CHAPTER 1

INTRODUCTION

As we begin the new millennium, our civilization's reliance on technology affected in some way by space weather continues to grow at a rapid pace. Space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. The National Space Weather Program (NSWP) emerged in 1994 from the efforts of several U.S. government agencies to prepare us to deal with the vulnerabilities of our technology. Through the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), these agencies documented the goals of that program in the *National Space Weather Program Strategic Plan* (FCM-P30-1995, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Silver Spring, MD, 1995). The interagency focus and cooperation continued in 1997 with the development of the *National Space Weather Program Implementation Plan* (FCM-P31-1997, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Silver Spring, MD, 1997) which provided more specific direction to the federal government's space weather efforts.

This *Implementation Plan* is a living document and this is its first revision. It has been developed concurrently with the National Security Space Architect's Space Weather Architecture and describes the linkage to and incorporation of that architecture into the National Space Weather Program. In this revision, we build on the previous plan and report on the significant accomplishments in research, operations, technology transition, education and outreach. We have updated the program's timelines and offer specific recommendations to carry us forward. This is the culmination of months of multi-agency coordination and cooperation and represents a dedicated effort by Federal agencies to improve capabilities in an area with critical societal impacts.

1.1 History of the Program

In 1993, members of the space science community visited the National Science Foundation (NSF) and raised the issue of improving the Nation’s ability to specify and forecast space weather. In response, NSF organized a meeting at which representatives from government, industry, and academia met and discussed the current status of space weather research and operational systems. These discussions highlighted deficits in current capabilities and suggested that much could be gained by better coordination of efforts across Federal agencies. Other issues presented at the meeting included the limitations imposed by budget constraints and the reluctance of industry to reveal problems with current systems. It became clear that an overarching program to coordinate space weather activities would help to more effectively apply limited resources, and that such a program should be overseen by an organization composed of only government agencies so that industrial participants would be more willing to identify problems with existing systems.

Because the Office of the Federal Coordinator for Meteorological Services and Supporting Research, more briefly known as the Office of the Federal Coordinator for Meteorology (OFCM), orchestrates multi-agency coordination, it became the focal point for developing the space weather program. Furthermore, the Committee for Space Environment Forecasting (CSEF) already existed within the OFCM structure. Planning for a space weather program represented a logical extension of the responsibilities of that committee. CSEF appointed the Working Group for the National Space Weather Program (WG/NSWP) and charged it with developing a strategic plan. Work began in the summer of 1994 involving representatives from NSF, Department of Defense (DOD), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), Department of Energy (DOE), and Department of the Interior (DOI). In parallel with these efforts, the Working Group recommended that a Program Council be created to provide high-level, multi-agency oversight for the emerging program. The Working Group developed a draft charter for the Program Council and on August 4, 1995, the Program Council met for the first time. They adopted the charter and approved the Strategic Plan. The Program Council then directed the Working Group to develop an implementation plan for the NSWP. This process began with the identification of customer requirements for space weather services. Once these requirements were specified, representatives from the research community met to develop a road map laying out research, modeling, and observational requirements that would lead to achievement of the goals. The Program Council approved the initial Implementation Plan in January 1997. The present document is the first update of that initial plan.

1.2 Scope of the Program

The NSWP encompasses all activities necessary for the timely specification and forecast of natural conditions in the space environment that may have an impact on technical systems and human life or health. The domains of primary interest to the program include the Sun and solar wind, the magnetosphere, the ionosphere, and the thermosphere. Because of the vastness and complexity of the region of interest, all traditional areas of space sciences can contribute to achieving the program goals.

Space weather begins at the Sun's surface, the source of radiative and particle energy impacting Earth. Solar activity changes the radiative and particle output of the Sun, producing corresponding changes in the near-Earth space environment, as well as at Earth's surface. The most dramatic events on the Sun, insofar as space weather effects are concerned, are solar flares and coronal mass ejections. Although longer term variations in solar emissions do not produce dramatic space weather effects, they are important in helping us understand the underlying processes behind the short-term variations.

Changes in the radiative output from the Sun directly affect the state of the upper atmosphere and ionosphere through the excitation and ionization of atoms and molecules. Particle emissions from the Sun include both the energetic particles and the low-energy plasma that constitute the solar wind. Both particles and electromagnetic fields evolve as they flow outward from the Sun, especially as they create or interact with interplanetary shocks.

