



Distributed Arrays of Small Instruments for Solar-Terrestrial Research: Report of a Workshop

Ad Hoc Committee on Distributed Arrays of Small Instruments for Research and Monitoring in Solar-Terrestrial Physics: A Workshop, National Research Council

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*Distributed Arrays of Small Instruments for
Solar-Terrestrial Research
Report of a Workshop*

Ad Hoc Committee on Distributed Arrays of Small Instruments
for Research and Monitoring in Solar-Terrestrial Physics: A Workshop
Space Studies Board
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Front, top, left to right: (1) Digital portable sounder receiver array at Chilton, United Kingdom. Courtesy of Chris Davis, Rutherford Appleton Laboratory. (2) Installation of SuperDARN SANA high frequency radar located at Vesleskarvet, Antarctic. Courtesy of Hercules Olivier. (3) Installation of a low-power magnetometer at the South Pole. Courtesy of Robert Clauer, University of Michigan.

Front, bottom: The aurora viewed from Alaska. Courtesy of Jan Curtis.

Back, top: Distributed Global Positioning System receivers provide a snapshot of a tongue of ionization stretching over the north polar region. Superimposed on the total electron content image is the instantaneous pattern of high-latitude electric field, derived from observations with the distributed network of SuperDARN radars and the DMSP satellites. SOURCE: Foster et al., *J. Geophys. Res.* 110(A9): A09531, 2005. [See Box 2.1, p. 12.]

Back, bottom: Computer representation of sound wave oscillations of the Sun. The helioseismology technique is at the heart of the program carried out by the Global Oscillation Network Group (GONG). SOURCE: Courtesy of the National Optical Astronomy Observatory.

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Preface

Among the programs recommended in the National Research Council's (NRC's) first decadal survey in solar and space physics was the Small Instrument Distributed Ground-Based Network, which the survey report described as an "NSF program to provide global-scale ionospheric and upper atmospheric measurements for input to global physics-based models."¹ The survey report noted that this concept would "combine state-of-the-art instrumentation with real-time communications technology to provide both broad coverage and fine-scale spatial and temporal resolution of upper atmospheric processes crucial to understanding the coupled AIM [atmosphere-ionosphere-magnetosphere] system" (p. 61). This concept was endorsed in the report from the decadal survey's Panel on Atmosphere-Ionosphere-Magnetosphere Interactions, which advised that the National Science Foundation (NSF) "begin an aggressive program to field hundreds of small automated instrument clusters to allow mapping the state of the global [atmosphere-ionosphere-magnetosphere] system."²

In response to a request from the NSF, an ad hoc NRC committee was formed under the auspices of the Space Studies Board's Committee on Solar and Space Physics to explore, via a community-based workshop, the scientific rationale, infrastructure needs, and issues related to implementation of what has become known as DASI—distributed arrays of small instruments. The statement of task is given in Appendix A. Participating in the June 2004 workshop held at Woods Hole, Massachusetts, were representatives of the thermosphere, ionosphere, magnetosphere, and solar-heliosphere research communities. In addition, agency representatives from NSF, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the Air Force Research Laboratory, and the Office of Naval Research attended and addressed the relevance of distributed instruments in their future program plans. The workshop agenda and a list of participants are presented in Appendix B. The Ad Hoc Committee on Distributed Arrays of Small Instruments for Research and Monitoring in Solar-Terrestrial Physics: A Workshop wishes to thank committee member John Foster for his leadership in organizing the workshop and the production of the workshop report that is presented here. As specified in the committee's statement of task (see Appendix A), this report summarizes the discussions at the workshop and does not present any consensus findings or recommendations.

¹ National Research Council (NRC). 2003. *The Sun to the Earth—and Beyond: A Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., p. 73.

² NRC. 2003. *The Sun to the Earth—and Beyond: Panel Reports*, The National Academies Press, Washington, D.C., p. 174.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

C. Robert Clauer, University of Michigan,
Dale E. Gary, New Jersey Institute of Technology,
Raymond A. Greenwald, Johns Hopkins University Applied Physics Laboratory,
W. Jeffrey Hughes, Boston University,
John D. Sahr, University of Washington, and
Roger W. Smith, University of Alaska.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Frank B. McDonald, University of Maryland. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

To explore the scientific rationale for arrays of small instruments recommended in the 2002 NRC decadal survey for solar and space physics,¹ the infrastructure needed to support and utilize such arrays, and proposals for an implementation plan for their deployment, an ad hoc committee established under the Space Studies Board's Committee on Solar and Space Physics organized the 1.5-day Workshop on Distributed Arrays of Small Instruments held in June 2004 at the National Academies' Jonnson Center in Woods Hole, Massachusetts. This report summarizes the discussions at the workshop; it does not present findings or recommendations.

Solar-terrestrial science addresses a coupled system extending from the Sun and heliosphere to Earth's outer magnetosphere and ionosphere to the lower layers of the atmosphere, which are connected via the thermosphere and lower ionosphere. Processes in each region can affect those in the other regions through coupling and feedback mechanisms. As the 2002 decadal survey and other related NRC reports have noted,² understanding and monitoring the fundamental processes responsible for solar-terrestrial coupling are vital to being able to fully explain the influence of the Sun on the near-Earth environment. These studies emphasize that monitoring the spatial and temporal development of global current systems and flows; the energization and loss of energetic particles; and the transport of mass, energy, and momentum throughout the magnetosphere and coupled layers of Earth's upper atmosphere is essential to achieving this scientific goal.

At the workshop, speakers asserted that deployment of distributed arrays of small instruments (DASI) would culminate decades of discipline-related local instrument development for the pursuit of aspects of solar-terrestrial science at the subsystem level. With the advent of the Internet and affordable high-speed computing, these local deployments can now become elements of a global instrument system. When different instrument techniques are then combined to observe all aspects of the physical system, the DASI concept will be realized.

Proponents of the DASI concept emphasized that DASI's strength is that it offers a cost-effective means of performing original and critically important science, with a development strategy that allows resulting new knowledge to enable and flow into future initiatives. DASI will complement and extend the capabilities of the next generation of space-based research and space weather instruments by providing a global context within which to understand in situ and remote sensing observations.

During the course of the workshop, three recurrent themes became evident: (1) the need to address geospace³ as a system, (2) the need for real-time observations, and (3) the insufficiency of current observations.

1. *Geospace as a system*—Understanding the Sun's influence on Earth's global space environment requires detailed knowledge of the atmosphere-ionosphere-magnetosphere system. This

¹ National Research Council (NRC), 2003, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., p. 73; NRC, 2003, *The Sun to the Earth—and Beyond: Panel Reports*, The National Academies Press, Washington, D.C., p. 174.

² For example, see NRC, 2004, *Plasma Physics of the Local Cosmos*, The National Academies Press, Washington, D.C.

³ "Geospace" is the term used to refer to the ensemble of regions including Earth's magnetosphere, ionosphere, and thermosphere.

extremely complex natural system involves many different interacting elements, and Earth is the only planetary system that scientists can expect to study in detail. Today, the science of space plasma physics has matured to the level of being able to both describe and model many of these interactions. A major goal in solar-terrestrial science now is to unify scientific understanding so as to achieve a more comprehensive computational framework that will enable prediction of the properties of this system—leading to conditions known as space weather that affect Earth and its technological systems. To do this accurately, however, requires an understanding of Earth’s global behavior as it exists, rather than as it occurs in an idealized representation. Realizing such goals requires the assimilation and integration of data from disparate sources.

2. *The need for real-time observations*—The magnetosphere-ionosphere-thermosphere (M-I-T) system is a highly dynamic, nonlinear system that can vary significantly from hour to hour at any location. The coupling is particularly strong during geomagnetic storms and substorms, but there are appreciable time delays associated with the transfer of mass, momentum, and energy between the different domains. Also, it is now becoming clear that a significant fraction of the flow of mass, momentum, and energy in the M-I-T system occurs on relatively small spatial scales and over a wide range of temporal scales. Consequently, elucidation of the fundamental coupling processes requires continuous, coordinated, real-time measurements from a distributed array of diverse instruments, as well as physics-based data assimilation models.

3. *Insufficiency of current observations*—Observational space physics is data-starved, leading to large gaps in the ability to both characterize and understand important phenomena. This is particularly true for space weather events, which often are fast-developing and dynamic and which extend well beyond the normal spatial coverage of current (ground-based or space) sensor arrays.

Issues addressed in presentations and discussion sessions at the workshop can be summarized in a number of fundamental science questions reflecting what participants saw as opportunities for the DASI concept to contribute to progress in understanding the Sun’s influence on the near-Earth environment. They included the following:

- What is the configuration of the magnetosphere-ionosphere-thermosphere system that is most vulnerable to space weather?
- What are the processes and effects associated with plasma redistribution during disturbed conditions?
- What is the role of the ionosphere-thermosphere system in the processes associated with particle energization?
- What are the effects of preconditioning in the ionosphere and magnetosphere on the evolution of disturbances?
- What processes affect ion-neutral coupling in the presence of particle precipitation?
- What are the causes of thermosphere-ionosphere variability during geomagnetically quiet periods?
- What are the structure and dynamics of the Sun’s interior?
- What are the causes of solar activity?
- How does the structure of the heliosphere modify the solar wind?
- Can low-frequency interplanetary scintillations be used to make global determinations of solar wind velocity?

Among the major ground-based remote sensing instruments described by workshop participants were the following:

- Very-low-frequency and high-frequency receivers and radio telescopes;
- High- and medium-power active radars and low-power passive radars;

- Ionosondes;
- Magnetometers;
- Passive and active optical instruments (interferometers, spectrometers, lidars); and
- Solar imagers, spectrographs, polimeters, magnetographs, and radio telescopes.

Speakers also noted the importance of computer models that are capable of assimilating the observations made with such instruments.

Attention at the workshop sessions was also devoted to issues regarding the infrastructure needs for future distributed arrays of ground-based instruments. Information technology was especially emphasized. Speakers cited the Virtual Observatory model that is being used in the solar and astronomy communities as an excellent starting point and template for DASI. Other information technology capabilities of note included the use of Internet and computer grid technology and high-data-rate, near-real-time communications systems. Finally, the workshop illuminated logistics considerations for the DASI concept, including key instrument spacing and size requirements for some classes of instruments as well as opportunities for and constraints on instrument placement in key locations for realizing DASI science objectives.

Throughout the workshop participants discussed a number of areas in which the space research community can begin an organized effort to develop a coordinated space-research instrumentation system. Although no consensus on priorities was sought or attempted, participants identified the following near-term actions as means to further evaluate the potential of the DASI concept and to prepare for its future development and implementation:

- Hold community workshops to address in greater detail the instrumentation, science, and deployment issues associated with DASI.
- Identify areas in which existing and planned instrument arrays and clusters can share technology, data distribution architectures, and logistics experience.
- Consolidate currently planned systems to form a regional implementation of next-generation coordinated instrument arrays.
- Establish closer connections with other research communities that are developing similar distributed instrumentation systems.
- Coordinate efforts in the U.S. community with similar international efforts.
- Move toward developing rugged, miniaturized instruments that use a common data format.
- Support efforts to establish standards for data communication technologies and protocols.
- Work with agency sponsors to begin a phased implementation of the DASI program.

Achieving the science objectives for DASI will require a global deployment of instruments and a large commitment of resources. Although the workshop did not go into detail on the areas of collaboration or opportunities to be pursued, participants felt strongly that international collaboration should be a fundamental part of the DASI plan.

1

Introduction and Workshop Background

SPACE PHYSICS AND SPACE WEATHER

The Sun is the primary source of energy at Earth, and the Sun's output determines the conditions in interplanetary space at Earth and throughout the solar system. Earth's magnetic field and associated electrical current systems are continuously reacting to changing conditions in the solar wind that are driven by processes occurring at the Sun. The characteristics of Earth's ionosphere and neutral thermosphere are influenced both by local processes and by coupling of the ionosphere and thermosphere to the overlying regions of the geospace¹ environment.

Solar-terrestrial science addresses a coupled system extending from the Sun and heliosphere to Earth's outer magnetosphere and ionosphere to the lower layers of the atmosphere, which are connected via the thermosphere and lower ionosphere. Processes in each region can affect those in the other regions through coupling and feedback mechanisms. Knowledge of this complex system requires a broad spectrum of observations that are continuous in time and that can provide measurements spanning the broad extent of the Sun-Earth domain. Study of Earth's magnetosphere and ionosphere formed the historical starting point for space physics research, and the two regions remain an important focus for study because they constitute the space environment in which most human activities occur and they provide important prototypes for understanding the magnetospheres and ionospheres of other planets and small solar system bodies. In addition, the basic physical phenomena of space plasmas, which occur in remote and therefore inaccessible locations in the universe, also can be studied directly in Earth's magnetosphere.

Despite the great advances made over the past 40 years, scientific knowledge of the complex Sun-Earth system is far from complete, and fundamental questions remain unanswered. For example, researchers are not able to completely specify the physical processes that transfer energy from the solar wind to Earth's space environment and have not yet established the nature of the global response of Earth's magnetosphere and ionosphere to the variable solar wind drivers under all conditions. These are the most basic and important questions that can be asked about geospace, but they have not received satisfactory answers. However, the maturity of the field now allows the deployment of highly capable observing systems, interrogation of large databases, development of sophisticated quantitative models, and construction of new definitive experiments both for Earth's space environment and for those of other solar system bodies.

Space weather describes the conditions in space that affect Earth and its technological systems. Through various complex couplings, the Sun, the solar wind, and the magnetosphere, ionosphere, and thermosphere can influence the performance and reliability of space-borne and ground-based technological systems. Solar energetic particle events and geomagnetic storms are natural hazards, just as are hurricanes and tsunamis. Severe geomagnetic storms can interfere with communications and navigation systems, disturb spacecraft orbits because of increased drag, and cause electric utility blackouts over wide areas. Ionospheric effects at equatorial, auroral, and middle latitudes constitute a major category of space weather effects that need to be better characterized and understood.

¹ "Geospace" is the term used to refer to the ensemble of regions including Earth's magnetosphere, ionosphere, and thermosphere.

DISTRIBUTED ARRAYS OF SMALL INSTRUMENTS—THE NEXT LOGICAL STEP

Space physics proper began in the late 1950s with the launch of the first Earth-orbiting satellites. The field is distinguished from astronomy and astrophysics as well as from earlier attempts to understand our space environment by its capability of measuring in situ the plasmas that surround Earth and pervade the solar system. However, despite the distinctive and defining role played by in situ observations, the importance of ground-based investigations (carried out with radars, magnetometers, riometers, ionosondes, all-sky cameras, coronagraphs, and neutron monitors) to pre-space-age knowledge of the Sun-Earth system has been crucial. Today, nearly half a century after the dawn of the space age, remote sensing from ground-based facilities remains essential to efforts to characterize and understand Earth's space environment and to investigate the workings of its ultimate energy source, the Sun.

One of the most serious obstacles to progress in understanding and predicting the space physics environment is the inadequate spatial distribution of ground-based measurements. This results, in part, because of the remoteness and lack of supporting infrastructure in some important regions, such as at polar latitudes, and, in part, because measurements in populated areas have been made and treated as single-point observations, as opposed to being the output of a coupled, distributed network. Effects of disturbances in the upper atmosphere occur as part of a complex, coupled system. Continuous observations spanning time and space with adequate resolution and good data accessibility are necessary to advance understanding of such processes. A global set of observations is needed especially to drive, validate, or assimilate into global models of the geospace environment. Due to the importance of cross-scale coupling in plasma processes, there is a need to resolve both high and low spatial scales in these global models.

