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# Paper Session I-B - USAF Space Weather Support

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### *History*

Military and other government agencies routinely operating in space have long recognized the potential impacts of "space weather" on their operations. This understanding led to the establishment of military (US Air Force, USAF) and civilian (National Oceanic and Atmospheric Administration, NOAA) units dedicated to the continuous, near real-time observation, analysis, and prediction of solar and geophysical conditions. The USAF Air Weather Service (AWS) has provided space environmental support to Department of Defense (DoD) operational systems impacted by the hostile near-earth space environment since the early 1960's. After the launch of Sputnik in 1957, the Air Force tasked AWS to establish an operational space weather support capability, similar to the meteorological support AWS has provided to aircraft operations for many years. The AWS issued its first solar forecast in 1962, and for the next three years the operation moved several times to eventually reside in the newly constructed Cheyenne Mountain Complex, where the North American Air Defense Command (NORAD) resides.

Probably the first significant operational impact came from a major solar flare and the resultant geomagnetic storm in May, 1967. AWS notified NORAD in real-time of the event and the associated mission impacts. However, outside agencies were not aware of the space environmental factors and made uninformed decisions without considering the drastic impacts the event imparted to NORAD's early warning systems, which have a direct bearing on decisions being made at the highest levels of the US government. As a result of this near-incident, the need to incorporate real-time space weather information into the Air Force decision-making process was made obvious to many, and several major efforts were undertaken to greatly improve the operational capability of the AWS Space Environmental Support System.

Starting in 1973, the DoD space weather support mission moved to the Air Force Global Weather Central (AFGWC), located at Offutt AFB, Nebraska. Use of the AFGWC computer facilities greatly enhanced the capability of AWS to process space environmental data from satellites and ground sites and exploit a variety of measurements, techniques, and newly-developed, first-generation space environmental models. In 1992, AWS established a new space weather support facility, the Air Force Space Forecast Center (AFSFC) at Falcon AFB, Colorado. State-of-the-art computer hardware and software, an immense variety of incoming space environmental data, a sophisticated on-site, real-time communication network, and highly-trained Air Force personnel were combined to form the most comprehensive space weather support facility in the world. Operational control of the AFSFC was shifted to Air Force Space Command (AFSPC) in October 1994, and the facility was renamed the 50th Weather Squadron (50 WS). 50 WS is the sole source of dedicated space-environmental support to all US military branches.

### *The Threat*

Solar flares are sudden, intense, and explosive releases of magnetic energy from the solar atmosphere, lasting from minutes to hours; huge amounts of energy are released in the form of radiation throughout the electromagnetic spectrum, from radio through gamma ray wavelengths. Flares are the most energetic events known in the solar system; the power released in a single solar flare can be on the order of 40 billion Hiroshima-sized atomic bombs. Solar flares often originate in close proximity to active sunspot regions, dark regions on the solar surface (photosphere) associated with locally intense, complex magnetic fields. The mechanism by which flares occur is likely related to the shearing and reconnection of the strong magnetic fields that reside in active sunspot regions. Sunspot, and therefore, solar flare activity, follow a regular pattern called the solar cycle. Peaks in the number of sunspots, and the associated increase in the occurrence of solar flares, occur approximately every eleven years; a peak in solar activity spans a three-four year period called solar maximum. The last solar maximum period occurred in 1989-1992, and the next is expected to occur from approximately 1999-2002.

Space systems operating at radio wavelengths, such as satellite communication links and surveillance, spacetrack, and ballistic missile early warning radars, can experience severe signal interference, fading, and other effects during the intense, impulsive release of solar-flare associated radio emissions known as a solar radio burst. A solar radio burst can last from minutes to hours, and can affect space systems across the radio spectrum. Energetic charged particles (electrons, protons, and ions, or collectively "plasma") are often also released during solar flares. During a particularly strong solar flare, highly energetic particles (mostly protons) can be accelerated to near relativistic speeds (approaching the speed of light), to reach the earth within 15 minutes to several hours and cause what is termed an "energetic particle event". A particle event can persist at highly elevated levels for several days. Once these energetic particles collide with a neutral atom or molecue, such as that contained within a solar panel or electronic component onboard a satellite, or living tissue within an astronaut or high-altitude aircraft passenger flying at high latitudes, the resultant effect can be a loss of electrical power, logic errors, false spacecraft commands, or an increased risk to long-term cancer.

