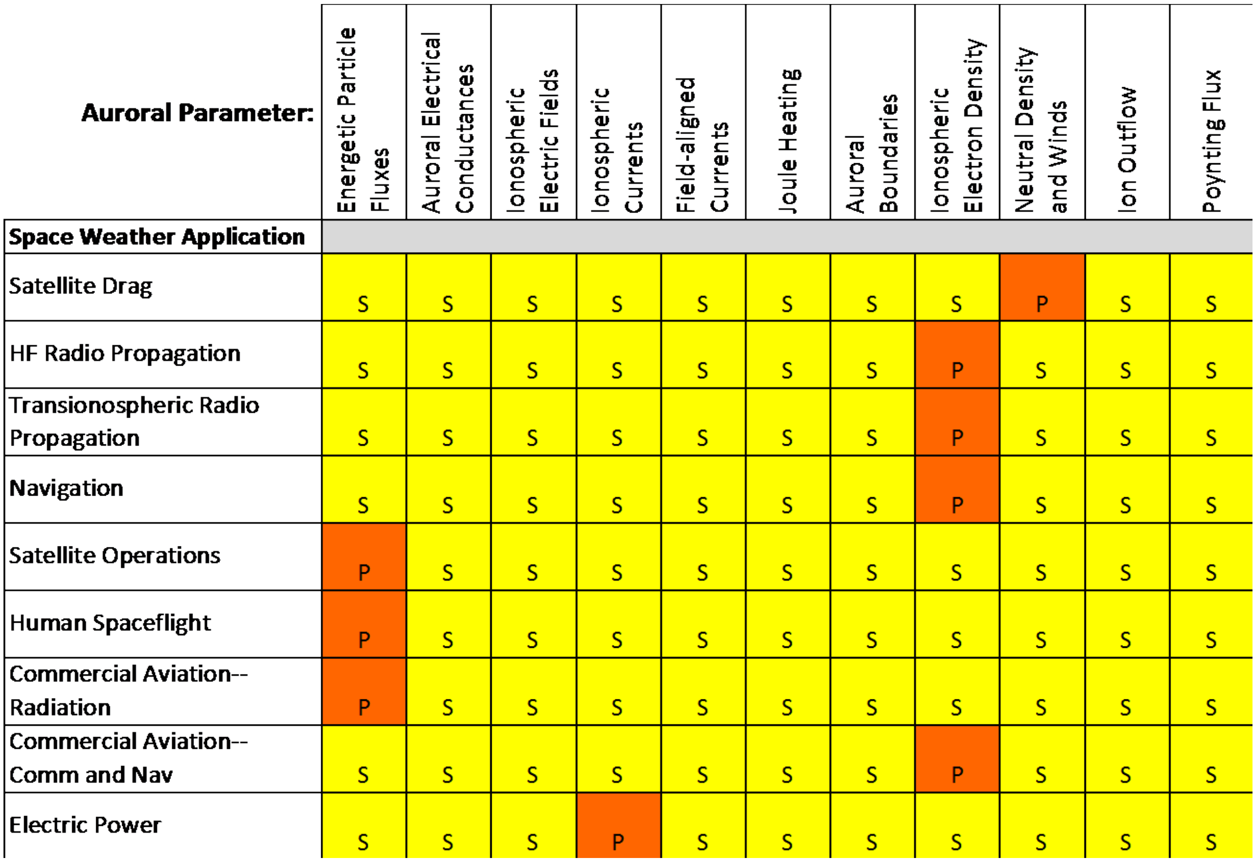
As part of its International Capabilities Assessment effort, the Community Coordinated Modeling Center initiated several working teams, one of which is focused on the validation of models and methods for determining auroral electrodynamic parameters, including particle precipitation, conductivities, electric fields, neutral density and winds, currents, Joule heating, auroral boundaries, and ion outflow. Auroral electrodynamic properties are needed as input to space weather models, to test and validate the accuracy of physical models, and to provide needed information for space weather customers and researchers. The working team developed a process for validating auroral electrodynamic quantities that begins with the selection of a set of events, followed by construction of ground-truth databases using all available data and assimilative data analysis techniques. Using optimized, predefined metrics, the ground-truth data for selected events can be used to assess model performance and improvement over time. The availability of global observations and sophisticated data assimilation techniques provides the means to create accurate ground-truth databases routinely and accurately.