Modern ground-based instrumentation can provide continuous real-time observations of the upper atmosphere in fixed regions of space, removing the spatial/temporal ambiguities that can arise in analyzing in situ observations from a moving platform. Advances in miniaturization techniques and in networked communications enable the fielding of large numbers of reasonably priced sensors in coordinated ground-based arrays of small instruments whose individual fields of view can be integrated to provide the spatial coverage and resolution needed to address space physics processes and space weather effects.

The expanding network of Global Positioning System (GPS) total electron content (TEC) receivers in the U.S. sector has provided an important example of the use of distributed small-instrument ground-based arrays to capture the extent and dynamics of ionospheric space weather disturbances (see Figure 1.1). In this instance, the effects of the dynamic atmosphere-space interface, namely the ionospheric plasma variability, present the single largest source of error in global positioning when using affordable single-frequency GPS receivers. A network of more-costly dual-frequency GPS receivers has been deployed globally to support high-precision geodetic and geophysical measurements, particularly for the study of earthquake hazards, tectonic plate motion, plate boundary deformation, and meteorological processes. These same receivers can be utilized to measure the ionospheric TEC. Using World Wide Web-accessible data from these GPS arrays, the ionospheric research community has identified space weather storm fronts that develop on a continental scale and, for the first time, has been able to describe the extent and severity of stormtime ionospheric variability.

Advances in technology have created opportunities for the development of new instruments to observe parts of the Sun-Earth system with unprecedented resolution and to measure crucial, heretofore undetectable, properties. Similarly, rapid-paced developments in computing and information technology will support the ability to merge and analyze large amounts of data from distributed arrays of space physics sensors in near-real time. Closely coordinated and coupled arrays of ground-based instruments, providing a variety of analyzed data products in real time to the research, education, and applications communities, are now feasible. The deployment of distributed arrays of small instruments (DASI) represents the next logical step in the development of space physics instrumentation.

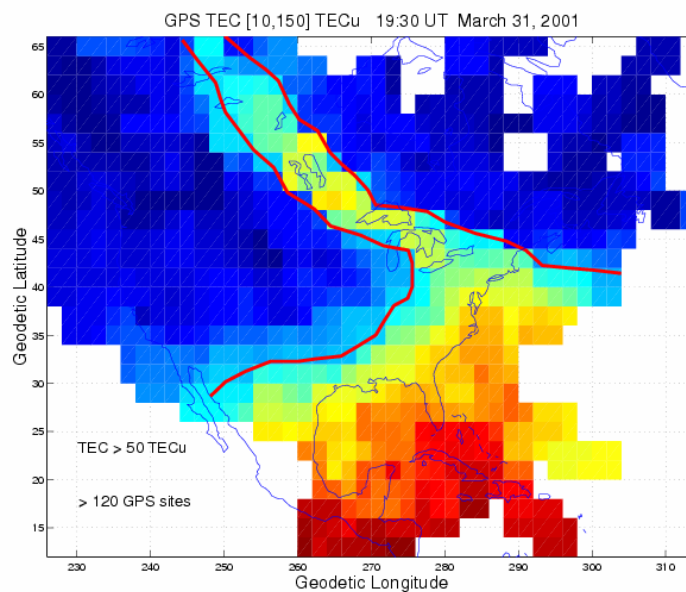


FIGURE 1.1 Combining observations from a distributed array of Global Positioning System receivers spanning the United States, snapshots of ionospheric total electron content (TEC) depict the formation of space weather storm fronts (plumes of storm enhanced density (SED)) during strong geomagnetic storms. The 50 TEC contour is outlined in red and defines the instantaneous position of the SED/TEC enhancement. SOURCE: Foster, J.C., P.J. Erickson, A.J. Coster, J. Goldstein, and F.J. Rich. 2002. "Ionospheric Signatures of Plasmaspheric Tails," *Geophys. Res. Lett.* 29(13): 10.1029/2002GL015067.

THE DECADAL SURVEY FOR SOLAR AND SPACE PHYSICS

The NRC decadal survey for solar and space physics, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*,² identified broad scientific challenges that defined the focus and direction of solar and space physics research for the decade 2003 through 2013 and recommended priorities for theoretical, ground-based, and space-based research programs of NASA and the National Science Foundation (NSF) as well as for complementary operational programs of other agencies such as the National Oceanic and Atmospheric Administration (NOAA), the Department of Defense (DOD), and the Department of Energy (DOE).

To provide continuous real-time observations with the resolution needed to resolve mesoscale phenomena and their dynamic evolution and to support the next generation of space weather data-assimilation models, the survey report recommended that the next major ground-based instrumentation initiative be the deployment of widely distributed arrays of small space physics research instruments. Analogous to the meteorological arrays that support terrestrial weather research, modeling, and predictions, space weather arrays would provide continuous real-time observations of geospace with the resolution needed to resolve mesoscale phenomena and their dynamic evolution. Ground-based arrays would address the need for observations to support the next generation of space weather data-assimilation models and would advance to a new level understanding of the physical processes that interconnect the spheres of geospace.

² National Research Council. 2003. *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C.

DASI WORKSHOP

The solar and space physics decadal survey report's recommendation for a Small Instrument Distributed Ground-Based Network is being developed further through an ongoing assessment of the DASI concept. DASI is a potential NSF ground-based initiative with emphasis on large-scale and system-wide programs offering an opportunity to address the Earth-ward boundaries and extent of the space weather connection. The DASI concept combines state-of-the-art instrumentation with real-time communications technology to provide both broad coverage and fine-scale spatial and temporal resolution of upper atmospheric processes crucial to understanding the coupled atmosphere-ionosphere-magnetosphere system. When implemented, data from the DASI instruments will provide the simultaneous real-time measurements that are needed for assimilation into physics-based models. Data from DASI is also vital to improve understanding of space weather processes and effects in the upper atmosphere. A complement of instruments, including GPS receivers and magnetometers, placed at educational institutions is meant to provide a rich hands-on environment for students, and instrument clusters at remote locations will contribute important global coverage. These detailed, distributed measurements will complement the capabilities of the larger ground-based facilities.

In response to a request from the NSF, an ad hoc committee was formed under the Space Studies Board's Committee on Solar and Space Physics to organize a workshop to explore the scientific rationale for such arrays, the infrastructure needed to support and utilize them, and proposals for an implementation plan for their deployment (see Appendix A). This report summarizes the workshop discussions. It does not provide consensus findings or recommendations.

The 1.5-day workshop was held in June 2004 at the National Academies' Jonnson Center in Woods Hole, Massachusetts. Workshop participants included representatives of the thermosphere, ionosphere, magnetosphere, and solar-heliosphere research communities. Agency representatives from NSF, NASA, NOAA, the Air Force Research Laboratory, and the Office of Naval Research attended and addressed the relevance of distributed instruments in their future program plans. The workshop agenda and a list of workshop participants are presented in Appendix B.

Participants at the workshop were asked to describe specific examples of compelling science that could be addressed by ground-based space physics instrument arrays. They were also asked to consider existing arrays and to present lessons that could be learned from their operations. As detailed below, several recurrent themes emerged during workshop discussions, specifically:

- The need to address geospace as a system,
- The importance of real-time observations for space weather,
- The value of coordinated and continuous observations, and
- The insufficiency of current observations.

To address these deficiencies, participants identified several areas for focused technology development, including development and deployment of reliable, remotely operated, ground-based ionospheric and geomagnetic measurement stations.

Geospace as a System

Understanding the Sun's influence on Earth's global space environment requires detailed knowledge of the atmosphere-ionosphere-magnetosphere system. This extremely complex natural system involves many different interacting elements, and Earth is the only planetary system that scientists can expect to study in detail. Today, the science of space plasma physics has matured to the level of being able both to describe many of these interactions and to model them. A major goal in solar-terrestrial science now is to unify scientific understanding so as to achieve a more comprehensive computational

framework that can predict the properties of this system—conditions known as space weather. To do this accurately, however, requires an understanding of Earth’s global behavior as it exists, rather than as it occurs in an idealized representation. Realizing such goals requires the assimilation and integration of data from disparate sources.

Geospace processes involve significant coupling across atmospheric layers and altitude boundaries, as well as coupling across multiple scale sizes from global (thousands of kilometers), to local (tens of kilometers), to micro-scale (meter-scale and smaller). Many of the associated phenomena have been studied extensively, but often at a subsystem level. It has become apparent that a systems approach—addressing geospace as a coupled whole—is needed to make significant progress in understanding the space weather environment. A combination of the multiple points of view provided by clustered DASI instruments will give greater understanding than can the individual measurements taken in isolation.

For example, continuous long-term distributed measurements are needed to advance understanding of the coupling of the neutral atmosphere and the overlying space environment. The neutral upper atmosphere cannot be considered in isolation, because the thermosphere and ionosphere are symbiotically connected. The neutral upper atmosphere is also profoundly affected by the lower atmosphere (dynamical coupling via planetary waves, tides, and gravity waves). An unanswered question is the extent to which the quiescent global variability pre-conditions the thermosphere-ionosphere response to space weather events.

Workshop participants highlighted two important roles for DASI: (1) providing the coordinated multi-technique observations needed to characterize these intercoupled processes simultaneously and (2) providing a means of digesting this information and disseminating it to a variety of users. The multiple scale sizes involved suggest that a variety of DASI instrument array configurations will be needed.

Need for Real-time Observations

The magnetosphere-ionosphere-thermosphere (M-I-T) system is a highly dynamic, nonlinear system that can vary significantly from hour to hour at any location. The coupling is particularly strong during geomagnetic storms and substorms, but there are varying time delays associated with the transfer of mass, momentum, and energy between the different domains. Also, it is now becoming clear that a significant fraction of the flow of mass, momentum, and energy in the M-I-T system occurs on relatively small spatial scales and over a wide range of temporal scales. Consequently, elucidation of the fundamental coupling processes requires continuous, coordinated, real-time measurements from a distributed array of diverse instruments as well as the perspective provided by physics-based data assimilation models. The DASI initiative will establish the required program. Because many instruments and instrument arrays can be operated in different modes to provide varying spatial, temporal, and parametric coverage, real-time observations are needed to set and coordinate the observing grids to provide optimal coverage in a dynamically evolving environment.

The ionosphere routinely causes space weather disturbances that result in satellite communications interruptions, GPS navigation errors and outages, and tracking inaccuracies that compromise the determination of the orbits of satellite and space debris. Space weather “nowcasting” involves monitoring and modeling a distributed, structured, and highly variable medium. Whereas a basic understanding of physical processes can be derived in detailed post-processing of the observational data sets, space weather forecast and nowcast requirements indicate a clear need for real-time data and the means to communicate them promptly to the user.

Insufficiency of Current Observations

Observational space physics is data-starved, leading to large gaps in the ability to both characterize and understand important phenomena. This is particularly true for space weather events, which often are fast-developing and dynamic and which extend well beyond the normal spatial coverage of current sensor arrays. A strong motivation for the DASI concept is to provide the coordinated, wide-ranging, continuous high-resolution data sets needed to guide the development of theory and models that will better describe and predict the characteristics and dynamics of Earth's space environment. Low-cost instrumentation that is widely deployed and running continuously can provide the spatial and temporal coverage needed to capture the evolution and characteristics of the weather in geospace.

2 Compelling Science

This chapter summarizes highlights of workshop discussions of major scientific challenges facing the solar-terrestrial research community and indications of what crucial observations are needed to elucidate the workings of the coupled Sun-Earth system. The focus at the workshop was on those observations that can be acquired from the ground and that are not provided by current and proposed space-based missions.

A brief description follows of a number of fundamental research areas to be supported by distributed arrays of small instruments. These represent several of the key topical areas discussed at the workshop, and they provide an overview and a framework for the broad science programs that can be supported by DASI observations. The strength of the DASI approach is in providing continuous, real-time, wide spatial coverage of a variety of interrelated parameters with the spatial and temporal resolution needed to resolve space physics phenomena. By monitoring the layers of the atmosphere and the electromagnetic fields above an observer, DASI instruments can provide new eyes with which to visualize the coupled processes of geospace. Science drivers discussed at the workshop span the coupled system from Earth's atmosphere, through the complex interactions of the magnetosphere with both the lower regions and the interplanetary environment, to the ultimate drivers of space weather in solar activity and variability.

MAGNETOSPHERE-IONOSPHERE

What Is the Configuration of the M-I-T System That Is Most Vulnerable to Space Weather?

The outer reaches of geospace, including the magnetosphere and ionosphere, form a buffer between the perturbations of the solar wind and the near-Earth environment in which humans live and work. Space weather is generated within this magnetized plasma environment, but the severity of a geospace disturbance in response to solar drivers is variable and is not understood. The configuration of the magnetosphere-ionosphere-thermosphere (M-I-T) system that is the most vulnerable to space weather remains a key outstanding research question. Current knowledge is not adequate to address this complex question with any confidence; moreover, each type of space weather impact could potentially be most adverse under different M-I configurations.

Role of DASI

A theme that emerged during the workshop was that answering fundamental questions, such as that regarding the configuration of the M-I-T most vulnerable to space weather, will be possible only when the entire coupled system from the Sun to the lower atmosphere is monitored and understood. Workshop participants noted frequently that widely distributed, continuous observations are required to

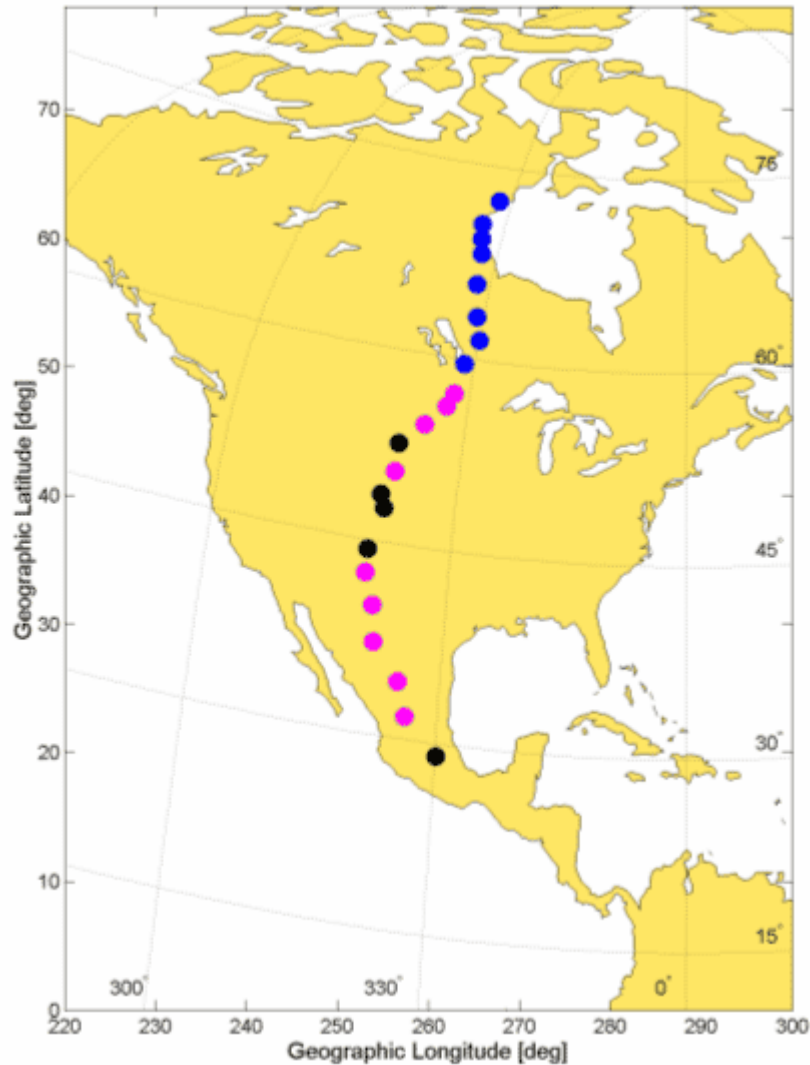


FIGURE 2.1 An example of a magnetometer array. The Mid-continent Magnetoseismic Chain is a National Science Foundation project that conducts research in magnetospheric sounding using ground magnetic field observations. Nine new magnetometers (locations shown in bright purple) are being added to parts of existing chains (locations shown in blue and black) to provide new research capabilities. SOURCE: Courtesy of University of California, Los Angeles. Available at spc.igpp.ucla.edu/mcmac.

characterize these coupled regions of geospace. As an example, they noted that the effectiveness of ground-based instruments in monitoring plasma regions and boundaries is being demonstrated by the use of arrays of magnetometers to track the position of the plasmopause (Figure 2.1) and by the current arrays of GPS receivers, which produce total electron content maps of coupled M-I disturbances (see Box 2.1).

