CHAPTER 3

RESEARCH

An operational space weather forecast system requires improved understanding in three broad areas of research: (1) the Sun and solar wind, (2) the magnetosphere, and (3) the ionosphere/thermosphere system. In June 1995, a working group for each of these research areas was assembled to formulate plans for addressing its space weather goals. Each of the three groups was given the goals listed in Table 2-7 and asked to identify what was needed in terms of physical understanding, models, and observations. The fifteen items in Table 2-7 were divided among the three groups, as indicated in Figure 3-1.

Solar/Solar Wind:
- Coronal mass ejections
- Solar activity/flares
- Solar and galactic energetic particles
- Solar UV/EUV/soft x-rays
- Solar radio noise
- Solar wind

Magnetosphere:
- Magnetospheric particles and fields
- Geomagnetic disturbances
- Radiation belts

Ionosphere/Thermosphere:
- Aurora
- Ionospheric properties
- Ionospheric electric fields
- Ionospheric disturbances
- Ionospheric scintillations
- Neutral atmosphere

Figure 3-1. Domains for Space Weather Research

A detailed description of the plan developed by these working groups is contained in Appendix A. Here we provide a summary of the overall plan, including a description of the physical understanding, model development, and observations required in each area.

3.1 Physical Understanding

3.1.1 Background

As outlined in Chapter 2, the National Space Weather Program (NSWP) goals involve the ability to predict the state of the space environment. Hence, basic scientific research must be conducted to improve our fundamental understanding of the physical processes involved.

Beginning with the Sun, a critically important basic research objective is to understand the processes by which coronal mass ejections (CMEs) occur, including the factors that influence their sizes, shapes, masses, speeds, and magnetic field configurations. Equally important is an understanding of solar activity in general. This requires studying how the solar dynamo works and the identification of precursors to solar activity, such as short-term development of active regions and long-term buildup of polar magnetic fields. This involves studying the dynamics of magnetic energy in the solar corona and the role of magnetic fields in the occurrence of flares. It is also important to understand the origins of high-energy solar particles and how they propagate through the interplanetary medium. Similar processes play a role in modulating the fluxes of cosmic rays originating in galactic space. Solar radiation at ultraviolet (UV), extreme ultraviolet (EUV), and soft x-ray wavelengths has a direct effect on Earth's atmosphere. Research in this area is aimed at understanding the variability of the Sun at these wavelengths and how this variability influences the state of the ionosphere and thermosphere. The origin of solar radio noise, which affects communication systems, must also be understood. Finally, the solar wind has a direct influence on the state of Earth's magnetosphere, so it is vital that we understand the processes by which the solar wind is heated and accelerated in the solar corona, as well as the transient perturbations and shocks created by flares and CMEs.

Many space weather applications require knowledge of the particle populations and electromagnetic fields throughout the magnetosphere. This dynamic environment can only be understood by studying the coupling processes between the solar wind and magnetosphere, the transport and energization of plasma in the magnetosphere, the processes involved in magnetic storms and substorms, and the coupling processes between the magnetosphere and the ionosphere. The strong magnetic coupling between the magnetosphere and Earth results in geomagnetic disturbances. The ability to predict geomagnetic disturbances depends on our understanding of the role played by the magnetosphere, ionosphere, and neutral atmosphere (the thermosphere and mesosphere) in modulating the strength of electric currents in space. It is also important to quantify the electrical currents induced in the ground by dynamic currents in the magnetosphere. The magnetospheric radiation belts represent a serious hazard to space systems. Because parts of the radiation belts have been observed to vary significantly, research must be conducted to understand the transport, production, and loss processes that determine the particle flux levels in both quiet and storm times.

Ionospheric properties, including electron density, electron and ion temperature, and composition, are determined by solar radiation, auroral particle impact, and Joule heating. Advances in predictive capabilities in this area depend on our understanding of the formation mechanisms responsible for large-scale and medium-scale electron density structures, and the production, transport, and loss mechanisms associated with these electron density structures. These mechanisms are dynamic in nature and respond to both geomagnetic storms and substorms. The day-to-day variability of large-scale ionospheric features and small-scale plasma density irregularities must be understood to determine their effects on radio wave propagation during quiet and disturbed times. It is also necessary to study the relation between ionospheric irregularities and radio wave scintillation, in particular, the interactions that control the formation and evolution of 10-kilometer to 50-meter electron density irregularities that produce scintillations. Understanding of auroral energy input requires knowledge of the processes that guide, accelerate, and otherwise control particle precipitation, both in quiet times and in times of magnetic storms or substorms. Ionospheric electric fields that drive currents and produce Joule heating must be accurately specified for accurate prediction of ionospheric properties. In particular, it is important to study the small-scale electric field (E-field) structures and the large-scale electrostatic fields and identify the ways in which they couple to the magnetosphere and respond to changes in the interplanetary magnetic field. Further research must be conducted on the process by which high-latitude E fields penetrate to low latitudes. Ionospheric and thermospheric research is strongly coupled, and advancements in the two areas must proceed in parallel. For the neutral atmosphere, basic research needs to be conducted to understand the chemical, radiative, and dynamical processes that act to modify and redistribute energy and constituents throughout the upper atmosphere.

3.1.2 Advances and Work in Progress

The following sections review research advances and work in progress supported under the focused space weather research competitions in 1996 and 1997. Where possible, results already achieved are distinguished from planned research.

3.1.2.1 Sun and Solar Wind

Recent research has focused on coronal mass ejections as one of the primary drivers for large geomagnetic storms. This has inspired much work in trying to understand the origins of CMEs and how they propagate into space.

Because coronal mass ejections can produce dramatic increases in the speed and density of the solar wind, it is important to understand the origin of these events. Scientists at the National Center for Atmospheric Research are studying the relationship between different types of solar prominences and CMEs. Preliminary investigations show that certain types of prominences are more likely to yield CMEs, an observation that holds promise in the use of ground-based observations to forecast CME occurrence.

The ability to predict storms on the Sun depends critically on our understanding of the coronal magnetic field structure. A number of models have been developed that compute the coronal field from vector magnetic field measurements at the photosphere. A project being carried out at the University of Hawaii will evaluate the performance of different codes using identical inputs. Both synthetic and real data will be used as input to the models, and discrepancies among the results will be analyzed and discussed in collaboration with the model developers.

Because coronal mass ejections are associated with coronal holes, there is much interest in monitoring and studying the properties of coronal holes. Scientists from Solar Physics Research Institute are investigating coronal holes using He1083 nm full-disk observations made at the National Solar Observatory/Kitt Peak. The study will also make use of photospheric and chromospheric line-of-sight magnetograms to map coronal holes and associated magnetic fields. Knowledge of the variability of coronal holes and their relation to solar activity provides important clues to understanding the short- and long-term evolution of the solar magnetic fields and their extension into space.

Ground-based observation of filaments also may be used for solar forecasting. Investigators from the New Jersey Institute of Technology are developing a procedure based on H-alpha images of the Sun obtained at the Big Bear Solar Observatory to detect filaments and issue an early warning of their occurrence. By creating an automatic system for such detections, the investigators hope to produce a filament index that will reflect the current state of solar activity.

A similar study is being conducted by scientists at Boston College who are studying the occurrence of disappearing filaments and soft x-ray arcades on the Sun. The investigators will use selected disappearing filaments and arcades binned by magnetic polarity and axial orientation to assess the usefulness of these parameters in prediction schemes. The study will show which characteristics of solar mass ejecta are most geoeffective and lead to moderate to large magnetic storms.

Another method for early warning of solar events is being studied by investigators at Hughes STX. Interplanetary type II radio bursts are observed remotely by both the Ulysses and WIND spacecraft. These emissions are generated when CME driven shocks propagate through the interplanetary medium. The investigators have already had some success in using the timing of these radio emissions to estimate the arrival time of the shock at Earth. If validated, this technique will provide a powerful means of estimating shock arrivals many hours in advance of the impact.

Coronal mass ejections produce interplanetary shocks that modulate and accelerate energetic particles. Investigators at Bartol Research are developing theoretical models for this acceleration and the subsequent propagation of the particles to Earth. The models will provide the particle spectrum, fluxes and upper limits for the most energetic particles accelerated at interplanetary shocks.

The ability to predict the effects of solar wind disturbances depends on modeling the solar wind. Satellites at L1 can help, but there is some uncertainty in the propagation of these disturbances from the point at which they are first observed. There have been several studies addressing this issue.

Scientists at SAIC-San Diego are developing a comprehensive, three-dimensional, magnetohydrodynamic model to use remote observations of the Sun to predict the state of the solar wind at Earth's orbit. The code has already been used to determine the coronal magnetic field and heliospheric current sheet structure during the period from February 1997 to March 1998. The model has also been used to simulate the triggering of a coronal mass ejection, including its appearance as seen by a space-based coronagraph.

A model being developed at Johns Hopkins University will use solar wind data obtained by satellites far upstream of Earth's location to calculate the property of the solar wind at Earth's orbit. The results will be analyzed to determine the scale size of solar wind features, the propagation speeds of different structures to Earth, the effectiveness of upstream measurements of the solar wind magnetic field for space weather predictions, and the interaction of the solar wind with Earth's bow shock.

A statistical approach to this same problem is being undertaken by investigators at MIT, who will determine correlation coefficients between plasma and magnetic field properties at the L1 point and at Earth. Because a solar wind monitor at the L1 point is critical to all space weather prediction systems, it is important to understand the relationship between the observed properties of the solar wind at L1 and the variations that occur at Earth's location.

