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Solar and Geomagnetic Space Environment Specification for Operations

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The short-term, variable impact of the Sun's photons, solar wind particles, and interplanetary magnetic field upon the Earth's environment can adversely affect technological systems and is known as space weather. Space Environment Technologies (SET) and Exploration Physics International (EXPI) have formed a strategic partner alliance to produce commercial space weather products that will reduce risks to space and ground operations. This is the first commercial service to predict solar photons, particles, and fields that affect technological systems at Earth and beyond. We describe an EXPI operational model of the solar wind density, velocity, and magnetic field and the SET operational models of solar irradiances and solar flare evolution prediction that jointly provide forecast parameters. The solar photons, particles, and fields generated by the solar wind, solar irradiance, and flare prediction models are used as fundamental energy inputs into other space physics models. The resulting information describes the dynamical changes in the near-Earth space environment that result from space weather. EXPI and SET have established their partner alliance to extend space weather services to communication, navigation, geolocation, satellite operation, and other industries.

Nomenclature

ap	=	planetary geomagnetic index
CME	=	coronal mass ejection
ESD	=	electrostatic discharge
E_{SRC}	=	145-165 nm solar irradiance index reported in $F_{10.7}$ units
EUV	=	extreme ultraviolet solar irradiances (10 – 121 nm)
HAF	=	Hakamada-Akasofu-Fry solar wind model
HF	=	high frequency radio
IMF	=	interplanetary magnetic field
MHD	=	magnetohydrodynamics
PCA	=	polar cap absorption
S2K	=	SOLAR2000 solar irradiance model
SEU	=	single event upsets
S_{EUV}	=	26-34 nm solar irradiance index reported in $F_{10.7}$ units
SSA	=	space situational awareness
TEC	=	total electron content

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The Challenges of Space Weather

The near-Earth space environment contains abundant energy that affects natural and technological systems. The primary energy sources in the space environment come from dynamical processes related to stellar (including galactic), solar, and planetary (including comets, gas, and dust) evolution. The energy exists in the form of *photons, particles (neutral and charged), and fields (magnetic, electric, and gravitational)* and it is conserved, transferred, or exchanged. In addition to the natural photons, particles, and fields, human activity has added a new component to the near-Earth space environment, i.e., orbital debris. Together, these comprise the domain of the *space environment* as shown in figure 1.

The short-term variable impacts of these photons, particles, and fields upon the Earth's environment, especially from sources such as solar irradiances, the solar wind, and the solar interplanetary magnetic field but also from debris, can adversely affect technological systems and, together, are colloquially known as *space weather*. The impacts include, for example, the effects from solar coronal mass ejections (CMEs), solar flares and irradiances, and energetic particles (electrons and protons) in the solar wind that are modulated by galactic cosmic rays. All these affect Earth's magnetospheric particles and fields, geomagnetic and electrodynamical conditions, radiation belts, aurorae, ionosphere, and the neutral thermosphere and mesosphere during perturbed as well as quiet levels of solar activity. Geomagnetic disturbances coupled with neutral winds, ionospheric currents, and atmospheric gravity waves can affect HF propagation while ionospheric scintillation related to small-scale plasma density changes, field-aligned irregularities, and turbulence can affect communication and navigation. Small debris objects randomly but regularly cause surface degradation to space systems. Large orbital objects can cause catastrophic damage to space systems upon impact. Given the breadth of phenomena from natural and artificial sources, we now recognize that space weather is the broad canvas upon which any human activity in near-Earth space must be drawn.

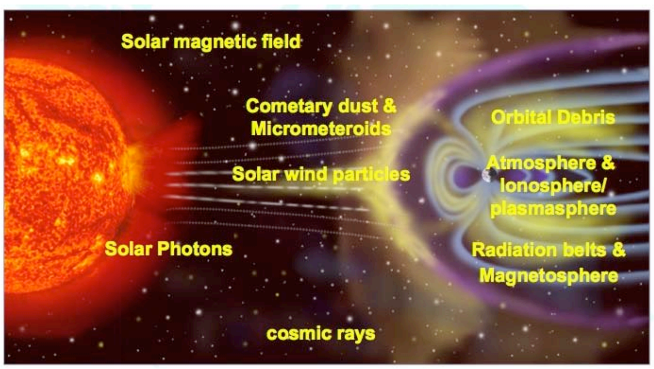

Fig. 1. Space environment components (photons, particles, fields) contribute to space weather.

