New space weather mitigation capabilities

W. Kent Tobiska*

Three new capabilities are being developed for mitigating space weather effects. First, the U.S. Geological Survey (USGS) real-time Disturbance storm-time index, Dst, provides an estimate of the magnetosphere ring current and is used by the JB2008 thermospheric density model as a high latitude energy input. An operational USGS Dst system has been prototyped in 2009 with 1-minute time granularity and a few minutes latency. A forecast capability to 72-hours is being developed for beta testing in 2010 and full implementation by 2011. Second, the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) system is developing radiation dose and dose rate real-time estimates for air-crew and passengers. Beta-system testing begins in 2010 with full system implementation in 2011. Third, the Global Assimilation of Ionospheric Measurements (GAIM) data assimilative system has been transitioned to commercial operations in 2009. This system provides accurate real-time ionosphere conditions needed for specifying HF communication outages and GPS uncertainties. We report on the progress in each of these three areas and their status towards operational implementation.

Legacy of the National Space Weather Program

The National Space Weather Program (NSWP) originally 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 realizing space weather goals among U.S. agencies and reached from assessing and documenting the impacts of space weather to identifying customer needs, setting priorities, encouraging and focusing research, and facilitating transition of research results into operations. The objective has been mitigation of hazards from space weather that include regional power blackouts, failure or disruption of high-value satellites, communications disruption (HF, VHF, satellite, long-line), navigation system errors from GPS uncertainties or loss, and excessive radiation doses to humans.

By 1997 the NSWP *Implementation Plan*[2] identified a roadmap, specific objectives, and recommended activities necessary for improving space weather predictive capabilities. By 2000, capabilities were not able to meet the requirements for warning, nowcasting, and forecasting although post-analysis capabilities had become more robust. Thus, a second edition *Implementation Plan*[3] was released and provided a new level of detail to guide researchers in the domains of the ionosphere/thermosphere, magnetosphere, and solar/solar wind. In that document 21 solar and solar wind, 21 magnetospheric, and 31 ionospheric research models were uniquely identified and physics-based modeling to improve predictive capabilities was emphasized.

In 2006 a reassessment of the NSWP was completed with findings described in a NSWP *Assessment Report*[4]. While overall progress had been made in the transition of research into opera-

* Director, Space Weather Center, Utah State University, 4405 Old Main Hill Logan, UT 84322; Chief Scientist, Space Environment Technologies, 1676 Palisades Dr., Pacific Palisades, CA 90272; AIAA Associate Fellow.

tions, a number of recommendations were made. These highlighted the need for space weather data continuity including the development of an L1 sensor and maintenance of the USGS ground-based magnetic observatories. Resource assistance for the transition of models to operational users was recommended along with support for an increased private sector role in supplying products and services.

The substantial progress made in creating systems of models within the context of the NSWP vision has been recently reported by Tobiska[5,6,7]. In this paper, we describe the maturation of three systems that have evolved within the NSWP legacy, that incorporate physics-based models and real-time data streams, and that will be playing major roles in mitigating space weather.

The first system is the U.S. Geological Survey (USGS) real-time Disturbance storm-time index, Dst, that provides an estimate of the magnetosphere ring current and is used by the JB2008 thermospheric density model as a high latitude energy input. JB2008 is slated to become part of the new COSPAR International Reference Atmosphere (CIRA08) and the International Standards Organization (ISO) standard on Earth atmosphere density above 120 km. An operational USGS Dst system was prototyped in 2009 with 1-minute time granularity and is running at Technology Readiness Level (TRL) 7. A forecast capability to 72-hours is being developed for beta testing in 2010 and full implementation by 2011.

The second system is the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) that will provide radiation dose and dose rate real-time estimates for air-crew and passengers. Physics-based models and real-time data streams have been developed and beta testing begins in 2010 with full system implementation in 2011.

The third system is the Global Assimilation of Ionospheric Measurements (GAIM) using data assimilation that has been transitioned to commercial operations in 2009. GAIM, in both global and high-resolution Continental U.S. (CONUS) subsystems, provides accurate real-time ionosphere conditions needed for specifying HF communication outages and GPS navigation uncertainties.

Within the next year these three systems will provide mitigation of space weather hazards for regional power blackouts, failure or disruption of high-value satellites, communications disruption (HF, VHF, satellite, long-line), navigation system errors from GPS uncertainties or loss, and excessive radiation doses to humans with warning, nowcast, and forecast capabilities. These systems use physics-based models and real-time data from the ionosphere/thermosphere, magnetosphere, and solar/solar wind domains.