The solar wind moves outward from the Sun and impinges on Earth. The plasma and magnetic field of the solar wind interact with Earth's atmosphere and geomagnetic field, creating a tear-drop-shaped region called the magnetosphere. The surface of this region is referred to as the magnetopause. The magnetopause is usually found near 10 Earth radii (R_E) in the sunward direction, although this distance is highly variable (roughly between 5 and 15 R_E) in response to solar wind dynamic pressure. In the antisunward direction, the magnetopause extends to distances beyond the orbit of the moon. The magnetopause represents a barrier that prevents all but a fraction of the energy carried by the solar wind from entering the magnetosphere. Under normal conditions, the energy that does penetrate the magnetopause is stored in the form of the particles and fields of the magnetosphere, but under some conditions it is impulsively released into Earth's atmosphere. This impulsive release of energy is referred to as a magnetospheric substorm. It is characterized by the appearance of bright, dynamic aurora and the development of intense ionospheric currents. During a substorm the magnetic field in the magnetosphere suddenly assumes a new configuration; after the substorm there is a recovery period that takes many hours.

Substorms are a relatively short-lived magnetospheric response to solar wind stimulus. Geomagnetic storms are a sustained, long-lived (days to weeks) response to a prolonged period of solar wind flow characterized by a strong southward interplanetary magnetic field. Geomagnetic storms lead to a substantial energization of the ring current, a belt of quasi-trapped electrons, protons, and heavier ions, as well as significant geomagnetic fluctuations at low geographic latitudes. Magnetospheric particles precipitate into the polar caps, heating the neutral atmosphere (thermosphere and mesosphere) and launching ionospheric disturbances. Substorms may also occur during the course of geomagnetic storms. Once the solar wind returns to its undisturbed state, the magnetosphere and ionosphere require hours to days to recover.

Because Earth's magnetic field permeates the magnetosphere, most magnetospheric processes are manifested in some way by changes in the properties of the ionosphere and thermosphere. Magnetospheric processes produce electrical currents, auroral emissions, frictional heating, ionization, and scintillation. All of these phenomena are elements of near-Earth space weather. The near-Earth space environment is also influenced by processes originating at lower altitudes, such as gravity waves, and direct energy deposition from solar radiation and cosmic rays. Space weather effects also include the electrical currents induced within Earth's surface as a result of changes in ionospheric currents.

This brief description of the space weather system demonstrates the vastness of the region of interest to the NSWP and the complexity of the physical processes that must be understood. Adding to this complexity is the high degree of coupling between the various regions. The program will emphasize the importance of dealing with the space environment as a seamless system in which processes occurring in one location cannot be understood without adequate knowledge of the way the entire system is linked.

The NSWP is primarily concerned with naturally occurring phenomena in the space environment but addresses Department of Defense concerns with man-made space environmental effects. Although the program does not specifically address the possible impact of orbital debris on satellite systems, it will contribute to the accurate tracking of objects in space by improving the specification and prediction of variations in atmospheric density, which affect the drag on orbiting objects.

Similarly, the NSWP does not deal directly with the engineering aspects that enter into the design and development of technical systems. Here again, the program can be of benefit to the community by providing detailed information about the space environment so that engineers can better design these systems. Often accurate specification of the range in environmental parameters to which a piece of equipment will be subjected can result in significant cost savings.

The goal of the NSWP is to provide products to a community of customers that is continually changing. Each of these customers may have different requirements, making it a formidable task to provide customized products. The routine production of information tailored to meet specific customer requirements is not within the scope of the NSWP. The specification and forecast information provided by the forecast centers will be sufficient to allow such tailored products to be developed either by the customers themselves or by others offering to provide these services. In particular, the need for these services provides opportunities for small businesses or other profit-making enterprises. In the case of Department of Defense (DOD) customers, DOD takes responsibility for its own tailored products. Agency representatives and customers involved in the NSWP will routinely evaluate the status of NSWP products and agree upon the level of information falling within the scope of the program.

1.3 Relevance to the Nation

Space weather is working its way into the national consciousness as we see an increasing number of problems with parts of our technological infrastructure, such as satellite disruptions and failures as well as electric power brownouts and blackouts. As our society grows more dependent on advanced technology systems, we become increasingly more vulnerable to malfunctions in those systems.

For example, electrical power networks connecting widely separated geographic areas have increased the probability of power grids absorbing damaging electric currents induced by geomagnetic storms. The miniaturization of electronic components and reduced radiation hardening on satellites makes them potentially more susceptible to damage by high-energy particles. Similarly, aircraft designed to fly at 60,000 feet (18.3 kilometers) have increased human risk to radiation exposure during severe space weather. Figure 1-1 lists sample significant space weather events and their impacts over the past several years.