Meeting Report

As part of its International Capabilities Assessment effort (see https://ccmc.gsfc.nasa.gov/assessment/forum-topics.php), the Community Coordinated Modeling Center (CCMC) initiated several working teams, one of which is focused on auroral precipitation and high latitude ionospheric electrodynamics model validation. The goal of the Auroral Precipitation and HIgh Latitude Electrodynamics (AuroraPHILE) working team is to establish quantitative means to measure the accuracy and reliability of modeled properties of the auroral ionosphere, including particle precipitation, conductivities, electric fields, neutral density and winds, currents, Joule heating, auroral boundaries, and ion outflow. The working team's objective is to establish a set of properties that describe the state of auroral particle precipitation and electrodynamics, and then quantify the accuracy and reliability currently achievable using a combination of data and models. Working team discussions were held during the International CCMC-Living With a Star Working Meeting: Assessing Space Weather Understanding and Applications, April 3-7, 2017, in Cape Canaveral, Florida (https://ccmc.gsfc.nasa.gov/CCMC-LWS_Meeting/) and in teleconferences before and after the meeting.

Properties of the auroral ionosphere are critical for improving resilience to impacts of space weather events. Auroral electrodynamic properties are needed as input to space weather models, to test and validate the accuracy of physical models, and to provide needed information for space weather customers and researchers. The aurora is a manifestation of energy input to the upper atmosphere that heats the thermosphere, resulting in increased satellite drag. Auroral precipitation modifies the ionospheric electrical conductivity, needed to specify and predict the currents causing ground-based magnetic perturbations that threaten the electric power grid. Through ionization and convection, the aurora modifies the ionospheric electron density, resulting in disturbances and disruptions to transionospheric radiowave transmissions needed for navigation and communication. Auroral electrodynamic parameters are also needed as input to and validation of many different types of space weather models. Finally, an accurate specification of auroral properties is important for assessing surface charging effects on space assets traversing through the auroral zones.

Figure 1 lists the space weather applications for which auroral parameters are important. For each application, the orange highlight indicates the primary ('P') auroral property that must be modeled or observed to mitigate the associated space weather effects. The yellow highlights indicate secondary ('S') properties that either indirectly impact the application or are needed as input to accurately model and predict the impact. Given the overall importance of auroral properties to mitigating space weather effects on applications, it is essential to quantitatively assess the accuracy with which those properties can be observed and modeled.



Auroral Parameter:	Energetic Particle Fluxes	Auroral Electrical Conductances	Ionospheric Electric Fields	Ionospheric Currents	Field-aligned Currents	Joule Heating	Auroral Boundaries	Ionospheric Electron Density	Neutral Density and Winds	Ion Outflow	Poynting Flux
Space Weather Application											
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HF Radio Propagation	S	S	S	S	S	S	S	P	S	S	S
Transionospheric Radio Propagation	S	S	S	S	S	S	S	P	S	S	S
Navigation	S	S	S	S	S	S	S	P	S	S	S
Satellite Operations	P	S	S	S	S	S	S	S	S	S	S
Human Spaceflight	P	S	S	S	S	S	S	S	S	S	S
Commercial Aviation--Radiation	P	S	S	S	S	S	S	S	S	S	S
Commercial Aviation--Comm and Nav	S	S	S	S	S	S	S	P	S	S	S
Electric Power	S	S	S	P	S	S	S	S	S	S	S

Figure 1: Auroral parameters important for mitigating impacts to space weather applications.

