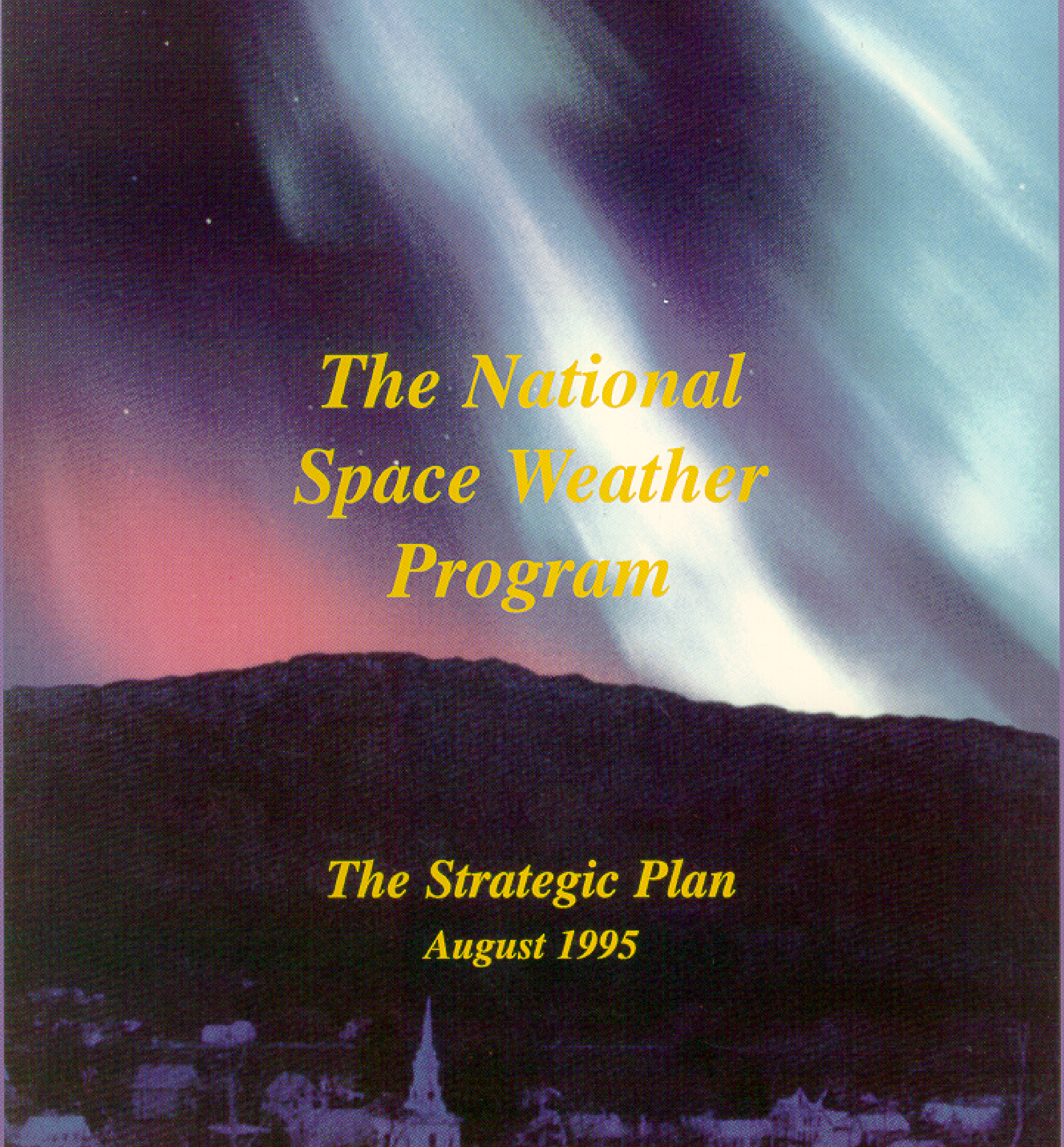

The National Space Weather Program

The Strategic Plan

August 1995

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NATIONAL SPACE WEATHER PROGRAM

Strategic Plan

FCM-P30-1995
Washington, DC
August 1995

FOREWORD

I am pleased to release the "National Space Weather Program Strategic Plan", a report prepared by the Working Group for the National Space Weather Program (WG/NSWP) of the Committee for Space Environment Forecasting (CSEF) of the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM).

A series of recent workshops and meetings attended by members representing the military, commercial, and research communities has revealed the pressing need for improved space environment understanding and forecasting over many time scales. A National Space Weather Program has been formulated to achieve, within the next 10 years, an active, synergistic, interagency system to provide timely, accurate, and reliable space environment observations, specifications, and forecasts. This Strategic Plan outlines a strategy to guide the planning and implementation of the National Space Weather Program. The document describes the National Space Weather Program, its priorities and goals, the national customer base, and the strategic elements essential to an integrated, goal-oriented capability dedicated to serving national needs.

I want to take this opportunity to express appreciation to Dr. Richard Behnke of the National Science Foundation and Colonel Thomas Tascione of the United States Air Force, co-chairmen of the working group which prepared the National Space Weather Program Strategic Plan, and to the additional contributors for their efforts in preparing and submitting material for the Plan.

Julian Wright

Julian M. Wright, Jr.
Federal Coordinator for
Meteorological Services
and Supporting Research

EXECUTIVE SUMMARY

"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. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socioeconomic losses.

The Nation's reliance on technological systems is growing exponentially, and many of these systems are susceptible to failure or unreliable performance because of extreme space weather conditions. Technology has reduced our risk to many kinds of natural disasters, but has actually increased the risk of some systems to space weather. Many risks could be mitigated or avoided if reliable space weather forecasts were available and if reliable, quantitative models were available to system designers. We now have the scientific knowledge and the technical skills to move forward to dramatically improve space weather understanding, forecasts, and services to meet customer needs.

The overarching goal of the National Space Weather Program is to achieve, within the next 10 years, an active, synergistic, interagency system to provide timely, accurate, and reliable space environment observations, specifications, and forecasts. It will build on existing capabilities and establish an aggressive, coordinated process to set national priorities, focus agency efforts, and leverage resources. The Program includes contributions from the user community, operational forecasters, researchers, modelers, and experts in instruments, communications, and data processing and analysis. It is a partnership between academia, industry, and government.