USGS Dst index

The U.S. Air Force (USAF) has a requirement for accurately specifying and forecasting thermospheric densities for use in Low Earth Orbit (LEO) satellite orbit calculations. The JB2008 empirical thermospheric density model (figure 1) provides the highest accuracy thermospheric densities compared to any thermospheric density model[8,9,10]. This is made possible, in part, due to its use of the Dst index. Dst characterizes the energy input into high-latitude regions during geomagnetic storms and substorms. Because of the advantages of JB2008 the USAF plans to operationally implement this model. JB2008 code and indices can be found at the http://spacewx.com site and the JB2008 menu links.

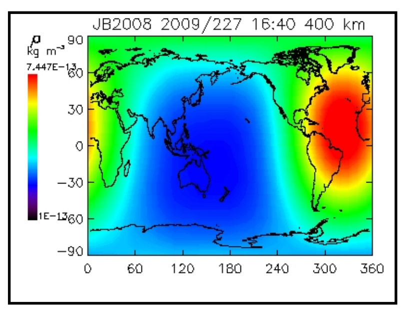

Fig. 1. JB2008 400 km thermospheric densities; Aug. 15, 2009 16:40 UT.

At present the Dst is not provided with the operational robustness required for AF operations. To correct this situation, the USGS Geomagnetism Program has recently developed a Dst index based on the same network of magnetic observatories as the ones used by the Kyoto Dst. The USGS team has demonstrated an excellent comparison between the USGS and Kyoto Dst indices for all levels of storm conditions[11] (figure 2). The USGS Dst prototype real-time system is now being demonstrated at a SET TRL 7 website where there is system and component demonstration in a relevant environment.

In addition to the current epoch specification of Dst, space and ground systems that use thermospheric densities produced by JB2008 will benefit from an accurate data stream of forecast Dst out to 72 hours. The achievement of this difficult objective is dependent upon accurate characterization of the solar wind between the Sun and the ACE spacecraft, and between ACE and the Earth. In a 2009 feasibility study, the path for providing the most accurate forecast possible, based on solar wind measurements and models, was identified and it includes ensemble solar wind modeling. On one hand, if one solar wind model consistently gives results leading to the best Dst forecast, then that model becomes consistently designated as the primary model. On the other hand, if models differ inconsistently from one another then an averaging technique may provide the best forecast. To the benefit of operational users, the range of variation in solar wind parameters between the models provides a way to quantify uncertainty. This forecast architecture is robust by not allowing the failure of a single model or measurement to prevent the forecast, is flexible by allowing the best forecast to become the primary forecast data stream, and is extensible by allowing improvements in empirical, hybrid, and physics-based models as well as measurements to be incorporated easily and transparently into the operational forecast system while maintaining version control.

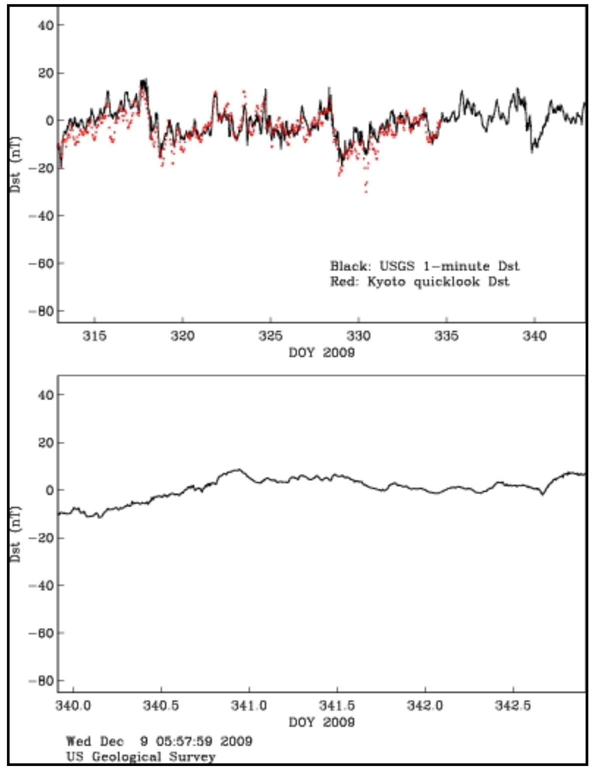

Fig. 2. USGS (black) 1-minute Dst and Kyoto (red/gray) 1-hour Dst from a TRL 7 prototype.