Release of a gaseous cloud of plasma called a Coronal Mass Ejection (CME) often occurs during a solar flare as the sun's outer atmosphere (corona) that is magnetically connected to the surface flare site is released into the interplanetary medium (solar wind) during the flare explosion. However, CMEs can also occur in the absence of a solar flare, or in conjuction with other solar events, such as an erupting prominence. Regardless of the cause, a CME accelerates radially away from the sun's surface through the solar wind at a speed of roughly 500-2500 km/sec, impacting any planets or spacecraft in its path; a CME can reach the earth within one-five days. Once the CME reaches the earth, the solar wind particles are further energized by earth's magnetosphere. Their associated electrodynamic properties cause intense disturbances in earth's magnetic field (magnetosphere) and the magnetosphere's internal charged particle population, in what is known as a geomagnetic storm. A typical geomagnetic storm persists for several days, but can extend to a week or more. During a geomagnetic disturbance, rapid and intense variations in the electrical currents and magnetic fields within near-earth orbit can cause serious problems to orbiting spacecraft, such as increased atmospheric drag to low-earth orbiting vehicles, and differential surface and internal charging and the resultant discharging (arcing) within electrical components, which can cause problems on many types of spacecraft systems. Communication, navigation, and surveillance systems whose propagation paths traverse the space environment are also disrupted by the disturbed electromagnetic conditions. The visual manifestation of geomagnetic activity is the high-latitude auroral phenomenon.

Another source of geomagnetic activity, especially predominant during the two-four year lulls in the solar cycle (solar minumum), is a solar feature called a coronal hole. A coronal hole is an extended, variable region of the solar corona characterized by a unipolar magnetic field ("open" magnetic field lines) and a low particle density; they are seen in X-ray images as large, dark regions ("holes"). Coronal holes are the primary source of high-speed solar wind streams; these high speed streams impact the earth's magnetosphere and cause geomagnetic activity because of the increased flow of energetic solar wind particles into the magnetosphere.

The space environment is also the source of several other phenomena which degrade or disrupt space systems. Long-term erosion and changes in spacecraft material properties can occur due to extended exposure to the hazards of the space environment. Spacecraft effects associated with electrodynamic or electrochemical interactions (power loss, electromagnetic interference, multipacting, dynamo/wake depletion effects, surface/sensor contamination) can be induced by the energetic plasma which constantly bathes spacecraft surfaces and electronics. Ionospheric effects on radiowave propagation can drastically disrupt a satellite communication link. Signal fading or interference can be caused by ionospheric scintillation, a degraded condition caused by abrupt variations in ionization along a signal path and characterized by rapid variations in amplitude and/or phase of a radio signal. Scintillation is especially common for Very High Frequency (VHF) through Ultra High Frequency (UHF) signal paths that cross equatorial regions or high-latitudes during solar maximum; scintillation effects decrease as the signal frequency increases. High Frequency (HF) radio communication through the high-latitude ionosphere can become entirely unusable during geomagnetically disturbed conditions for a period of hours to days; degradation can also occur in mid latitudes during especially intense activity. Any electromagnetic wave that traverses the ionosphere will experience a certain amount of refraction, as a function of the signal frequency, angle of incidence, and degree of ionization across the signal path.

## *Mission*

**The 50 WS mission is to provide timely, high-quality solar-geophysical observations, forecasts, warnings, and tailored analyses to enhance the operational capability of worldwide DoD forces.** Customers include mission planners and operators of satellites, surveillance/space-tracking radars, and communication systems that operate in or through the space environment (altitudes of roughly 50 km and above). Support areas include observation, specification, and prediction of background solar radiation flux, solar flare and radio burst activity, geomagnetic disturbances, energetic charged particle events, ionospheric and magetospheric variability, and solar and geomagnetic indices used to specify atmospheric density variations. 50 WS also performs customer-tailored anomaly assessments of space weather impacts for spacecraft, radars, and communication systems. Experience has shown that space environmental support, when properly integrated into military operations, can be an effective force multiplier and thereby enable space system operators to avoid or reduce the impacts of the space environment on vital DoD space surveillance, communication, and navigation systems. This valuable lesson was especially apparent during Operation DESERT STORM, the first "space war".