3.1.2.2 Magnetosphere

For many years, the Rice University Convection Model has been the mainstay for specifying the magnetospheric response to solar wind inputs. Using the properties of the solar wind impinging on the magnetosphere, the model computes energetic particle fluxes and the convection electric field. In response to the NSWP project solicitation, Rice University scientists are updating the model by incorporating a new open magnetic field model, a magnetofriction equilibrium relaxation technique to achieve particle and field self-consistency, and an algorithm to account for internal plasma sources and losses.

Whereas the Rice Convection Model specifies magnetospheric properties by following the motion of particles in magnetic and electric fields, magnetohydrodynamic (MHD) models solve self-consistently for the particle distributions and fields. Scientists at George Mason University are testing the Lyon-Fedder-Mobarry MHD code using a set of simulated solar input conditions. Such validations are essential to assess the practical limitations of MHD models for space weather applications.

An MHD model developed under the High Performance Computing and Communication program, and now continuing under the Knowledge and Distributed Intelligence Program, is being adapted and tested for space weather applications by researchers at the University of Michigan. This code has many features that make it especially promising, including the use of an adaptive grid to handle both large and small-scale processes. The investigators will develop the code using realistic inputs for solar wind forcing and test the results using other models and observations.

One of the most difficult aspects of magnetospheric modeling is accounting for the dramatic changes in configuration that arise from magnetic substorms. Investigators from UCLA are using an MHD code to study key aspects of substorms. They plan to use real solar wind data as input and compare the model results with magnetospheric and ionosphere observations.

Another group at UCLA is using a combination of MHD simulations and single particle tracing to examine the processes by which energetic particles from the solar wind enter the magnetosphere during storms.

Another validation and testing program for the Lyon-Fedder-Mobarry MHD model is being conducted at Dartmouth University. A large number of solar wind intervals will be selected as input to the MHD model. They will be chosen to include periods of magnetic storms, substorms, and high solar wind dynamic pressure in order to exercise the behavior of the model under a wide range of circumstances. This group is also planning on running a Beowulf cluster to predict the magnetospheric state from real-time solar wind data.

Because of the many satellites in geosynchronous orbit, it is essential that models accurately predict the energetic particle environment at these locations. Researchers at Los Alamos National Laboratory are collecting data from energetic particle detectors on geosynchronous satellites spanning the years from 1989 to the present. These measurements will be used to develop a model of the particle environment in terms of mean fluxes, maxima, minima, and standard deviations.

Researchers at Los Alamos are also working with scientists at Rice University to incorporate a data assimilation capability to the Rice Convection Model. Eventually this capability could be transitioned to the operational Magnetospheric Specification Model as a real-time capability.

Many magnetospheric properties are tied to magnetic indices that have been measured continuously for several decades. It is important to accurately associate these magnetic indices to physical properties of the magnetosphere so they can be used as proxies for quantities that are difficult to measure directly. A study conducted by UCLA scientists will define a better Dst index, create a quick-time index for scientific investigations, and provide insight into the way Dst responds to solar wind input.

Another project to develop more physically meaningful indices is being undertaken at The Johns Hopkins University Applied Physics Laboratory (JHU/APL). These investigators will use data from DMSP and NOAA satellites from 1984 to the present to statistically rate different parameters such as the location of the inner edge of the plasma sheet at midnight, plasma pressure, and conductivity. The relationship between the elements of the database and the geosynchronous field, convection, and substorms will also be investigated.

Other scientists at JHU/APL are using the SuperDARN radars to determine the dayside magnetic merging rate by measuring the transport of magnetic flux across the dayside merging gap in the ionosphere. Work is also underway to extend this technique to include reconnection on the nightside.

Several models have been developed to study the temporal behavior of magnetospheric indices in response to solar wind inputs. These models provide a means to predict the state of the ionosphere from a given time series of input data. Scientists at the University of Maryland are taking these models a step further by constructing models capable of predicting regional properties. The investigators will make use of ionospheric data, ground magnetometers, and solar wind measurements to develop a multivariate model of the dynamical behavior of the different components of geomagnetic activity.

Several different groups are examining the processes by which electrons in the radiation belts are energized during magnetic storms. A group at Rice University is using new mathematical techniques to examine the problem from a theoretical standpoint. A group at the University of Colorado is using a large database of satellite measurements to determine where the maximum phase-space density is located. That location is likely to be the source of the electrons injected into the outer radiation belt.

3.1.2.3 Ionosphere/Thermosphere

There are many different types of ionospheric models. These have arisen as a result of different approaches to the problem, or in response to specific requirements. Some models predict the large-scale ionosphere. Some attempt to account for small-scale structure. Others concentrate on specific geographic areas. The goal of the NSWP is to develop a single overarching model for all applications. However, such a model may be composed of several types of interacting models, including physics-based models, empirical models, and data-driven assimilative models. The following projects reflect a multi-pronged approach to ionospheric model development.

A University of Southern California project aims to develop a data assimilation model based on a physics-based model of the ionosphere and measurements of total electron content determined from GPS satellite signals. Tomographic techniques based on GPS signals received at a single station work well only when the ionosphere is relatively unstructured. When combined with a physics-based model, these tomographic determinations can be made more accurately. The investigators will also study the benefits gained from using data from a satellite-borne GPS receiver in low Earth orbit.

This approach has the potential to provide a means to specify the global state of the ionosphere on a continuous basis.

Another study based on GPS signals is being conducted by University of Colorado scientists. This study makes use of GPS signals received in low Earth orbit by the TOPEX/POSEIDON satellite. The research will concentrate in particular on the ionospheric effects produced by large magnetic storms. A second award to University of Colorado scientists will lead to the development of a mid- and high-latitude ionospheric storm-time correction map. If such a correction map is successful, it can be used in conjunction with empirical ionospheric models to better specify the changes that occur during magnetic storms.

Because the topside ionization can contribute 70 to 80 percent of the total column density, it is important to understand how the electron density profile behaves above the F region peak. This is the topic of a study conducted by scientists at Hughes STX who will use data from topside sounders on satellites, incoherent scatter radars, and in situ measurements of electron density to develop a topside ionosphere model. The model will provide a global specification of the topside ionosphere as a function of UT, local time, season, solar cycle, and magnetic activity.

Although several models have been successful in reproducing the large-scale behavior of the ionosphere, the specification and prediction of ionospheric irregularities still poses a serious problem to modelers. The NSWP has supported several projects whose aim is to better understand these irregularities, particularly at the equator and high latitudes where their effects produce serious problems in communication and navigation systems.

A project being undertaken at SRI International involves the deployment of a meridional chain of ionospheric sounders spanning the magnetic dip equator and referred to as the WestPac Chain. The data will be used to study the development of equatorial spread F, including its spatial structure and dependence on ionosphere properties in the conjugate E regions.

Equatorial spread F is being studied in a similar manner by scientists at the Space Environment Corporation. Using data from the WestPac chain of ionospheric stations, the investigators will examine the parameters that control the onset of the Rayleigh-Taylor instability. The observations will be assimilated into models to identify the driving mechanisms and establish the existence of possible precursor events for equatorial spread F.

Another study of equatorial spread F is being conducted at Utah State University using data from the Jicamarca Radar in Peru, along with ionosonde and satellite measurements. The measurements will be used to determine the height-dependent ambient electrodynamic conditions immediately prior to the occurrence of spread F, the location of the initial unstable layer, and its temporal and spatial evolution for different seasons and flux conditions. The combined data set will also allow the investigators to study the role of meridional neutral winds and magnetic declination on spread F formation. When the initial conditions for spread F have been determined, the results will be merged with a global ionosphere model.

A theoretical study being undertaken at Cornell University also strives to achieve a predictive capability for bottomside and equatorial spread F. This study makes use of numerical simulation modeling of the F layer along with observational data from the Jicamarca radar to formulate a theoretical basis for the observations.

A different approach to the prediction of equatorial spread F is being studied by scientists at the University of Texas at Dallas. This involves the development of a neural network using input data from the DMSP satellite and various ground-based observing systems. Historical data are used to determine the combination of circumstances likely to lead to equatorial spread F development. Once the technique has been validated, the model will be examined in detail and contrasted with the output of models based on fundamental plasma physics in order to identify the most critical driving elements of such models.

High latitude ionospheric structure is being studied by Boston College scientists using the Global Thermosphere Ionosphere Model. The model will be run with varying inputs to account for the spatial distribution of ionospheric plasma enhancements in the polar regions, how they form, and how they move in the convection electric field. This study will help to identify the most important processes that need to be included in physics-based models of the high latitude ionosphere.

A study of ionospheric irregularities will also be conducted at Utah State University using the Time Dependent Ionospheric Model. The goal is to develop a model which, when interfaced to a time-evolving ionospheric representation, will yield instantaneous instability growth rates that can be tracked as a function of time along the convecting flux tube. If successful, the study will show that small-scale instability processes can be handled within the context of large-scale ionospheric models.

An important element in all global ionospheric modeling is the ability to accurately specify high latitude inputs, including the convection electric field and auroral currents and precipitation. A study being conducted at the University of Texas at Dallas will provide a means to evaluate the accuracy of models of the high-latitude electric potential distribution. The validation will be based on the deviations between the model predictions and the in situ measurements of electric field made by the DMSP satellite. The study will lead to a set of reliability factors for the electric field models for different ionospheric conditions.

Scientists at Johns Hopkins University are using data from the SuperDARN radar array to study how the convection electric field changes in response to solar activity. An IMF dependent model of the high-latitude electric field potential has been derived from these observations. They are also developing a capability to provide a real-time estimate of the high-latitude convection based on real-time data from multiple radars.