BOX 2.1 Global Redistribution of Solar-produced Low-latitude Ionospheric Plasma

Distributed arrays of ground-based Global Positioning System (GPS) receivers have been used to identify solar-produced low-latitude ionospheric plasma forms as a strong source of the plasmaspheric erosion plumes that couple the inner and outer magnetosphere. (See Figure 2.1.1.) Distributed GPS observations suggest that this enhanced total electron content (TEC) results from a rapid poleward redistribution of post-noon-sector low-latitude thermal plasma during the early stages of geomagnetic disturbances. Eastward electric fields near dusk produce a poleward displacement of the equatorial anomalies and enhancements of TEC in the post-noon plasmasphere and mid-latitude ionosphere. Strong magnetospheric electric fields are generated as storm-injected energetic particles fill the enhanced ring current. These subauroral electric fields erode the plasmasphere boundary layer, producing plasmaspheric drainage plumes that carry the high-altitude material toward the dayside magnetopause. The near-Earth footprint of the plasmaspheric erosion events is seen as the mid-latitude streams of storm-enhanced density that sweep poleward across the North American continent. These processes produce storm fronts of dense thermal plasma that extend continuously from low latitudes into and across the polar regions.

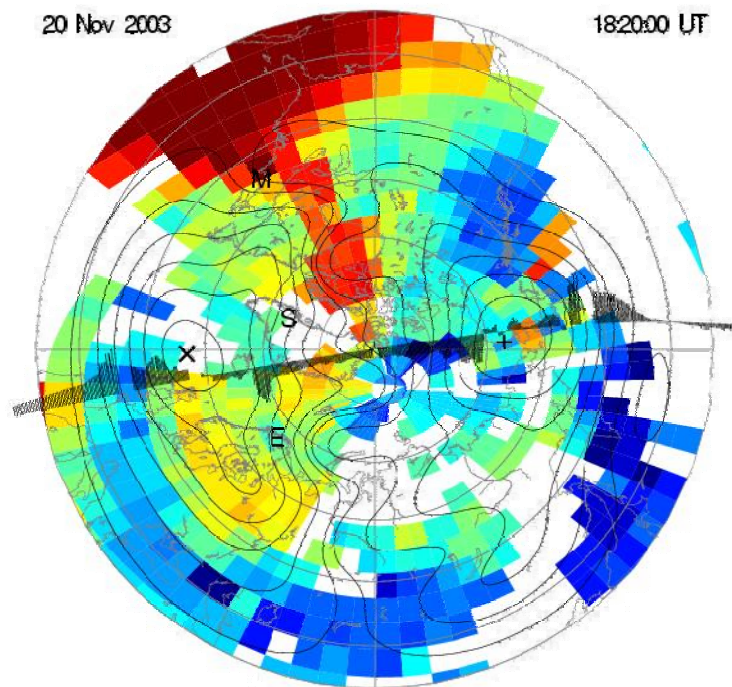


FIGURE 2.1.1 A snapshot of ionosphere total electron content over the northern polar region derived from distributed GPS TEC receivers. Superimposed on the TEC image is the instantaneous pattern of a high-latitude electric field, which is derived from distributed SuperDARN radar observations. Also shown (and included in the analysis) are in situ observations from space (Defense Meteorological Satellite Program driftmeter observations along the satellite trajectory) and the positions of the distributed large incoherent-scatter radars that provided detailed altitude profiles through the major space weather feature (polar tongue of ionization) during the event. SOURCE: Foster, J.C., A.J. Coster, P.J. Erickson, J.M. Holt, F.D. Lind, W. Rideout, M. McCready, A. van Eyken, R.J. Barnes, R.A. Greenwald, and F.J. Rich. 2005. "Multiradar Observations of the Polar Tongue of Ionization," *J. Geophys. Res.* 110(A9): A09S31, doi:10.1029/2004JA010928.

What Are the Processes and Effects Associated with Plasma Redistribution During Disturbed Conditions?

The problem of plasma redistribution pertains to the various regimes that have historically been used to describe the magnetosphere, ring currents, plasmasphere, radiation belts, and ionosphere. Each region is distinguished by its plasma density and temperature. Some have sharp boundaries between them, whereas others are diffuse. The common problem is that during severe space weather events these boundaries and plasma regimes redistribute in ways that researchers can only glimpse, and yet it is these redistributions that lead to space weather effects such as (1) spacecraft charging in rarefied density regions with enhanced high-energy particles, (2) satellite-ground communication problems and high-frequency communications disruptions due to the effects of scintillations disrupting propagation paths, and (3) satellite orbital drag effects due to enhanced neutral densities. Workshop discussions focused on plasma redistribution processes in the inner M-I system.

The electric fields that drive plasma redistribution arise from a number of sources. Earth's interaction with the solar wind drives the circulation of the magnetosphere and the electric field associated with the large-scale circulation of the auroral ionosphere. Internal magnetospheric processes and feedback between the ionosphere and magnetosphere result in additional regional and temporally varying electric fields. One of the most important electric fields generated by the M-I system is created by the divergence of the asymmetric ring current. The electric field and currents resulting from the ring current are at low latitudes and are typically quite strong and variable during disturbed periods. Strong subauroral electric fields perturb the outer plasmasphere, and large, variable, magnetic perturbations give rise to ground-induced currents that have the potential for disrupting terrestrial electrical power grids. It is important to understand fully the subauroral electric and magnetic disturbances that result from the ring current.

Unknowns

A major present-day problem is that although they have shown how dynamic, how rapid, and even how regionally localized the effects of space weather can be, space- and ground-based resources are so isolated (outside the correlation distances and times from each other) that knowledge of or ability to specify or forecast such effects cannot meet the need either to understand the severe response mechanisms or to provide users with space weather mitigation strategies based on realistic specification of the events, let alone forecasts.

Related Questions

- What are the sources and effects of disturbance electric fields?
- What is the temporal relationship between the equatorial effects of undershielded (penetration) electric fields and the onset of strong erosion plumes in the subauroral ionosphere?
- What are the causes of longitude effects in the geospace response to disturbances?
- What is the relationship of the occurrence of low-latitude (off-equatorial) scintillation to the occurrence of redistribution events?
- In what ways are enhanced events similar to and different from equatorial anomalies formed on quiet/normal-days?
- In what way does the redistribution of low-energy plasma affect the development of magnetospheric storms? Of particular significance are feedback and modification of magnetospheric processes by the redistributed cold plasma.

Role of DASI

During the workshop participants noted that all of the above questions demand the types of coverage and multi-technique measurements afforded by distributed, continuously operating instrument arrays that can resolve temporally changing structures. Arrays of instruments attuned to boundary region phenomena and processes are required (see Box 2.2). DASI will be able to interrelate the variety of parameters associated with these regions as such disturbances evolve, and with a resolution that will enable identifying and following their boundaries. Extension of the needed monitoring capability into hard-to-access regions constitutes a major goal of DASI.

BOX 2.2 Boundary Region Processes

Transport of magnetic flux and plasma across the open-closed field line boundary is one of the most important processes in the magnetospheric system, and it plays a central role in both the supply of plasma to the central plasma sheet, and the supply of energy to the overall convection process. CADI, the Canadian Advanced Digital Ionosonde project, is a good example of the use of distributed instrumentation to provide continuous, real-time monitoring of an important boundary region. The high-latitude SuperDARN high-frequency radars (Figure 2.2.1) monitor the electric fields and plasma redistribution pattern across this region.

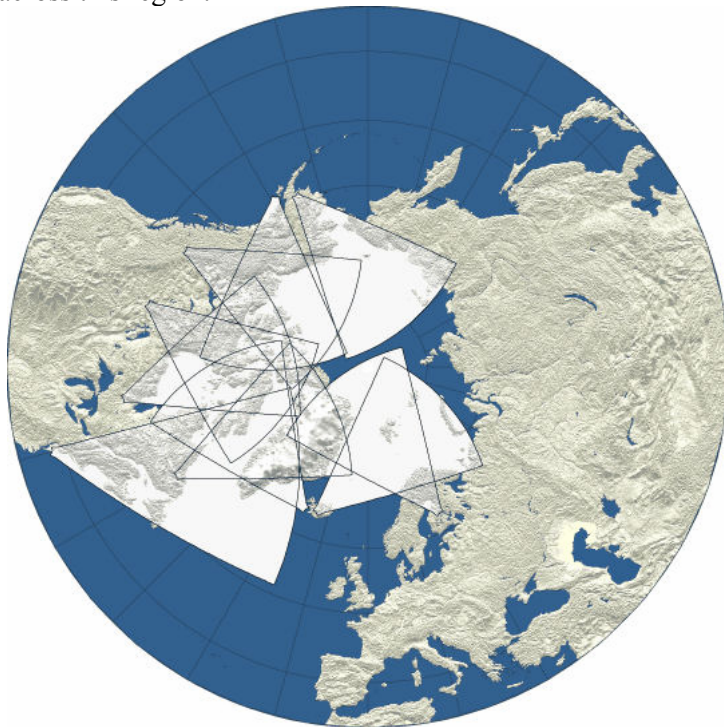


FIGURE 2.2.1 Graphic from the SuperDARN home page on the World Wide Web that shows the fields of view of the northern SuperDARN radars. SuperDARN sites are also present in the Southern Hemisphere. See superdarn.jhuapl.edu/. SOURCE: Johns Hopkins University Applied Physics Laboratory.

What Is the Role of the Ionosphere-Thermosphere System in the Processes Associated with Particle Energization?

Some of the most severe ramifications of space weather are associated with particle energization during geospace disturbances. The acceleration processes themselves are not fully understood, but their adverse geoeffectiveness is beyond doubt. They lead to extremely high-energy electrons and ions that create the ring currents and radiation belts that have a direct impact on space travelers and hardware. Energetic particles can damage satellite components, circuitry, and systems via spacecraft surface charging, as well as deep dielectric charging caused by the penetration of MeV-energy electrons. Large fluxes of MeV-energy electrons are also of concern with respect to doses of radiation received by crew on the International Space Station, by space shuttle astronauts undertaking space walks, and even by airplane crews who regularly fly high-altitude polar routes. Whereas the acceleration of many of the high-energy-particle populations results from heliospheric or magnetospheric processes, the ionosphere-thermosphere system contributes to auroral acceleration associated with intense field-aligned currents that close in the ionosphere. The locations and strengths of these acceleration regions, their energy sources, and consequent precipitation of particles can be inferred occasionally via detection of mid- to low-latitude auroras or magnetic perturbations. Ionospheric conductance is modified by particle precipitation, and in turn, the characteristics of the magnetospheric acceleration mechanism can depend on ionospheric feedback.

Unknowns

The processes involved with, and the effects of, particle energization are manifested in coupled, global variations in density, optical emissions, currents, and waves. Simultaneous observations of these features can reveal the evolution of magnetospheric particle populations. The topic of plasma redistribution (noted in the preceding section) is tied to this issue in that the high-altitude extension of plasma erosion features influences the development of energetic particle distributions in the magnetosphere. The interrelationship of cold plasma redistribution (see above) and M-I coupling and control of auroral and subauroral fields and currents in the system-wide particle energization needs to be understood.

Related Questions

- What is the low-altitude mapping of the current-closure regions and boundaries of the magnetosphere-ionosphere system?
- What processes are involved in the formation of new energetic particle belts in the inner magnetosphere during storms?
- What is the role of ionospheric polarization electric fields in modulating magnetospheric processes?

Role of DASI

Workshop participants considered the application of distributed instrument arrays, including monitors of the aurora and associated currents, ionospheric density and conductivity, electric fields, and thermospheric winds, to address the questions listed above. Such arrays could include an extension of THEMIS instrumentation (see Box 2.3.) to lower latitudes, especially in optics and magnetometers. However, high-frequency, ultralow-frequency, and very-high-frequency radio propagation techniques could all be brought to bear on this problem.

BOX 2.3 THEMIS

The THEMIS ground array provides a current example of the synergy of space- and ground-based coordinated studies to address significant auroral-latitude processes (substorms). (See Figure 2.3.1.) Carefully planned arrays of auroral optical imagers and magnetometers provide real-time coverage of the auroral region across North America. The major THEMIS science objective is to locate and time the substorm onset as seen at ground level. At onset, the aurora intensifies and expands, and the magnetic field caused by the ionospheric current intensifies.

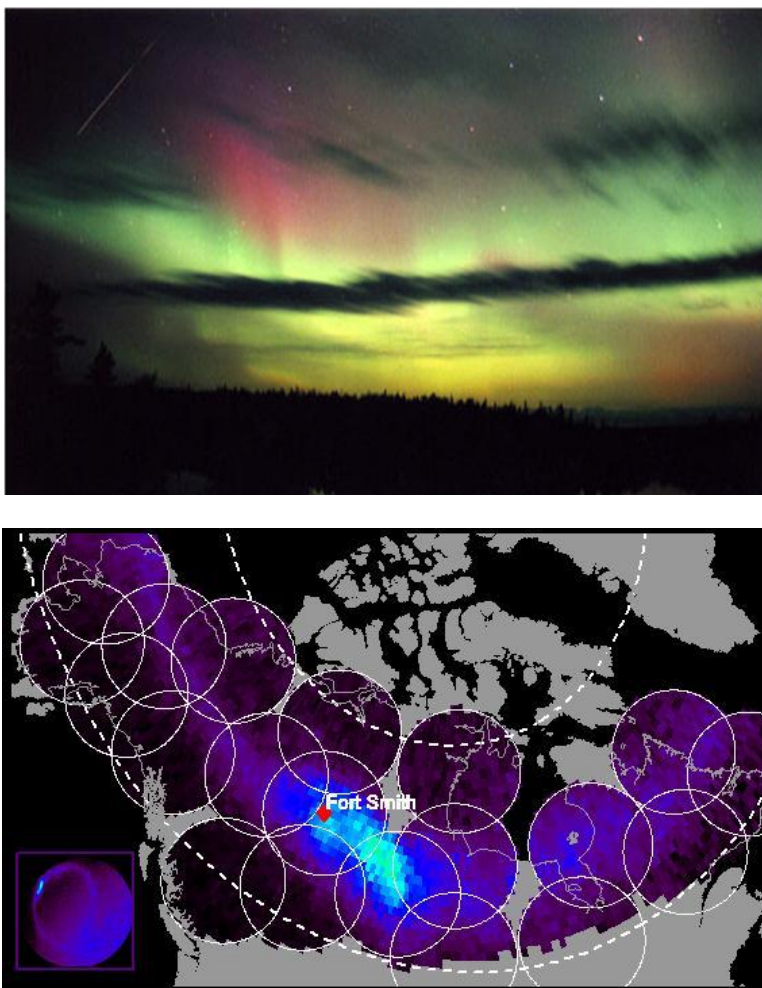


FIGURE 2.3.1 The rapid evolution of the aurora across the midnight sector (see illustration at pluto.space.swri.edu/image/glossary/local_time.html) provides a near-Earth image of the development of magnetospheric substorms. A distributed array of ground-based white-light auroral imagers is being deployed across North America as an essential part of the NASA THEMIS MIDEX mission. The imager array will provide high-resolution observations of auroral characteristics in the North American sector, with the specific objective of characterizing the spatio-temporal evolution of the electron aurora during expansive phase onset. Shown here is a composite figure that displays the combined field of view of the ground-based THEMIS auroral imager array (bottom) with an auroral snapshot by the ultraviolet imager on the Polar spacecraft (top). SOURCE: Images courtesy of Eric Donovan, University of Calgary; Polar UVI data provided by Kan Liou, Johns Hopkins University Applied Physics Laboratory.