The AuroraPHILE working team began by compiling comprehensive lists of models, data, and data sources (both ground-based and space-based) available over the past 25 years that can be used to test and validate knowledge of the auroral ionosphere and the capability to both specify and forecast high latitude ionospheric properties. These lists are accessible on the CCMC web site (https://ccmc.gsfc.nasa.gov/assessment/topics/iono-joule.php). Based on a careful consideration of the available models and data and their associated uncertainties, the working team developed a methodology for assessing the accuracy with which auroral precipitation and high latitude electrodynamic quantities can be specified and forecast. For a preselected group of events, all available data would be used to determine the most accurate values of auroral electrodynamic parameters. We refer to this as the 'ground-truth' data set, although the values may be determined by a combination of direct measurements, data assimilation, and other models needed to fill in gaps and extend observations. Once the optimum ground-truth data set has been determined, any model can be tested with respect to its accuracy in replicating 'reality'. Thus, all models will be evaluated against the same standard and for the same events. New models, or upgrades to existing models would be tested against the same events so that improvements can be unambiguously tracked over time.

In considering the set of events to include in the ground-truth database, the AuroraPHILE working team noted the importance of including a broad range of geomagnetic conditions. Overlap with events selected by other working teams will help facilitate the assembly of observations for ground-truth data sets. For example, the AururaPHILE working team overlaps with the Geospace Environment Modeling (GEM) Challenge working group and other CCMC working teams developing metrics for ionospheric parameters and geomagnetic indices (see, for example, Liemohn et al., 2018; Welling et al., 2018).

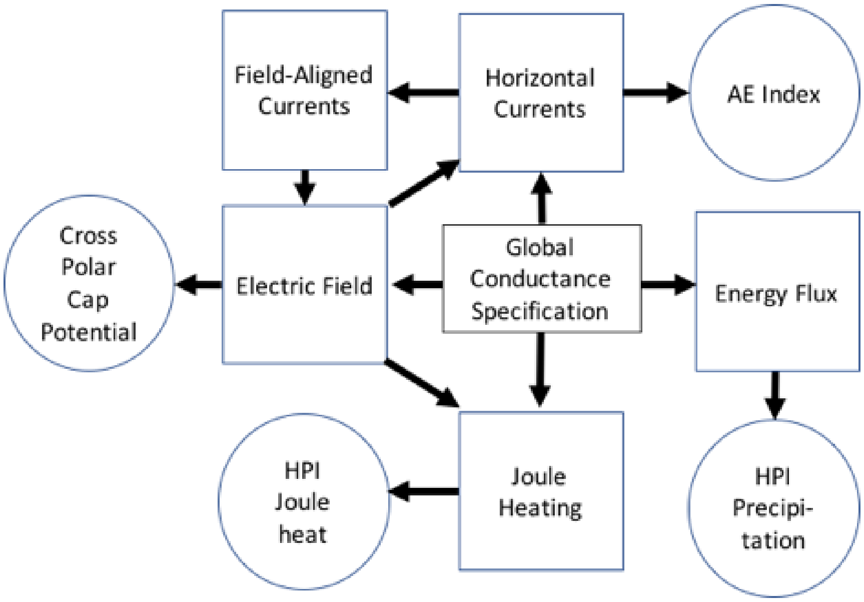

Figure 2. Functional relationship between two dimensional (in rectangles) and global (in circles) auroral electrodynamic parameters. HPI is the Hemispheric Power Index (Evans, 1987).