Because of the importance of space weather, there are substantive efforts underway in this decade to operationally characterize space weather as a coupled, seamless system from the Sun-to-Earth. This coupling links data streams and models to provide a capability for quantifying recent, current, and future conditions. In particular, near-term improvements to operations are needed and these include monitoring the effects from CMEs and orbit debris (OD) which affect the neutral atmosphere and ionosphere as well as adversely impact low Earth orbit (LEO)/higher altitude orbiting systems and communication/navigation systems. If the occurrence, geoeffectiveness, and timing of CME shocks and the detection of catastrophic debris conjunctions with high value space assets can be made, a major milestone will have been achieved for mitigating space weather risks.

Space Environment Technologies (SET) and Exploration Physics International (EXPI) have formed a strategic partner alliance to address these space weather challenges by producing commercial space weather products through coupled models and data streams that will reduce risks to space and ground operations and improve space situational awareness. This is the first commercial service to predict solar photons, particles, and fields that affect technological systems at Earth and beyond.

Mitigation of Space Weather Effects to Enhance Space Situational Awareness

Space situational awareness (SSA) has been described as the perception (measurement) of space environment elements within a volume of time and space, the comprehension (interpretation) of their meaning, and the projection (prediction) of their status into the near future. There are many space weather challenges to SSA including making observations, warnings, forecasts, and analyses with the accuracy, precision, resolution, and timeliness that are required to meet existing and future requirements. The requirements derive from classes of missions (communication, navigation, manned space, radar operations, satellite operations, or surveillance) and there are three common challenges between these classes: *making measurements rapidly*, *interpreting them quickly*, and *reacting to the real-time and predicted information with appropriate and timely actions*. The capability we are building will directly improve each of these mission classes by providing a fundamental technical capability that addresses the three challenges.

On-orbit and ground-components of space systems serve these mission classes and there are numerous examples of space weather effects upon them. Examples include electronic component anomalies or catastrophic loss, loss of communications, increased navigation uncertainty, and vehicle or debris orbit change from drag. The capability we are providing supports the mitigation of space weather risks to each of these areas:

Electronics:

- SEU – single event upsets occur from local ionization in semiconductor material causing a burst of free electrons and ions; this can lead to a short electrical pulse and an unplanned change in the state of the circuit; it is a transient effect caused by *penetrating radiation of high energy photons, electrons, and protons*;
- latchup – is similar to an SEU but leads to a high current state in which a device no longer accepts input signals; CMOS PROM devices may be most sensitive; it can result in catastrophic loss of the system and/or spacecraft; it is a permanent effect caused by *penetrating radiation*;
- surface charging – is a difference in spacecraft surface electrostatic potential with respect to the surrounding plasma; discharge occurs between relatively large potential differences and can cause spurious electronic switching, breakdown of thermal coatings, amplifier and solar cell degradation, and optical sensor degradation; most reported problems are at high altitudes > 5 Earth radii (R_E) where there is a greater susceptibility to magnetotail particle fluxes; it is a transient effect caused by the *photoelectric effect (extreme ultraviolet (EUV) photon removal of surface electrons)* and *low energy plasma (electron and ion) bombardment*;
- ESD – electrostatic discharge occurs when the potential difference between two components increases and a sparking potential is reached; it is often associated with deep dielectric charging/discharge; discharge occurs with a large current flow over large distances, at low pressures, and on a short time scales (a few microseconds or less); it is a transient effect caused by *energetic particle* charge deposition in dielectric materials during periods of spacecraft charging.