What Are the Effects of Preconditioning in the Ionosphere and Magnetosphere on the Evolution of Disturbances?

Disturbances in or across key regions of geospace involve the characteristics of the external drivers (for example, the interplanetary magnetic field and solar wind) as well as the pre-existing state and structure of the regions. There are strong reasons to believe that a storm's effectiveness does not depend on its "energy" content alone but also on the current state of the plasma environment in which it develops. The environment is, in ways not fully understood, both a plasma source and also an "elastic" topology that can store energy at levels that can be extremely effective in particle acceleration when triggered by the arrival at Earth of a solar coronal mass ejection. If the geospace system is in an unfavorable condition (either depleted of plasma or already configured in such a way that energy cannot be stored efficiently), then the resulting disturbance may be lessened.

Unknowns

The evolution of plasma processes and the system response throughout space weather events may depend in poorly understood ways on the initial conditions of the geospace system.

Related Questions

- Are there pre-existing states or features of the magnetosphere-ionosphere system that are important in the development of a superstorm?
- What are the mechanisms involved?
- Is the magnitude of the geospace response to a solar driving event predictable based on the pre-existing condition of the geospace system?
- In what ways does the ionospheric conductivity distribution affect the development of geomagnetic storms?

Role of DASI

Participants at the workshop noted that global data from a wide variety of DASI instruments will have to be integrated over the hours and possibly days prior to a storm to establish the preconditioned environment in order to address the variability in storm response. Because of the currently limited predictability of coronal mass ejections and resultant storms, continuous distributed observations are needed.

IONOSPHERE-THERMOSPHERE INTERACTIONS

Earth's ionosphere-thermosphere system is the site of complex electrodynamic processes that redistribute and dissipate energy delivered from the magnetosphere in the form of imposed electric fields and precipitating charged particles. Previous studies have revealed much about the composition and chemistry of this region and about its structure, energetics, and dynamics. However, a quantitative understanding has proved elusive because of the inability to distinguish between temporal and spatial variations, to resolve the variety of spatial and temporal scales on which key processes occur, and to establish the cross-scale relationships among small, intermediate, and large-scale phenomena.

What Processes Affect Ion-Neutral Coupling in the Presence of Particle Precipitation?

Neutral winds in the upper atmosphere play an important role in the global response of the atmosphere to geomagnetic disturbances:

1. Neutral winds can significantly change the chemical distribution of the thermosphere, changing heating, cooling, and ionization rates.
2. Neutral winds advect temperature perturbations to low latitudes, such that the polar heating is spread over the whole globe.
3. Neutral winds push ions up field lines and across field lines. The motion up (and down) field lines redistributes the plasma significantly. The dragging motion across field lines can cause changes in the ionospheric currents and may induce ground currents.
4. By dragging ions the neutral wind can change the electric field and dynamics in the magnetosphere.

During events in which the ionospheric electric field becomes large, the ions flow very quickly. The resulting friction between the thermospheric neutral winds and the ions can result in significant heating of the thermosphere. This heating causes the atmosphere to lift, increasing drag on satellites. During magnetic substorms all of the above elements are very important, since large electric fields, combined with large particle precipitation, increase the frequency of collision between the neutrals and ions.

Related Questions

- How does the global thermosphere-ionosphere respond to geomagnetic storms?
- How does the global response vary with altitude?
- How does the global response vary with time?
- What are the local and global responses to solar proton events?
- How deep into the atmosphere do such effects penetrate?

Role of DASI

The effects that couple the thermosphere with geomagnetic storms occur on a large-scale, system-wide level. Properties of the interacting layers of the upper atmosphere must be sampled over a wide range of latitudes and local times before, during, and following the magnetospheric disturbance. Workshop participants described the need to obtain thermospheric measurements from an extended and relatively dense array of measurement sites over a range of latitudes. For example, deployed arrays of autonomous Fabry-Perot interferometers or Michelson interferometers would monitor thermospheric temperature, composition, and dynamics at distributed sites and within many important coupling regions.

What Are the Causes of Thermosphere-Ionosphere Variability During Geomagnetically Quiescent Periods?

The dynamic coupling between the lower and upper atmosphere is described in recent work that has reported variability in the principal (F2) peak of ionospheric density observed at middle latitudes in both the Northern and Southern Hemispheres during quiescent periods. That variability has been attributed to global-scale waves, including tides and planetary waves that originate in the lower

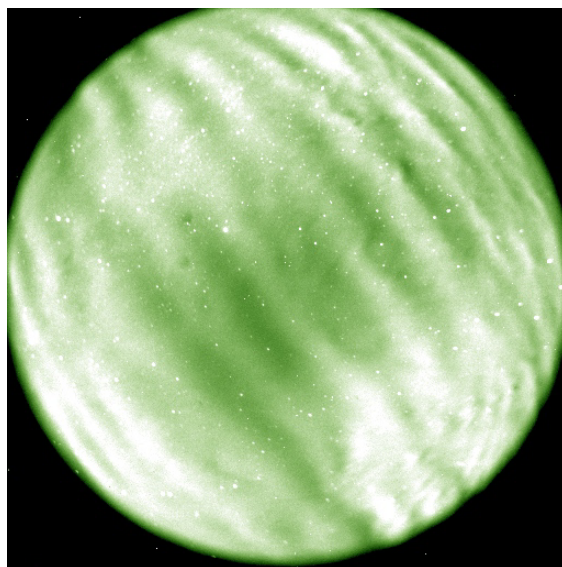


FIGURE 2.2 All-sky image acquired in the atomic oxygen “green line” (>557.7 nm) airglow showing a coherent short-period gravity wave. This photochemical emission originates from a well-defined layer in the upper atmosphere at an altitude of approximately 96 km. Gravity waves transport large amounts of momentum into the MLTI (Mesosphere and Lower Thermosphere/Ionosphere) region where they create profound effects on the background wind and temperature fields. SOURCE: Courtesy of Michael J. Taylor, Utah State University; data shown were obtained from Bear Lake Observatory, Utah, on June 5, 2002, using a monochromatic charge-coupled device imager as part of a coordinated measurements program with the NASA TIMED satellite.

atmosphere and propagate upward into the thermosphere-ionosphere (T-I). This interpretation has been borne out by “whole atmosphere” modeling studies, which treat a combined domain that extends from the ground through the thermosphere.

The quantification of T-I-ionosphere variability during quiescent periods is a fundamental research problem that has very practical consequences. It is impossible to quantify accurately the T-I impact of any space weather event unless the underlying state is known. There are identical implications for the development of any capability to provide realistic T-I space weather forecasts.

Unknowns

Upward-propagating lower atmospheric waves, including atmospheric tides, planetary waves, and gravity waves (see Figure 2.2), are a major source of quiescent T-I variability. The mesopause region (ca. 80 to 110 km) is the gateway between the lower atmosphere and the T-I. Even though the mesopause is well monitored by medium-frequency and meteor radars, resonance (for example, Na, K, Fe) lidars, imagers, and Fabry-Perot interferometers, significant gaps in current spatial and/or temporal sampling of the mesopause region preclude accurate determination of global-scale wave characteristics.

Related Questions

- What is the effect of thermosphere-ionosphere variability during quiescent periods on the development of space weather disturbance events?

- In what ways do the characteristics and structure of the lower atmosphere influence the development of geospace space weather events?
- How do lower-atmosphere effects couple into the magnetosphere?

Role of DASI

Workshop discussions revealed that simultaneous correlative mesopause region and T-I diagnostics are needed to resolve the upward-propagating global-scale wave effects on the T-I system. Participants noted that DASI can provide multiple longitudinal instrument chains at a select series of latitudes. Optimally, these measurements should be continuous, because tides with frequencies that are harmonics of a solar day are persistent and ubiquitous, whereas traveling planetary waves are transient, with periods that range between 2 and 16 days.

SOLAR: THE SUN AS A DRIVER

The Sun is the primary source of energy input to the geospace environment. Its output determines the conditions in interplanetary space at Earth and throughout the solar system. Earth's magnetic field and associated current systems are continuously reacting to changing conditions in the solar wind that are driven by processes occurring at the Sun. During periods of high solar activity, highly energized particles can be accelerated near the Sun and in the heliosphere and propagate toward Earth, endangering astronauts and satellites. Propagating solar disturbances, known as coronal mass ejections, can generate geomagnetic storms, which can damage power grids and satellites and affect GPS and other important navigation and communication systems. Despite the great advances made over the past 40 years, current knowledge is far from complete, and unanswered questions remain that are of fundamental importance to comprehension of solar and space physics, and to space weather in particular.

What Are the Structure and Dynamics of the Sun's Interior?

The cyclic solar magnetic field is generated by dynamo processes occurring in a thin region at the base of the convection zone known as the tachocline. The discovery of propagating sound waves in the Sun in the 1960s and their characterization in the 1970s have led to the development of an exciting new observational technique called helioseismology, which allows the sounding of the structure and dynamics of the Sun's interior. The discovery of the tachocline, along with the identification of large-scale meridional flows, has revolutionized dynamo models of the magnetic field. These models describe the way in which the global field is generated in a cyclical fashion, bringing researchers closer to understanding and ultimately predicting the sunspot cycle.

The most dramatic new insights into solar interior dynamics in the near future will likely come from the emerging field of local helioseismology, which has already provided unprecedented insight into the structure underlying active regions and large-scale flow patterns such as meridional circulation. Imaging of magnetic activity on the farside of the Sun using a local technique called acoustic holography can provide information on the generation and evolution of active regions and up to 2 weeks' advance notice of the formation of regions likely to produce space weather phenomena such as flares and coronal mass ejections. Here as in global helioseismology, continuous long-term monitoring is necessary in order to understand how subsurface dynamics vary over the course of a solar activity cycle. Longer-term monitoring is also necessary in order to understand and predict periodic or chaotic modulations of the solar activity cycle such as the Maunder minimum, an extended period in the 17th century in which sunspot activity largely ceased.

Unknowns

Despite this recent progress, much uncertainty remains regarding the physical mechanisms responsible for field generation and the precise role of the meridional circulation.

More information is needed about the structure and evolution of subsurface flows and magnetic fields. Workshop participants regarded as particularly important (1) long temporal baseline studies of global oscillations and large-scale flow patterns such as meridional circulation that vary on time scales of the solar activity cycle and (2) high-temporal-cadence observations of the dynamics and evolution of localized structures such as those found beneath active regions. Time-series of Doppler-shifted light emitted at the Sun's surface can address these needs because they can specify distinct, resonating, sound waves that, in turn, probe the Sun's interior.

Role of DASI

Workshop participants highlighted the importance of continuous helioseismic observations so as to prevent periodic data gaps that are detrimental to frequency resolution. Although this can be and indeed is done in space, ground-based observations have the crucial additional benefits of (1) providing long temporal baseline observations to allow ongoing studies on time scales of solar cycles and (2) providing high-temporal-cadence observations that do not suffer from satellite telemetry constraints. Consequently, the workshop discussions emphasized continuation of the type of missions conducted by the Global Oscillations Network Group (GONG), thereby extending the long temporal baseline of observations with multiple ground stations to keep coverage continuous.

GONG is a community-based program to conduct a detailed study of solar internal structure and dynamics using helioseismology. In order to exploit this new technique, GONG has developed a six-station network (Figure 2.3) of extremely sensitive and stable velocity imagers located around Earth to obtain nearly continuous observations of the Sun's "5-minute" oscillations, or pulsations (Figure 2.4). Spaceship Earth is a successful constellation of neutron detectors. It has 11 stations, with 9 in the Northern Hemisphere and 2 in Antarctica. The station locations were chosen to give good coverage of the equatorial plane. There is very sparse directional coverage at mid-latitudes, degrading the detection capability.

What Are the Causes of Solar Activity?

Transient solar disturbances such as flares, coronal mass ejections (CMEs), and prominence eruptions range in frequency from one event every few days to as many as four events per day at the maximum of the sunspot cycle. These transient events are driven by magnetic energy that ultimately originates in the solar interior and that is stored and then released in an often spectacular fashion in the corona. CMEs and prominence eruptions are sudden expulsions of magnetized plasma into the solar wind. A flare is a rapid localized increase in radiative output, particularly at shorter wavelengths, generated by a process of magnetic reconnection that converts magnetic energy to heat. The various forms of solar activity do not occur in isolation as separate events, but rather tend to occur in concert because of changes in the state of the magnetic field. The sunspot cycle, which is the most well known manifestation of solar activity, is driven by variations in the magnetic field.

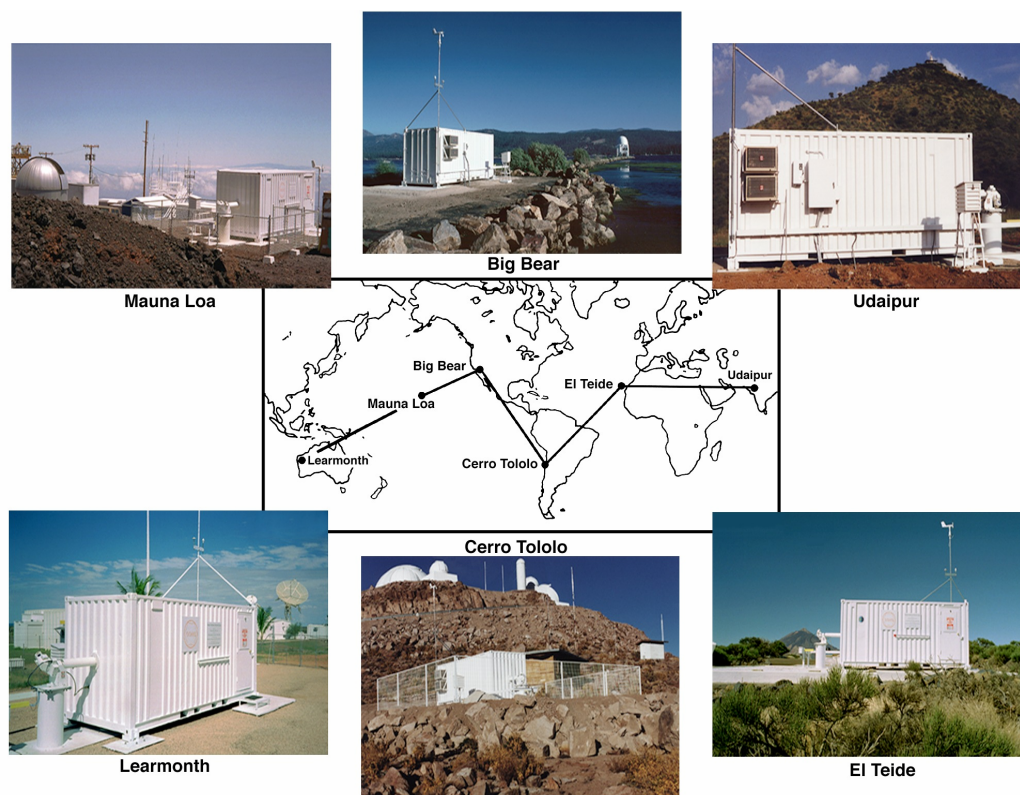


FIGURE 2.3 The Global Oscillations Network Group helioseismology network. SOURCE: Courtesy of the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy under a cooperative agreement with the National Science Foundation.