Currently, space environmental support services are provided through the National Oceanic and Atmospheric Administration's Space Environment Center and the US Air Force's 50th Weather Squadron. Bulletins, forecasts, alerts, warnings, and data are routinely disseminated to a broad range of customers. Forecast and specification services are supported by four strategic elements--research, observations, models, and education--and by a process that transfers and integrates knowledge into the operational forecast system. Improving forecasting and specification services provides the focus for the other contributing elements.

An X-ray image of the sun, obtained by the Yohkoh satellite as part of a joint Japanese-U. S. space mission.

The vehicle to implement and manage the Program is the National Space Weather Program Council within the Office of the Federal Coordinator for Meteorological Services and Supporting Research. The Council consists of representatives from Federal agencies involved in space weather activities; they are the official spokespersons on matters such as program scope, requirements, and resource commitments. The Council will establish policy, develop an implementation plan, focus and coordinate interagency efforts and resources, and approve interagency agreements developed within the scope of the Program. The Council will provide oversight and policy guidance to ensure common needs are met and the interests of each agency are addressed.

NATIONAL SPACE WEATHER PROGRAM
Strategic Plan

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1. Introduction

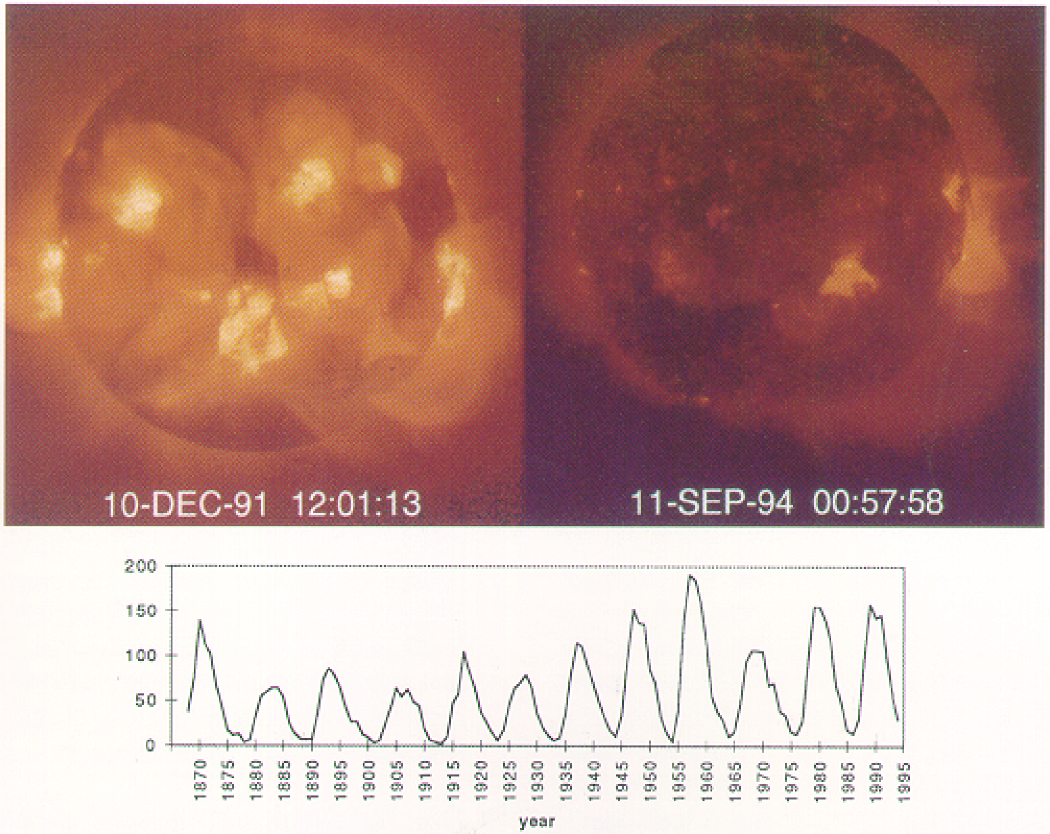
"Space weather" refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socioeconomic losses.

a) Background

Throughout history, people have stood in awe of the wildly changing patterns of the Northern Lights, the aurora. Normally seen only in the polar regions, these lights mystified observers by occasionally appearing far south of their usual location. In 1934, Bartels noticed that periodic disturbances in the Earth's magnetic field corresponded with the sun's rotation rate and postulated "M" regions on the sun as their cause. Once during World War II, radio operators in England were convinced they were foiled by enemy jamming when all HF radio communications ceased. All of these related events are early examples of the effects of "space weather".

Today, we have far more knowledge of the space environment, from the turbulent surface of the sun, with its continuous solar wind and periodic spewing of clouds of energetic ionized particles, to the protective boundary of the Earth's magnetic field, which provides a partial shield against deadly solar corpuscular radiation. The Earth's magnetic field is highly reactive to the onslaught of energy and pressure originating from the solar particles and fields. In a complex way, the Earth's magnetosphere redistributes its particle populations, often sending a rush of energetic particles along magnetic field lines into the atmosphere over the polar caps and creating the swirling red, green, and white auroras. Other particles pour into the Van Allen radiation belts and encircle the Earth in a ring of electric current. The Earth's magnetic field itself can distort to such an extent that compasses at the surface swing 10° away from the magnetic pole. The ionosphere--80 to 1000 kilometers above the Earth's surface--changes in ways that affect radio transmissions, absorbing some radio frequencies, distorting others, and creating electric currents that affect systems on the ground.

This fascinating and intricate picture of the connection between the sun and the Earth's space environment has been uncovered in the last few decades. However, our understanding of the physical processes that drive and couple this complex weather system in space is still rudimentary. In terms of the quantity of observations, basic understanding of processes, and physical models, our current knowledge of space weather is about as advanced as that of tropospheric weather over a half century ago. Meanwhile the Nation's reliance on technological systems is growing exponentially, and many of these systems are susceptible to failure or unreliable performance because of extreme space weather conditions. The risks involved could be mitigated or avoided if reliable space weather forecasts were possible and available with sufficient lead time or, in some cases, if representative, quantitative models were available to systems designers. But this is beyond the capability of today's space weather forecasting. Fortunately the technical skills, and to a large extent the means, are now available to move



Two X-ray images obtained by the Yohkoh satellite showing the difference in the dynamic behavior of the sun's surface between solar maximum and solar minimum conditions. Solar activity is indicated by the "sunspot number" calculated from a daily count of the number of sunspot groups and the number of individual spots observed on the sun. The plot of annual averages of sunspot number reveals a clear pattern of cycles of approximately 11 years in length.

forward to provide dramatically improved space weather understanding, forecasts, and services. Moreover, the "information superhighway" makes it possible to collect and to disseminate nearly instantaneously any data or modeling result that is of interest to a user. Such a system is ripe for development, and the scientific, technological, and operational communities are ready for this challenge.