Communications:

- HF signal loss – high frequency (HF) signal loss occurs from a change in the electron density profile and thus the reflecting layer of the ionosphere; this can lead to ground-to-ground and ground-to-air communication interruption or loss; it is a transient effect caused in low and mid latitudes by *EUV photons* and in high latitudes by *precipitating electrons*;

- PCA – polar cap absorption occurs from event-driven ionization of the mesosphere (D-region) altitudes; this can lead to radar scatter or ground-to-ground and ground-to-air communication interruption/loss of HF communications; it is a transient effect caused by *solar energetic protons* penetrating into high latitudes;

Navigation:

- TEC – total electron content variation occurs from a change in the integrated electron density and thus ionosphere column through which GPS signals pass from transmitter to receiver; this can lead to received signal timing error and thus position error in precision navigation systems; it is a transient effect caused in low and mid latitudes by *EUV photons* and in high latitudes by *precipitating electrons*;

Orbit change:

- Drag – satellite drag occurs at low Earth orbit (LEO) altitudes from density changes in the neutral thermosphere; this can lead to unmodeled in-track position error that affects satellite operations; it is particularly effective upon satellites without active propulsion and upon orbit debris particles of all sizes including re-entering vehicles; it is a cumulative effect caused in low and mid latitudes by *EUV photons* and in high latitudes by *precipitating electrons*.

We note that a few space weather phenomena are common to these mission classes. They are a) high energy solar photons, electrons, and protons that produce penetrating radiation (SEUs, latchup, ESD, PCAs) or lead to increased populations of magnetospheric and radiation belt energetic particles and b) moderate energy solar EUV photons, electrons, and ions that ionize (surface charging, HF signal loss, TEC change) and heat (drag) the neutral atmosphere. The sources for these solar photons, electrons, and protons at all wavelengths and energies are the flare, active region, plage, network, internetwork (irradiances), and coronal hole (background solar wind) features as well as coronal mass ejections (energetic particle injection into the solar wind). We particularly want to characterize how the photons and particles at all energies will be effective at or near the Earth by monitoring (observing through time) and predicting (modeling into the future) the irradiance and particle fluxes with an accuracy and precision that meets current and future operational requirements. The coupled data–model system we are developing will directly lead to improved information content for monitoring and modeling requirements of operational systems in the communication, navigation, manned space, radar operations, satellite operations, and surveillance missions.

Operational Models that improve SSA

It is important to have warnings, forecasts, and analysis capabilities for space weather-related phenomena such as surface charging, SEUs, latchups, ESDs, PCAs, HF signal loss, TEC change, and satellite drag that result from solar photons, electrons, and protons. As a foundation for this capability, SET and EXPI have provided two operational models to the Air Force Weather Agency (AFWA) and NOAA Space Environment Center (SEC). These two models, described below, are also being cross-linked in a distributed network through the SET and EXPI servers to provide access to real-time and forecast solar and geomagnetic indices for thermospheric density and ionospheric applications.

HAF. The Hakamada-Akasofu-Fry (HAF) solar wind model was developed by Exploration Physics International, Inc. (EXPI) and the Geophysical Institute at the University of Alaska, (Fairbanks – GI/UAF). The HAF model provides quantitative forecasts, days in advance, of solar wind conditions. Specifically, it tracks interplanetary disturbances as they propagate from their source at the Sun. HAF also provides temporal profiles of the solar wind speed, density, dynamic pressure, and interplanetary magnetic field (IMF) anywhere in the solar system.

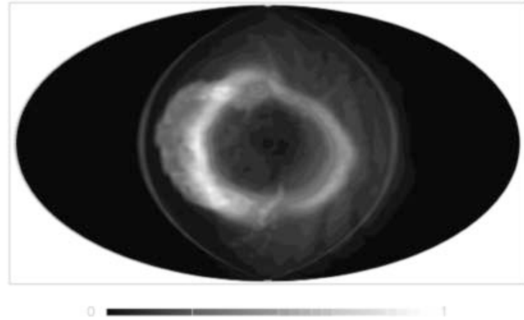

Fig. 2. Heliospheric imager synthetic product for May 29, 2003, T=10 UT derived from the HAF solar wind model. This is an example of CMEs that are tracked and used by HAF. The occulted Sun is at the center of the image.