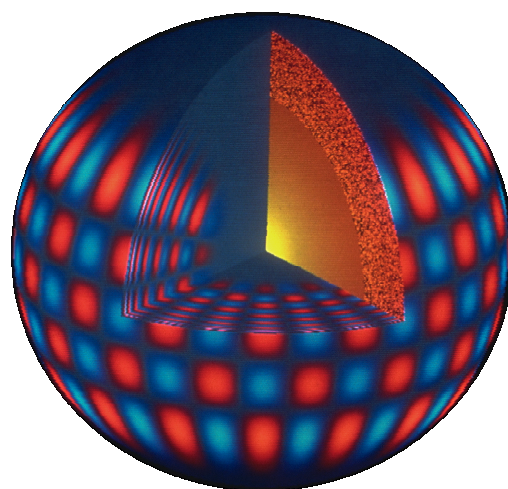


FIGURE 2.4 A computer representation of one of nearly ten million modes of sound wave oscillations of the Sun, showing receding regions in red tones and approaching regions in blue. By measuring the frequencies of many such modes and using theoretical models, solar astronomers can infer much about the internal structure and dynamics of the Sun. This technique is called helioseismology, because of its similarities to terrestrial seismology, and is at the heart of the program carried out by the Global Oscillations Network Group (GONG). SOURCE: Courtesy of the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy under a cooperative agreement with the National Science Foundation.

Flares and CME-generated shocks can accelerate particles that move toward Earth at relativistic speeds and that have the potential to harm astronauts and damage satellites. Most major geomagnetic storms are the result of CMEs and CME-produced shocks, which propagate through the solar wind and impact the space environment at Earth. Strong and/or sustained southward-pointing heliospheric magnetic fields can drive geomagnetic storms, because these southward-pointing fields are favorably configured to allow magnetic reconnection to transfer energy and momentum from the solar wind to Earth's magnetic environment. Accurate predictions of geomagnetic activity depend critically on knowledge of the magnetic structure and plasma properties of Earth-directed CMEs and the surrounding solar wind.

Unknowns

More information is needed about the magnetic field and plasma conditions in the solar atmosphere in order to (1) understand CME formation, (2) provide information about the magnetic structure of Earth-directed CMEs and solar wind, (3) predict the onset of large solar flares, and (4) learn how and where solar energetic particles are accelerated. Many critical aspects of solar activity are not currently being observed at enough sites around the globe to provide continuous temporal coverage. To address solar activity, continuous measurements are needed, from active regions to global scales, of plasma and magnetic field properties from the photosphere through the corona.

Role of DASI

Understanding the origins of solar activity and monitoring it in detail as it occurs require continuous time coverage. Some critical observations of solar activity are best done from the ground, for example because of lower costs or large telescope size. Solar activity monitors should incorporate complementary instruments that capture crucial aspects of solar activity, including photometric and polarimetric measurements over wavelengths that sample a range of heights from the deep photosphere up into the corona.

How Does the Structure of the Heliosphere Modify the Solar Wind?

The solar corona gives rise to the solar wind, which dominates the space environment of Earth and all the planets, forming the heliosphere. The heliosphere is a highly structured, rapidly evolving extension of the corona, and hence it reflects the evolution of the solar atmosphere on all spatial and temporal scales. Long-lasting coronal holes near solar minimum are the source of fast co-rotating interaction regions (CIRs) in the solar wind. Near solar minimum, these CIRs dominate the structure of the heliosphere near the ecliptic plane, and hence Earth's space environment. Similarly, erupting CMEs evolve, grow through interactions with streams that are swept up, and drive extended shocks throughout the heliosphere. These shocks are the source of the vast majority of energetic particles accelerated near the Sun. The heliosphere is therefore an active participant in the generation and modulation of space weather.

Unknowns

There are critical obstacles to understanding of the Sun-Earth connection relating to these heliospheric processes. For example, the relationship between the closed field regions of the solar atmosphere and the open field regions, which extend into the deep heliosphere, is still not understood.

Predicting how Earth-bound CMEs will interact with Earth depends strongly on the ability to predict the heliospheric interactions and processes that lead to particle acceleration, as well as the ability to determine when the evolving CME and surrounding solar wind will lead to a sustained southward-directed magnetic field. More information is needed about the structure and physical properties of the heliosphere in order to:

1. Identify the magnetic processes that accelerate the solar wind,
2. Provide the three-dimensional structure of the heliosphere,
3. Understand the interactions of CMEs and solar wind streams,
4. Predict the acceleration of energetic particles resulting from these interactions, and
5. Understand the interactions of these particles and galactic cosmic rays (GCRs) with the heliospheric magnetic field.

As a result of their high-energy interaction with the heliospheric magnetic field, GCRs can also be used as a tracer for the large-scale (~ 1 AU) and mesoscale (1 to 0.01 AU) structure of the heliospheric magnetic field near Earth.

Role of DASI

Neutrons and muons are secondary products of >1 -GeV particles in Earth's atmosphere. At the workshop, participants noted that measuring particles' angular distribution at Earth's surface provides direct information about the transport of these particles. Galactic and solar cosmic ray angular distributions need to be measured with complete sky coverage so that transport phenomena can be analyzed under all geometrical conditions. Due to the refracting effects of Earth's magnetic field, multiple stations are needed to determine the full flux and angular information of the primary particles.

Can Low-Frequency Interplanetary Scintillations Be Used to Make Global Determinations of Solar Wind Velocity?

A key limitation in understanding the connection between solar activity and the interplanetary disturbances that eventually produce storms has been the difficulty in linking coronagraph observations of regions near the Sun with the shocks that are detected at greater distances and at later times by satellites near Earth. Planar wave fronts from compact radio sources (for example, quasars) are distorted as they pass through the solar wind, creating a moving diffraction pattern at Earth. Observations of this shifting pattern, known as interplanetary scintillation (IPS), allow properties of the solar wind, such as velocity, flow direction, and density, to be determined.

By drawing on the diagnostic strengths of measurements of physical effects—for example, Faraday rotation and, at low frequencies, IPS (which is obtained with the wide instantaneous fields of view possible with a digital array)—it is possible that these ground-based radio telescopes could be used to measure magnetic field and density structures from the lower corona out to 1 AU. In addition, the antennas could be used to monitor continually for transient events, such as solar and planetary radio bursts, as well as astrophysical phenomena. For solar wind velocity measurements, the regions of different speeds can be resolved by using simultaneous observations from an array of antennas.

Role of DASI

At the workshop participants noted that the DASI concept for IPS velocity measurements could involve a global array of single-antenna sites or an array of multiple-antenna sites. IPS measurements

from multiple sites can be used to make maps that are more complete in shorter periods. Since solar disturbances are unpredictable, multiple IPS sites situated at different longitudes around Earth will increase the probability that a propagating solar disturbance will intersect the line of sight between a source and the receiver. IPS sites arranged at different longitudes around the globe will enable continuous time coverage of solar events. Multiple antennas at each site will provide more velocity measurements toward more sources. Longer baselines will provide velocities that are more accurate.

3 Instruments

The upper atmospheric physics community has developed and deployed a variety of ground-based instruments that are returning high-quality information about the state of the upper atmosphere. Individually, these instruments and their data products are quite mature. However, significant progress in space physics research requires better geographic distribution of the instruments and enhanced coordination of their data products, which in turn will facilitate focused research and assimilation of the data into advanced computer models.

Workshop participants discussed the major ground-based remote sensing instruments, summarizing their capabilities and requirements. These instruments all rely on direct sensing of electromagnetic fields, which carry information from the region of interest by direct emission of radiation or by scattering or selectively absorbing the radiation emitted.

RADIOWAVE INSTRUMENTS

Detection of Natural Radio Emissions

Earth's magnetosphere and plasmasphere spontaneously emit distinctive electromagnetic radiation, including forms called "whistler" and "chorus." Analysis of these emissions provides information about the location of the plasmopause, the density of plasma in the plasmasphere in the equatorial plane, and loss cone kinetics in the plasma. In general, instruments that are sensitive to these emissions are deployed at high latitude and require very little maintenance once installed. Such receivers require little power and network connectivity, although these minimal requirements still may stress the limited infrastructure at high latitudes. Whistler and chorus receivers provide magnetic field-integrated information about plasma distribution in the plasmasphere. These instruments require very radio-quiet locations. As in all radio systems, the advent of digital receivers permits unprecedented flexibility, dynamic range, data quality, and convenience.

Riometers (see Figure 3.1) can be more widely deployed. They measure the extent of absorption of cosmic high-frequency (HF) radio waves by the lower ionosphere, thus providing a clue to plasma density in the ionospheric D region (60 to 100 km).

Detection of Anthropogenic Radio Emissions

Radio signals broadcast by humans frequently interact with the upper atmosphere. Analysis of the absorption, scattering, and dispersion of these signals leads to useful geophysical information. Very-low-frequency receivers observe high-power transmitters, yielding path-integrated information about the Earth-ionosphere cavity. High-frequency receivers that observe AM broadcasts (for example, from the National Institute of Standards and Technology station WWV) provide integrated measurements of plasma density in the D, E, and F regions over very long paths. Very-high-power broadcasts provoke nonlinear plasma processes (the radio Luxembourg effect). Receivers for this frequency range are inexpensive, typically about \$5,000. They require little power and modest network access for real-time



FIGURE 3.1 Photo of a riometer that employs a traditional or classic design. Shown here is the 30-MHz High Frequency Active Auroral Research Program (HAARP) riometer, which is part of a major ionospheric research facility located near Gakona, Alaska. This riometer uses a 2×2 array of five-element yagi antennas and a low-noise receiver to achieve a very sensitive receiver capability. SOURCE: HAARP, Office of Naval Research and the Air Force Research Laboratory. Image available at www.haarp.alaska.edu/haarp/rioImages/rio.jpg.

operation. Miniaturized, automated, low-cost receivers can be placed in widely distributed locations (for example, at schools and at remote sites). The combination of data from many receivers will provide a new dimension in observing capabilities.

Some spacecraft carry stable transmitter beacons whose amplitude and phase yield superb line-integrated estimates of plasma density and detection of plasma turbulence. These receivers are somewhat more costly, perhaps \$20,000, and have modest network and power requirements. The premier example of such systems is the GPS TEC network, now very well established in North America, Japan, and Western Europe. Recently available digital receivers offer new flexibility, performance, and convenience of operation. The extension of the GPS network to cover remote regions, including oceans, would provide global, continuous observing of the useful TEC data.

High-Power Radar

Incoherent scatter radars (ISRs) are flagship instruments for ground-based ionospheric remote sensing. These radar systems have very large antennas and megawatt-class transmitters. The United States operates a chain of four such radars in the U.S. sector—in Greenland, Massachusetts, Puerto Rico, and Peru. Additional ISRs exist in Norway, the Norwegian Svalbard archipelago, Russia, and Ukraine.

ISRs directly detect Thomson scatter of VHF and UHF radio waves at ionospheric heights from 90 km to about 1000 km. The measurements permit reliable estimation of plasma density, temperature, drifts, and major ion composition, and with additional physics, it is possible to estimate electric fields and conductivities. Interconnection of the ISRs in real time through high-speed data distribution networks will enable coordinated high-resolution observations of interrelated regions of Earth's atmospheric system. Modern ISRs have significant data communications and storage needs on site; it is highly desirable to have at least T1 (1.54 Mbps) connectivity to the Internet.

Most ISRs have steerable antennas that permit scanning a three-dimensional volume whose horizontal extent is (roughly) 2000 km. The capital cost of an ISR is approximately \$25 million, and the annual operating cost is on the order of \$1.5 million. Incoherent scatter radars can be operated in remote environments, but they have significant electricity needs to supply the powerful transmitters. Currently, most ISRs require significant staff for maintenance and operations. Workshop participants thought it unlikely that in the near future ISRs would be routinely operated without a human presence.

The Advanced Modular Incoherent Scatter Radar (AMISR) is a good example of a current high-power radar array (see Figure 3.2). AMISR is a phased-array, transportable ISR that is currently being put into operation. It represents a modern, flexible implementation of the ISR technique. AMISR augments and enhances the research capabilities of the current distribution of large ionospheric research radars by combining a powerful, state-of-the-art incoherent scatter radar with supporting optical and radio instrumentation in a transportable format. This flexibility enables the AMISR to study a wide range of ionospheric phenomena at polar, auroral, equatorial, and mid-latitudes and to act in close conjunction with other ground-based, suborbital, and satellite investigations of the geospace environment. The initial AMISR installation at Poker Flat, Alaska, will come on line in 2006.

Medium-Power Radar (Including Coherent Scatter and Meteor Radar)

Medium-power radars operate in the frequency range from a few megahertz to several hundred megahertz using transmitters that typically deliver from 1 to 50 kW of pulsed RF power. The lower power levels and smaller antenna sizes yield sensitivity that is 40 to 60 dB lower than an ISR's sensitivity. Thus, medium-power radars do not have the sensitivity to detect incoherent scatter signals from the ionosphere. Nevertheless, meteor trails, field-aligned irregularities, and plasma frequency reflection provide large scattering cross sections that these smaller radars can detect.

There is a large class of medium-power radars known as "coherent" radars. Generally these radars detect some "coherent" feature whose scattering cross section is much larger than Thomson scatter. At the low-frequency end, medium-power radars interact with the D region and provide estimates of plasma drifts. At higher frequencies, 30 to 150 MHz, coherent radars detect magnetic field-aligned irregularities that are usually created by instabilities associated with electric currents or density gradients in the E (90 to 150 km) and F (150 to 1000 km) regions. Also, meteor ionization trails provide a small, high-density plasma column that can scatter detectable radiation. Plasma irregularities are intriguing in their own right; in the context of DASI these irregularities provide a means of detecting regions of unstable plasma and of tracing mean plasma flow. Careful study of meteor trails also provides information about winds and temperatures in the E region.

Essentially all of the coherent radars can be automated, and most require little, if any, intervention. The cost of medium-power radars is highly variable and dependent on the sophistication of the instrumentation. A fixed-frequency radar operating with a simple fixed beam antenna probably could be developed for under \$50,000. However, most of the existing research instruments have been developed for \$100,000 to \$200,000, and the SuperDARN HF radars that utilize large HF antenna arrays have cost from \$350,000 to \$500,000 depending on site development costs and the extremity of the local wind and weather conditions (Figure 3.3).

The SuperDARN coherent HF radar network is an example of current medium-power radars. It employs nearly identical, largely automated HF radars to observe scattering of plasma irregularities in the E and F regions of the ionosphere. Currently, the network covers most of the northern and southern polar caps, with many of the stations reporting in real time.