Other scientists at Johns Hopkins University are studying the possible use of magnetometer data from the Iridium satellites to determine the location of the auroral oval. Though relatively insensitive, the Iridium magnetometers are able to detect perturbations from field-aligned currents in the auroral zone. The combined information from the 60 or 70 Iridium satellites in orbit could provide a means of specifying the instantaneous location of the auroral oval almost continuously on a global basis. The technique has been validated for several selected passes, but further work is needed to assimilate data from the entire fleet of satellites. Unfortunately, the bankruptcy of the Iridium group leaves the future availability of these data in doubt.

A Boston University project aims to study the response of the ionosphere and ionospheric currents to the semi-annual variation in geomagnetic activity stemming from the geometric orientation of the dipole relative to the Sun. Because the solar wind is coupled to the ionosphere through the magnetosphere, this study will elucidate the physical processes that connect these extended regions of space.

3.1.2.4 Geomagnetic Storm Studies

Several of the awards made in response to the NSWP project solicitation involved studies of geomagnetic storms from their origin on the Sun to their impacts on the magnetosphere/ionosphere/thermosphere system. Early in the NSWP planning, scientists identified a large storm in November of 1993 as an ideal candidate for such an end-to-end study. Led by an investigator at the U. S. Air Force Academy, a series of concurrent studies was conducted examining the detailed observations of this storm, applying the data to various models, and testing the predictions against observed effects.

Measurements made by incoherent scatter radars are an important element in studying the ionospheric effects of storms, but these instruments do not run continuously and operation must be scheduled in advance. An award was made to SRI International to develop a protocol in which the possible onset of a magnetic storm was predicted using solar observations from the SOHO satellite. An early warning system was set up that successfully allowed for the initiation of radar operations at Sondrestrom, Millstone Hill, and EISCAT for the entire duration of several storms in 1997 and 1998. This procedure will greatly enhance the number of magnetic storm data sets for which incoherent scatter radar data will be available.

3.2 Research Model Development

3.2.1 Background

Many different types of models are important for achieving the goals of the NSWP. The ultimate goal is to develop an operational model that incorporates basic physical understanding to enable specification and forecasting of the space environment by following the flow of energy from the Sun to Earth. This coupled system of models is to be constructed by merging parallel models for the solar/solar wind, the magnetosphere, and the ionosphere/thermosphere. In addition to this, several other types of models will be necessary. Any forecast model must begin with a detailed specification of the current state of the system, which is provided either by empirical models or by assimilative models that take in available observations and fill in gaps. Also, during the course of development of the full operational model, other approaches including empirical predictive methods will be developed and tested to ensure that the most efficient and accurate method is used in the final system.

The ability to predict coronal mass ejections and their subsequent effects requires models of the initiation process and three-dimensional magnetohydrodynamic (3D MHD) simulations of the resulting disturbances in the solar wind. Models of particle acceleration in the CME-driven interplanetary shocks are also necessary for predicting the intensity and time of arrival of particle events at Earth's orbit. Models of radio emissions from CMEs are important for optimizing the use of radio noise as a remote sensing tool.

In modeling solar flares, it is necessary to know the magnetic field in the corona. The only method for determining this field is to observe it at the photosphere and use numerical modeling to extrapolate it into the corona. Simulating the flare itself requires 3D models of magnetic reconnection in active regions, including consideration of the processes that determine the distribution and magnitude of resistivity. Models relating to the processes by which solar flares accelerate particles and generate UV, EUV, and x-ray bursts are also necessary for accurate prediction of flare effects.

Models for the solar wind include 3D MHD simulations of the coronal acceleration region and the solar wind extension into interplanetary space. A coupled version of these two models can be used as a proxy for specifying solar wind velocity prior to its expansion into interplanetary space. Because it is likely that interplanetary magnetic field (IMF) data will come from a satellite at the Lagrangian (L1) point, a model is also necessary to predict solar wind and IMF conditions at the magnetosphere as extrapolated from the available information.

To predict solar UV, EUV, and x-ray emissions, it is necessary to develop 3D models of the solar atmosphere and improve the solar spectrum calculations covering all significant lines and bands from atoms, ions, and molecules.

Although there are several models in existence that specify and predict the particles and fields in the magnetosphere, the Magnetospheric Specification Model (MSM) and the Magnetospheric Specification and Forecast Model (MSFM) are in operational use. Both of these models depend on accurate specifications of magnetic and electric fields, and ionospheric conductances, including the effects of auroral precipitation. Continuing development of these models will improve and extend the capabilities of the MSM and MSFM. The MSFM represents only one approach to numerical magnetospheric prediction codes. Another approach incorporates global MHD simulations that self-consistently solve for the plasma distributions and electric and magnetic field configuration. Because MHD simulations do not account for thermal drifts where spatial gradients are strong, a merger of an MSFM-like code and a global magnetospheric MHD code may represent an important step toward developing a physics-based predictive magnetospheric model. Approaches that utilize adaptive grids show new promise to resolve features over many scale lengths. A desired byproduct of the magnetospheric model is the specification of currents throughout the magnetosphere and ionosphere system. From this information, other codes can be developed that predict geomagnetically induced currents and the magnetic disturbance indexes derived from them. The MSM and MHD models do not specify the energetic particle populations in the radiation belts. Static models for the radiation belts already exist, but there is an urgent need to develop dynamic models to account for the variations in energetic particle fluxes that are observed during storm conditions.

Approaches to modeling the ionosphere include empirical models based on worldwide data sets, assimilative models that incorporate real-time observations, and 3D time-dependent physical models. The Parameterized Real-time Ionospheric Specification Model (PRISM) is an operational system being used at the 55th Space Weather Squadron to ingest real-time ionospheric data from ground- and space-based sensors and produce electron density profiles. To achieve predictive capabilities, it is important to focus future work on dealing with large-scale and medium-scale structures in a self-consistent manner, and to incorporate the effects of storms and substorms. This may require the development of nested-grid and adaptive-grid models. More realistic boundary conditions must be applied with the eventual goal of developing a fully coupled model that encompasses the mesosphere, thermosphere, and ionosphere using computationally fast, empirical-numerical hybrid models. As with magnetospheric models, the E-field configuration is an important element in accurate predictions of ionospheric behavior. The E-field can be specified, analytically, semi-analytically, or empirically, but in all cases is driven by interplanetary parameters and magnetospheric processes. These models must be able to account for the penetration of high-latitude E-fields to low latitudes, and the coupling to neutral atmosphere winds. Ionospheric structures, such as sporadic E, descending layers, equatorial plasma bubbles, auroral blobs, and polar cap patches, must be accounted for in specifying the state of the ionosphere. From the standpoint of satellite-based communication and navigation systems, it is most important to also include the effects of small-scale irregularities associated with these structures that cause ionospheric scintillations. To be operationally useful, the currently available climatological model that specifies scintillation for any radiowave propagation path at any frequency needs to be driven by real-time data from a network of stations. The ultimate goal is to develop a physics-based model incorporating the processes that lead to structuring at all scale sizes.

Neutral atmosphere modeling efforts focus on numerical Thermosphere-Ionosphere-Electrodynamics General Circulation Models (TIEGCMs) that can self-consistently calculate density perturbations and neutral wind systems on a global, 3D, time-dependent basis from physical principles. These models must continue to be upgraded, validated, and tested. Empirical, semi-empirical, and assimilative models of the neutral atmosphere are also important to specify the starting point for physics-based models.

3.2.2 Advances and Work in Progress

Many research models are being developed under the basic research awards funded in response to the NSWP project solicitation. The bulk of the development of these models, however, is being performed through on-going projects funded by NSF, NASA, the DOD, and NOAA.

The following tables catalog current research models, breaking them out into solar and solar wind models, magnetospheric models, and ionospheric models. However, these divisions are not strict and a number of the models have applications in more than one category.

The first column in each table lists an identification number for the particular model for use in the timeline charts presented in Chapter 4. The second column list the model's name and any acronym associated with it while the third column lists the developers and or the points of contact for each model. Electronic mail addresses and World Wide Web Universal Resource Locator (URL) information are provided where available. The fourth column provides a brief description of the type and purpose of the model. The fifth column provides a mostly objective status of the model based on the inputs to the Committee for Space Weather during the development of this plan. The legend for this column is:

- M - Mature model
- D - In Development
- UD - Useable but under development
- MD - Mature, but undergoing improvements

A "mature" model is one that is essentially complete and is not undergoing continued refinement. Useable models provide outputs that can be used by the general scientific community. Models that are neither "mature" nor "useable" are still in a development stage and should only be used with the assistance of the primary investigator. Finally, the last column lists the funding agencies for each model from among the federal agencies participating in the NSWP.