Because auroral properties span a broad range of temporal and spatial scales and are highly variable in space and time, assembling the necessary measurements to create ground-truth databases is a major challenge. The current availability of ground-based and space-based measurements of auroral properties, coupled with the improving sophistication of assimilative models has made specification of high latitude electrodynamic parameters more accurate and more global than ever before. Figure 2 shows how auroral electrodynamics parameters are functionally connected. Two-dimensional parameters are in rectangular boxes and global quantities are indicated by circles. With the availability of global field-aligned currents from the Iridium satellite constellation (Anderson et al. 2000) and Active Magnetosphere and Planetary Response Experiment (AMPERE, Anderson et al. 2014), one very important piece of the puzzle is now in place. Conductances are also critical to the calculation of electrodynamic parameters as they are used to compute electric fields, currents, Joule heating, and precipitating particle energy flux.

Accurate identification of auroral boundaries is important for many space weather applications. Both poleward and equatorward boundaries are often necessary, and boundaries may differ depending on the process or phenomenon that is most important to the application. Boundary identification algorithms have used optical observations from the IMAGE satellite (Longden et al., 2010) and from the Global Ultraviolet Imager (GUVI) on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite (Christensen et al., 2003; Zhang et al., 2010), and from DMSP measurements of precipitating particles (Redmon et al., 2010, Ngwira et al., 2013, Kilcommons et al., 2017). A novel approach to auroral boundary identification is the Aurorasaurus project database (MacDonald et al., 2015, Case et al., 2016), which offers a collection of geo-tagged and time-stamped signals of auroral visibility collected from citizen scientists.

The AuroraPHILE working team identified a number of different observations that can be used with sophisticated assimilative mapping programs to fill in gaps, constrain measurements, and minimize inconsistencies (e.g., Cosgrove et al. 2009, 2014). In some cases, quantities such as Joule heating cannot be measured directly, but are calculated with certain assumptions from other validated measurements (Thayer, 1998; Verkhoglyadova et al., 2016, 2017). When the ground-truth data are model-dependent, all the model assumptions must be thoroughly documented for future review and possible revision. Another important aspect of constructing a ground-truth database is specifying the errors and uncertainties in the results. These errors and uncertainties can arise not only from the measurements, but also from the models used to derive physical quantities from the observations.

The working team discussed approaches to quantitatively assess model results using a carefully selected collection of metrics. For any given auroral electrodynamic parameter, there may be several metrics by which to compare model output and ground-truth data. Metrics can be user dependent (e.g., operational vs scientific metrics). In one case the timing of an event may be more important than the amplitude of the parameter. For some applications, the ability to capture small-scale or highly time-varying features will be more important than capturing the large-scale changes taking place. To constrain the number of metrics for auroral electrodynamic parameters, some compromises are inevitable. A good metric is one that will reflect overall improvement in model capability for all or most applications. Additionally, metrics are most useful when they not only assess the validity and accuracy of models, but also provide information about the source of model strengths or weaknesses. Quantifying model accuracy in the presence of rapidly time-evolving patterns can lead to different results depending on the resolution of the model and the data (see, for example, Merkin et al., 2007, 2013). Different metrics should be used for two-dimensional (or three-dimensional) images as opposed to time series data. An example is a multi-dimensional correlation coefficient, including both spatial and temporal variables. The metric multi-dimensional root mean square error is another approach. Other approaches include calculation of the median absolute deviation (MAD) (see, for example, McGranaghan et al., 2016). Alternatively, image recognition software used for other applications may be appropriate for comparing model results with global measurements (e. g. Wiltberger et al., 2017). Specific metrics for forecast evaluation have been described by Murphy et al. (1991) and Kubo et al. (2017).

The AuroraPHILE working team recommended next steps to implement the planned model validation activities. Essential to the process is the construction of the ground-truth data sets for selected events. The working team discussions highlighted the improved capabilities currently available for global and continuous specification of auroral electrodynamic parameters. Although far from ideal, the AuroraPHILE working team concluded that accuracies are sufficient for model validation and testing, and for monitoring the improvement in models over time.