The 50 WS supports several critical AFSPC missions. For instance, 50 WS bolsters the "Missile Warning/Defense" missions by providing time-critical space weather information to NORAD to enable the NORAD Commander in Chief (CINCNORAD) to determine if space environmental factors, such as solar radio bursts or auroral activity, could be causing interference or false target detections on NORAD's Ballistic Missile Early Warning System (BMEWS) radars or Defense Support Program (DSP) satellites. For the "Counter Space" and "Satellite Control" missions, 50 WS provides timely, high-quality observations, alerts, warnings, and forecasts of hazardous space environmental events and tailored analyses related to specific system effects to help spacecraft operators protect their orbiting assets and continually sustain their mission operations. To support the "Space Surveillance" mission, 50 WS generates geophysical specifications and forecasts to correct for atmospheric drag effects which limit the ability of the AFSPC's Space Surveillance Network (SSN) to detect, track, identify, and catalog space objects. 50 WS supports the "Communication" mission across the radio spectrum, from HF to UHF bands, by providing timely observation, forecasts, and alerts of solar and ionospheric conditions which directly cause signal interference or degradation. This enables system operators to identify the problem as environmentally-induced, as opposed to enemy jamming or equipment failure, thereby allowing the operators to switch to alternate frequencies or communication systems.

50 WS maintains a reciprocal support agreement with its civilian counterpart, the Space Environmental Services Center (SESC), a subcomponent of NOAA's Space Environment Laboratory in Boulder, Colorado. Jointly operated by NOAA and the USAF, SESC's primary mission is to provide forecasts and warnings of solar and geophysical disturbances to civilian users in government, industry, and the private sector. Though SESC primarily serves civilian customers and 50 WS supports the DoD, the two centers cooperate daily to share data, tools, and expertise. Through this productive collaboration, the nation's only two space weather support centers work together to fulfill the space environmental needs of all US space systems, civilian and military.

### *Support Capabilities*

50 WS is the most advanced and complete space weather support facility in the world. Advanced computer hardware and software is used to process incoming space environmental measurements to build a comprehensive, accurate real-time database from which to generate analysis and forecast products tailored to customer requirements. A sophisticated on-site, real-time communication network gives 50 WS the ability to receive an assortment of space environmental measurements and disseminate numerous support products to a wide variety of DoD users. Support to such vital national interests and complex environmental phenomena require highly specialized personnel. A highly trained forecast team, composed of three Air Force personnel and headed by a Captain with a Master of Science degree in Space Physics, provides a variety of support services 24-hours per day, 7-days per week. Types of support include real-time event notification and prediction of space weather phenomena that impact DoD operational systems, to include solar flare and radio burst activity, geomagnetic storms, and energetic proton and electron enhancements. Other support includes routine specifications and forecasts of solar, geomagnetic, and ionospheric indices used as crucial inputs to numerous models and other applications needed to characterize the contribution of the space environment to operational aerospace systems. 50 WS also conducts comprehensive investigations and post-analysis studies to assess the potential for the space environment to cause anomalous behavior for spacecraft, radars, and commmunication systems.

### *Ground-Based Observational Systems*

<u>Solar Observatories:</u> 50 WS maintains a real-time solar optical and radio observing network to

ensure continuous, global coverage of solar activity. All solar sites include a dedicated solar observing team and automated equipment to ensure rapid notification of solar flare and radio burst events and dissemination directly to 50 WS for ultimate transferal to DoD users. To monitor the sun in visible wavelengths, the Solar Observing Optical Network (SOON) 10-inch refracting telescopes collect data from the sun's surface (photosphere) and lower atmosphere (chromosphere), to include information on localized magnetic fields inherent in solar active regions where sunspots reside and solar flares erupt. Additional visible and infrared observations of the sun's outer atmosphere (corona) are available from civilian solar observatories at Sacramento Peak, New Mexico and Kitt Peak, Arizona. From these collective observations, information can be collected on solar flare potential, occurrence, and evolution. Five optical sites in Hawaii, New Mexico, Puerto Rico, Italy, and Australia comprise the SOON.