Table 3-1. Solar and Solar Wind Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
S1	SOLAR2000	W. Kent Tobiska kent.tobiska@jpl.nasa.gov	Solar irradiance from x-ray to visible wavelengths.	UD	NASA, NSF, NOAA
S2	Evolving PFSS Coronal Model	Janet Luhmann jgluhman@ssl.berkeley.edu	Coronal magnetic field structure derived from observed photospheric field.	UD	NSF, NASA, DOD
S3	3D MHD Model of the Corona and Solar Wind	Jon Linker and Zoran Mikic linker@iris023.saic.com	3D MHD simulation of the corona and solar wind using observed photospheric magnetic fields as boundary condition.	UD	
S4	Solar Active Region Evolution and Stability	Stephen Keil skeil@sunspot.noao.edu	3-D MHD simulation of solar active region evolution.	D	
S5	Magnetic Breakout of the Sun's Atmosphere (MagBrst)	Spiro Antiochos spiro@zeus.nrl.navy.mil	Ejection of solar flux.	UD	DOD
S6	Wang and Sheeley Expansion Factor Model (WS Model)	Yi-Ming Wang ywang@yucca.nrl.navy.mil	Predicting solar wind speed at Earth from magnetic file observations of the photosphere.	M	
S7	3D Interplanetary Propagation Model (3D IPP)	Victor Pizzo vpizzo@sec.noaa.gov	MHD simulation of global, time-dependent solar wind flow.	UD	NOAA
S8	Shock Time of Arrival/Shock Propagation Model (STOA/ISPM)	Murray Dryer murraydryer@msn.com	Empirical and 2-D MHD interplanetary shock wave.	UD	NOAA

M = Mature D = In development UD = Useable but under development MD = Mature but undergoing improvements

Table 3-1 (continued). Solar and Solar Wind Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
S9	3D MHD/Kinematic Time-Dependent Shock Propagation-Solar Wind Hybrid Model (HSEM)	Murray Dryer murraydryer@msn.com	Kinematic and 3D MHD code which extrapolates solar magnetic field and wind speed from source surface.	D	NOAA
S10	Global Bimodal Corona and Solar Wind Model (GBMCSW)	Shi Tsan Wu wus@cspar.uah.edu	Quasi-steady state 2D MHD model of helmet-streamers and coronal hole.	UD	NSF and NASA
S11	Streamer and Flux-Rope Interaction Model (SFRI)	Shi Tsan Wu wus@cspar.uah.edu	2D MHD model of helmet streamers and flux ropes.	UD	NSF and NASA
S12	Interplanetary Global Model for Simulating the Evolution of Dynamic and Magnetic Disturbances in the Solar Wind	Marek Vandas vandas@ig.cas.cz	2.5D and 3D MHD simulation of solar wind structures from the Sun to 1 A.U.	D	
S13	3D MHD model for Interplanetary Shock, Stream/Stream and CME propagation through the Solar Wind (Han-Detman 3D Code) also known as the Interplanetary Global Model Vectorized (IGMV)	Tom Detman tdetman@sec.noaa.gov tdet@noaasel.sel.bldrdoc.gov	3D, time-dependent MHD simulation of solar wind beyond 18 solar radii.	MD	NOAA
S14	Bats R Us	Tamas Gambosi tamas@umich.edu	3D MHD Simulation.	UD	NASA, NSF

M = Mature D = In development UD = Useable but under development MD = Mature but undergoing improvements

Table 3-1 (continued). Solar and Solar Wind Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
S15	Filament and Coronal Chirality Model	Sara Martin sara@helioresearch.org	Statistical Event Predictor based on pattern recognition.	UD	NOAA
S16	Halo Coronal Mass Ejection Model	David Webb webb@phl.af.mil Chris St. Cyr cst@sclc.nascom.nasa.gov	Statistical Event Predictor based on pattern recognition.	UD	NASA, USAF
S17	Coronal Emissions Patterns (Sigmoids) Model	Richard Canfield canfield@helicity.physics.montana.edu	Statistical Event Predictor based on pattern recognition.	UD	NASA
S18	Solar Wind	Syun-Ichi Akasofu sakasofu@dino.gi.alaska.edu	Simulation of solar wind based on solar conditions.		
S19	Solar Wind	Arcadi Usmanov usmanov@snoopy.niif.spb.su	Simulation of solar wind based on solar conditions.		
S20	Solar Wind	Y. Q. Hu	Simulation of solar wind based on solar conditions.		
S21	Magnetic Flux Rope Model	Peter Cargill p.cargill@ic.ac.uk	MHD simulation of solar wind.		

M = Mature D = In development UD = Useable but under development MD = Mature but undergoing improvements

Table 3-2. Magnetospheric Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
M1	Shue, et al. Model of Magnetopause size and shape	J.-H. Shue and J. K. Chao	Empirical model of magnetopause size and shape.	M	
M2	Petrinec and Russell [1995] Magnetopause size and shape	S. Petrinec	Empirical model of magnetopause size and shape.	M	NASA
M3	Roelof and Sibeck model of Magnetopause size and shape	E. Roelof Ed.Roelof@jhuapl.edu D. Sibeck David.Sibeck@jhuapl.edu	Empirical model of magnetopause size and shape.	M	NASA
M4	Magnetopause location	J. K. Chao T272362@twncu865.ncu.edu.tw	Prediction of location of magnetopause given IMF and solar wind dynamic pressure.	D	
M5	Tsyganenko Magnetic field model [T96_01]	N. Tsyganenko kolya@ndadsb-f.gsfc.nasa.gov	Empirical magnetic field model based on IMF, solar wind dynamic pressure, Dst index, and dipole tilt angle.	MD	NASA, NSF
M6	Ogino/Walker Global MHD and large-scale kinetic model of solar wind particle entry into the magnetosphere	R. Walker rwalker@igpp.ucla.edu	Global MHD simulation with additional kinetic calculation of particle entry at the magnetopause.	MD	NASA
M7	Equilibrium Tail Model	J. Birn	Self-consistent model of magnetic field and isotropic pressure for the tail (beyond 10 Re). Available in 2-D and 3-D versions.	UD	DOE

M = Mature D = In development UD = Useable but under development MD = Mature but undergoing improvements

Table 3-2 (continued). Magnetospheric Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
M8	Time Dependent MHD code	J. Birn	Time-dependent resistive MHD code.	UD	DOE
M9	3-D Electromagnetic Particle Model (EMPM)	K.-I. Nishikawa kenichi@rouge.phys.lsu.edu	Global electromagnetic particle simulation of magnetosphere.	D	NSF
M10	Rice Field Model (RFM) also known as the Toffoletto-Hill [1993] model (TH93)	F. Toffoletto toffo@alfven.rice.edu T. Hill hill@alfven.rice.edu URL http://rigel.rice.edu/~ding/rfm.html	Theory based model of magnetospheric magnetic and electric fields.	UD	NSF, NASA
M11	Rice Convection Model (RCM)	R. Wolf wolf@alfven.rice.edu	Inner-magnetosphere model.	UD	NSF, NASA
M12	Magnetospheric Specification Model	R. Wolf wolf@alfven.rice.edu	An operational version of RCM.	M	DOD
M13	Fully-adiabatic response model for relativistic electrons	A. Chan aac@landau.rice.edu	Physics-based radiation belt flux mapping model.	UD	NSF, DOD
M14	Substorm electron injection model	A. Chan aac@landau.rice.edu	Hybrid test particle calculation of energetic electrons using the Birn and Hesse MHD model.	UD	NSF, DOE
M15	Hydromagnetic wave-particle interaction model	A. Chan aac@landau.rice.edu	Gyrocenter test particle calculation of wave-particle interactions in inner magnetosphere.	UD	NSF

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Table 3-2 (continued). Magnetospheric Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
M16	Linear Prediction Filter (LPF) model of relativistic electron flux at geostationary orbit	Dan Baker baker@lynx.colorado.edu	Prediction of "killer electrons" at geostationary orbit given solar wind speed at 1 AU.	M	NASA, DOE
M17	UCLA Global Geospace Circulation Model (UCLA-GGCM)	J. Raeder jraeder@pallas.igpp.ucla.edu URL http://www-ggcm.igpp.ucla.edu/gem-ggcm-phase1	Global MHD simulation of magnetosphere using solar wind speed and density, IMF and F10.7 flux data as inputs.	UD	NSF, NASA
M18	Ogino S-M Coupling model	T. Ogino ogino@stnet1.stelab.nagoya-u.ac.jp	Global MHD simulation of magnetosphere.	UD	
M19	Dartmouth-NRL-UMD MHD model	J. Lyon, J. Fedder	Global MHD simulation of magnetosphere using solar wind speed and density, IMF as inputs.	UD	NSF, DOD
M20	BATS-R-US magnetospheric simulation model	T. Gombosi	Global MHD simulation of magnetosphere using solar wind speed, density and IMF as inputs.	UD	NSF, NASA
M21	Integrated Space Weather Prediction Model (ISM)	Bill White bwhite@mrcnh.com	Integrated 2-fluid MHD model of magnetosphere with coupling to physics based ionosphere/thermosphere model.	UD	DOD

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Table 3-3. Ionospheric Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
I1	Polar Cap Potential Drop Model [1981]	P. H. Reiff	Empirical model of potential drop across the polar cap based on solar wind velocity and IMF.	M	
I2	Heppner-Maynard-Rich convection model	F. Rich rich@plh.af.mil	Empirical model of ionospheric convection based on IMF.	M	
I3	Izmiran Electrodynamic Model (IZMEM)	V. Papitashvili papita@pitts.sprl.umich.edu	Empirical model of ionospheric convection based on IMF and solar wind speed and density.	MD	
I4	IZMEM/DMSP	V. Papitashvili papita@pitts.sprl.umich.edu F. Rich rich@plh.af.mil	Empirical model of ionospheric convection based on IMF and solar wind speed and density.	D	DOD, NSF
I5	Weimer Electric Potential Model (W96)	D. Weimer dweimer@mrcnh.com	Empirical model of ionospheric convection based on IMF.	MD	NSF
I6	Space Weather Ionospheric Forecast Technologies (SWIFT)	N. Maynard nmaynard@mrcnh.com	Empirical prediction of ionospheric potential patterns, currents and Joule heating driven by L1 solar wind data.	D	NSF, NOAA
I7	APL ionospheric convection model	J. M. Ruohoniemi Mike.Ruohoniemi@jhuapl.edu	Empirical model of ionospheric convection based on IMF.	UD	NSF
I8	Kamide-Richmond-Matsushita (KRM) model	Y. Kamide kamide@stnet1.stelab.nagoya-u.ac.jp	Derivations of ionospheric convection and currents from magnetometer data and conductivity model.	M	
I9	Assimilative Mapping of Ionospheric Electrodynamics (AMIE)	A. Richmond	Derivation of ionospheric convection and currents based on a conductivity model and inputs from magnetic and electric field measurements.	MD	NOAA, NSF