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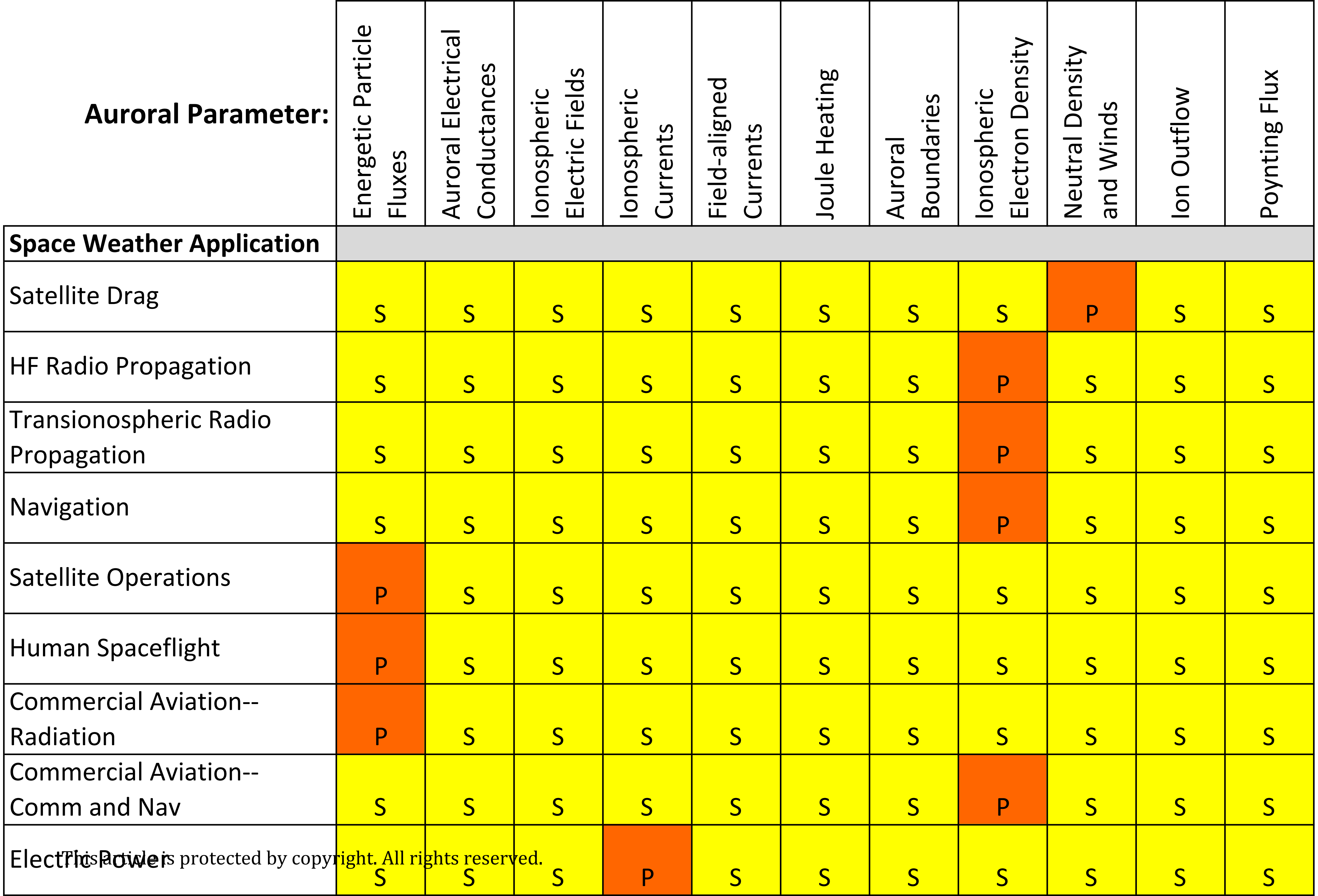

