Space weather management

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There have been notable successes during the past decade in the development of operational space environment systems. Examples include the *Magnetospheric Specification Model* (MSM) of the Earth's magnetosphere, 2000; *SOLAR2000* (S2K) solar spectral irradiances, 2001; *High Accuracy Satellite Drag Model* (HASDM) neutral atmosphere densities, 2004; *Global Assimilation of Ionospheric Measurements* (GAIM) ionosphere specification, 2006; *Hakamada-Akasofu-Fry* (HAF) solar wind parameters, 2007; *Communication Alert and Prediction System* (CAPS) ionosphere, high frequency radio, and scintillation S_4 index prediction, 2008; and *GEO Alert and Prediction System* (GAPS) geosynchronous environment satellite charging specification and forecast, 2008. Operational systems that are in active operational implementation include the *Jacchia-Bowman 2006/2008* (JB2006/2008) neutral atmosphere, 2009, the *Nowcast of Atmospheric Ionizing Radiation for Aviation Safety* (NAIRAS) aviation radiation model, 2010, and a U.S. Dst ring current index, 2010. U.S. national agency and commercial space weather monitoring assets will soon reach a state where specification and prediction will become ubiquitous and where coordinated management of the space environment and space weather will become a necessity. We describe the state of industry initiatives for operational space weather and conclude that space weather management is needed to meet challenges beyond specification and prediction.

Role of the National Space Weather Program

The National Space Weather Program (NSWP) first outlined a *Strategic Plan*[1] for a U.S. interagency effort in 1995 to define the space weather discipline, prioritize national goals, identify customers, and develop a support base for characterizing, specifying, and predicting space weather. That effort produced a strategy for achieving space weather goals among U.S. agencies that included NSF and NASA as well as the Departments of Commerce, Defense, Energy, Interior, and Transportation. These goals included assessing and documenting the impacts of space weather, identifying customer needs, setting priorities, determining agency roles, coordinating interagency efforts and resources, ensuring exchange of information and plans, encouraging and focusing research, facilitating transition of research results into operations, and fostering education of the public and customers. A stated aim of that effort was to mitigate the hazards from space weather that included under/over-design of technical systems, regional power blackouts, failure of high-value satellites, communications disruption (HF, VHF, satellite, long-line), navigation system errors, and excessive radiation doses to humans.

In 1997 the NSWP *Implementation Plan*[2] identified a roadmap, specific objectives, and recommended activities necessary for improving space weather predictive capabilities. By the early part of the decade, the capabilities still fell short of requirements for warning, nowcasting, and

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forecasting while post-analysis capabilities became more robust. In this context, a second edition *Implementation Plan*[3] in 2000 provided the next level of detail and guided researchers to use metrics to better quantify progress in the domains of the ionosphere/thermosphere, magnetosphere, and solar/solar wind. In addition to the 21 solar and solar wind, 21 magnetospheric, and 31 ionospheric research models uniquely identified, the document emphasized physics-based modeling to improve predictive capabilities. NASA initiated the Living With a Star (LWS) Program and, along with the National Security Space Architect Space Weather Architecture, linked it with the NSWP. NOAA's Space Environment Center (SEC - now Space Weather Prediction Center - SWPC) and the U.S. Air Force's 55th Space Weather Squadron were identified as operational arms of the nation's agency space weather support capabilities. NOAA SEC started hosting Space Weather Week (SWW) in 1999 to bring users, researchers, developers, and agencies together in an annual space weather conference. NOAA SEC and Air Force Space and Missile Command (SMC) Rapid Prototyping Centers (RPCs) were started to adapt space weather models for use in the operational centers. While those RPCs are no longer in existence, the Community Coordinated Modeling Center (CCMC) that was developed at the same time remains as the sole arena, outside the growing space weather industry, that currently aids researchers in the comparison of models for operational uses.