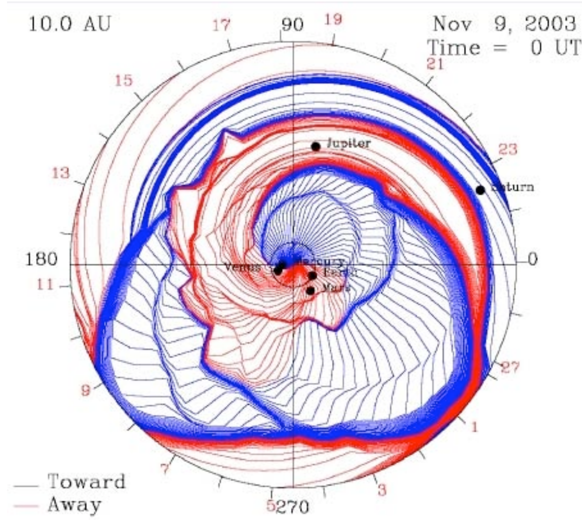

Fig. 3. Ecliptic plane interplanetary magnetic field (IMF) derived from the HAF solar wind model. Pre-November 9, 2003 CMEs and their propagation into the heliosphere are shown and shock arrival times at Earth can be predicted.

The HAF model is driven using synoptic solar observations, CME tracking (figure 2), and solar event reports. This information is used to predict the timing and severity of space weather disturbances following solar events, or the passage of co-rotating interaction regions (CIRs). The HAF model maps the disturbed and the undisturbed solar wind, so it is applicable to all phases of the solar cycle. Additionally, HAF produces chronological sequences of ecliptic-plane plots of the IMF (figure 3) and other solar wind parameters. The HAF kinematic procedure follows fluid parcels and the frozen-in IMF field lines. This approach to first principles conserves mass and momentum but not energy. This methodology is described in a body of literature[1,2,3,4,5]. The HAF model internal parameters have been calibrated with a 1-D MHD model[6] and recent model improvements have been described[4] as have model validation results[5]. This model can use CME tracking information, for example, to generate improved solar wind shock arrival times at Earth. Shocks impact the IMF and solar wind features, perturb Earth's magnetosphere, and change the magnetospheric energetic particle populations. HAF model results are converted to the planetary geomagnetic index (an equivalent ap) (figure 4) which can be used by the new Jacchia-Bowman thermospheric density model[7].

SOLAR2000. The SOLAR2000 (S2K) model[8,9,10] was developed by Space Environment Technologies through NASA research support and provides solar spectral irradiances and integrated solar irradiance indices for space researchers as well as ground- and space-based operational users. The S2K model provides empirical and physics-based solar irradiances and integrated irradiance indices covering the spectral range from the X-rays through the far infrared (figure 5). Daily variability is provided for time frames ranging from 1947 to 2052. The variability in daily, hourly, minutely time frames, with spectral formats that range from resolved emission lines to integrated irradiance indices, is a unique feature providing researchers and operational users the same solar energy suitable for their distinctly different applications.

There have been 25 formal releases of S2K since October 7, 1999. The Operational Grade (S2K OP) version of the model provides high time resolution data and is operationally produced at both NOAA SEC and SET servers. S2K will soon include solar flare evolution from 0.1–30 nm at 0.1 nm resolution and is incorporating real-time data streams from GOES XRS, GOES SXI, TIMED SEE, and SOHO SEM satellite instruments. This enables data-driven 1-minute cadence 6-hour flare evolution prediction, 3-hour cadence 72-hour forecast, and 1-day cadence 7–day forecasts. These irradiances cause spacecraft charging (photoemission) and directly result in ionospheric formation as well as neutral density variations that create satellite and debris drag. Two new indices[7], S_{EUV} (26-34 nm) and E_{SRC} (145-165 nm proxy – currently the Mg II index converted to $F_{10.7}$ units – Mg_{10}), will soon be provided through S2K OP and can be used by the new Jacchia–Bowman thermospheric density model.