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Table 3-3 (continued). Ionospheric Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
I10	APL Spherical Harmonic Expansion of Polar Cap Potential	J. M. Ruohoniemi Mike.Ruohoneimi@jhuapl.edu K. Baker Kile.Baker@jhuapl.edu	Global Polar Cap potential and ionospheric conductivity derived from radar electric field measurements.	UD	NSF, NASA
I11	Weimer field-aligned current model	D. Weimer dweimer@mrcnh.com	Empirical model of field-aligned currents.	D	NSF
I12	Millstone Hill Electric Field Model	J. Foster jcf@haystack.mit.edu	Empirical electric field model derived from incoherent scatter radar measurements.	MD	NSF
I13	Fejer-Scherliess storm-time zonal electric field model	B. Fejer bfejer@cc.usus.edu	Empirical low-latitude electric field model.	UD	NSF
I14	Scherliess-Fejer quiet-time equatorial vertical drift model	B. Fejer bfejer@cc.usus.edu	Empirical equatorial model of vertical plasma drifts.	UD	NSF, NASA
I15	International Reference Ionosphere [1995] (IRI 95)	D. Bilitza bilitza@nssdc.gsfc.nasa.gov	Empirical model of ionospheric electron density, electron temperature, ion temperature, ion composition.	M	
I16	Mass spectrometer Incoherent Scatter Radar Model of Thermosphere (MSIS)		Empirical model of thermospheric temperature, composition and mass density as function of time, F10.7 flux and magnetic activity.	M	
I17	TIME-GCM Thermosphere-ionosphere-mesosphere electrodynamic general circulation model	R. Roble	Physics-based simulation of the thermosphere, ionosphere and mesosphere.	UD	NSF, DOC

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Table 3-3 (continued). Ionospheric Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
I18	Three-Dimensional Ionospheric Model (TDIM)	Bob Schunk and J. Sojka	Physics-based simulation of the ionosphere using MHD magnetosphere model as input.	UD	NSF
I19	Thermosphere-Ionosphere Nested Grid Model (TING)	T. Killeen	Physics-based but semi-empirical model of coupled thermosphere ionosphere at high latitudes.	UD	
I20	Coupled Thermosphere Ionosphere (CTIM), Coupled Thermosphere, Ionosphere, Plasmasphere (CTIP) and Coupled Thermosphere, Ionosphere, Plasmasphere with self-consistent Electrodynamics (CTIPE)	T. Fuller-Rowell tjfr@sec.noaa.gov	A hierarchy of global, physics based models of the thermosphere, ionosphere and plasmasphere.	MD	NSF, NASA, DOD
I21	Sheffield University Plasmasphere-Ionosphere Model (SUPIM)	G. Bailey	Physics-based.	M	
I22	Field Line Interhemispheric Plasma Model (FLIP)	P. Richards	Physics-based, 1-D, time-dependent model of ionospheric and plasma sphere.	M	
I23	Ionospheric Irregularity Model	J. Sojka	Physics-based model of ionospheric plasma density irregularities. Driven by the TDIM ionospheric model.	D	NSF, DOD

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Table 3-3 (continued). Ionospheric Research Models

ID	Model Name/Acronym	Contact information	Type and Purpose	Status	Funding Source(s)
I24	Coupled Ionospheric Scintillation Model (CISM)	S. Basu	Physics-based model of equatorial scintillation.	D	DOD
I25	Wideband Scintillation Model (WBMOD)	A. J. Coster and S. Basu	Climatological model of ionospheric scintillation.	UD	DOD
I26	Hardy, et al. model of ionospheric conductivity	D. A. Hardy	Statistical model of auroral particle precipitation and conductivity	M	DOD
I27	Wallis and Budzinski model of height integrated conductivities	D. D. Wallis	Empirical model of height integrated conductivities in the ionosphere.	M	
I28	Spiro, Reiff and Maher model of auroral conductances	R. W. Spiro	Empirical model of precipitating electron energy flux and auroral conductances.	M	
I29	Fuller-Rowell and Evans model of height-integrated Pedersen and Hall conductivity patterns	T. Fuller-Rowell or D. S. Evans devans@sec.noaa.gov	Empirical model of ionospheric conductances derived from TIROS-NOAA particle precipitation data.	M	NOAA
I30	Precipitating Electron Model of ionospheric conductances (PEM)	H. Kroehl	Statistical model of particle precipitation and ionospheric conductances.	U	NOAA
I31	Ahn, et al. model of ionospheric conductances	B.-H. Ahn	Empirical model of ionospheric conductances based on ground magnetic disturbance data.	UD	NOAA

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3.3 Research Observations

3.3.1 Background

Observations in support of the NSWP include both operational and research-oriented data. Ground-based operational sensors include magnetometers and ionosondes, and sensors for ground-based solar observations at both radiowave and optical wavelengths. Enhancements in ground-based operational sensors include extending the current networks, adding scintillation monitoring systems, upgrading solar observations, and adding a network of solar coronagraphs and interplanetary scintillation monitors. Ground-based sensors for research purposes include the array of high frequency (HF) and incoherent scatter radars, riometers, and optical instrumentation. Future enhancements include the Relocatable Atmospheric Observatory (RAO) designed to fill gaps in the existing chain of incoherent scatter radars.

Space-based sensors for the NSWP must be deployed in many different orbital configurations. Low-Earth orbiting satellites, such as those of the Defense Meteorological Satellite Program (DMSP) and the future National Polar-orbiting Operational Environmental Satellite System (NPOESS), are measuring properties of the ionosphere and thermosphere, as well as the plasma processes at low altitudes along auroral field lines. Highly elliptic, polar-orbiting spacecraft are needed to study ionosphere-magnetosphere coupling. Ideally, they should also carry optical and x-ray imagers for determining the instantaneous distribution of auroral precipitation. Sensors on geosynchronous satellites must continue to monitor the energetic particle populations in the magnetosphere and the solar x-ray emission. The particle monitors on the Global Positioning System (GPS) satellites can also be used to specify radiation belt flux levels. Extremely critical to the success of the NSWP is a satellite at the L1 point between the Earth and Sun to monitor the solar wind. This requirement is being filled currently by the Advanced Composition Explorer (ACE) satellite. Plans are in development to supplement or replace ACE with GEOSTORM, ideally incorporating solar imaging capability in addition to the plasma monitors. The satellites described here will all provide operational data for space weather forecasters. Also important to meeting NSWP objectives is the existing and planned satellites that are part of the Department of Defense and National Aeronautics and Space Administration space missions.

One concern is that many of the existing research satellites are approaching the end of their funded mission lifetimes, and they will effectively be turned off just as we are starting solar maximum. These satellites could provide invaluable research data for understanding the basic science of the Sun, and they could also provide critical operational observations such as solar wind speed, interplanetary magnetic field orientation, etc. It is especially important to continue research observations until they are replaced by operational sensors.

3.3.2 Space-Based Research Observing Systems

The NSWP Implementation Plan timelines included a set of observations expected to be available for space weather research activities. These are distinguished from observations used for operational purposes described in Section 2.2.1. However, many observations are used for both research and operations. This section describes observing systems whose primary mission is research.

3.3.2.1 ACE

The Advanced Composition Explorer (ACE) was launched in August 1997 and was placed in a halo orbit about the sunward Lagrangian point in December 1997. The prime objective of this mission is to determine and compare the elemental and isotopic composition of several distinct samples of matter: the solar wind and energetic solar particles, the local interstellar medium, and matter from nearby regions in the galaxy. The spacecraft also transmits data concerning the solar wind and solar energetic particles that are made available on the World Wide Web by NOAA within about five minutes of real time, thus serving as a monitor of solar weather which can produce geomagnetic storms and other effects upon the Earth. More highly processed data is also distributed on the World Wide Web with a delay of several days.

3.3.2.2 ARGOS

In December 1998 the Air Force Space Test Program (STP) launched the Advanced Research and Global Observation Satellite (ARGOS). This 6000 pound satellite was launched aboard a Delta II rocket into a 0230/1430 sun-synchronous polar orbit at 850 km. ARGOS contains nine separate experiments developed by the Navy, Air Force and Army to test a number of new space technologies and to make measurements of the space environment. Five of the nine experiments are designed for remote sensing of space weather and include:

- High Resolution Airglow/Aurora Spectroscopy (HIRAAS) experiment;
- Global Imaging Monitor of the Ionosphere (GIMI);
- Unconventional Stellar Aspect (USA);
- Coherent Electromagnetic Radio Tomography (CERTO); and the
- Extreme Ultraviolet Imaging Photometer (EUVIP).