Currently, space environmental support services are provided through the Space Weather Operations of NOAA's Space Environment Center in Boulder, Colorado, and the 50th Weather Squadron at Falcon Air Force Base in Colorado Springs, Colorado. Bulletins, forecasts, alerts, warnings, and data are routinely disseminated to a broad range of customers, including satellite operators, power companies, telecommunications operators, navigational systems users, and research institutions. In a broader context, the user community includes everyone who uses these services: the general public, industry, and the government, particularly the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the military.

A series of recent workshops and meetings attended by members representing the military, commercial, and research communities has revealed the pressing need for improved space environment understanding and forecasting over many time scales--minutes, months, years. The National Space Weather Program will be built upon the idea that strong interaction among the various stakeholders is essential.

The National Space Weather Program will

- ⇒ **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**

b) Purpose and Scope

This document outlines a strategy to guide the planning and implementation of a National Space Weather Program. The document describes the National Space Weather Program, its priorities and goals, the national customer base, and the strategic elements essential to an integrated, goal-oriented capability dedicated to serving national needs. The priorities and goals in this report form the frame of reference to which an implementation plan must cohere.

> "There is now a well recognized linkage between solar activity, geomagnetic disturbances and disruptions to man-made systems...these vulnerabilities will continue and may perhaps increase as technological developments are made..."
>
> --Arend J. Sanbulte
> Chairman and President
> Minnesota Power

The Program includes the contributions of the user communities; operational forecasters; researchers; modelers; and experts in instruments, communications, data processing, and analysis. Guided by these inputs, this Strategic Plan was developed by representatives from the National Science Foundation (NSF), the Department of Defense (DOD), the Department of Commerce (DOC), NASA, and the Department of the Interior (DOI), as an official working group of the Committee for Space Environment Forecasting, Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM).

c) Program Goals and Implementation

The overarching goal of the National Space Weather Program is to achieve an active, synergistic, interagency system to provide timely, accurate, and reliable space environment observations, specifications, and forecasts within the next 10 years.

By building on existing capabilties and establishing an aggressive, coordinated process to set national priorities, focus agency efforts, and leverage resources, the National Space Weather Program provides the path to attain this goal.

The vehicle to implement and manage the Program is the National Space Weather Program Council within the OFCM. The Council consists of designated representatives from Federal agencies involved in space weather activities. Each representative is the official spokesperson for that agency on matters such as program scope, requirements, and resource commitments. The Council will establish policy, develop an implementation plan, focus and coordinate interagency efforts and resources, and approve interagency agreements developed within the scope of the Program. The Council will provide oversight and policy guidance to ensure common needs are met and the interests of each agency are addressed. Member agencies are responsible for planning, programming, and budgeting their own resources to meet agency obligations to the National Space Weather Program. This Strategic Plan and the follow-on implementation plans will establish the basic reference documents to guide the Program as it evolves.

Hydro-Quebec Power Failure

"On March 13, 1989, in the early morning hours, technicians at the Hydro-Quebec power company in Montreal were in their control room as usual, watching the maplike 'mimic board' that allows them to monitor the condition of their power grid. That grid supplies electricity not only to Montreal but to all of Quebec Province, to a total of 6 million people. At 2:44 A. M., a light started flashing on the mimic board: there was trouble up north. A voltage regulator had shut down on one of the main lines that run from the La Grande hydroelectric complex in northern Quebec to Montreal and other cities in the south. As the startled technicians looked on helplessly, a cascade of broken circuits rippled around the province, cutting off the rest of Hydro-Quebec's generators. In all, it had taken less than 90 seconds for power to collapse in the entire grid. The mimic board was now blinking like a Christmas tree. But all over Quebec the lights were out.

"The blackout cost Hydro-Quebec more than $10 million, and it cost the power company's customers tens if not hundreds of millions. Although power was restored to most of the province within nine hours, some places remained dark for days. In the post-mortem analysis, Hydro-Quebec engineers had little trouble figuring out what had happened. Their conclusion was reassuring in one sense, scary in another. The blackout had not been caused by a design flaw, nor by operator negligence, nor indeed by any human error at all. The source of the problem had been the sun."

Eric Lerner/(c)1995 The Walt Disney Co.
Reprinted courtesy of Discover Magazine.

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 via satellite, HF, and VHF radio
- disruption of long-line telecommunications
- errors in navigation systems
- excessive radiation doses dangerous to human health

2. Space Weather: Relevance to America

As our society grows to depend more and more on advanced technology systems, we become increasingly more vulnerable to malfunctions in those systems. Some failures are not just inconveniences, but can have major economic impacts and potentially result in the loss of lives. Technology has reduced our risk to many kinds of natural disasters, but has actually increased the risk of some systems to space weather. For example, long-line 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 on satellites makes them potentially more susceptible to damage by energetic particles; aircraft designed to fly at 60,000 feet have increased human risk to radiation exposure during severe space weather.

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 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, 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.

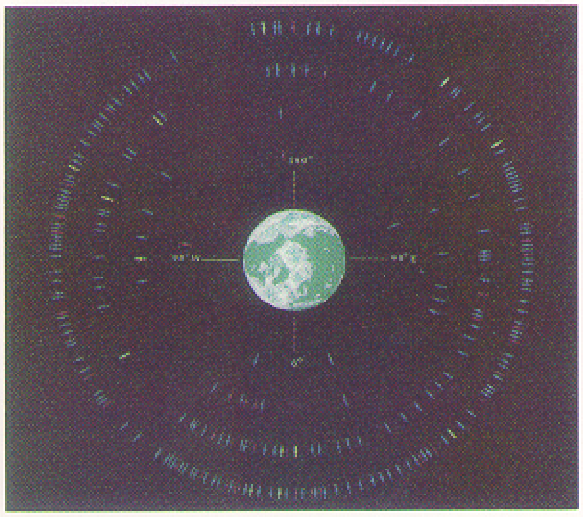
Energetic particles that originate from the sun, from interplanetary space, and from the Earth's magnetosphere continually impact the surfaces of spacecraft. Highly energetic particles penetrate electronic components, causing bit-flips in a chain of electronic signals that can result in spurious commands 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.