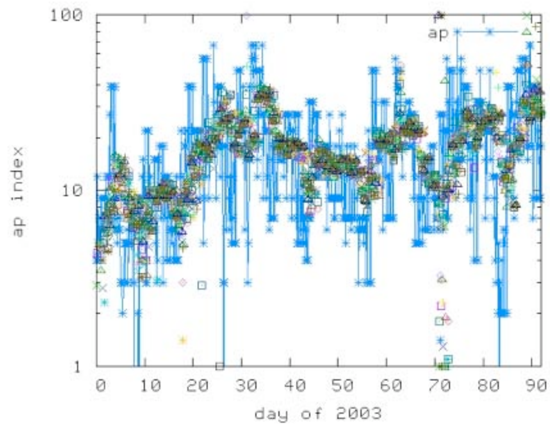

Fig. 4. ap forecast in 2003 derived from the HAF solar wind model (symbols of various shapes except asterisks) versus the actual ap (3-hour planetary geomagnetic index) (asterisks).

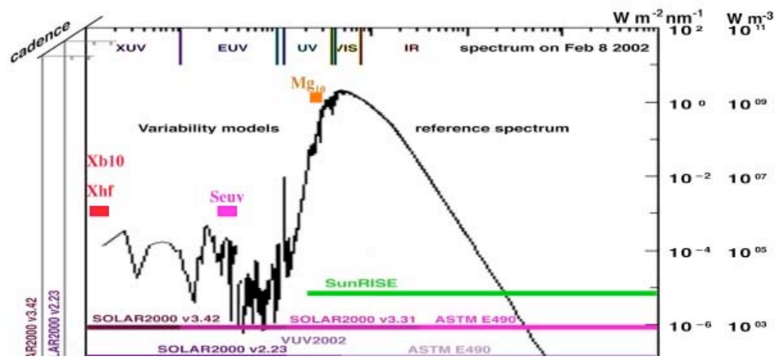

Fig. 5. The SOLAR2000 model provides irradiances and indices across the entire solar spectrum from X-rays to infrared with a daily, hourly, minutely cadences. The Mg_{10} and S_{EUV} indices are used in the Jacchia-Bowman thermospheric density model.

Application. The cross-linked SET and EXPI operational models' output is designed to meet SSA challenges. Near real-time data stream inputs (HAF: solar magnetograms, CME tracking, and solar event reports; S2K: NOAA, GOES, SOHO, and TIMED irradiances) into these two operational models result in accurate thermospheric density information for quick interpretations that can dramatically reduce reaction times. An example application for the combined SET and EXPI cross-linked system is for vehicle re-entry and debris collision avoidance. The Air Force Space Command (AFSPC) is operationally improving the 72-hour forecast of thermospheric densities for orbit determination purposes through the Sapphire Dragon project. It can use the solar (S_{EUV} and E_{SRC}) and geomagnetic (ap) indices developed by SET and EXPI and delivered through the S2K and HAF models.

Conclusion

The overarching objective of the SET–EXPI partner alliance is to provide a system-level capability that enables risk mitigation of space weather phenomena. Examples of natural phenomena include energetic particles and photons that come from solar CMEs and flares as well as dynamical solar wind and irradiance variability. Our cross-linked system is designed to address the

SSA challenges of *making measurements rapidly*, *interpreting them quickly*, and *reacting to the real-time and predicted information with appropriate and timely actions*.

Our current capabilities combine near real-time solar irradiance and particle data streams with operational models to produce current epoch and forecast geoeffective solar irradiances (S_{EUV} and E_{SRC}/Mg_{10}) and geomagnetic indices (ap). These are designed for use in new thermospheric density models such as Jacchia-Bowman to provide a significantly improved 72-hour thermospheric density forecast. These forecasts provide operational satellite users the information they need to interpret space weather events quickly and react with appropriate actions.

Acknowledgments

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