In mid-decade, NOAA SEC was moved into the National Weather Service, which was seen by the community as a positive development. In 2006 a reassessment of the NSWP was completed with findings described in a NSWP *Assessment Report*[4]. While overall progress was found in the transition of innovative research into operations, there were a number of recommendations. For increasing the effectiveness of the NSWP, a cross-agency space weather organization was recommended (Center for Space Weather Research to Operations), combined with the need to establish focal points and expertise within the White House Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB). The need for data continuity was recognized, including the development of an L1 sensor and maintenance of the USGS ground-based magnetic observatories. Strengthening the science-to-user chain was identified as a goal for targeted and strategic space weather research. Resources for transition of models to operational users were recommended and an increased private sector role in supplying products and services was requested. It was emphasized that national benefits arising from the NSWP should be quantified for raising public and user awareness of space weather. Finally, it was noted that enhanced academic and professional education programs for new space weather professionals were needed.

Current state of space weather specification and forecasting

Nearing the end of the decade in 2009, and with the benefit of nearly 15 years of the NSWP, we can review at the current state of space weather specification and forecasting with an eye to identifying important tasks ahead of us. Due to the breadth and diversity of activity by agencies, research universities, and industry, we limit this review to the industry or private sector role in supplying products and services for space weather specification and forecasting.

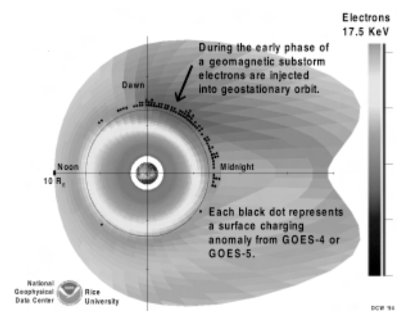

Fig. 1. MSM from Rice Univ.

The first industry application in 2000 was the validated *Magnetospheric Specification Model* (MSM)[5] of geosynchronous real-time energetic electron and ion fluxes, which was developed by Rice University and implemented at NOAA SEC by Sterling Software through a Cooperative Research and Development Agreement (CRADA). While MSM is no longer used operationally at SWPC, its implementation represented a breakthrough in industry-agency partnering for an operational space physics model. Soon thereafter in 2001, the *SOLAR2000* (S2K)[6] daily solar spectral irradiance model was also implemented operationally at NOAA SEC under a CRADA with Space Environment Technologies (SET). This implementation represented a milestone for expanded cooperation between NOAA and a company that was explicitly formed as part of the nascent space weather industry. It was the first time solar irradiances were produced operationally for multiple users. SET improved upon the daily irradiances with the SOLARFLARE (SFLR)[7] model in 2005-2008 to provide 1-minute temporal and 0.1 nm spectral resolution in 6-hour forecasts during solar flares. No further CRADAs were established between NOAA and industry, mostly as a result of NOAA SWPC's core mission consolidation after 9/11 and a very difficult budget climate that is still not fully resolved. S2K output is still provided operationally at SWPC via the SET servers (http://spacewx.com) while SFLR output comes solely through SET servers.

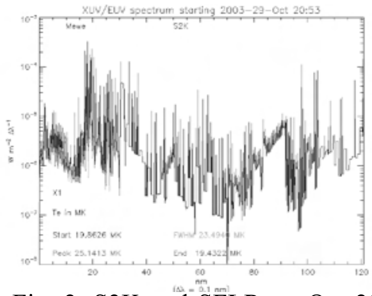

Fig. 2. S2K and SFLR on Oct 29 2003 from SET.

In a parallel development, the U.S. Air Force Space Command's (AFSPC) *High Accuracy Satellite Drag Model* (HASDM)[8] for neutral atmosphere densities was developed early in the decade and was made operational in 2004. Industry organizations of Lockheed Martin, Omitron, and SET developed the applications under direction from AFSPC's Space Analysis (A9AC) group. HASDM was important in that it provided the first significant improvement in current epoch thermospheric density specification in 30 years since the release of the CIRA 72 (Jacchia 1971) model and it was operational. Subsequent to HASDM, the AFSPC Sapphire Dragon and Fiery Dragon projects made additional improvements upon HASDM and resulted in the *Jacchia-Bowman 2006/2008* (JB2006/2008) neutral atmosphere models[9,10]. JB2008 reduces the mass density 1-sigma uncertainty at an epoch to ~8% compared with 15-20% for previous Jacchia and MSIS type models and, for this reason, was selected for incorporation into the CIRA 2008 reference atmosphere and the International Standards Organization (ISO) Earth Atmosphere Density >120 km standard. SET and Omitron supported AFSPC in developing JB2006 and JB2008. The daily updated indices that drive both models are provided by SET servers such as http://sol.spacenvironment.net/~JB2008/ and http://sol.spacenvironment.net/~JB2006/. It is anticipated that JB2008 will be operationally implemented by AFSPC in 2009; SET began providing commercial operational access to JB2006 and JB2008 for aerospace organizations in 2008.