The SuperDARN radar system primarily detects F-region irregularities, which are approximately "frozen in" to the mean convection. Although the irregularities are not always present, they are sufficiently ubiquitous to permit production of convection and electric field maps covering the high latitudes. With additional analysis, it is occasionally possible to characterize E-region scatter and gravity wave disturbances. The data rates are relatively low (for integrated data products), although even these

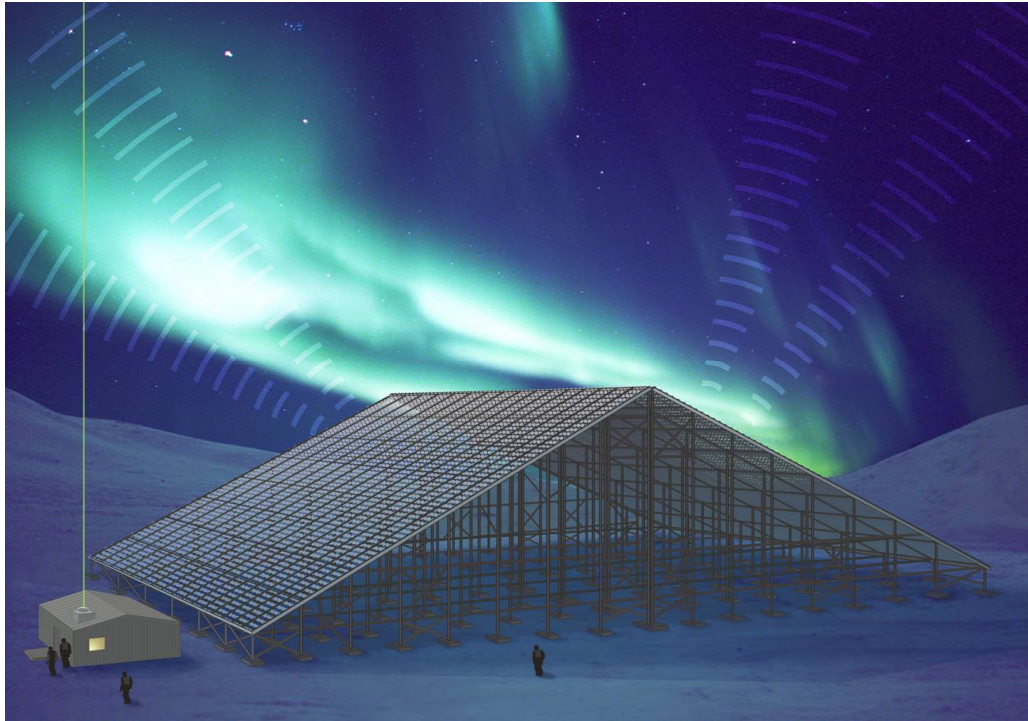


FIGURE 3.2 Artist's concept of the portable Advanced Modular Incoherent Scatter Radar deployed at a high-latitude site to study the response of the upper atmosphere to auroral activity. SOURCE: Courtesy of J. Kelly and C.J. Heinselman, SRI International.



FIGURE 3.3 SuperDARN radar at Stokkseyri, Iceland. SOURCE: Courtesy of Jean-Paul Villain, French National Centre for Scientific Research.

low data requirements can stress communications capacity in Antarctica and Greenland. The SuperDARN network has a disciplined system of collecting and archiving data, an organizational model that may be very useful for DASI to draw on.

Low-Power Passive Radar

In recent years, several technology developments have enabled the creation of “passive” radars for atmospheric research. Passive radar systems are comparable in sensitivity and function to medium-power coherent scatter radars, but they have no dedicated transmitter and instead rely on existing transmitters of opportunity, in particular, commercial FM broadcasts. Systems using a variety of other transmitter types (such as digital TV transmitters) have been demonstrated for aerospace applications. Two passive radar networks for geophysical studies have been established to date and these systems have demonstrated, with high resolution in range (km), time (seconds), and azimuth (<0.1 deg), the detection of ionospheric turbulence, meteor trails, and aircraft. It is likely that such radars will also be able to detect polar mesospheric summer echoes if deployed in the correct location. Passive radars, which are typically operated in networks using several receiver locations separated by 100 to 400 km, provide ionospheric coverage of up to 4000 km² per receiver pair. The network itself may provide significantly greater coverage by using the large number of available transmitters combined with multiple receiver locations.

The operation of passive radar systems differs from the operation of traditional radar systems. As receive-only systems, passive radars require electrical power similar to that of typical computer systems (under 1 kW). They also are characterized by modest antenna deployments (a few small yagi-type antennas) and moderate to high network communication bandwidths (100 kbps, and preferably far greater). The basic modes of operation are well within the capabilities of modern desktop computing systems. However, passive radar systems are most effective when large signal bandwidths are able to be transported over a data network to be analyzed using powerful correlation and signal-processing systems. Passive radar networks can be deployed incrementally to increase spatial coverage; in addition, the capability of these systems improves as more network bandwidth and computational power become available. Passive radar systems are able to operate continuously with very little manual intervention; the typical cost of a passive radar system is currently between \$10,000 and \$50,000 per site, depending on the level of system capability (see Figure 3.4).

For DASI deployment, spaced arrays designed to provide overlapping coverage can be established to monitor the occurrence of strong irregularities due to enhancements of the electric field over wide areas, and thereby provide an inexpensive global electric field monitor.

Ionosondes

Ionosondes are medium-power, frequency-agile radars that operate at high frequency. They provide a means to estimate the bottom-side density profile of the ionosphere by measuring the time of flight of radio waves to the altitude at which the local plasma frequency is equal to the radar frequency. Modern enhancements that include more complex antenna systems permit the study of large-scale waves and mean drifts. Ionosondes require several kilowatts of electricity, and their transmitters must be licensed. Ionosondes use relatively low frequencies, which means that the antennas require considerable space (on the order of 1 hectare), as well as several towers on the order of 20 m. Because they can perform all analysis automatically on site, they require only medium network speeds to distribute their data. In nearly all cases, ionosondes are highly automated. Depending on its capabilities, the cost of an ionosonde may vary from \$40,000 to \$500,000. Existing networks of digital ionosondes provide real-time information in support of developmental ionospheric data assimilation models.

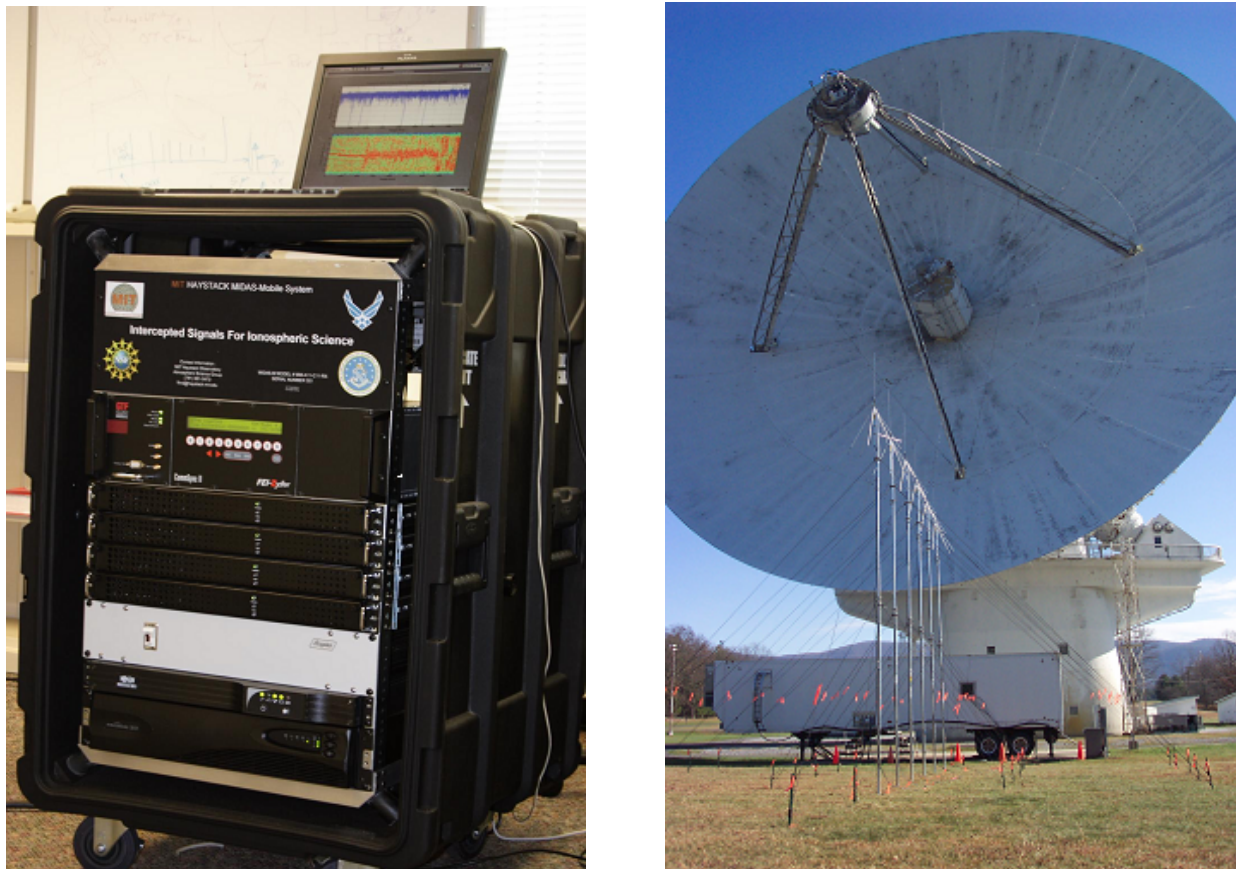


FIGURE 3.4 *Left*, an ISIS receiver deployed in the field at the National Radio Astronomy Observatory (NRAO) at Green Bank, W.Va. Courtesy of Massachusetts Institute of Technology. *Right*, foreground, is the Discone antenna array used by the ISIS node at Green Bank. In the background is the Green Bank 140-ft antenna. Courtesy of Glen Langston, NRAO. NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

The Canadian Advanced Digital Ionosonde (CADI) array is being deployed around the ionospheric projection of the boundary between open and closed magnetic field lines (that is, the polar cap boundary). Each CADI instrument provides two basic types of ionospheric measurements: (1) ionograms that give information about ionospheric electron densities and vertical ionospheric structuring and (2) fixed frequency measurements that measure the Doppler shifts of the reflections and from which ionospheric flows can be calculated. CADI convection measurements have been validated against both SuperDARN convection measurements and velocities inferred from optical measurements of drifting auroral polar cap patches. The temporally continuous CADI data set complements the SuperDARN data set.

Distributed Arrays of Low-Frequency Antennas

The pace of advancements in computational power and network capacity will soon usher in a new era for radio astronomy in the form of next-generation, low-frequency, digital aperture synthesis radio interferometers. In a digital array, the signals from each antenna are digitized and sent to a central

processing facility for simultaneous viewing in multiple directions. Tracking of sources from many locations coupled with sophisticated real-time models of the ionosphere permits the extension of measurements down to previously unexplored low frequencies. Here the instrument itself is a distributed array that might consist of 10,000 dipole antennas distributed in a graduated pattern over 400 km.

At low frequencies, radiation from the sky exhibits temporally and spatially variable propagation delays as it passes through the ionosphere. By using tomographic restoration techniques, it will be possible to construct a precise three-dimensional view of ionospheric electron content on spatial scales and time scales far beyond anything currently available. Study of the plasma structure and variation on many size scales from tens of meters to hundreds of kilometers can advance understanding of the ionospheric response to solar-terrestrial disturbances and space weather events and will provide important input to ionospheric modeling.

MAGNETOMETERS

Arrays of magnetometers have contributed to understanding the ionosphere, magnetosphere, and solar wind ever since the creation of the first global network in the late 1830s. The successors to this first array have allowed researchers to understand geomagnetic storms, substorms, and the coupling of the solar wind with the magnetosphere and of the magnetosphere with the ionosphere. Indices such as K_p , D_{st} , and AE provide a measure of geomagnetic activity, and the study of ULF waves and their propagation enables probing the three-dimensional magnetosphere from the ground. Modern arrays of appropriately spaced digital magnetometers can monitor the plasma density distribution in the magnetosphere as well as help scientists understand the physics of MHD-wave resonance and propagation.

Magnetometer arrays are perhaps the simplest and most easily achieved autonomous instrument platform. Over a hundred ground magnetometer stations currently exist that can be used for space physics research, with a vast majority of these stations located at auroral and polar latitudes. But large swaths of Earth lack coverage, including most of Africa, Russia, South America, and the oceans.

Several autonomous magnetometer arrays are currently in operation, and next-generation autonomous platforms could support magnetometers and other instruments using only solar power and appropriate energy storage units (Figure 3.5). Autonomous data acquisition and communication via Iridium satellite links are also feasible. This type of installation would be intended for cold polar regions where power must be stored for the dark winter. Scientific magnetometers cost around \$10,000 to \$15,000. The need for autonomous low-power instruments for deployment in remote areas could add additional costs from \$30,000 to \$100,000, depending on the environmental requirements.

OPTICAL INSTRUMENTS

Passive Optical Instruments

The upper atmosphere contains atomic and molecular species that, under certain circumstances, can be energized to produce distinctive optical emissions. The most spectacular of these are the auroras, which can be seen with the unaided eye. Because atmospheric processes can take place on global scales, observations from a single site present a very limited view. Much information of great use can be obtained if instrument clusters can be operated as longitudinal and latitudinal chains. Optical observations are carried out most effectively when various types of instruments are operated in close proximity, viewing the same set of phenomena. Passive optical aeronomy has focused on studies of the

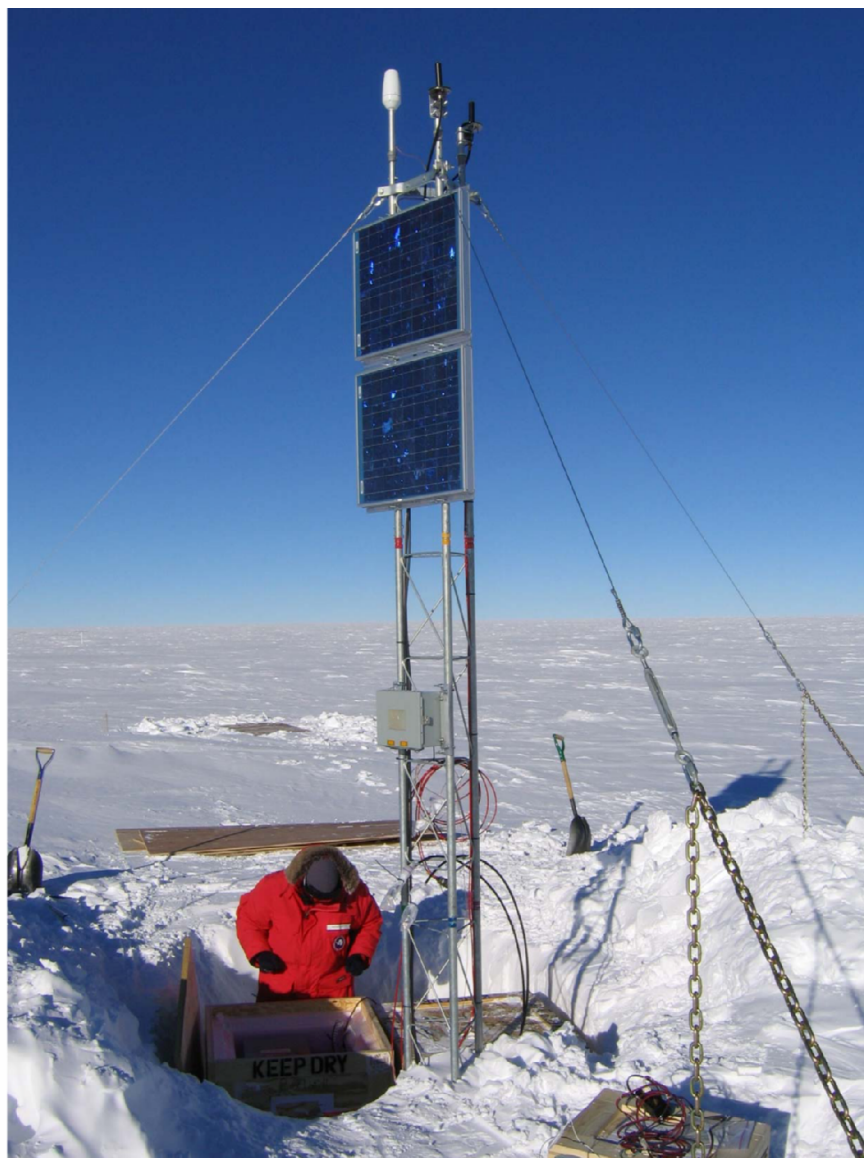


FIGURE 3.5 Installation of a prototype low-power magnetometer at the South Pole. The system is being designed to operate unattended for up to 3 years on the Antarctic plateau. SOURCE: Courtesy of Robert Clauer, University of Michigan.

mesosphere, thermosphere, and geocorona using three types of instruments—the all-sky imager, the Fabry-Perot interferometer, and the spectrograph.