System and human vulnerabilities to space weather effects include the following:

Engineering Aspects. Engineers use space environment information to specify the extent and types of protective measures that are to be designed into a system and to develop operating plans that minimize space weather effects. However, engineering solutions to some problems may be very costly or impossible to implement. After the fact, engineers use space environment information to determine the source of failures and develop corrective actions. Significant economic and societal benefits can be realized if designers of emerging technology can (1) anticipate the properties of the space environment to which the hardware will be subjected, (2) depend on accurate and timely predictions of space weather, and (3) take advantage of post-event analysis to determine the source of system anomalies and failures and to build a database for future planning.

Satellite Systems. Space weather affects satellite missions in a variety of ways, depending on the orbit and satellite function. Our society depends on satellites for weather information, commercial television, communications, navigation, exploration, search and rescue, research, and national defense. The impact of satellite system failures is more far-reaching than ever before, and the trend will almost certainly continue at an increasing rate.

Energetic particles that originate from the Sun, from interplanetary space, and from Earth's magnetosphere continually impact the surfaces of spacecraft. Highly energetic particles penetrate electronic components, causing changes in electronic signals that can result in spurious commands within the spacecraft or erroneous data from an instrument. These spurious commands have caused major satellite system failures that might have been avoided if ground controllers had had advance notice of impending particle hazards. Less energetic particles contribute to a variety of spacecraft surface charging problems, especially during periods of high geomagnetic activity. In addition, energetic electrons responsible for deep dielectric charging can degrade the useful lifetime of internal components. Overall radiation dose can ultimately determine satellite lifetime.

Highly variable solar ultraviolet radiation continuously modifies terrestrial atmospheric density and temperature, affecting spacecraft orbits and lifetimes. Major geomagnetic storms result in heating and expansion of the atmosphere, causing significant perturbations in low-altitude satellite trajectories. At times, these effects may be severe enough to cause premature re-entry of orbiting objects, such as Skylab in 1979. It is important that satellite controllers be warned of these changes and that accurate models be in place to realistically predict the resulting atmospheric effects. The Space Shuttle is also vulnerable to changes in atmospheric drag; re-entry calculations for the orbiter are highly sensitive to atmospheric density, and errors can threaten the safety of the vehicle and its crew.

Power Systems. Modern power grids are extremely complex and widespread and potential changes in the industry will increase the interconnection of regional grids. The long power lines that traverse the Nation are susceptible to electric currents induced by the dramatic changes in high-altitude ionospheric currents that occur during geomagnetic storms. “Surges” in power lines from induced currents can cause massive network failures and permanent damage to multimillion-dollar equipment in power generation plants. Considering the significant national dependence on reliable electrical power, the resulting social chaos, economic impact, and threat to safety during widespread power outages are far more serious than the simple cost of repairing the systems.

The electric power distribution system has developed an increased susceptibility to the phenomenon of geomagnetically induced currents because of widespread grid interconnections, complex electronic controls and technologies, and large inter-area power transfers. The phenomenon occurs globally and simultaneously, and industry operations allow for little redundancy or operating margin to absorb the effects. Mitigation of such effects is fairly straightforward provided advance notice is given of an impending storm; specific strategies currently exist within the power industry. Advanced warnings of storms are needed, but of equal economic importance to industry is that the forecasts be reliable. False alarms are counterproductive and must be minimized.

Navigation Systems. The accuracy of maritime navigation systems using very low frequency signals, such as Long-Range Navigation (LORAN), depends on knowing accurately the altitude of the bottom of the ionosphere. Rapid vertical changes in this boundary during solar flares and geomagnetic storms can introduce errors of several kilometers in location determinations.

The Global Positioning System (GPS) operates by transmitting radio waves from satellites to receivers on the ground, aircraft, or other satellites. These radio signals are used to calculate location very accurately. However, significant errors in positioning can result when the signals are refracted and slowed by ionospheric conditions significantly different from normal. In addition, receivers can experience loss of GPS signal lock when the signal traverses an ionospheric disturbance (scintillation). Future high-resolution applications of GPS technology will require better space weather support to compensate for these induced errors. Accurate specification and prediction of the properties of the ionosphere will aid in the design and operation of emerging systems.

March 24, 1940. A "great" geomagnetic storm rendered inoperative 80% of all long-distance telephone connections out of Minneapolis, Minnesota. Electric service was temporarily disrupted in portions of New England, New York, Pennsylvania, Minnesota, Quebec, and Ontario.