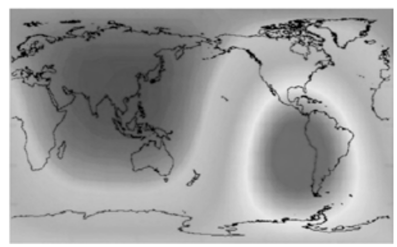

Fig. 3. JB2008 at 400 km from AFSPC and SET.

With activity that began when the NSWP was first organized in the mid-1990's, the Office of Naval Research (ONR) funded the development of data assimilation into ionospheric models for operational ionosphere accuracy. In 2004-2005, the two efforts by Utah State University (USU) and University of Southern California/Jet Propulsion Laboratory (USC/JPL) were

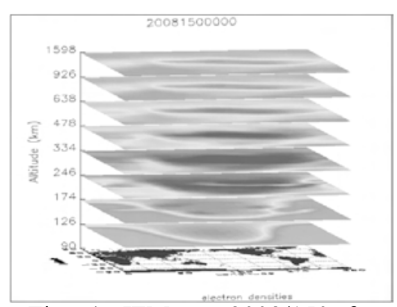

Fig. 4. IFM on 2008/150 from SEC.

compared by independent organizations. The Air Force Weather Agency (AFWA) selected the USU GAIM model called *Global Assimilation of Ionospheric Measurements*[11] for operational implementation to provide current epoch ionosphere specification. GAIM became operational in 2006 at AFWA and marked a major benchmark of increased ionosphere accuracy using data assimilation in physics-based ionosphere models. While USU holds rights to GAIM, Space Environment Corporation (SEC) provided its physics-based Ionosphere Forecast Model (IFM)[12] for the core of GAIM.

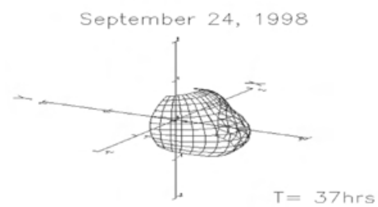

Fig. 5. HAF on Sep 24 1998 from EXPI.

AFWA continued its update of space weather forecasting by operationally incorporating the *Hakamada-Akasofu-Fry* (HAF)[13] solar wind model in 2007. HAF was developed for operations by Exploration Physics International (EXPI); in 2008 GAIM and HAF were coupled at AFWA to go beyond current epoch specification and produce ionosphere forecasts based on solar wind events. This was a significant step by AFWA that used the expertise of SEC and EXPI to couple together systems of models into a larger space weather forecasting system.

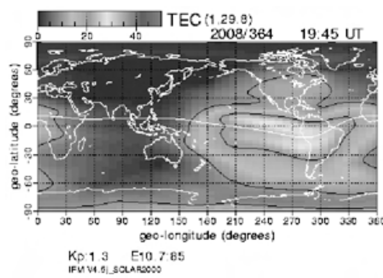

Fig. 6. CAPS on Dec 29 2008 from SET and SEC.

Building on the successes of S2K/SFLR and IFM in operational environments, SET and SEC joined those models in a collaborative commercial effort in 2007-2008. Along with researchers at the Air Force Research Laboratory (AFRL), they created the *Communication Alert and Prediction System* (CAPS) (http://sol.spacenvironment.net/~ionops/index.html). CAPS, released publicly in 2008 at SWW (now called Space Weather Workshop) via a NASA LWS press release/presentation, provides ionosphere parameters' specification and prediction for high frequency (HF) radio users. It also provides the low latitude S_4 scintillation index from the Physics-Based Model (PBMOD) for satcom UHF and L-band users. Commercial aviation and military organizations are testing CAPS and the application, especially in the popular Earth Space 4D (ES4D) application in Google Earth, is widely used in the ham radio community for real-time ionosphere conditions. IPS MeteoStar, a commercial aviation weather services provider, distributes CAPS data as a third party provider. CAPS achieved four major milestones that meet the intent of the NSWP Assessment Report: i) NASA LWS targeted space weather research funding enabled SFLR to be developed as a research tool used that could be used for operations, i.e., strengthened the science-to-user chain; ii) SET and SEC, as private sector organizations, created a joint product for commercial space weather users for the first time; iii) wide public education about space weather was promoted with the Google Earth real-time ionosphere of ES4D, and iv) the SFLR irradiances driving CAPS forecasts are certified compliant with the ISO standard for solar irradiances, IS 21348:2007[14], which enhances its utility for aerospace professionals.