Geosynchronous Satellite Anomalies

In January 1994, enhanced fluxes of energetic electrons caused anomalies in three geosynchronous communications satellites, Intelsat-K, Anik E-1, and Anik E-2. All three suffered a loss of attitude control caused by a failure in their momentum wheel circuitry. Although none suffered permanent damage, television, radio, telephone, and satellite operations were affected for hours to days. These satellites provide critical communication functions to Canadian news, weather, and entertainment programming.

Subsequent analysis has shown that the failures were due to deep dielectric charging, an anomaly produced by the impact of highly energetic electrons. The enhanced fluxes of these electrons are associated with high speed solar wind streams. Although large magnetic storms tend to occur during solar maximum conditions, these highly energetic electrons are more common during solar minimum. The enhanced fluxes can persist for days and tend to repeat at the 27-day rotational period of the sun. The improved understanding and predictive capabilities resulting from the National Space Weather Program will help satellite operators prepare for the potential effects these events may have on space systems.

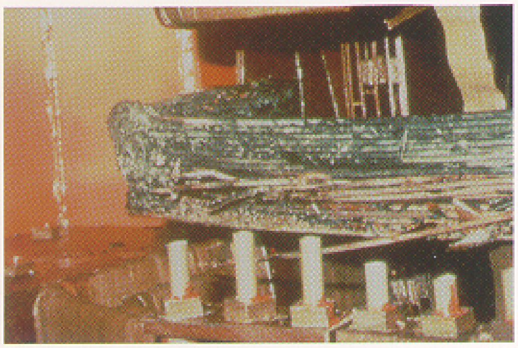
Highly variable solar ultraviolet radiation continuously modifies terrestrial atmospheric density and temperature, affecting spacecraft orbits and lifetimes. Major geomagnetic storms result in heating and expansion of the atmosphere, causing significant perturbations in low-altitude satellite trajectories. At times, these effects may be severe enough to cause premature re-entry of orbiting objects. It is important that satellite controllers be warned of these changes and that accurate models are in place to realistically account for 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.



Distribution of satellites at geosynchronous orbit. These satellites are subject to charging, bit-flips, and other adverse effects of the space environment.

Power Systems

Modern power grids are extremely complex and widespread. 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 multi-million dollar equipment in power generation plants. The resulting social chaos, economic impacts, and threat to safety during widespread power outages could far outweigh the cost of improving the electricity availability problem.



An electric power transformer destroyed by induced currents during a large magnetic storm. In April 1994, five transformers in the Chicago area failed in association with elevated geomagnetic activity.

The electric power distribution system has developed an increased susceptibility to 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 presently exist within the power industry. An economic issue almost equally important to the industry is to minimize costly false alarms.

Navigation Systems

The accuracy of maritime navigation systems using very low frequency signals, such as LORAN and OMEGA, 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 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. 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 these emerging systems.

Communications

Communications at all 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 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 that 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 the Earth's surface. This may cause degradation of signals, but more importantly can prohibit critical communications, such as those used in search and rescue efforts, military operations, and other computer-linked networks.

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 the atmosphere, which absorbs all but the most energetic cosmic ray particles. During space missions, astronauts performing extra-vehicular activities are relatively unprotected. The fluxes of energetic particles can increase hundreds of times, following an intense solar flare or during a large geomagnetic storm, to dangerous levels. 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., SST, U-2) are also susceptible to radiation hazards during similar events.

Relevance to America

Given accurate space weather warnings, system operators could:

satellites	◆ turn off sensitive spacecraft subsystems ◆ increase monitoring of satellite operations for anomalies ◆ calculate best time to adjust a low Earth orbit for drag ◆ avoid sensitive instrument commands during adverse space weather conditions
electric power	◆ reduce load on transmission circuits ◆ confidently reset tripped protective relays on power networks ◆ selectively ground capacitor banks to prevent large potential drops ◆ delay power station maintenance and equipment replacement
communications	◆ look for alternate frequencies ◆ plan means and timing to minimize communications outages
navigation	◆ delay compass calibration on aircraft inertial navigation systems ◆ adjust flight altitude on polar routes to minimize health hazard
surveying	◆ delay high-resolution geological surveying, exploration, or other research using GPS ◆ delay high-resolution magnetic surveying degraded by geomagnetic disturbances
space flight	◆ delay space walks