February 9-10, 1958. A geomagnetic storm caused severe interruptions on Western Union's North Atlantic telegraph cables and made voice communications very difficult on the Bell System transatlantic cable from Newfoundland to Scotland. Toronto, Canada, experienced a temporary blackout.

August 4, 1972. A severe geomagnetic storm caused a 30-minute shutdown of the Bell System coaxial cable link between Plano, Illinois, and Cascade, Iowa. A power transformer failed at the British Columbia Hydro and Power Authority.

November 26, 1982. The Geostationary Operational Environmental Satellite (GOES) 4 visible and infrared spin-scan radiometer, which maps cloud cover, failed 45 minutes after the arrival of high-energy protons from a major solar flare. The untimely failure occurred as a series of intense storms hit the California coast.

March 13-14, 1989. A severe geomagnetic storm caused a system-wide power failure in Quebec, Canada, resulting in the loss of over 20,000 megawatts. The blackout cut electric power to several million people. Time from onset of problems to system collapse was about 90 seconds. High frequency (HF) radio frequencies were virtually unusable worldwide, while very high frequency (VHF) transmissions traveled unusually long distances and created interference problems. A Japanese communications satellite lost half of its dual-redundant command circuitry. A National Aeronautics and Space Administration (NASA) satellite dropped 3 miles (4.8 kilometers) in its orbit due to the increase in atmospheric drag.

January - March, 1991. Coalition military forces experienced occasional high frequency radio communications interruptions due to scintillation.

April 29, 1991. A transformer at the Maine Yankee Nuclear Plant catastrophically failed within a few hours of a severe geomagnetic storm onset.

January 20-21, 1994. Two Canadian communications satellites failed, interrupting telephone, television, and radio service for several hours. The failures occurred after an extended period of high electron levels in the satellite environment.

May 1998. Solar activity may have been the cause of a significant disruption of pager service across the United States when the Galaxy 4 satellite experienced problems.

Figure 1-1. Impacts of Significant Space Weather Events

Communications. Radio communications over a broad range of frequencies are affected by space weather. High Frequency (HF) radio wave communication is more routinely affected because this frequency depends on reflection from the ionosphere to carry signals great distances. Ionospheric irregularities contribute to signal fading; highly disturbed conditions, usually near the aurora and across the polar cap, can absorb the signal completely and make HF radio propagation impossible. Accurate forecasts of these effects can give operators more time to find an alternative means of communication. Telecommunication companies increasingly depend on higher frequency radio waves, such as ultrahigh frequency (UHF), which penetrate the ionosphere and are relayed via satellite to other locations. Signal properties can be changed by ionospheric conditions so that they can no longer be accurately received at Earth's surface. This may cause degradation of signals, but more important, can prohibit critical communications, such as those used in search and rescue efforts and military operations.

Manned Space Flight. Besides being a threat to satellite systems, energetic particles present a hazard to astronauts on space missions. On Earth we are protected from these particles by geomagnetic shielding and the atmosphere. The geomagnetic field shields Earth’s atmosphere from all particles of millions of electron-Volt (MeV) energy except in the polar regions. The atmosphere absorbs all but the most energetic cosmic ray particles. During space missions, astronauts performing extra-vehicular activities are relatively unprotected at high latitudes in the spacecraft orbit. This could be particularly problematic during the ongoing construction of the International Space Station during solar maximum. The fluxes of energetic particles can increase hundreds of times following an intense solar flare or to dangerous levels during a large geomagnetic storm. Timely warnings are essential to give astronauts sufficient time to return to their spacecraft prior to the arrival of such energetic particles. High altitude aircraft crews and passengers on polar routes, e.g., on supersonic transports (SSTs) or U-2s, are also susceptible to radiation hazards during similar events.

1.4 Summary of the Strategic Plan

Recognizing the need for a more coordinated effort to improve present capabilities in specifying and forecasting conditions in the space environment, Federal agencies representing the research, operations, and user communities initiated the NSWP, as outlined in *The National Space Weather Program Strategic Plan.* The overarching goal of the program is to achieve an active, synergistic, interagency system to provide timely, accurate, and reliable space weather warnings, observations, specifications, and forecasts within the next 10 years. By building on existing capabilities and establishing an aggressive, coordinated process to set national priorities, focus agency efforts, and leverage resources, the NSWP provides the path to attain this goal. The activities that the NSWP will conduct are listed in Figure 1-2 and the specific goals of the program are enumerated in Figure 1-3.