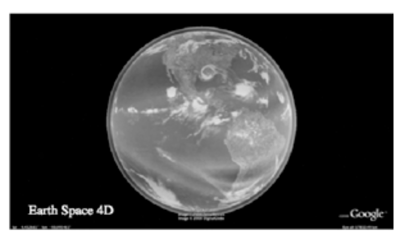

Fig. 7. ES4D on Sep 1 2008 from SET and SEC.

In 2008, SET released the *Geosynchronous Alert and Prediction System* (GAPS) (http://terra1.spacenvironment.net/~gapops/index.html) that provides geosynchronous environment satellite charging specifications and forecasts to geosynchronous satellite operators. Forecasts are out to 72-hours with 3-hour time granularity, 48-hours history, and 1-hour update cadence. The GEOPOT08 model is used with the Ap index driver to produce statistical electron fluxes for satellite surface charging using a two-Maxwellian temperature model for electrons and ions. Eclipse periods and deep dielectric discharge probabilities based on daily GOES 0.6 MeV electron fluences are also provided. The release of this application marks the first time an operational geosynchronous charging application has been provided to the satellite operator community by the private sector.

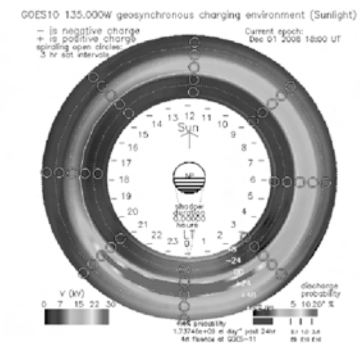

Fig. 8. GAPS for GOES10 from SET.

Two new operational systems are being operationally implemented by SET in 2009-2010. The *Nowcast of Atmospheric Ionizing Radiation for Aviation Safety* (NAIRAS) radiation model for aviation users has been developed by a team led by NASA Langley Research Center. Dose and total dose will be provided at aviation altitudes in real-time. In addition to NOAA SWPC and SET public access, SET will provide these data for commercial users through the *Radiation Alert and Prediction System* (RAPS). SET is also leading a team to develop a real-time and forecast U.S. Dst in conjunction with USGS under an AFRL contract. These data will be derived from the USGS global magnetic observatory network and will be released publicly via a USGS server. SET will provide these data for commercial users through the *Magnetic Alert and Prediction System* (MAPS).

With this overview of industry space weather activity, we conclude that major progress has been made in 7 areas for the operational specification and forecasting of: i) electron flux at geo-synchronous orbit (MSM, GAPS) for use by geosynchronous satellite operators; ii) solar irradiance spectra and indices (S2K, SFLR) for ionospheric and thermospheric data users; iii) neutral thermospheric densities (HASDM, JB2006, JB2008) for LEO satellite operators; iv) solar wind parameters (HAF) for magnetospheric and ionospheric data users; and v) ionosphere electron densities, TEC, MUF3000, foF2, low latitude S4 scintillation index (GAIM/HAF, IFM, PBMOD, CAPS, ES4D) for communications and navigation users. In addition, the near-term future will see the emergence of operational specification and forecasting of: i) radiation dose and dose-rate (NAIRAS/RAPS) for aviation users and ii) a U.S. Dst index (MAPS) for magnetic field data users.