The Radio Solar Telescope Network (RSTN) monitors the sun in radio wavelengths at eight discrete frequencies (245, 410, 610, 1415, 2695, 4995, 8800, and 15,400 MHz) using Radio Interference Measuring Sets to detect the intense, impulsive radio-wave energy releases during solar radio bursts. The RSTN telescope also performs swept frequency spectral radio observations over a VHF band using the Swept Frequency Interferometic Radiometer to detect and characterize an energetic solar event known as a radio sweep, an indication that a cloud of energetic charged particles (CME) may have been released into the solar wind during an energetic solar event. Four radio sites in Hawaii, Massachusetts, Italy, and Australia make up the RSTN. Supplementary solar radio observations are also available from Culgoora Observatory, Australia. 50 WS also disseminates the daily 10.7-cm solar radio flux (2800 MHz), often called the "F10" index. The F10 index provides a measure of the general level of solar activity, and it is used as a primary input to many ionospheric and neutral atmospheric models. The F10 index is measured daily at the Penticton Solar Observatory, British Columbia, Canada; the F10 measurement, and a 45-day forecast, is available to 50 WS via NOAA.

**Magnetospheric Observations:** 50 WS employs a ground-based network of automated magnetometers owned and operated by the US Geological Survey (USGS) to monitor the variations in the earth's magnetic field associated with geomagnetic activity. The USGS network is composed of nine North American magnetometer sites, and this data is used to compute a near real-time planetary geomagnetic index (called "ap" or "kp") which covers a three-hour synoptic period. 50 WS also disseminates an estimate of the three-hour synoptic value during the two off-hours between the official synoptic values. The ap index provides a measure of the general level of planetary geomagnetic activity and is used by NORAD orbital analysts as a key input to orbital element prediction models to correct for atmospheric drag effects on low-earth orbiting satellites.

**Ionospheric Observations:** Data from vertical incidence ionospheric sounders (ionosondes) are needed to specify the ionosphere's structure and degree of ionization for use in characterizing the effect the ionosphere has on radiowave propagation from HF through UHF frequency bands. Measurements from ionosondes are used to generate parameters, such as the critical frequencies of the various ionospheric layers from altitudes of approximately 50-500 km, that characterize the effects of the ionosphere on radiowave propagation. 50 WS uses polarimeters to measure the Total Electron Content (TEC) of the ionosphere along a slant range path from the ground-based instrument to a geosynchronous reference satellite. Ionospheric data are used to create correction factors for radar antenna look angles to adjust for errors in satellite range and bearing caused by ionospheric refractive effects. The Ionospheric Measurement System (IMS), which uses signals from Global Positioning System (GPS) satellites to measure TEC, is scheduled to replace outdated polarimeters by the end of 1996.

Other ground-based ionospheric sensors used by 50 WS are riometers and neutron monitors. Riometers measure the strength of high-frequency cosmic radio noise; the absorption of cosmic noise, as measured by riometers, is an indirect measure of the degree of absorption experienced by HF radio waves. Thus, riometers can be used to characterize absorption events associated with strong solar flares, energetic particle events, or geomagnetic activity which greatly reduce the effectiveness of HF radio communication. 50 WS uses data from a neutron monitor positioned in Thule, Greenland to measure the collective (solar and galactic) cosmic ray flux. A neutron monitor is used to detect secondary neutrons released during energetic collisions between cosmic rays and atmospheric atoms or molecules, thus providing an indirect measure of the cosmic ray flux. Enhanced periods of cosmic ray flux associated with extremely intense solar flares are known as "ground-level events", which are especially hazardous to orbiting spacecraft.

### *Space-Based Observational Systems*

**Low-Earth Polar Orbit Measurements:** Several space weather sensors onboard Defense Meteorological Satellite Program (DMSP) spacecraft provide real-time data from a relatively low orbital altitude (840 km) at all latitudes. Two orbiting DMSP vehicles survey the entire earth four times each day. One DMSP vehicle is located in a "dawn-to-dusk" orbit (0600-1800 local time of ascending node), while the other is positioned in a quasi "noon-to-midnight" orbit (1030-2230 local time). A sensor onboard DMSP measures low-energy (30 ev -30 KeV) proton and electron counts during passes through the high-latitude auroral regions, and 50 WS processes this data to produce accurate, near-real time specification of the location of the equatorward edge of the auroral oval. Another DMSP sensor provides in-situ measurements of ion and electron densities, drift velocities, and temperatures, which can be used as inputs to various advanced space weather models. Visual imagery from the DMSP Operational Linescan System (OLS) can provide detailed information on the actual location and structure of the nighttime visual aurora, as well as an indication of the overall level of high-latitude geomagnetic activity. The DoD and NOAA plan to converge the DMSP and NOAA/TIROS satellite programs into a three-satellite constellation within a decade, which will provide better coverage at a more cost-effective price.