A typical, modern, all-sky imager is a high-performance, solid-state imaging system that can be optimized to gather data indicative of particular kinetic processes occurring at relatively specific ranges of altitude. Imaging systems provide important information about neutral drifts as well as low- and high-latitude coupling through modification of airglow emission by plasma depletions along the magnetic field. The advent of modern digital photon sensors (such as charge-coupled devices) has made automatic operation with prompt reporting possible. Imaging sensors require clear, dark skies, which are achieved in regions with substantial clear weather, and little light pollution from human activities (the latter feature can impede network access).

The THEMIS ground array provides a current example of the synergy of space- and ground-based coordinated studies to address significant auroral-latitude processes (substorms). Program objectives are to utilize arrays of auroral optical imagers and magnetometers to provide real-time coverage of the auroral region across North America in order to locate and time the substorm onsets while simultaneously measuring plasma processes in the tail using a radial chain of satellites. At onset the aurora intensifies and expands, and the magnetic field caused by the ionospheric current intensifies.

The Fabry-Perot interferometer can now be employed in all-sky configurations. Dynamic and thermodynamic properties of the atmosphere can be determined from the Doppler shift and Doppler broadening of the emissions originating from various atmospheric species as a result of chemical reactions. New Fabry-Perot designs are suitable for deployment in low-power autonomous units.

Medium-resolution spectrometers are used to measure spectral bands from emitting species in the upper atmosphere. With a resolution of about 0.1 nm and a suitable low-light-level photodetector, it is possible to determine the rotational temperature of an atmospheric layer that is in thermal equilibrium with a molecular population that is the source of the emission. This is particularly useful in the stratosphere, mesosphere, and lower thermosphere. In most cases, such instruments are usable only for nocturnal and late-twilight conditions. Examples of such instruments include the Ebert-Fastie grating spectrometer, the echelle spectrograph, and the Fourier transform infrared spectrometer. Such instruments are available in automated form capable of unattended operation for extended periods and are able to report data over a network link. Figure 3.6 shows the complement of passive optical instruments deployed at a research site near Stockholm, Sweden.

Active Optical Instruments

It is also possible to probe the upper atmosphere with optical radars, called lidars. These instruments fall in two general classes: Rayleigh lidars, which collect light from the bulk medium, and resonance lidars, which probe individual quantum-mechanical transitions.

The Rayleigh lidars permit estimates of temperature profiles by studying the brightness of the scatter return as a function of altitude, and they are effective at altitudes up to about 75 km. With careful control of the powerful laser's wavelength, some Rayleigh lidars can measure the Doppler shift of the scatter and therefore provide wind estimates for the middle atmosphere. Rayleigh lidars can also provide detection of mesospheric clouds (that is, noctilucent clouds) in which large particles significantly enhance the scatter of the laser light.

Resonance lidars are carefully tuned to probe quantum-mechanical resonances in the medium being sampled. Some resonances are especially bright, particularly for metal ions and atoms. By careful analysis of the spectral emission, it is possible to measure drifts and temperatures in the mesopause region with remarkable precision.

Active optical instruments are somewhat more tolerant of ambient light than are the passive systems. However, using currently available technology, precision optical systems and very-high-power laser emitters do not lend themselves to unattended operation. Although data network requirements usually are not large, the site costs for such systems can approach \$1 million.

SOLAR MONITORING INSTRUMENTS

Ground- and space-based observations of the Sun and the heliosphere are complementary. Above Earth's atmosphere, observations can be made at ultraviolet, X-ray, and gamma-ray wavelengths, and direct measurements can be made of the flux of energetic particles that make up the solar wind and solar flares. However, space-based instruments must be defined years to decades in advance, and repair and modification normally are not possible. In contrast, ground-based instruments can use state-of-the-art technology and can be configured and optimized for problems of current interest.



FIGURE 3.6 Instruments deployed in the field at Sandkullen, Sweden. *Left:* Ebert-Fastie spectrometer with an extremely high throughput that usually operates in the ultraviolet (instrument on loan from Johns Hopkins University). *Right:* A set of filter photometers that measure the atomic oxygen green line, molecular oxygen A-band, and hydroxyl radical Meinel band in the visible and near IR (as well as the scattered mercury green line at 540.6 nm and relevant continua). SOURCE: Stockholm University Department of Meteorology optical site at Sandkullen, Sweden. See <www.misu.su.se/~jacek/Ground/optsite.html>.

Ground-based optical, infrared, and radio observatories enable the study of the photosphere, chromosphere, and corona of the Sun with a spatial resolution and time span that cannot be duplicated from space platforms. In addition, high-temporal- and/or high-spatial-resolution observations in some cases require prohibitively large telemetry rates for satellite transmission, an issue that is largely avoided by ground-based observations. Ground-based instruments can also be deployed for a fraction of the cost of their space-based counterparts and can be maintained and upgraded for decades to provide the long time-series of observations required for understanding and ultimately predicting the solar cycle, solar variability, and the impacts these changes have on Earth.

Workshop participants noted two particular advantages that would be derived from deploying arrays of ground-based instruments across Earth:

- *Spatial distribution*—In certain types of observations, the terrestrial location of the detection encodes information. For such observations, a widely distributed array of detectors is necessary to provide a broad field of view or to provide a wide range of energy sensitivity. Using Earth's magnetic field as a spectrometer, the energy and direction of incoming solar or galactic energetic particles determine the location on Earth where the particles' secondary products can be detected by a ground-based neutron monitor. Measuring the energy-resolved anisotropy of these particles requires an array of detectors covering a range of latitude and longitude.

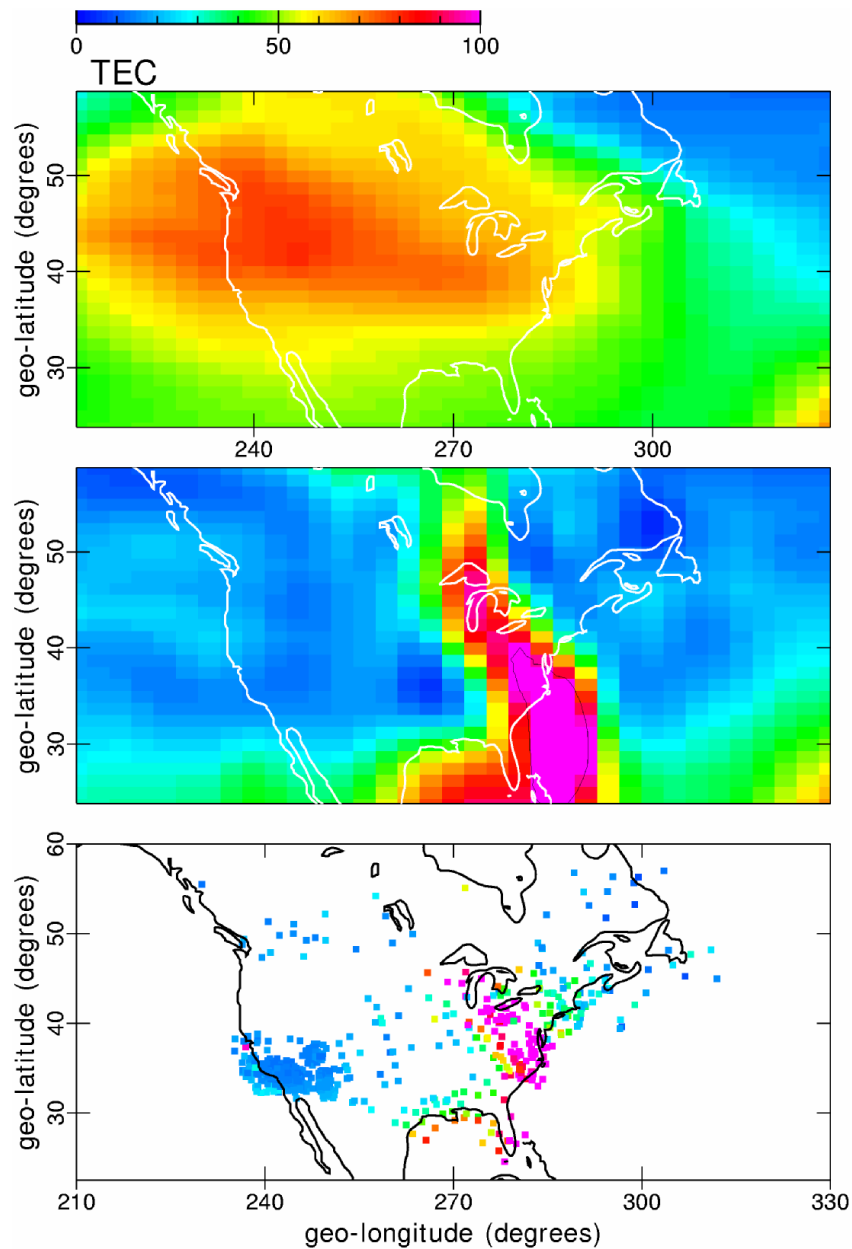


FIGURE 3.7 Data assimilation: a snapshot reconstruction of ionospheric total electron content for the geomagnetic storm in November 2003 shows (top) the output from a physics-based ionosphere forecast model with no data assimilation, (bottom) the measured TEC assimilated into the Utah State University GAIM data-assimilation model, and (middle) the final reconstruction combining the climatological background with the event-specific observations. SOURCE: Courtesy of J. Sojka, Utah State University.

- *Continuous temporal coverage*—Distributed ground-based arrays are particularly suited for studies of the Sun that require long, continuous temporal coverage. Because such coverage is not possible from any single terrestrial vantage point, these types of observations require a globe-girdling chain of detectors. This capability is of particular importance for studies, such as in helioseismology, where periodic data gaps are detrimental to frequency resolution. It is also critical for capturing the key stages of solar dynamics. For example, a single ground-based facility cannot be used to study the complete emergence of an active region, because this process takes 24 hours or more. On the other hand, CMEs and flares are each brief enough that individual events can be observed from a single vantage point. However, since a single ground station would observe for only part of the day, all or part of these dynamic events could be missed. Furthermore, observing conditions preceding, during, and following CMEs and flares are vital to understanding these events, each of which is unique. Ground-based observations will be the only resource for white light coronagraph observations of CMEs once existing space-based coronagraph missions end (~2008). Although such solar activity monitors would necessarily be relatively large systems, only three to six would be needed for full temporal coverage. Distributed arrays dramatically increase the continuity of temporal coverage by maximizing observing time and minimizing the loss of observations due to weather conditions.

DATA-ASSIMILATING COMPUTER MODELS

Although not instruments per se, computational models linked to observational data are a key requirement for major advances in upper atmosphere research and in space weather “nowcasting” and forecasting. Computational models can employ increasingly accurate mathematical representations of the physics of the upper atmosphere, both in the detail of theory and in the temporal and physical resolution of the medium. By including data assimilation in the modeling algorithms, it is possible to evaluate the models with real-time input from geographically distributed sensors. The underlying mathematical physics models can provide excellent results if they are constrained by well-distributed data (see Figure 3.7).

These modeling efforts provide key technology guidance for the development of new instrumentation for DASI. The most useful data input to the models is not necessarily that of very-high-resolution measurements made at a few locations. Instead, the computational models readily accept lower-resolution data that has wide spatial coverage and continuity in time.

4

Infrastructure Issues

Presentations and discussions at the workshop highlighted the complexity of issues related to the design, development, and implementation of the DASI concept. The following sections illustrate the range of topics that will require careful attention as plans for DASI move forward.

INFORMATION TECHNOLOGY

Successful implementation of the DASI program will require development of cyber infrastructure to enable the requisite coordination and communication among widely distributed sensors and research facilities. Sensors sample at different rates, are distributed at various locations, and are often operated by different groups and organizations. Furthermore, an analysis and data access and distribution program linked to modeling and computer simulation activities is necessary to provide closure between measurement and theory. In some cases, significant data processing is required to obtain the physical parameters required for assimilation in models. Many workshop participants emphasized that the development of tools that facilitate location, retrieval, and analysis of geophysical data from different instruments, locations, archives, and catalogs worldwide must be a central tenet of the DASI infrastructure requirements. These cyber tools also need to allow for real-time comparisons between simulations, models, and observations. When fully implemented, DASI should enable researchers to assimilate and interpret data in order to specify near-instantaneous space weather conditions, and possibly predict future conditions based on the “nowcast.”

The emergence of new data sets that result under DASI will add to the volume of experimental data that has been increasing significantly in recent years. Already there are new magnetometer chains, new polar orbiting satellites that allow a simultaneous view of the southern and northern polar regions, new ionospheric radars (SuperDARN, AMISR, and EISCAT), new instruments for making mesospheric/thermospheric wind measurements (via meteor radars, Fabry-Perot interferometers), and new digisondes to gather total ionospheric electron content data. Thus, workshop participants agreed that opportunities now exist to begin to create hardware and software cyber tools capable of studying the coupled elements of geospace as a single system. A framework is needed that can utilize DASI observations and other available geospace data and be flexible enough for the creation and inclusion of new data sets. Several general principles regarding key elements of an information system framework emerged from workshop discussions:

- Data must be simple to find, simple to query, and simple to download.
- Development of analysis tools must begin with the consideration of the needs of users.
- Ideally, the entire distributed instrument array should appear to a user as a single instrument, that is, as a DASI virtual observatory.

The Virtual Observatory Concept

The solar and astronomical communities have spearheaded the virtual observatory concept, and that prior experience provides an excellent starting point and template for DASI. Virtual observatories can be built in several ways. A top-down approach has been most common to date. In this paradigm, specialized computer code enables access to diverse underlying data sources, providing a single user interface to all end users. A fundamental problem is that this approach does not scale well. A bottom-up approach starts with the development of standards for extracting geophysical measurements. These standards are defined as succinctly as possible, describing what data are available. As an example, the National Virtual Observatory for optical astronomy created a system in which the vast astronomical archives and databases around the world, together with analysis tools and computational services, are linked together into an integrated facility. Exploitation of the virtual observatory is facilitated by the development of standard protocols that, for example, allow searches of the observatory databases and return catalog entries for a specified location and search radius on the sky, or pointers to sky images given similar selection criteria.¹

Many lessons regarding database management from groups such as CEDAR will also be useful to the DASI program. For example, a very simple description of a standard file format is not sufficient. The standard must include well-defined measured parameters and a method for easily adding new parameters. Well-defined standards for specifying position and time, as well as standards for converting between frames of reference, are essential. The standard must expose summary data in a consistent way as well. While such a standard may seem burdensome at first, it is beneficial to data providers. The distributed instrument array is a natural platform for this data-standard approach. Thus, a major DASI infrastructure goal is to provide an easily accessible geophysical data set from combined instrumentation and arrays by incorporating standard tools such as

- Standard toolkits to expose data, for example, a Web site cyber toolkit; and
- Standard toolkits for exporting the data to other formats, for example, Matlab and Interactive Data Language.