The scope of space weather monitoring that has been implemented by industry reaches from the Sun (S2K/SFLR solar irradiances and HAF solar wind) to the Earth's magnetosphere (electron and ion flux at geo from MSM and GAPS, which includes deep dielectric discharge probabilities; ring current index of Dst from MAPS), ionosphere (electron densities, TEC, MUF3000, foF2, S4 from GAIM/HAF, IFM, PBMOD, and CAPS, which includes the public outreach Google Earth real-time space weather application ES4D), thermosphere (neutral mass densities from HASDM, JB2006, JB2008), and troposphere (radiation doses from NAIRAS/RAPS). Because of this progress, new challenges are emerging requiring new solutions.

Challenges ahead for space weather specification and forecasting

Given the progress during the past decade and the volume of activity in the research community at large, U.S. agency and commercial space weather monitoring capabilities will soon reach a state where specification and prediction are ubiquitous. This is a paradigm shift from the mid-1990's when the NSWP was first envisioned.

No longer is the goal simply to create better models and forecasts. Instead, there is a growing need for coordinated management of space environment monitoring. This need arises at a time when the number of space weather information stakeholders is growing rapidly and where no single organization has the capability of identifying, much less organizing, the universe of activity. A broad vision of space weather management is now needed for the tasks ahead.

Space weather management as a solution

The objective of space weather management is to provide effective, timely mitigation of space weather risks to our technological systems through stakeholder coordination.

The context of space weather management is a multiplicity of U.S. and international agencies, research universities, and industrial organizations that provide space environment related models, data, products, and services. We contend that the scope of activity is so broad, and necessarily global in reach, that no single agency or national organization can be successful at providing overarching management. Instead, a coordination of stakeholder actions is now required that can be motivated by common problems and common solutions[15].

We consider that space weather is beginning to operate in a supply chain fashion. It is a system of organizations, people, technology, activities, information and resources that are all involved in moving space weather products or services from suppliers to customers. Space environment data are the raw materials, production of information content is accomplished with model outputs, and derivative or specialized information is provided as a finished product that can be delivered to an end customer.

Challenges that must be answered in organizing and managing this supply chain include:

- ensuring uninterrupted, quality data from space and ground assets – a traditional task of government but data sale by the private sector will emerge;
- supporting ongoing research to improve data gathering and modeling – NASA LWS TRT, NSF space weather, AFOSR, and ONR funding activities have been very useful but new funding sources, including revenue from customers will appear;
- maintaining a cross-TRL (Technology Readiness Level) prototyping system for transitioning lower TRL components to higher TRLs – these were formerly called RPCs although CCMC is still an ongoing example and private sector prototyping processes have been in existence for nearly a decade;
- validating high TRL components that are ready for operations – independent assessment organizations, with funding for them, are found and continually needed;
- identifying customer needs and requirements for specialized products – this is a continually iterative process from beginning to end of the supply chain development and there is a need to bring in active customer discussion through conferences, private forums, and contractual relationships; and
- summarizing state-of-the-art best practices – this continues through professional society, agency, national, regional, and international standards, guidelines, and technical reports.

We recommend that the NSWP consider that space weather is becoming a supply chain with a need for management by vision as it develops future agency space weather coordination.

Conclusion

The National Space Weather Program (NSWP) has guided U.S. space weather efforts among agencies, research universities, and industry during the past decade and a half. In addition, the private sector has contributed substantial progress in 7 areas of operational space weather including electron flux at geosynchronous orbit, solar irradiance spectra and indices, neutral thermospheric densities, solar wind parameters, ionosphere parameters (electron densities, TEC, MUF3000, foF2, low latitude S4 scintillation index), radiation dose and dose-rate, and a U.S. Dst index. The scope of industry-implemented space weather monitoring now reaches from the Sun to the Earth's magnetosphere, ionosphere, thermosphere, and troposphere.

No longer can our goal be to simply create better models and forecasts. At a time when the number of space weather information stakeholders is growing rapidly and where no single organization has the capability of organizing the universe of activity, we need a vision for space weather management. That vision will understand that space weather monitoring enhances our access to space so that its resources can be used for human benefit. Space weather management by vision requires understanding the challenges ahead, the supply chain context, and the new opportunities for solutions. These opportunities include raw data sale by the private sector, research supported by revenue from customers, private sector prototyping processes, active customer discussions, and continuing standards development for the space environment. We recommend that the NSWP consider that space weather is becoming a supply chain with a need for management by vision as it develops its next level of agency space weather coordination.

Acknowledgments

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