Space Environment Technologies (SET) is leading the 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 as the current epoch Dst via a USGS server. SET will mirror these public data for users through the *Magnetic Alert and Prediction System* (MAPS) at http://sol.spacenvironment.net/~maps/ and will also provide a forecast for operational users.

In 2011 a TRL 8 ready-for-deployment, robust and redundant, validated and verified operational system will be demonstrated that provides current epoch Dst with 1-minute time granularity and latencies, along with cadences, of approximately 5 minutes. The operational system will also provide an accurate Dst forecast with time granularity of minutes to 1 hour and 1-hour to 72-hours.

NAIRAS radiation dose and total dose

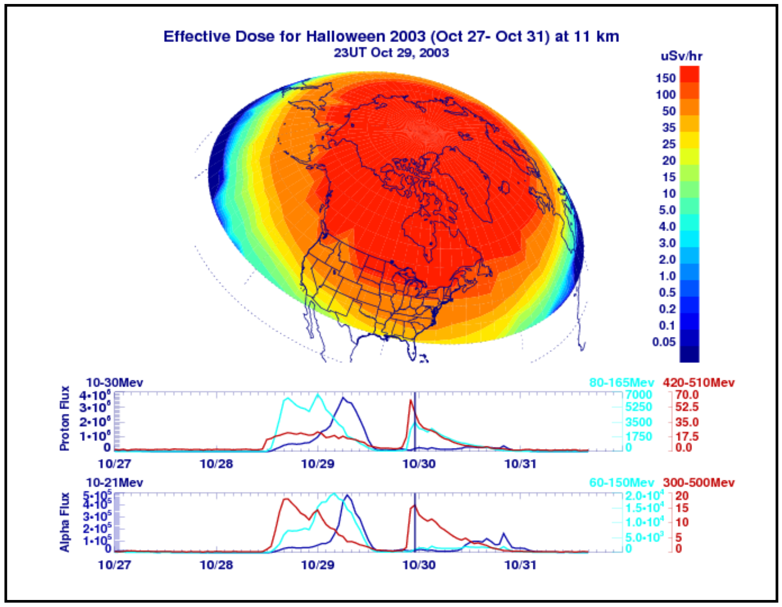

Fig. 3. NAIRAS effective dose for Halloween 2003 storm at 11 km altitude from a TRL 6 prototype.

The *Nowcast of Atmospheric Ionizing Radiation for Aviation Safety* (NAIRAS) radiation model system for aviation users has been developed by a team led by NASA Langley Research Center[12]. Dose and total dose will be provided at aviation altitudes in real-time. The development of this system comes from a need for nowcast prediction of air-crew radiation exposure from both background galactic cosmic rays (GCR) and from solar energetic particle (SEP) events that may result from solar storms. NAIRAS is being developed to provide global, data-driven, real-time radiation exposure predictions of biologically harmful radiation at commercial airline altitudes. Observations are utilized from the ground (neutron monitors), from the atmosphere (the NCEP Reanalysis and NCEP Global Forecasting System), and from space (NASA/ACE and NOAA/GOES). Atmospheric observations provide the overhead shielding information and the ground- and space-based observations provide boundary conditions on the incident GCR and SEP particle flux distributions for transport and dosimetry simulations. Exposure rates are calculated using the physics-based HZETRN (High Charge and Energy Transport) code. In addition to NOAA SWPC and SET public access, SET will provide these data for operational users through the *Radiation Alert and Prediction System* (RAPS). A public website for the system is located at the http://sol.spacenvironment.net/~nairas/index.html.

GAIM global and high-resolution CONUS ionosphere

Government and commercial users have a critical need for reliable high-frequency (HF) communications and for accuracy knowledge in GPS-based navigation systems. To satisfy this need requires an accurate specification of the effect that the upper atmosphere/ionosphere has on operational communication links and navigation systems. Like the Earth's lower atmosphere, the Earth's upper atmosphere and ionosphere (ionized gas) display highly variable and turbulent densities, temperatures, and winds, and these features are manifestations of space weather. These disturbances can adversely affect systems and operations, including over-the-horizon radars, HF communications, Global Position System (GPS) navigation, and GPS aided geo-location. Ionospheric corrections are particularly important for accurate location knowledge and for obtaining usable communication frequencies between two geographic locations.

The Utah State University team at the Space Weather Center (http://spaceweather.usu.edu/) has developed a data assimilation model of the Earth's upper atmosphere/ionosphere that is similar to the tropospheric weather models run by NOAA. This space weather model, which is called the *Global Assimilation of Ionospheric Measurements* (GAIM), provides real-time specifications and forecasts for global distributions of upper atmosphere/ionosphere densities, temperatures, and winds[13]. The GAIM space weather model became an operational Air Force model at the AFWA in December 2006.