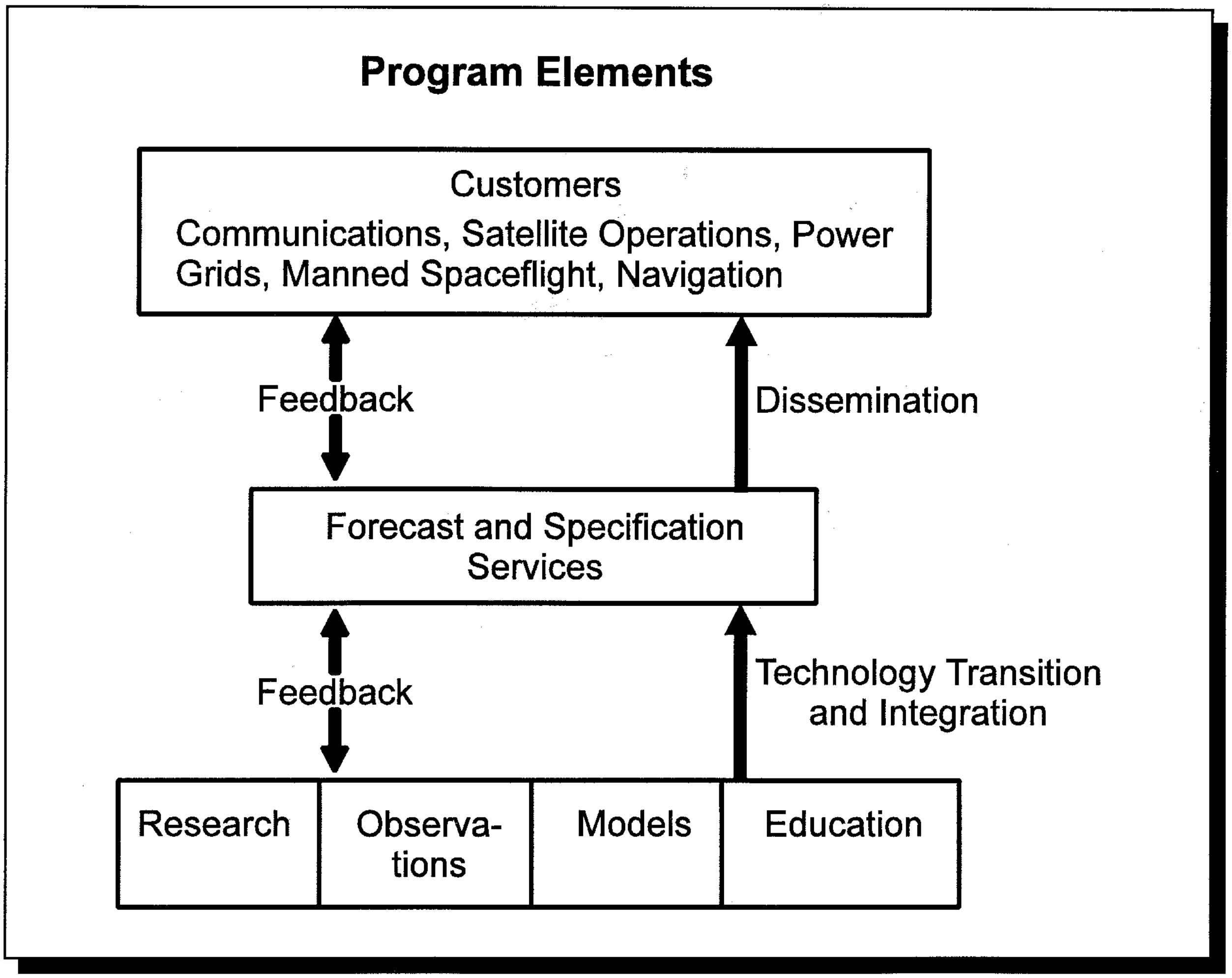
3. Strategic Elements

Forecast and specification services are supported by four pillars--research, observations, models, and education--and by a process that transitions and integrates knowledge into the operational forecast system.

a) Forecasting and Specification

Improving forecasting and specification services is the end goal of this Program. It is the element that directly addresses national needs in natural disaster reduction, and provides the focus for the other contributing elements. Operational forecasts cover multiple lead-times: minutes to hours (warnings), days, and years (solar cycle forecasts). Dependability of services is essential to users. The products must be available on a regular, recurring basis in standard formats.

Space weather forecasters do a commendable job given the resources at hand. But present forecasts are often not sufficient for customers to



take specific mitigation actions or make specific planning decisions. Three measures of useful forecasts are: accuracy, reliability and timeliness. Accuracy means the forecast values closely approximate the subsequently observed condition. Reliability means the conditions that are forecast do, in fact, occur. Timeliness means the customer receives the needed information in time to make decisions or take action. Requirements for forecasts, alerts and warnings are established by the users of these services. Few of the current requirements can be fully met; some can not be met at all.

"Specification" (or nowcasts) refers to the fusion of all available observations into a coherent and realistic representation of the state of the space environment at the time of the observations. Synchronizing and merging the diverse observational data sets pose significant scientific and technical challenges. Sophisticated, physics-based models are needed to fill in areas where there are no observations. Today's space weather models are just starting to approach this goal.

Data Collection and Processing

The National Space Weather Program will guide improvements of the capability to process, assimilate, and analyze increasingly complex data sets. Rapid advances in computer technology have opened a realm of possibilities for development of expert systems, image feature recognition, real-time data access, and database systems. Near-real-time data assimilation is also required for initialization and updating of forecasting models.

Space weather services depend on data collection and processing in the same way that tropospheric weather forecasts do. Data need to be collected from a large number of sensors strategically placed on the Earth's surface, in Earth orbit, and in interplanetary space. The forecast centers need computer systems that can rapidly process and analyze large volumes of observational data; run fairly complex models in real-time; display and manipulate imagery; derive, generate, and disseminate useful products; and facilitate data sharing and back-up responsibilities. Acquisition of new data sets and development of advanced models, with complex calculations, will require greatly enhanced computer systems at the core of space weather services. The forecast centers must replace and continually upgrade both hardware and software to deal with the growing computational needs.

Climatological studies and products also need improving to satisfy the need of planners and engineers to know the range of conditions their systems may encounter and the probabilities of those conditions.

Information Dissemination

New technology will greatly improve the dissemination of space weather information to users of systems affected by the space environment. Space weather products have been limited to simple indices, a few data points, and generalized global forecasts. New models will produce maps, images, specific forecasts, and precise data summaries of disturbances. New standard products will include maps showing the location of intense radiation zones, ionospheric

> "The AFSATCOM system provides critical satellite communications support to the President, Joint Chiefs of Staff, and the Commanders in Chief of US forces, globally....We are learning that space weather can have a significant effect on our communications....We must provide either reliable communications or at least a forecast of when there will be disruptions, so that other means can be planned for and employed."
>
> --Jack Miller
> Chief, AFSATCOM Systems Division

variations that compromise satellite-to-ground communications, and magnetic field variations sufficient to interfere with electric power grid operation. Easy, timely access to the new products will significantly enhance the quality of the information available to forecast users and their ability to safeguard or profitably improve their own operations.

Development of the "information superhighway", the capacity of networks to distribute data-intensive graphics and images rapidly over computer-to-computer links, and the access of thousands of users, civilian and military, to these enhanced communication networks, will be exploited for optimal dissemination of space weather services.

b) Research

An effective National Space Weather Program requires a strong commitment to basic research in many areas of space-related science. Research is needed to advance state-of-the-art instruments and data gathering techniques, to conduct future space missions, to understand the physical processes, to develop predictive models, to provide systems designers with input on conditions in the space environment, and to perform detailed analysis of data associated with past events that have caused significant impacts to space systems. New and creative experiments, employing present and planned space-based and ground-based sensors, will be required.

> "While it is true that important applications will result from the National Space Weather Program, the science that will be accomplished will be first rate.... Indeed, the initiative provides a context in which much of solar-terrestrial physics can and should be done."
>
> --Louis Lanzerotti
> A. T. & T. Bell Laboratories

Because of the importance of observations in both the development of models and post-event analysis, space weather research will take advantage of data obtained by both scientific and operational instruments and missions. Close cooperation among the agencies that support such instruments and missions will make these data more widely available to the research community. In addition, basic research will be conducted in developing and refining techniques for monitoring the space environment. The Program will enable effective planning, communication, and cooperation between the research and operations communities. This will ensure that the latest advancements in the understanding of physical processes and space sensing techniques are verified and put into operations as quickly as possible, and also that future space missions will effectively contribute to Program goals.