These five experiments consist of eight separate instruments including ultraviolet imagers, and limb-scanning spectrographs, an x-ray detector and radio beacon to measure the composition, density, temperature and dynamics of the thermosphere and ionosphere. The HIRAAS experiment contains three limb scanning spectrographs covering the wavelength range from 50 nm to 340 nm at resolutions varying from 0.05 nm to 1.7 nm. The GIMI experiment consists of two ultraviolet cameras with 10-degree square fields of view and 3 arcmin resolution. The two cameras are mounted to gimbals on two axes and are designed to image the dayside and nightside ionosphere. The USA experiment is a large x-ray detector mounted to a two-axis gimbal and is capable of measuring neutral density profiles from the occultation of x-ray sources. CERTO consists of a two-frequency UHF radio beacon and will provide tomographic images of the ionosphere to ground receivers. The EUVIP experiment contains an ultraviolet imager with a 5-degree field of view and three separate filters to image the ionosphere and magnetosphere.

3.3.2.3 Arizona Airglow Instrument (GLO)

The GLO Instrument has been flown on multiple space shuttle missions to observe the Earth's auroral and airglow emissions both in daylight and at night. Star tracking capability has been added to the most recent GLO experiments. This allows absolute absorption measurements on the topside of the neutral atmosphere by tracking stars into the limb. Stars are used as calibration sources. Limb tracking removes pointing variations caused by the limit cycle of the shuttle as data are being recorded.

GLO has a set of imaging spectrographs that simultaneously observe a wavelength range from 115 nm to 900 nm with a resolution of ~0.5nm in the UV and visible regions of the spectrum, and with a resolution of ~1 nm in the near IR. The GLO spectrographs consist of five modules, each with its own CCD detector. One spectrograph is unintensified and has been found to be too insensitive to be useful for airglow observations. The CCD detectors in the other spectrographs are coupled to image intensifier tubes and have two gratings each, so that two spectra are imaged on each detector. The instrument is also equipped with a set of 13 imagers: a support imager that observes in the red to near IR and 12 that are intensified and fitted with band-pass filters. The purpose of the support imager is to provide a pointing reference for the spectrographs, which are co-aligned with the center pixel of this imager. The field of view of each of the co-aligned spectrographs is 0.2° X 8°, while the field of view of each of the monochromatic imagers is 15° X 17°. The support IR imager has a field of view of about 3° X 5°.

3.3.2.4 ASTRID-2

ASTRID-2 is an advanced auroral microprobe with the primary objectives of making high-quality in situ measurements of the physical processes behind the aurora, and to demonstrate the usefulness of microspacecraft as advanced research tools. Instruments for measuring such space weather parameters as local electric and magnetic fields, plasma density and density fluctuations, energetic ions and electrons, as well as remote imaging of auroral emissions will be on board. ASTRID-2 should also be able to demonstrate the feasibility of making inexpensive multi-point auroral in situ measurements. It was launched in 1998, piggybacked on a Kosmos-3M launcher from Plesetsk, Russia.

3.3.2.5 CNOFS

Communications Navigation Outage Forecasting System (CNOFS) is a planned Air Force satellite in a 700-km low inclination equatorial orbit for specifying and forecasting equatorial scintillations that cause outages in communication and navigation systems. Another objective is to understand the fundamental physics governing space weather at low latitudes. For this, the satellite will carry a wide range of sensors that will include an UV photometer, ion density, ion drift, electric field and neutral wind probes as well as a GPS occultation sensor and a multi-frequency beacon. The CNOFS data stream will be ingested into a Coupled Ionosphere Scintillation Model (CISM), which is expected to provide nowcast and 6-hour forecast of the background equatorial ionosphere and the onset and magnitude of scintillations.

3.3.2.6 COSMIC

The National Space Program Office (NSPO) of Taiwan is planning, in cooperation with the University Corporation for Atmospheric Research (UCAR), to build and fly a constellation of eight microsatellites in low Earth orbit to measure profiles of ionospheric electron density and tropospheric density/temperature/water vapor using on-board GPS receivers during GPS occultations. This program is based on the GPS/MET receiver which flew on the Micro-Lab 1 satellite in 1995. The NSPO satellites, called the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), will include a GPS occultation receiver, a UHF radio beacon (for computer ionospheric tomography), and a nadir viewing ultraviolet photometer. All eight satellites will be launched on a single vehicle and maneuvered into separate orbits spanning a variety of local times, latitudes and longitudes at any given moment. Electron density limb profiles are derived from the refraction of the navigation signal from a GPS satellite in higher orbit. The beacon and photometer are used to determine the horizontal gradients in electron density.

3.3.2.7 FAST

The FAST satellite mission (1996) investigates plasma processes occurring in the low altitude auroral acceleration region where magnetic field-aligned currents couple global magnetospheric current systems to the high latitude ionosphere. In the transition region between the hot tenuous magnetospheric plasma and the cold, dense ionosphere, these currents give rise to parallel electric fields, particle beams, plasma heating, and a host of wave-particle interactions. In concert with the ISTP/GGS spacecraft, WIND, POLAR and GEOTAIL, FAST will provide several measurements which are essential to our understanding of “Sun-Earth Connections,” including energy input measurements to the upper atmosphere, which are highly desirable for the upcoming TIMED mission, as well as information relevant to the nation’s space weather program.

3.3.2.8 GPS Particle Detectors

At present, six of the GPS satellites have detectors that measure fluxes of electrons above 100 keV and solar protons with coarse energy resolution and no angular resolution. These data are used primarily to monitor the health and status of the satellite, but are also used for scientific research. Replacement for the current fleet of satellites will begin in 2001 with the Block 2F series, all of which will have particle detectors. These data may be available in near real time provided a sufficient number of ground stations is available. When every GPS satellite eventually carries a particle detector, global, instantaneous snap shots of radiation belt particle fluxes will be possible.

3.3.2.9 HESSI

The primary scientific objective of the High Energy Solar Spectroscopic Imager (HESSI) Small Explorer mission is to understand particle acceleration and explosive energy release in solar flares. The hard x-ray/gamma-ray continuum and gamma-ray lines are the most direct signatures of energetic electrons and ions, respectively, at the Sun.

HESSI will provide imaging spectroscopy of the hard x-ray continuum and high-resolution spectroscopy of gamma-ray lines in solar flares. HESSI utilized a single instrument which combines an imaging system consisting of rotating modulation collimators (RMCs) with high-spectral resolution, cryogenically cooled germanium detectors covering from soft x-rays (3 keV) to high energy gamma-rays (20 MeV). HESSI is planned for launch in November 2000.

3.3.2.10 IMAGE

IMAGE is a MIDEX class mission, selected by NASA in 1996, to study the global response of the Earth's magnetosphere to changes in the solar wind. IMAGE will use neutral atom, ultraviolet, and radio imaging techniques to: 1) identify the dominant mechanisms for injecting plasma into the magnetosphere on substorm and magnetic storm time scales; 2) determine the directly driven response of the magnetosphere to solar wind changes; and, 3) discover how and where magnetospheric plasmas are energized, transported, and subsequently lost during substorms and magnetic storms. The spacecraft was launched in March 2000. Real-time data transmission through NOAA and the Air Force has been arranged.

3.3.2.11 International Solar Terrestrial Physics (ISTP)

The full observational assets of ISTP have been operational now for several years. The strategic locations of the ISTP/GGS spacecraft, WIND, POLAR, Geotail, and SOHO allow fundamental measurements to be obtained on the flow of energy, mass and momentum from the Sun, through the heliosphere, into the magnetosphere, with eventual dissipation in the Earth’s atmosphere. The extended mission plan is to quantitatively analyze the fundamental global characteristics of the Solar-Terrestrial system before and during solar maximum to complement the seminal achievements by ISTP near solar minimum. The planned scenario for the WIND trajectory through early CY2002 consists of four distinct phases: L1 halo, lunar swing-bys, high inclination petal orbits, Earth return trajectory.

> *WIND*. The goals of WIND are to determine the characteristics of the solar wind upstream of the Earth and to investigate basic plasma processes occurring in the near-Earth solar wind. During the first two years of operation WIND was positioned in a highly elliptical orbit utilizing multiple double-lunar swing-by's to remain mainly sunward of Earth with a maximum apogee of 250Re. This was followed by a halo orbit at the L1 point along the Earth-Sun line. Real-time solar wind data were distributed via NOAA to the World Wide Web preceding ACE launch for the few hours of WIND data reception.
>
> *POLAR*. The goals of the POLAR mission are to measure the entry of plasma into the polar magnetosphere; to determine the ionospheric plasma outflow; to obtain auroral images and to thereby determine the energy deposited into the ionosphere and upper atmosphere. POLAR has an elliptical 2 x 9 Re polar orbit with a period of approximately 18 hours.

Geotail. The goal of Geotail (led by ISAS) is to measure global energy flow and transformation in the magnetotail to increase our understanding of fundamental magnetospheric processes. The mission, which carries fields and particle instrumentation, has two phases. During the initial phase, the spacecraft spent most of its time in the distant magnetotail (maximum apogee about 200 Earth radii) while during the second phase apogee was reduced to 30 Earth radii.

Solar and Heliospheric Observatory (SOHO). As part of the ISTP program, the goal of SOHO is to study the internal structure of the Sun, its outer atmosphere and the origin of the solar wind. The spacecraft carries instruments devoted to helioseismology, remote sensing of the solar atmosphere and in situ measurement of solar wind disturbances one hour before they strike Earth. SOHO is permanently positioned at the L1 point where it enjoys uninterrupted viewing of the Sun (cooperative with ESA).

3.3.2.12 Interplanetary CME Imager

The Solar Mass Ejection Imager (SMEI) experiment is designed to detect and measure transient plasma features in the heliosphere, including coronal mass ejections (CMEs), shock waves, and structures such as solar wind streamers which co-rotate with the Sun. SMEI will be flown on the CORIOLIS satellite as part of the Air Force's Space Test Program, with a planned launch in December 2001.