In 2009 funding for a new Space Weather Center (SWC) at Utah State University (Logan) was provided by the Utah Science Technology and Research (USTAR) initiative. SWC is developing real-time operational solutions that mitigate adverse space weather effects on communication and navigation systems. These will provide current epoch and forecast information across multiple platforms to warn of navigation errors and communication outages through automated systems. These capabilities will help prevent loss of radio communications for military, first responder, commercial aviation, amateur radio users, and will improve precision and accuracy of location knowledge derived from GPS-based applications.

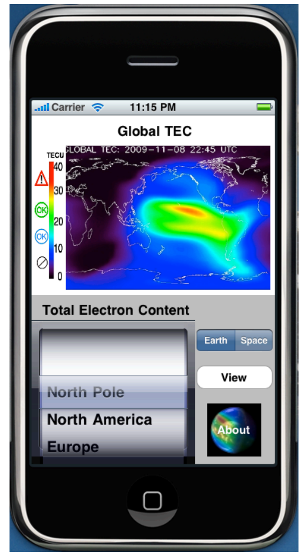

Fig. 4. SWC and SET iPhone app *Space WX*.

During the Fall of 2009 SWC released three major capabilities. On September 1, SWC and SET released, as a joint product, the first iPhone and iPod touch app for hand-held real-time space weather called *Space WX* (figure 4). This is available at the Apple iTunes store. On September 1, the commercially operational GAIM Gauss-Markov global ionosphere data was released (figure 5) and on November 18 the GAIM high resolution Continental U.S. (CONUS) data was released (figure 6). GAIM global uses 357 TEC stations (IGS network) in real-time with up to 10,000 measurements ingested every 15 minutes. GAIM CONUS uses 424 USTEC stations (CORS network) in real-time with up to 10,000 measurements ingested every 15 minutes. The real-time data is assimilated into the Ionosphere Forecast Model (IFM), a background physics-based ionosphere[14].

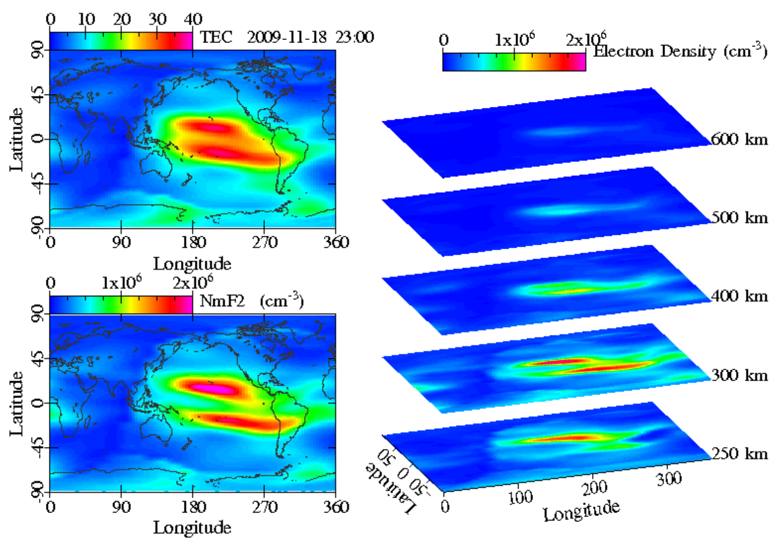

Fig. 5. GAIM Gauss-Markov global total electron content (TEC).

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. Three new capabilities are being developed for mitigating space weather effects. The USGS real-time Dst index provides an estimate of the magnetosphere ring current and is used by the JB2008 thermospheric density model as a high latitude energy input. An operational USGS Dst system has been prototyped in 2009 with 1-minute time granularity and a few minutes latency. A forecast capability to 72-hours is being developed for beta testing in 2010 and full implementation by 2011. The

NAIRAS system is developing radiation dose and dose rate real-time estimates for air-crew and passengers. Beta-system testing begins in 2010 with full system implementation in 2011. The GAIM data assimilative system has been transitioned to commercial operations in 2009. This system provides accurate real-time ionosphere conditions needed for specifying HF communication outages and GPS uncertainties.