The areas of space research that are relevant to space weather include studies of the sun, the solar wind and interplanetary medium, the magnetosphere, the ionosphere, and the upper atmosphere. In conducting this research, we must emphasize understanding of the coupling of these regimes. An interdisciplinary approach is required, with a strong dependence on merging observations, theory, and modeling. The research goal is to synthesize the scientific phenomenologies into a coherent and unified picture of the coupled sun-Earth system. Research will lead to the development of quantitative prediction models, capable of assimilating data obtained by widely separated and disparate instruments on the ground and in space.

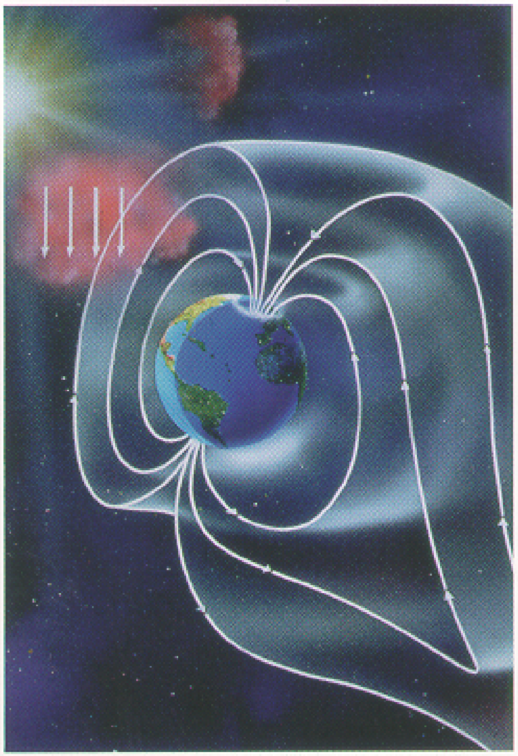
The Sun and Interplanetary Medium

Although it has long been suspected that sporadic geomagnetic disturbances are due to eruptive events on the sun, it is only in the last 20 years that research on the solar corona and interplanetary medium has identified a mechanism by which this could occur. Interactions of high-speed solar wind with the slower ambient flow give rise to compressed regions of plasma. When these reach the magnetosphere they can disturb it significantly, especially if the imbedded interplanetary magnetic field has a large southward component. Coronal mass ejections are a source of non-periodically recurring perturbations in the interplanetary plasma and magnetic field and the resulting effects on Earth's space environment. The propagating plasma disturbances also accelerate energetic particles, which can then be directly injected into the magnetosphere. In addition, the short-wavelength, high-energy radiation emitted from flare sites on the sun, sometimes in association with other eruptive events, reaches Earth in eight minutes, causing almost immediate effects on the current systems in the upper atmosphere.

A focused research goal is thus to understand and predict the timing and location of eruptive solar events, both mass ejections and flares, and to establish whether individual solar events, once observed, are destined to cause disruptions at Earth. To successfully forecast events a day or more in advance, we must have better knowledge as well as better monitoring of the sun and interplanetary medium.

Magnetosphere

The magnetosphere is determined by the interaction between the Earth's magnetic field and the solar wind. The solar wind drives processes that couple large regions of space both magnetically and electrically. The outer boundary of the Earth's magnetosphere forms a barrier that prevents large amounts of energy, particles, and momentum carried by the solar wind from entering the magnetosphere. This barrier is not impenetrable. By a sequence of complex processes that are still incompletely understood, part of the solar wind's particle and energy content penetrates into the Earth's space environment. Strong electric fields and currents are generated and induced within the magnetosphere, the ionosphere, and the Earth's surface.



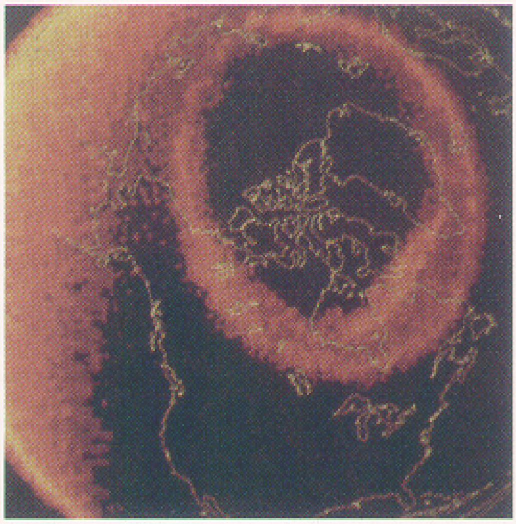
An artist's conception of the magnetosphere showing magnetic field lines that connect to the aurora in Earth's polar regions.

Dana Berry/(c)1995 The Walt Disney Co.
Reprinted courtesy of the artist and Discover Magazine.

Our present knowledge of the magnetospheric phenomena basic to space weather prediction and forecasting is quite rudimentary. Models exist, but they often rely on many free parameters that can be adjusted somewhat arbitrarily. Simulations need to be three-dimensional, cover an immense volume, and include processes occurring over multiple scale sizes. Progress will depend on improved understanding of the following: (1) transfer of energy from the solar wind to the magnetosphere; (2) generation, time dependence, and relative strength of the electric current system; (3) generation and distribution of energetic particles in the magnetosphere; (4) processes by which the magnetosphere abruptly releases energy into electric currents and energetic particles; (5) time dependence of the impulsive heating of the upper atmosphere and the redistribution of this energy; and (6) auroral electrojets.

Ionosphere and Atmosphere

The ionosphere and neutral atmosphere are important to space weather, not only because they are regions where adverse effects commonly occur, but also because they are strongly coupled to each other and to other regions of space. Both the ionosphere and neutral atmosphere vary significantly in response to changing solar energy input on time scales of days to years. Understanding the dynamics of the neutral atmosphere is critical to the development of models that adequately account for many effects, including low-orbit satellite drag. Ionospheric researchers are developing the capability to predict the behavior of variations that affect the propagation of radio waves, with widespread applications. Still incompletely understood is the way in which the ionosphere and atmosphere respond to magnetic storms. These storms provide a large, sudden, impulsive input of energy into the top of the ionosphere in the forms of energetic particles and electrical currents. Research in these areas must encompass the physical processes that govern the regions as well as the development of techniques for remotely monitoring atmospheric properties.



A picture of the aurora as detected by an imaging instrument on the Dynamics Explorer Satellite.