SMEI consists of three cameras, each imaging a 60 x 3 degree field of view, for a total image size of 180 x 3 deg. As the satellite orbits the Earth, subsequent images are used to build up a view of the entire heliosphere. SMEI will provide measurements of the propagation of solar plasma clouds and high-speed streams, data to forecast their arrival at the Earth from one to three days in advance, and the baseline parameters for space weather environmental forecasting.

Characterization of size, mass, and frequency will serve as input to models describing solar activity events, flux shedding by the Sun, and generation of the solar wind. SMEI data will provide the physics of CME propagation, interaction of CMEs with solar wind streams (acceleration and deceleration mechanisms), compression of the Interplanetary Magnetic Field, and interplanetary shock formation. SMEI will also provide data on solar wind streams and other co-rotating structures.

The measurements made by SMEI will be highly complementary to NASA's Global Geospace Science program (GGS) of the International Solar-Terrestrial Physics Science Initiative (ISTP), as well as the National Space Weather Program. SMEI measurements, when coordinated with the imaging and in-situ experiments on the YOHKOH, SOHO, TRACE, ACE, and Ulysses missions, will greatly enhance the productivity of the GGS mission.

3.3.2.13 Interplanetary Monitoring Platform 8 (IMP-8)

Interplanetary Monitoring Platform (IMP) 8 is a 1973-launched spacecraft with a suite of detectors which continue to measure *in situ* magnetic fields, plasmas, and energetic particle populations. It is in a nearly circular 225,000-km (35 R_e), 12-day geocentric orbit. IMP 8 is a source of uniquely situated data for use in correlation with data from other magnetospheric missions (most notably ISTP) and deep-space missions (Voyager, Ulysses) and of a single uniquely long data set for long-term variation studies.

3.3.2.14 Living with a Star (LWS)

NASA's new Living with a Star Program (LWS) seeks to advance understanding of solar variability and its effect on life and society. A more detailed description of the program is presented in Appendix B. LWS consists of an observational portion, based on dedicated missions, and a supporting theory and modeling program. The observational portion of LWS is divided into a Solar Dynamics Network and a Geospace Network. The Solar Network is composed of the Solar Dynamics Observatory and Solar Sentinels. The Geospace Network is made up of Radiation Belt Mappers and Ionospheric Mappers. The networks are designed to complement the currently planned suite of spacecraft developed as part of NASA's Solar Terrestrial Probe line. The LWS networks are planned for launches beginning in 2007. Maximum overlap between LWS missions and Solar Probe missions is desired to take advantage of the simultaneous observations available from the multiple spacecraft.

3.3.2.15 MSX

The MSX satellite was launched on April 24, 1996. Its primary mission is to gather information that will aid in the design of missile defense systems. The satellite has several optical instruments acquiring excellent observations to support basic research in atmospheric airglow and aeronomy. The mission duration is four years. All instruments are operating nominally.

3.3.2.16 ØRSTED

The main purpose of the ØRSTED satellite is to provide a precise global mapping of the Earth's magnetic field. Provisionally, collection of data is planned for a period of 14 months. The measurements shall be used to improve the existing models of the Earth's magnetic field and to determine the changes of the field. The variations both of the strong field from inside the Earth and of the weaker, rapidly varying, field resulting from the interaction between the ion/particle streams from the Sun (the solar wind) and the Earth's magnetosphere are included in the studies. Furthermore, the transfer of energy from the solar wind to the magnetosphere and further down to the lower layers of the atmosphere will be studied. All of these studies will benefit not only from the magnetic field measurements but also from the measurements of the flow of energetic particles around the satellite. ØRSTED was launched in December 1998 together with the ARGOS satellite.

3.3.2.17 SAMPEX

The Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) mission studies solar, heliospheric, and magnetospheric energetic particles observed from a nearly polar, low Earth orbit. SAMPEX was launched in July 1992. Objectives are to: 1) determine the global flux levels of the magnetosphere in response to interplanetary inputs, and assess the influence of magnetospheric precipitating electrons on upper atmospheric chemistry, 2) characterize the magnetospheric radiation levels relevant to space weather issues including satellite performance and anomalies, 3) determine the ionization states of solar energetic particles over a broad energy range, and 4) determine the fluxes of trapped interstellar material (anomalous cosmic rays) and their solar cycle dependence.

3.3.2.18 Solar Probe

Solar Probe, which will make the very first measurements within the atmosphere of a star, will provide unambiguous answers to long-standing fundamental questions about how the corona is heated and how the solar wind is accelerated. The spacecraft, which will provide both imaging and in situ measurements, is targeted to pass within 3 solar radii of the Sun's surface.

3.3.2.19 Solar Terrestrial Probes (STP)

The STP program is a series of missions specifically designed to perform a systematic study of the Sun-Earth system. Its major goals are: 1) providing an understanding of solar variability on time scales which range from a fraction of a second to many centuries, and 2) determining planetary and heliospheric responses to this variability. The line began with TIMED and is expected to continue in the near-term with Solar-B, STEREO, Magnetospheric Multiscale, Global Electrodynamic Connections, and Magnetospheric Constellation. The new NASA initiative "Living with a Star" seeks to speed up the development and deployment of these systems. See Appendix B and Section 3.3.2.14 for more information on the initiative.

> *TIMED*. The Thermosphere, Ionosphere, and Mesosphere Energetics and Dynamics (TIMED) mission will investigate the basic energetics and dynamics of the region where the sensible atmosphere transitions to space. Major mission objectives are: 1) to determine the Mesosphere Lower Thermosphere/Ionosphere (MLTI—60 to 180 km altitude) structure, including variations with local time, latitude, and season, and 2) to understand the MLTI balance between diverse sinks and sources of energy. Instruments are to measure density, temperature, and wind fields at a spatial resolution of 10° x 10°, and an altitude resolution of 5 km. Launch is scheduled for October 2000.
>
> *Solar-B*. The goal of Solar-B (led by ISAS) is to reveal the mechanisms which give rise to solar variability and study the origins of space weather and global change. The spacecraft, which will be placed in polar Earth orbit, will make coordinated measurements at optical, EUV, and x-ray wavelengths and will provide the first measurements of the full solar vector magnetic field on small scales.
>
> *Solar Terrestrial Relations Observatory (STEREO)*. The goal of STEREO, which is one of the near-term Solar-Terrestrial Probes, is to understand the origin of coronal mass ejections and their consequences for Earth. The mission will consist of two spacecraft, one leading and the other lagging Earth in its orbit. The spacecraft will each carry instrumentation for solar imaging and for in situ sampling of the solar wind.

Magnetospheric Multiscale. The goal of Magnetospheric Multiscale, which is one of the near-term Solar-Terrestrial Probes, is to characterize the basic plasma processes which control the structure and dynamics of the Earth's magnetosphere, with a special emphasis on meso- and micro-scale processes. The mission will consist of six spacecraft, four identical platforms, which will fly in formation in order to determine the three dimensional structure of plasma boundaries, and two smaller satellites which will provide images of the context in which the in situ measurements are made.

Global Electrodynamic Connections (GEC). The science objective of the planned NASA GEC Mission is to establish the role of the ionosphere in the electrodynamic environment of near-Earth space. Within this theme two major thrusts are identified:

- Resolve the mechanisms responsible for electrical interactions within the ionosphere/atmosphere system and for its interconnection with the magnetosphere
- Determine the important spatial and temporal scales for electromagnetic energy transfer and dissipation processes in the ionosphere/atmosphere system.

A mission definition team that has already been selected by NASA will establish the measurement requirements and spacecraft characteristics.

Magnetospheric Constellation. The goal of this mission is to understand the interactions between the localized and time-dependent drivers of magnetospheric dynamics. These processes can only be understood by monitoring the entire system, both locally and globally. Plans for Magnetospheric Constellation thus envision the placement of up to several tens of autonomous micro-satellites into a variety of orbits, each carrying a minimum set of fields and particles instruments.

3.3.2.20 Ulysses

Ulysses is a joint NASA-ESA out-of-the-ecliptic investigation of the heliosphere as a function of latitude. Ulysses is for the first time studying in three dimensions the effects of explosive solar processes and the major changes in solar wind and solar magnetic field associated with an active Sun. The current phase comprises a Ulysses Solar Maximum Mission, when the structure of the heliosphere is expected to be radically different from that explored during the pole to pole pass conducted during 1994-95. Ulysses will be part of an unprecedented armada of spacecraft investigating solar maximum, but it will be the only one observing from out-of-the-ecliptic plane.

3.3.2.21 Yohkoh/SXT

Yohkoh is a high energy solar physics mission of ISAS in Japan with collaboration of the US and UK. Yohkoh scientific instrumentation includes a Hard X-ray Telescope (HXT), a Wide Band Spectrometer (WBS), a Bragg Crystal Spectrometer (BCS), and the Soft X-ray Telescope (SXT) provided by NASA. Yohkoh was launched in September 1991 and has successfully observed the decline of solar cycle 22, the solar minimum in 1996, and the subsequent rise in cycle 23 activity. The primary scientific objective of Yohkoh is to relate energetic solar flare phenomena and dynamic coronal structures such as CMEs to the changing topology of the solar magnetic field. The extended Yohkoh mission is expected to continue this observational program into CY 2002—at which time an entire 11-year sunspot cycle will have been recorded. Data from all Yohkoh instruments are archived for public access in the GSFC Solar Data Analysis Center and have been available via NOAA.