**Geosynchronous Measurements:** NOAA provides a variety of real-time space environmental measurements from the Geosynchronous Operational Environmental Satellite (GOES) to 50 WS, which is updated every one-five minutes. The GOES X-ray sensor provides whole solar disk X-ray fluxes in two wavelength bands, soft (1.0-8.0 Angstroms) and hard (0.5-4.0 Angstroms). The soft X-ray flux is used to provide real-time solar flare warnings, forecast energetic proton events, and predict HF radio propagation absorption events associated with solar flare X-ray fluxes (shortwave fades). GOES also provides energetic proton and electron flux measurements in a variety of energy bands, as well as magnetometer data to characterize the level of geomagnetic activity at geosynchronous orbit. Other satellites used by 50 WS also provide a variety of real-time energetic particle flux measurements at geosynchronous altitudes and beyond; these particle measurements are primarily used to assess the potential for surface/internal charging and logic upsets on spacecraft which require a detailed anomaly investigation.

**Interplanetary Measurements:** In late 1994, NASA launched the Solar Wind Interplanetary Measurements (SWIM) satellite into a double-lunar swingby interplanetary orbit to study the upstream solar wind between the earth and sun. SWIM will greatly improve the ability of 50 WS to predict short-term geomagnetic activity; SWIM will provide approximately 30-60 minutes of lead time for solar wind disturbances that impact the near-earth space environment and cause geomagnetic disturbances. Real-time solar wind plasma measurements (density, wind speed and direction, magnetic field, temperature) are required inputs to the Solar Wind Transport (SWT) model and the Magnetospheric Specification Model (MSM); both models will be operational at 50 WS in 1995.

Although SWIM is a cooperative R&D experiment between NASA, NOAA, and the USAF, NASA has agreed to transmit two hours per day of real time data to 50 WS, and the remaining 22 hours of playback data will arrive within 1-2 days of receipt at NASA. Additionally, 50 WS is negotiating with the AF Satellite Control Network (AFSCN) to secure 12-hours per day of real-time SWIM coverage, on a 2-hours on, 2-hours off schedule. However, SWIM is an R&D satellite with a design lifetime of one year. SWIM serves as a prototype for an improved spacecraft, the Advanced Composition Explorer (ACE), to be launched in 1997 by NOAA into a similar (Lagrangian-1) orbit. ACE will provide 22 hours of real-time solar wind measurements per day; negotiations to procure this data for operational use by 50 WS are underway.

### *Advanced Space Weather Models*

In cooperation with scientists at the Air Force Phillips Laboratory (PL) Geophysics Directorate, civilian universities, and private corporations, 50 WS is currently preparing to implement state-of-the-art space weather models to accurately characterize environmental conditions within the solar wind, magnetosphere, and ionosphere. These advanced models will be based on physical principles, as opposed to climatology or empirical data. They will not exist in an operational capacity at any other locations other than 50 WS, and they represent a quantum leap in potential as compared to the limited climatological and statisical models currently in use.

**Solar Wind Transport (SWT) Model:** RMA Aerospace developed the SWT model primarily to provide 50 WS with a capability to make a prompt, accurate forecast of magnetospheric boundary conditions, for potential input into the MSM. The SWT model requires near real-time, upstream measurements of solar wind particle density, velocity, temperature, and magnetic field strength and direction, such as that provided by the SWIM and ACE solar wind satellites. 50 WS can also use the SWT model to generate quantitative predictions of when approaching "gusts" released into the solar wind by energetic solar events or phenomena (solar flares, coronal mass ejections, coronal holes) will impact the earth's magnetosphere and lead to disturbed geomagnetic conditions. Output from the SWT model can be used to identify periods when geosynchronoua spacecraft will cross over the magnetopause into the solar wind, thereby alerting satellite operators of impending anomalies caused by single event upsets. SWT will be operational in 1995.