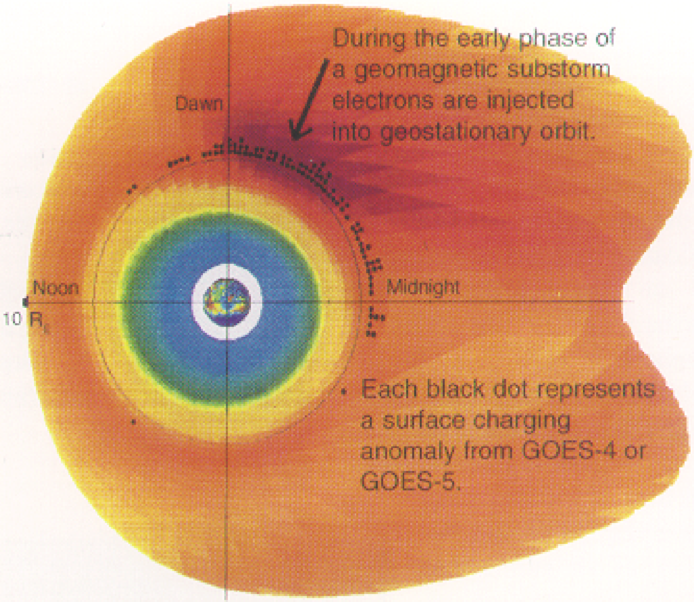
An important exception to the "trail of energy flow" from the sun to Earth is the type of severe ionospheric disturbance that occurs at night near Earth's magnetic equator. Here, the intensity of disruption of communication and navigation systems is the most severe on the planet. The triggering of these disturbances is an open area of active research, but it is clear that the onset mechanism, which is fairly well understood, is largely independent of processes going on in the magnetosphere.

c) Observations

Users of space weather information are concerned with both the background environment and the time of arrival, intensity, and duration of space weather disturbances as they manifest themselves at specific locations. The variations occur on time scales from minutes through days to years. To have a complete picture of the environment from the present into the future, forecasters need observations from key locations beginning with the origin of the disturbances at the sun and continuing along their propagation routes into the near-Earth environment.

Today, space weather forecasting is in a situation similar to that of weather forecasting half a century ago. Even with the present and planned instruments, the data are sometimes too sparse, and some critical data, such as in-situ solar wind parameters, are not available at all. The gaps in our ground-based observations are particularly acute at very high latitudes, where the magnetic field maps out to the distant regions of the magnetosphere. New ground- and space-based instruments, coupled with quantitative modeling, will provide an enormous improvement in space weather specification and forecasting quality.

An adequate suite of data sources must be established, expanding on the current networks and exploiting new sensors evolving out of research programs. The networks must be global, with dense enough coverage to provide regional specifications, and include real-time or near-real-time communications. An exciting prospect is to proceed from current methods of in-situ measurements to an imaging capability of vast three-dimensional volumes of nearby space. The data must also provide the right input to optimize the use of models and support accurate climatologies for system designers. A key benefit of the National Space Weather Program will be to evaluate observational needs and guide the most cost-effective solutions.



Model results showing the predicted distribution of energetic electrons in the magnetosphere. Surface charging anomalies experienced by two geosynchronous satellites occurred in the region between midnight and dawn.

d) Model Development

Physics-based, quantitative models are required to provide a predictive capability not presently available. The new models will replace the limited heuristic algorithms, statistical relationships, and human estimates used today in space weather forecasting and engineering design systems. The US Air Force (USAF) has procured a first generation of space weather models. Initial specification models will allow the use of current observations to represent conditions at different locations in near-Earth space; forecast capabilities will be added as soon as possible.

The major elements of this effort are incorporation of scientific results into research models, the transfer into operational models, the validation and testing of models, the implementation of the models into operations, and the improvement of forecast services. The NSF, NASA, and DOD (USAF and US Navy) conduct research to incorporate new understanding of the solar-terrestrial environment into research and development models. DOD and NOAA have joint responsibility for transitioning the improved models into operations. Research models must be tailored to meet operational needs. Models must be integrated with each other and with empirical forecast techniques into a system that provides the best possible answer to the forecaster's question. The system must have a user-friendly interface, be easy to upgrade, and run on a variety of hardware.

e) Education

Educational opportunities in space weather apply to engineers, operational forecasters, students, and the general public. Space weather forecasting can both educate and excite students worldwide. To further national science and mathematics education goals, the Program will encourage efforts to make space weather an important element of science curricula in grade schools, secondary schools, and college. Improved methods for disseminating space weather data will allow students to witness space phenomena in a classroom setting. They will be able to see real-time displays of variable solar radiation, solar eruptions, the impact of energetic particles on Earth, auroral events, ionospheric currents, and other unique phenomena. Students could use data to make their own space weather forecasts and warnings, while considering the practical aspects of cost versus benefits.

Educational activities supported under the National Space Weather Program will heighten public awareness of the impact of space weather on human activities. It is conceivable that future space weather reports will become a regular feature of nightly news broadcasts. Efforts in this area have already been undertaken at the university level. Growing media exposure will foster an appreciation for the dynamic space environment in which the Earth is encompassed and will help to foster a scientifically literate citizenry.

In the operational arena are space weather observers and forecasters, military weather personnel supporting communications and space launch operations, space operations controllers, satellite designers and engineers--all requiring some form of education to improve their performance. Training courses using modern media capabilities are needed to meet the gamut of applications, from in-depth, resident courses, to portable, self-taught modular courses. Improved user and operator awareness will increase the effectiveness of space weather support and will produce better feedback to help focus further improvements.

f) Technology Transition and Integration

A coordinated program for technology transition is a key building block of the National Space Weather Program. Agencies will expand the ways in which they work together to determine requirements and set priorities for implementation of new technologies based on ongoing research and development work. Each agency will contribute its respective expertise to a streamlined technology transfer process that emphasizes the transition from new observations and improved scientific understanding into the development of improved scientific models; the conversion of those improved models, sensors, and insight into operational versions; the testing and validation of the operational versions; and their implementation into space weather services. Trade-offs, reprioritization, major changes in observing systems, and shifts in operational responsibility will be coordinated more closely among participating agencies.

4. Areas of Strategic Priority

Forecasting. 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 forecasting efforts 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. New operational models, instrumentation, and techniques will be evaluated according to their potential to improve forecasting services.

Research in the initial phase of the Program will include intensive efforts in understanding the fundamental physical processes that affect the state of the sun, magnetosphere, ionosphere, and atmosphere, with a focus on answering research questions that impede progress in improving forecasting capability. Radiative, dynamical, electrical, and chemical coupling between different regions will be studied using data from existing ground- and space-based instrumentation. Greater effectiveness will arise from the emphasis on physical measurements rather than the conventional indices. Theoretical investigations in these areas will help to define the needed observations and will aid the development of operational models.