3.3.3 Ground-based Research Observing Systems

3.3.3.1 Automatic Geophysical Observatories (AGOs)

During the austral summer of 1996-97 NSF deployed and made operational the sixth, and last, of the Automatic Geophysical Observatories (AGO). These are small (8x8x16 ft), low powered (50W) autonomous observatories which operate unattended on the East Antarctic Plateau for periods of about a year. They provide some real-time state-of-health and meteorological data via satellite, but most of the science data are stored on optical discs for annual retrieval by aircraft. The AGOs were originally built for studies of the polar ionosphere and magnetosphere, but are also being increasingly used for other Earth related studies. When combined with data from several of the manned Antarctic stations, as well as AGOs which have been developed by other nations, a wealth of information is becoming available on the high geomagnetic latitude ionosphere. AGOs are providing information leading to a much better understanding of the Earth's response to solar activity. Because of the arrangement of land masses, these very high latitude distributed observations are better done from Antarctica than the Arctic; much of the geomagnetically similar regions in the Arctic are over water. The AGO program is a collaboration of scientists from the US, Japan, and the United Kingdom.

3.3.3.2 Balloon-borne Vector Magnetograph

A balloon-borne vector magnetograph was launched over the Antarctic in the summer of 1995-96. The Flare Genesis Experiment, funded by NSF, incorporated an 80 cm diameter telescope to make measurements of the Sun's magnetic field with very high resolution. The experiment had limited success due to technical problems. Two additional launches occurred in December 1998 and January 1999. Each of the experiments circled Antarctica at an altitude of about 120,000 feet for about two weeks before being parachuted to the ice for recovery. The balloons, supplied and launched by NASA, have volumes of about 30,000,000 cubic feet and can lift payloads heavier than a ton.

3.3.3.3 Coronal Magnetic Field Measurements

The magnetic field of the solar corona can be measured in principle by exploiting three physical effects: gyroresonance radiation, the Zeeman effect and the Hanle effect. At present only the first of these techniques is in use on an occasional basis. A proposed Frequency-Agile Solar Radiotelescope would be able to map the magnetic field strength of active regions at coronal heights on a regular basis. The proposal is only in the discussion stage now. The Zeeman effect has been used to measure the line-of-sight component of the corona above the limb from the ground, and it was also used in the EUV to measure sunspot magnetic fields with the SMM satellite. There are no current proposals or plans to use either the Zeeman or Hanle effects for space observations of coronal fields. The University of Hawaii has recently proposed the construction of a 40 cm aperture coronagraph to explore the possibility of making coronal magnetic field measurements above the limb from the ground using infrared emission lines.

3.3.3.4 Incoherent Scatter Radars

The four U.S.-supported incoherent scatter radars in Greenland, Massachusetts, Puerto Rico, and Peru are all operating for approximately 1000 hours per year. There is a move toward coordinating observations in response to the impending arrival of large geomagnetic storms. This will improve the availability of incoherent scatter radar data during storm intervals. An exciting aspect in the operation of the radars is the development of the Upper Atmospheric Research Collaboratory by the University of Michigan. In April, 1998, this group successfully demonstrated the ability to simultaneously display on a computer work station data from all four of the radars, as well as the SuperDARN network, EISCAT, other ground- and space-based instruments, and concurrently running model output. This collaboratory holds great promise in conducting space weather campaigns, coordinated workshops involving a distributed community of scientists, and educational and outreach activities on a global basis. This project is continuing under NSF's Knowledge and Distributed Intelligence initiative as the Space Physics and Atmospheric Research Collaboratory (SPARC).

Another improvement to the incoherent scatter radar chain involves the JULIA radar modification to the Jicamarca facility. JULIA uses the large Jicamarca antenna, but because it operates at low power, can be run continuously to monitor the occurrence of irregularities in the equatorial ionosphere.

3.3.3.5 Interplanetary Scintillation Monitoring

The interplanetary scintillations (IPS) aspect of remote sensing of propagating solar-generated disturbances has been used several times in real-time situations. Scintillations of distant radio sources are detected by ground-based radio telescopes as a result of solar wind density fluctuations along lines-of-sight that pass the Sun at many heliospheric latitudes and at their closest approach. The experiences noted above (published in Solar Physics by Manoharan et al., 1995, and Janardhan et al., 1996) were conducted jointly by the National Centre for Radio Astronomy in Ootacomund, India (Ooty) and NOAA's SEC staff. This collaboration is continuing with observations made on a daily basis with short periods of maintenance.

Several universities have also been working in this area, including the Nagoya University in Japan, the Lebedev Institute in Russia, Beijing University, Santa Maria University in Brazil, and the Universitas Autonomous of Mexico.

Telemetry signals, passing through the inner heliosphere, from interplanetary spacecraft can also be used (given Deep Space Network) to monitor traveling interplanetary disturbances.

3.3.3.6 Relocatable Atmospheric Observatory (RAO)

This proposed transportable system would provide new capabilities for studying the properties of the Earth's upper atmosphere and ionosphere. This collection of instruments, centered on a state-of-the-art phased array incoherent scatter radar with electronic steerability, would give this observatory unique capabilities in addressing problems in solar wind-magnetosphere-ionosphere coupling and its effects on the global atmosphere. For example, locating the observatory near the north magnetic pole would allow observations critical to our understanding of the way Earth's atmosphere is magnetically and electrically coupled to the solar wind. Other possibilities include sites such as Hawaii and New Mexico near large existing lidar facilities, and Poker Flat, Alaska, near the NASA rocket launching facility. The new observations would complement others made by state-of-the-art facilities around the world as well as those made by an international array of satellite-borne instrumentation.

3.3.3.7 Riometers

Riometers measure the absorption of cosmic radio noise originating from ionization below about 120 km altitude. Because this ionization is produced by auroral precipitation, radiation belt particles, and solar flare protons, riometers are an important diagnostic tool for space weather effects. In the past decade, imaging riometers using multiple-beam, phased-array antennas have been deployed in the polar regions, providing enhanced capabilities in the study of dynamical processes. At present, there are 23 imaging riometers operating globally, 14 in the Antarctic and 9 in the Arctic. Real-time data are available from riometers at Gakona, Alaska, and Sondestrom, Greenland. Real-time data from riometers at the South Pole will be available.

3.3.3.8 Scintillation Network

AFRL maintains an extensive network of stations to perform research on the generation, convection, and lifetime of sub-kilometer scale irregularities by monitoring scintillation of radio signals from communications, weather, and GPS satellites. At high latitudes, 250 MHz scintillation receivers are deployed at Sondestrom and Thule, Greenland and at Ny Alesund, Svalbard. Two of these receivers are collocated with incoherent scatter radars whereas all are clustered with other radio and optical instruments. These measurements are focused on the entry of macroscale plasma structures through the cusp, their mesoscale structuring and transit through the polar cap into the auroral oval.

In the equatorial region, 250 MHz and L-band scintillation measurements are performed using a wide array of receivers dispersed in latitude and longitude to provide data on climatology. They are also used in a clustered form with other radio and optical instruments to provide information on irregularity trigger mechanisms, their structure and motion.

3.3.3.9 SuperDARN

The northern hemisphere SuperDARN radar network is currently undergoing an expansion with the construction of radars in Prince George, British Columbia, and Kodiak and King Salmon in Alaska. The radars at Prince George and Kodiak will provide vector plasma drift measurements over Alaska and western Canada. The radar at

King Salmon, Alaska, will provide line-of-sight plasma drift measurements over western Alaska and eastern Siberia.

In the Southern Hemisphere, a new SuperDARN radar became operational in 1999 in Tasmania. A radar at Kerguelen in the south Indian Ocean is under construction and is expected to become operational in 2000. All the SuperDARN radars operate continuously (except for brief maintenance periods).

3.3.3.10 Vector Magnetographs

There are currently several instruments that produce vector field maps of solar active regions fairly routinely: The High Altitude Observatory/National Solar Observatory (HAO/NSO) Advanced Solar Polarimeter, the NASA Marshall Vector Magnetograph, the University of Hawaii/Institute for Astronomy Imaging Vector Magnetograph, the National Astronomy Observatory of Japan Solar Flare Telescope vector magnetograph, and the Hairou, China, filter vector magnetograph.

There are no instruments at present that produce magnetographs for the full solar disk. At least three full-disk magnetographs are under construction. The NSO SOLIS project is building a 50 cm vector spectromagnetograph intended to provide regular 1 arc sec full disk vector field measurements in a period of 15 minutes. It will also provide line-of-sight magnetic field component measurements that refer to the solar chromosphere. A proposal has been submitted to the NSF from HAO to build two more of these instruments to be deployed at other locations to achieve nearly continuous solar coverage. Two instruments are under construction in Japan. At the National Astronomical Observatory, a 30 cm aperture infrared Stokes polarimeter will provide 2 arc second pixel images of the full disk in 17 minutes. At the Hiraiso Solar Terrestrial Research Center, a 30 cm aperture Spectroscopic Polarimetry Telescope has been designed to provide improved measurements of active regions. A vector magnetograph is also under construction at the Instituto Astrofisica de Canarias. The US Air Force Improved Solar Observing Optical Network (ISOON) project will allow for future upgrades of the new ISOON instruments to obtain vector magnetograms. A recent MIDEX proposal to NASA called Hale will allow vector magnetograms of the full solar disk to be made from space.

3.4 Summary

Progress in pursuit of NSWP goals has been and will continue to be enabled by synergistic advances in physical understanding, model development, and observations. The next chapter presents the timelines to carry forward this research and development. A critical challenge for the space weather research effort is to provide the linkage between the broad regions (solar/solar wind, magnetosphere, and ionosphere/ thermosphere) of the Sun-Earth system.