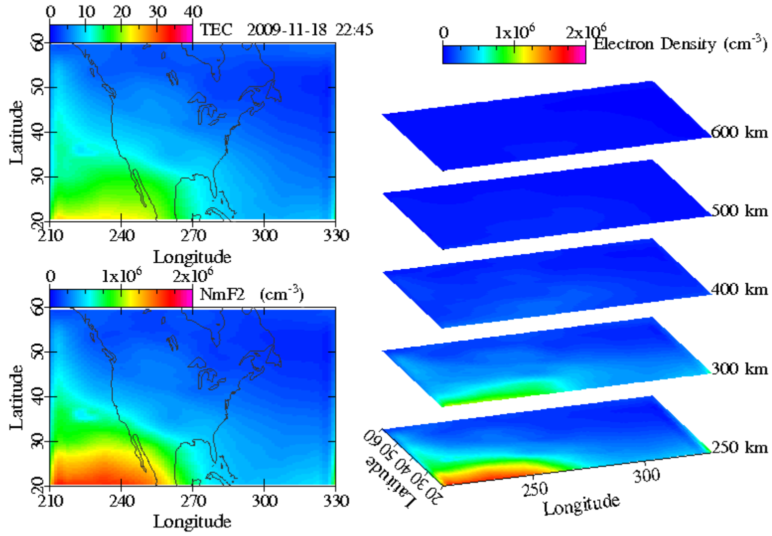

Fig. 6. GAIM Gauss-Markov CONUS total electron content (TEC).

Acknowledgments

Support for this work has been provided by the Space Weather Center at Utah State University under the auspices of the USTAR program. SET provides forecast, current epoch, and historical space environment data and models, including JB2008, Dst, and NAIRAS, at http://www.spacewx.com/. The Space Weather Center at Utah State University provides GAIM system data at http://spaceweather.usu.edu/.

References

[1] *The National Space Weather Program. The Strategic Plan: August 1995.* FCM-P30-1995. Working Group for the National Space Weather Program, Committee for Space Environment Forecasting, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, D.C.

[2] *The National Space Weather Program. The Implementation Plan: January 1997*. FCM-P31-1997. Working Group for the National Space Weather Program, Committee for Space Environment Forecasting, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, D.C.

[3] *The National Space Weather Program. The Implementation Plan: 2nd Edition. July 2000.* FCM-P31-2000. Committee for Space Weather, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, D.C.

[4] *Report of the Assessment Committee for the National Space Weather Program.* FCM-R24-2006. Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, D.C.

[5] Tobiska, W.K., International Standards Will Enhance Space Weather Management, *Space Weather, 6*, S06001, doi:10.1029/2008SW000410, 2008.

[6] Tobiska, W.K, Space Weather Management, AIAA-2009-1494, 2009.

[7] Tobiska, W.K, Tobiska, W.K., Operational Space Weather Entering a New Era, *Space Weather, 7*, S10003, doi:10.1029/2009SW000510, 2009.

[8] Bowman, B.R., W.K. Tobiska, F.A. Marcos, C. Valladares, The JB2006 empirical thermospheric density model, *J. Atm. Solar Terr. Phys.,* **70**, 774, 2008.

[9] Bowman, B.R., W.K. Tobiska, F.A. Marcos, C.Y. Huang, C.S. Lin, and W.J. Burke, A New Empirical Thermospheric Density Model JB2008 Using New Solar and Geomagnetic Indices, AIAA/AAS Astrodynamics Specialist Conference, AIAA 2008-6438, 2008.

[10] Tobiska, W.K., S.D. Bouwer, and Bowman, B.R., The development of new solar indices for use in thermospheric density modeling, *JASTP*, **70**, 803-819, 2008.

[11]Love, J.J. and J.L. Gannon, Revised Dst and the epicycles of magnetic disturbance: 1958–2007, *Ann. Geophys.,* **27**, 3101–3131, 2009.
[12]Mertens, C.J., W.K. Tobiska, D. Bouwer, B.T. Kress, M.J. Wiltberger, S.C. Solomon, and J.J. Murray, Development of Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) model, AIAA 2009-3633, 2009.
[13]Schunk, R.W., L. Scherliess, J.J. Sojka, D.C. Thompson, D.N. Anderson, M. Codrescu, C. Minter, T.J. Fuller-Rowell, R.A. Heelis, M. Hairston, B.M. Howe, Global Assimilation of Ionospheric Measurements (GAIM), *Radio Sci.*, **39**, RS1S02, 2004.
[14]Schunk, R.W. and J.J. Sojka, USU model of the global ionosphere, *Solar-Terr. Energy Program: Handbook of ionospheric models*, ed. R. Schunk, SCOSTEP, 153, 1996.