National Space Weather Program Activities

- Assess and document the impacts of space weather
- Identify customer needs
- Set priorities
- Determine agency roles
- Coordinate interagency efforts and resources
- Ensure exchange of information and plans
- Encourage and focus research
- Facilitate transition of research results into operations
- Foster education of customers and the public

Figure 1-2. National Space Weather Program Activities

The key elements of the NSWP are described as follows:

Forecast and Specification Services. The predominant driver of the program is the value of space weather forecasting services to the Nation. The accuracy, reliability, and timeliness of space weather specification and forecasting must become comparable to that of conventional weather forecasting. Early warning capabilities of impending dangerous conditions must become equally reliable to be valuable for mitigation purposes. The strengthening of services includes modernization of facilities; implementation of new models and other analysis and forecast techniques; improved education and training; improved production, design, and dissemination of forecast products; and improved communication with the users of the services. Proposed operational models, instrumentation, and techniques are evaluated according to their potential to improve forecasting services.

Research. This includes ongoing, intensive efforts to understand the fundamental physical processes that affect the state of the Sun, solar wind, magnetosphere, ionosphere, and atmosphere, with a focus on resolving research problems that impede improvements in forecasting capability. Radiative, dynamical, electrical, and chemical coupling between different regions have been and will continue to be studied using data from existing ground- and space-based instrumentation. Theoretical investigations in these areas will help to define the needed observations and will aid the development of operational models.

Observations. The program builds on existing observational capabilities and determines the value of current data and new data needs. Observations in support of research and forecasting are growing as critical parameters for forecasting are identified, measurement techniques are defined, and new space- and ground-based platforms are developed. The initial focus is on better coverage of data-void or data-sparse regions, and on the

The National Space Weather Program Goals

To advance

- observing capabilities
- fundamental understanding of processes
- numerical modeling
- data processing and analysis
- transition of research into operational techniques and algorithms
- forecasting accuracy and reliability
- space weather products and services
- education on space weather

To prevent or mitigate

- under- or over-design of technical systems
- regional blackouts of power utilities
- early demise of multi-million dollar satellites
- disruption of communications by satellite, HF, and VHF radio
- disruption of long-line communications
- errors in navigation systems
- excessive radiation doses, dangerous to human health

Figure 1-3. National Space Weather Program Goals

deployment of systems that provide data with appropriate accuracy, resolution, and timeliness. Because instrumentation development is an evolutionary process, the program emphasizes rapid exploitation of observational capabilities, bridging gaps between research observing systems and subsequent operational observing systems, and efficient communication between data analysts, researchers, and instrument designers.

Modeling. These efforts for specifying and predicting the space environment have been under way for several years and some operational benefits have been realized. The program continues to coordinate modeling and integration activities to ensure the consistency and optimal performance of the models. A primary goal is to develop physics-based specification and forecast models covering the forecast period out to 72 hours for solar events and 48 hours for near-Earth space weather phenomena. These models are evaluated in close collaboration with research and observation efforts and with regard to user requirements. Gaps and deficiencies in these models are identified and used to set requirements for future models.

Education. The education activities supported by the program enhance public awareness of space weather and its impacts; help ensure a sufficient supply of educated scientists and engineers to maintain expertise in all space-weather-related fields; and improve training of forecasters, observers, and system operators. An educated public and commercial sector are better able to utilize space environment forecasting services; student research will supply fresh ideas to explore; and knowledgeable government officials and the media will help realize the socioeconomic benefits.

Technology Transition and Integration. Although significant strides have been made through the Community Coordinated Modeling Center and the Rapid Prototyping Center, these processes must be continually improved to facilitate the transfer of tools, techniques, and knowledge from the research or commercial communities to the operational forecasting activities. This effort, often a bottleneck, is critical to the success of the program. Innovative means must be explored to nurture a dynamic process for technology exploitation and transition to improve forecasting capability, utilize all relevant research, and rapidly realize benefits.

1.5 The Implementation Plan

The preceding paragraphs describe space weather's range of impacts on our society and the context of the National Space Weather Program's overarching objectives. The remainder of this document reviews significant progress made since the original *Implementation Plan* was published in 1997 and reiterates and refines the means by which the various Federal agencies will achieve the program's objectives. The individual agencies are responsible for appropriate related actions under the Government Performance Results Act. The Act will not be specifically addressed by this document. The next chapter describes current capabilities and updates the Program's goals and strategy.