**Magnetospheric Specification Model (MSM):** Rice University developed the computationally-fast MSM for 50 WS to specify 100 eV - 100 KeV electron and ion fluxes in a range of 2-10 earth radii within the magnetospheric equatorial plane. Applications software will be used to map particle fluxes, specified by MSM in the equatorial plane, along magnetic field lines to higher latitude locations, such as the location of a high-inclination satellite. This capability will enable 50 WS analysts to objectively assess whether surface charging conditions may have induced a given spacecraft anomaly. MSM will also include a routine to compute the daily geosynchronous flux variations of >3 MeV relativistic electrons for use in assessing spacecraft anomalies potentially caused by internal charging. MSM will require real-time inputs of 3-hour kp index, ring current strength index (Dst), equatorward boundary of the auroral oval and polar cap potential drop derived from DMSP measurements, and magnetopause standoff distance from SWT output (or solar wind velocity and density data from SWIM). 50 WS will use geosynchronous particle flux data to perform error checks on MSM outputs. MSM will be operational in 1995.

A future upgrade to MSM, called the Magnetospheric Specification and Forecast Model (MSFM), will provide a predictive capability to warn satellite operators, with one-two hours leadtime, of impending electron enhancements which might lead to surface charging anomalies. MSFM will also make use of more high time-resolution DMSP measurements and be more reliable over a larger portion of the magnetosphere. MSFM will also include a new capability to improve specification of precipitating ion and electron fluxes in the high-latitude auroral oval. 50 WS will primarily use MSM, and eventually MSFM, as a diagnostic tool to quantitatively assess the contribution of enhanced magnetospheric electron fluxes to spacecraft charging conditions, and ultimately, anomalous spacecraft behavior. If model results indicate the anomaly was likely caused by a charging condition, the amount of time spent investigating the anomaly can be greatly reduced, thereby resulting in a quicker recovery to a fully operational capability.

**Parameterized Real-time Ionospheric Specification Model (PRISM):** PRISM is a global model of the ionosphere designed to specify vertical profiles of ionospheric electron (or ion) density in near real-time at altitudes of 100-1600 km. Built to be computationally fast, PRISM is a parameterized model combining several sophisticated physical ionospheric models developed by PL, Computational Physics Incorporated, and Utah State University, each corresponding to different latitudinal/vertical regimes that are combined at their boundary interfaces. PRISM inputs include the 3-hour kp index, the F10 solar radio flux, real-time ionospheric parameters measured from ground-based ionosondes, Total Electron Content observations (TEC) from IMS sensors, and space-based, in-situ measurements of ionospheric plasma density, temperature, and drift velocity, and auroral electron and ion fluxes derived from DMSP special sensor data. By 1997-98, two new ultraviolet imaging sensors, SSUSI and SSULI, will be flown onboard DMSP vehicles to provide a means to derive vertical electron density profiles, which will be used to drive PRISM with highly accurate, real-time data. These real-time ionospheric measurements will be used to adjust the preliminary PRISM output and significantly increase the accuracy locally. PRISM can specify the number density of electrons (ions) in two general formats: (1) electron density versus altitude above a certain location (a vertical electron density profile), and (2) electron density analyzed for a latitude/longitude grid at a constant altitude. 50 WS will use PRISM output in a variety of ways, to include incorporation of PRISM output fields into a radiowave propagation application program used to improve frequency planning guidance for HF communication users. PRISM is scheduled to be operational in 1995.

**Ionospheric Forecast Model (IFM):** The IFM is a three-dimensional, time-dependent, physics-based, computationally-efficient global ionospheric model designed to produce a 6-24 hour predictive capability at altitudes of 90-1000 km. It requires various types of input data from ground- and space-based sensors to take into account interactions with the magnetosphere and neutral atmosphere, thereby realistically initializing the model specification. Utah State University designed IFM to be modular, so it will be capable of ingesting a variety of data and being coupled to neutral atmospheric and magnetospheric models. IFM is to be implemented at 50 WS by 2000.