Service to Society

A hydrogen gas fire, a signature of the overheating caused by induced currents, erupted at the Zion Nuclear Power Plant on April 3, 1994. Due to the great expense of operating without the necessary transformers, Commonwealth Edison planned to put a replacement transformer into service sometime after midnight April 16. As the date approached, the Sun, as seen in X-ray images taken by the Japanese satellite Yohkoh, ejected a large massive structure. Such structures are frequently associated with geomagnetic disturbances at Earth. Based on these observations, NOAA's Space Weather Operations raised the probability for geomagnetic storm conditions for April 16 and 17 to 55%. Personnel at Commonwealth Edison consulted in depth with NOAA staff during April 16 because of concerns about the possible disturbance and its effects on the new transformer. As a result, Commonwealth Edison decided that the risk to the transformer justified the cost of postponing the installation until April 17, when the disturbance was predicted to subside. The disturbance began Saturday evening and proved to be intense. Aurora could be seen as far south as Boulder, Colorado. By late Sunday, the severe storm level had declined and the new transformer was successfully installed.

Observations. The Program will build on existing capabilities and include a determination of new data needs and the value of current data. As the Program progresses, observations in support of research and forecasting are expected to grow, as critical parameters for forecasting are identified, measurement techniques are defined, and new space- and ground-based platforms are developed. The initial focus will be on better coverage of data-void or data-sparse regions, and on the deployment of systems that will provide data with appropriate accuracy, resolution, and timeliness. Because instrumentation development is an evolutionary process, the Program will emphasize rapid exploitation of observational capabilities and efficient communication between data analysts, researchers, and instrument designers.

Modeling efforts for specifying and predicting the space environment have been under way for several years, but operational benefits have not yet been realized. The Program will coordinate these modeling efforts and guide integration of the models to ensure their consistency and optimal performance. A primary goal is to develop first-principle, 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. Evaluation of these models will be conducted in close collaboration with research and observation efforts and with regard to user requirements. Gaps and deficiencies in these models will be identified and used to set requirements for future models.

Education activities supported by the Program will enhance public awareness of space weather and its impacts; will help ensure a sufficient supply of educated scientists and engineers to maintain expertise in all space weather related fields; and will improve training of forecasters, observers, and system operators. An educated public and commercial sector will be 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 processes must be improved and focused to facilitate the transfer of tools, techniques, and knowledge from the research or commercial communities to the operational forecasting activities. This effort, now often a bottleneck, is critical to the success of the Program. Innovative means must be explored to establish a dynamic process for technology exploitation and transition to improve forecasting capability, utilize all relevant research, and rapidly realize benefits.

Educational activities will be aimed at students at all grade levels as well as Space Weather forecasters, customers, and the general public.

5. Agency Roles and Missions

Department of Commerce (DOC). Within DOC, NOAA has the mission of describing and predicting the Earth's environment. NOAA's Space Environment Center hosts an operational forecast center and research activities. The forecast center, operated jointly with the US Air Force, provides space weather forecasts and warnings to users in government and industry and to the general public. NOAA maintains unique space weather expertise to assist in the design of new systems and to reduce effects on existing systems. NOAA collects, provides, and archives space environment data from its polar-orbiting and geostationary satellites, from other agencies, and through international data exchange. Research is directed toward understanding processes and interactions as energy leaves the sun, propagates through the interplanetary medium, and arrives at the Earth's atmosphere.

Department of Defense (DOD). The Air Force and the Navy conduct research and development to minimize adverse space weather impacts on operational readiness and to minimize the resources needed to restore these capabilities. DOD develops operational models of the solar-terrestrial system and develops and flight-tests new sensors. To meet daily operating requirements, the USAF forecast center provides basic and specialized support for military electromagnetic communications, surveillance, and warning systems that operate in or through the upper atmosphere or near-Earth space. DOD provides rapid notification to all levels within the military chain of command for decision assistance. USAF and the Navy also operate and fund a variety of ground-based and space-based sensors contributing to the common database, and USAF provides space climatological support for DOD users.

National Science Foundation (NSF). NSF is responsible for maintaining the health of basic research in all areas of the atmospheric sciences. The Foundation supports theoretical, observational, and numerical modeling research with the goals of increasing fundamental understanding of space environment processes and improving space weather predictive capability. Research areas of emphasis are: (1) solar region evolution and eruptive events; (2) interplanetary transport; (3) magnetospheric physics and dynamics; (4) ionospheric physics and dynamics; and (5) upper atmospheric physics and dynamics. Knowledge of the processes which are fundamental to each of these areas is enhanced by a multi-disciplinary approach to investigating the basic mechanisms through which these areas interact.

National Aeronautics and Space Administration (NASA). NASA will continue its traditional role of space exploration and study of the solar-terrestrial system. NASA's missions in Space Physics, current and planned, are designed to fulfill important complementary requirements: to answer specific scientific questions; to improve and advance our empirical understanding of events and conditions in space; to develop and use new technology; to establish proof of concept and the value of new observational methods in space; to develop a database that determines the empirical nature of space weather conditions; and generally to observe and interpret the variable corpuscular and electromagnetic radiation that emanates from the sun and affects the space environments of Earth and other planets. Much of the Space Physics research grants program also contributes to developing basic principles and methods by which space weather may be understood and accurately described.

Department of the Interior (DOI). Within DOI, the US Geological Survey (USGS) manages a growing international network of 60 or more geomagnetic sensors (INTERMAGNET), many of which contribute data in real-time to the USAF forecast center for hourly computations of geomagnetic indices. The data are also valuable input to ionospheric and magnetospheric forecasting models. Collection nodes for INTERMAGNET are located in Golden (Colorado), Paris, Ottawa, Edinburgh, and Kyoto. The monitoring network contributes to natural disaster mitigation by providing the information needed to quickly and accurately assess significant changes in the Earth's magnetic field (geomagnetic storms).

Department of Energy (DOE). Within DOE, Defense Programs supports research concerned with space weather in the context of its missions regarding nuclear event detection by satellite surveillance. Programs in Energy Efficiency and Renewable Energy are concerned with space weather issues regarding possible impacts on electrical energy transmission. Research programs in the Office of Basic Energy Sciences are concerned with fundamental aspects of solar-terrestrial interactions.

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