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Navigation	S	S	S	S	S	S	S	P	S	S	S
Satellite Operations	P	S	S	S	S	S	S	S	S	S	S
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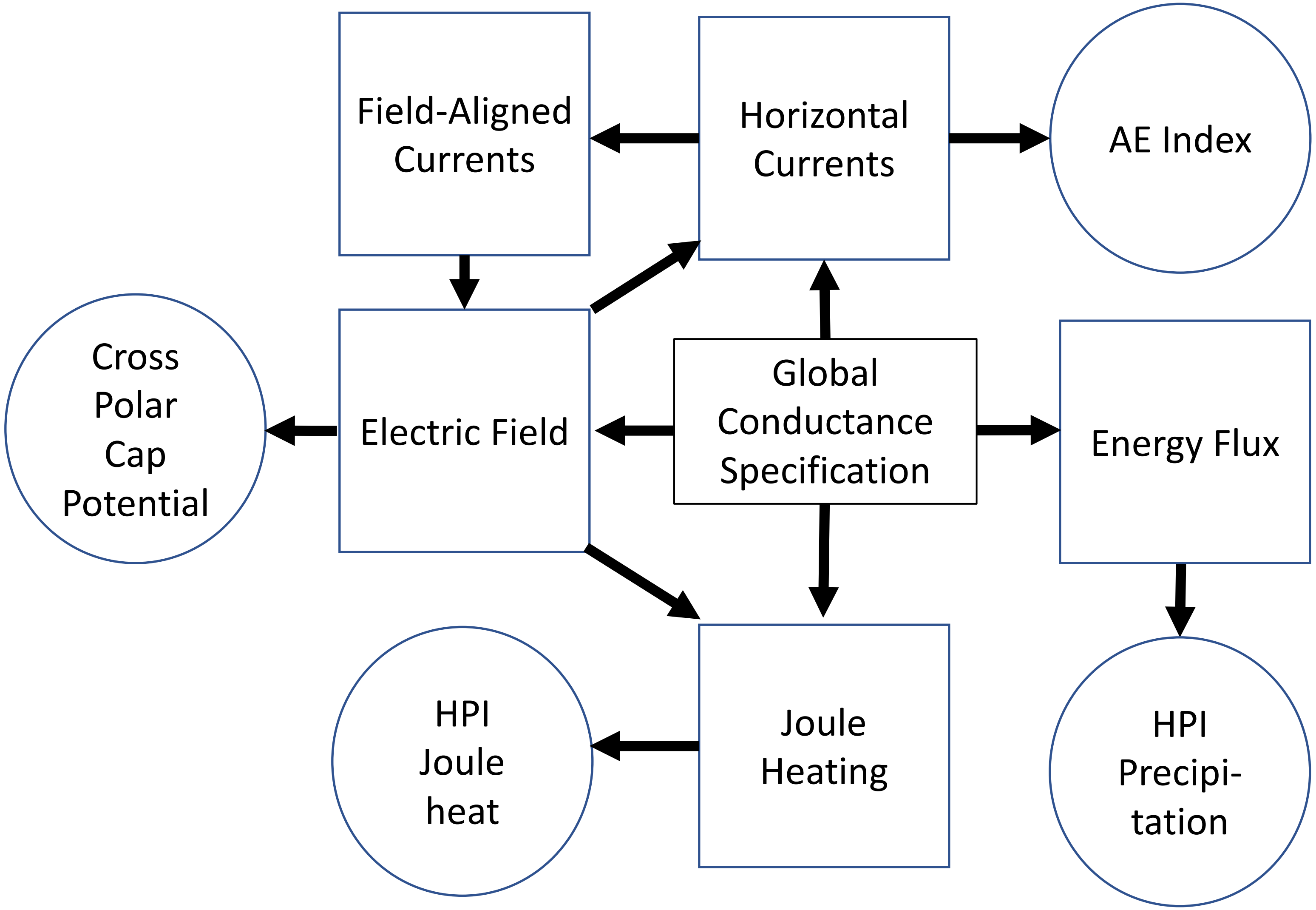

Field-Aligned Currents
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Global Conductance Specification
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