Virtual Observatory Web Portal

Once data are acquired from various arrays, the utilization of the data by the broader geoscience community is the next concern. Many types of data are stored by different instrument operators in a variety of formats. Web technologies now are able to recognize the various data formats and obtain data from user-selected stations and then supply that data to the user or provide plots in a preferred digital format. Using a single Web portal to geophysical data, the user should be able to identify the type of data, network, or station location and to obtain the combined set of data in the specified format. There are a variety of virtual observatory projects in development to implement Web portals to do this.

The virtual observatory Web data portal will allow transparent and seamless integration of distributed related data sets into a systems view. This will be true of magnetometer networks, image networks, and global radar networks, among others. Rather than being another data archive, the virtual observatory will be a Web-based cyber tool that permits researchers to easily access data from multiple distributed databases with the following attributes:

- Development of a virtual repository for data and models as well as a network to facilitate collaborations;
- Collection and organization of data within a unified database structure;

¹ See “U.S. National Virtual Observatory” on the Web at <www.us-vo.org/about.cfm>. For more detail, also see the International Virtual Observatory at <www.ivoa.net/pub/info/TheIVOA.pdf>.

- Standardization of the format for input of newly collected data;
- Testing and validation of new data with mass balance and statistical approaches;
- Utilization of visualization for quantitative understanding; and
- Integration of the cyber-networked infrastructure architecture to facilitate user access.

Internet/Computer Grid Technology

Grid technology is providing a powerful new open, Internet-based infrastructure that combines the resources of multiple sites and that includes unprecedented computing power and storage, as well as specialized data analysis and visualization resources, all of which are connected via a dedicated high-speed national network.² Although grid technology is still evolving, it should be open to all researchers since the Internet is now available to almost all scientists. The seamless sharing of data is one possibility and is potentially one of the main infrastructure goals of the DASI program. The creation of visualization tools that can utilize globally distributed data sets will push the limits of current technologies and could spark the creation of new grid functions. In addition, enabling the convergence of data and models is another strong goal of grid technology that is synergistic with DASI program goals. Grid technology has the potential to supply the underlying infrastructure for connecting the thousands of data-collecting instruments, analysis tools, and modeling computers that are integral to the DASI concept.

Communication Infrastructure Needs

The science objectives of DASI will determine whether real-time communication is a necessity for all instruments at all sites. Instruments and sensors on the Internet or grid can be easily accessed and controlled from remote locations, and workshop participants discussed how this capability could form the backbone of the virtual observatory paradigm. However, participants noted that developing the capacity for Internet access to remote sensors will also be critical to the success of DASI.

Acquisition of near-real-time data from remote polar stations is already possible and is being accomplished by the Automated Geophysical Observatory team from its Antarctic stations.³ An Iridium-based data acquisition system is used, providing 20-megabytes/day data throughput (7 GB/year, 98 percent on duty cycle). This system could provide an immediate communication solution for remotely fielded DASI instruments. To address remote communications needs in the future, initiatives to develop communication capabilities on microsattellites may be necessary. Participants envisioned microsattellites with UHF transmission compatible with ARGOS,⁴ but with enhancements such as significantly higher bandwidth, two-way delay-tolerant communication, and Internet-Protocol-like message packaging.

WiMax is an emerging technology with a potential for enabling high-speed connections between clusters of instruments.⁵ A single WiMax base station with a connection to the Internet will be able to provide very-low-cost, high-speed connectivity to instruments within a 50-km radius. Base stations can be connected together to extend the size of the cluster even further.

A possibility for improving data coverage over the sparsely connected oceans would be an extension of the World Meteorological Organization's Voluntary Observing Ships Scheme to include instruments such as GPS receivers.⁶ Currently more than 4000 ships worldwide transmit meteorological data on a regular basis using their own satellite communications equipment.

² See <www.teragrid.org/about/>.

³ See <sprg.ssl.berkeley.edu/atmos/ago_science.html>.

⁴ See <noaasis.noaa.gov/ARGOS/>.

⁵ See <www.intel.com/netcomms/technologies/wimax/>.

⁶ See <www.vos.noaa.gov/vos_scheme.shtml>.

INSTRUMENT DEPLOYMENT AND LOGISTICS

Instrument Spacing and Array Sizes

Workshop discussions highlighted the point that science goals will drive DASI infrastructure requirements related to the physical placement and distribution of instruments. The fundamental science grid size (spacing of instruments needed to achieve science goals) can vary greatly, as the examples in Table 4.1 illustrate.

TABLE 4.1 Examples of Varying Measurements and the Grid Size Required to Achieve Them

Instrument or Measurement	Preferred Spacing or Coverage
Magnetometer observations	100-km grid
SuperDARN ionospheric radars	3 sites for complete coverage of the United States
GPS and optical measurements	100-km grid (GPS); 1000-km grid (optical)
Solar measurements	3 to 6 instruments for continuous coverage

Speakers also noted that any desired science grid size and spacing must be considered within the context of practical operational limits. The science benefit must be balanced against the logistics and overall operations budget as well. It is also important that planning for DASI not be done in isolation. In an effort to understand the global dynamical response, DASI should be well coordinated with existing distributed instrument arrays. (Included here should be Antarctic arrays monitoring the southern polar cap and auroral zones, CARISMA (previously CANOPUS) and MACCS in Canada, and the PENGUIn and the BAS/LPM Japanese stations in the south. Other aspects pertaining to existing and future arrays that workshop participants identified for further consideration included the following:

- Status of existing arrays and whether the arrays will be operational in the future,
- Resources needed for coordinating existing arrays,
- Scale sizes for different instruments and science drivers, and
- Communication infrastructure needed to coordinate subarrays of the DASI system.

Logistics of Instrument Placement

The placement of instruments at populous locations worldwide can be easy and straightforward. Colleges and universities are usually willing to host experiments and provide instrument oversight and Internet access. Discussions at the workshop envisioned hundreds of DASI-related instruments throughout the United States and Canada. However, only a limited number of attended sites and/or towns in remote locations—in the Arctic and Antarctic—would be possible. The need for additional instrument sites together with the practical limitations of supporting additional attended observing stations at high geomagnetic latitudes has led to the development of remote observatory programs by many countries, including the United States, Britain, and Japan. The learning curves have been steep in the development of autonomous systems capable of operating successfully in the extreme polar environments, but such facilities should be available to DASI in the near future.

Polar Deployment

The polar region is one of the most important regions of geospace, because the direct connection between the solar wind and the magnetosphere can be measured within this region. The asymmetry with respect to Earth's rotation axis introduces asymmetry in the distribution of various parameters and the characteristics of the two polar ionospheres even during equinox conditions. For that reason workshop participants noted that it is necessary to investigate both polar regions in an inter-hemispheric, coupled context in order to achieve the global understanding of the geospace system required for accurate modeling of space weather.

The workshop highlighted a great need for distributed autonomous Antarctic instrument arrays that can operate in the extremely cold and isolated polar environment. A technological challenge for the DASI program will be to deploy a sufficient number of autonomous systems in both polar regions at an affordable cost. Autonomous systems are obviously more expensive than instrument clusters placed at developed sites, because they must have special instrumentation for storing and generating electricity throughout the year. In addition, instrumentation has to use as little power as possible. Finally, deployment costs are much higher in such remote site locations. Because of the cost and danger of travel to remote sites for data retrieval, data links via satellite communication must be included in the design of polar instrument arrays.

Systems for remote environments should be designed for unattended operation for a period of at least 2 years and possibly longer, have real-time remote data retrieval, provide at least 2 years' worth of on-site data backup, and be suitable for the environmental conditions in which they are intended to operate.

5

Summary of Principal Workshop Themes

As the decadal survey and other related NRC reports have noted, understanding and monitoring the fundamental processes responsible for solar-terrestrial coupling are vital to being able to fully explain the influence of the Sun on the near-Earth environment.¹ These studies emphasize that monitoring the spatial and temporal development of global current systems and flows; the energization and loss of energetic particles; and the transport of mass, energy, and momentum throughout the global magnetosphere is essential to achieving this scientific goal.

At the workshop speakers argued that DASI will be the culmination of decades of discipline-related local instrument development that has pursued aspects of solar-terrestrial science at the subsystem level. With the advent of the Internet and affordable high-speed computing, these local deployments can become elements of a global instrument system. When different instrument techniques are then combined to observe all aspects of the physical system, the DASI concept will be realized.

Proponents of the DASI concept emphasized at the workshop that DASI's strength is that it offers a cost-effective means of performing original and critically important science, with a development strategy that allows resulting new knowledge to enable and flow into future initiatives. DASI will complement and extend the capabilities of the next generation of space-based research and space weather instruments by providing a global context within which to understand in situ and remote sensing observations. Other strengths of the DASI concept cited by various speakers and splinter groups included the following:

- Ground-breaking science, enabled by distributed global measurements that allow researchers to continually gauge the role of solar-terrestrial processes;
- The enablement of global modeling initiatives, which have long suffered from the lack of availability of data that specifies the space environment on appropriate spatial and temporal scales;
- The ability to combine resources within different DASI projects to save cost, streamline schedules, and provide a more standard analysis environment for a broad user base;
- A gradual development time line, allowing the optimization, co-development, and eventual upgrading of investigations at a reasonable cost to the sponsoring agencies;
- The continued development and enablement of distributed data analysis environments and virtual observatory initiatives, which are an expensive yet fundamental part of the infrastructure of all investigations;
- International cooperation in a flexible environment that allows researchers from around the globe to participate and contribute to the benefit of the entire international scientific community; and
- Renewed enablement of programs that provide exposure and experience to graduate students and other young scientists, thus preparing the principal investigators of the future.

¹ National Research Council (NRC), 2003, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C.; NRC, 2004, *Plasma Physics of the Local Cosmos*, The National Academies Press, Washington, D.C.

With respect to education and public outreach, workshop participants often made the point that distributed arrays of instruments are inherently well suited to provide opportunities in education, public outreach, and workforce development. Because they are well distributed, have required infrastructure such as power and Internet access, and are home to scientifically knowledgeable staff, secondary schools, community colleges, and small colleges are logical sites for many or most DASI instruments. The instruments themselves provide an opportunity for training in advanced instrumentation techniques and design and could be a focal point for science classes. This would greatly enhance student and public awareness of space weather and its impact on society. Internet access to data from the entire array further enhances the educational value of DASI, for example, by introducing students to distributed computing and space-weather modeling. Participation in DASI can provide research opportunities for faculty at non-research institutions and could enhance faculty members' ability to apply for research grants. Furthermore, participation in DASI would encourage students to consider careers in technology, science, and information technology by directly involving them in these areas at an early stage.

NEXT STEPS

The NRC solar and space physics decadal survey report recommended that “the relevant program offices in the NSF should support comprehensive new approaches to the design and maintenance of ground-based, distributed instrument networks, with proper regard for the severe environments in which they must operate” (p. 12).

The DASI workshop participants discussed a number of areas in which the space research community can begin an organized effort to develop a coordinated space-research instrumentation system. Although consensus priorities were neither sought nor identified, the following ideas were especially prevalent in approaches discussed during the sessions:

- Hold community workshops to address in greater detail the instrumentation, science, and deployment issues associated with DASI.
- Identify areas in which existing and planned instrument arrays and clusters can share technology, data distribution architectures, and logistics experience.
- Consolidate currently planned systems to form a regional implementation of next-generation coordinated instrument arrays.
- Establish closer connections with other research communities that are developing similar distributed instrumentation systems.
- Coordinate efforts in the U.S. community with similar international efforts.
- Move toward developing rugged, miniaturized instruments that use a common data format.
- Support efforts to establish standards for data communication technologies and protocols.
- Work with agency sponsors to begin a phased implementation of the DASI program.

Achieving the science objectives for DASI will require a global deployment of instruments and a large commitment of resources. Although the workshop did not go into detail on the areas of collaboration or opportunities to be pursued, participants felt strongly that international collaboration should be a fundamental part of the DASI plan.

Appendixes

A Statement of Task

Background The 2002 NRC report *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, recommended that the next major ground-based instrumentation initiative be the deployment of arrays of space science research instrumentation. Such arrays would provide continuous real-time observations of Earth-space with the resolution needed to resolve mesoscale phenomena and their dynamic evolution. In addition, ground-based arrays would address the need for observations to support the next generation of space weather data-assimilation models.

Science Issues

Mesoscale and spatially and temporally localized processes and effects play a significant role in the interconnection between the high-altitude magnetosphere and Earth's ionosphere and lower atmosphere. The various latitude and altitude regimes of Earth-space constitute a highly coupled system. Advances in understanding these regions require widely distributed, continuous observations capable of high spatial and temporal resolution.

Of particular interest because of its influence on “space weather” and effects on Earth is the plasmasphere boundary layer (PBL). The PBL separates the cold plasmas of the inner magnetosphere from the hot particles and solar-driven dynamics of the auroral regions. Dramatic boundary-layer physical processes have been discovered in this region, and these are both highly structured and variable in their spatial and temporal occurrence characteristics. Electric fields unique to the PBL lead to plasmasphere erosion, which distributes the thermal plasmas of the inner region throughout the mid, high, and polar regions of both the ionosphere and magnetosphere. These thermal plasmas constitute a source for the energetic plasmas of the magnetosphere and control many magnetospheric processes. Ionospheric feedback through modification of electric fields alters the development of the magnetospheric ring current which is important for the evolution of geomagnetic storms.

The inner regions of the system, consisting of the low-latitude ionosphere and overlying plasmasphere, exhibit large-scale structure whose causes are not understood. The sources and effects of the causative electric fields are to be investigated. All of these processes and phenomena have significant space weather consequences. Plasma and electric field gradients drive scintillations, and the thermal plasma structures affect the precision of radio navigation.

A partial list of the scientific drivers for the deployment of distributed arrays of small instruments follows:

- Temporal/Spatial Variability of Mesoscale Global Structure in Thermal Plasma, Electric Fields, and Currents
- 3-D Tomography of Plasma Structure
- Distribution of Currents Interconnecting the Magnetosphere and Ionosphere near the PBL
- Continuous Observations That Provide a New Perspective of the Ionosphere-Magnetosphere

- Imaging SAPS Electric Field (2-D) over broad Spatial Regions
- Evolution and Effects of Undershielded Disturbance Electric Fields which Penetrate to Equatorial Latitudes
- Resolution of Longitudinal Asymmetries and Regional Perturbations
- Thermal Plasma Source to Magnetosphere
- Space Weather Effects of Thermal Plasma
- Relationship of Electric Fields, Particle Precipitation, and Thermal Plasma Structuring in Driving Scintillations
- Causes and Evolution of Plasmaspheric Structure

Instruments

Deployment of DASI will require the development of miniaturized and robust instruments and instrument clusters, real-time communication capabilities, and a system to distribute the resultant data to a wide variety of users. A partial list of the types of instruments that could contribute to space weather distributed arrays includes the following:

- Broad-Band Radio Receivers: GPS TEC, Scintillation, Tomography, VLF
- Passive Radar: Intercepted Signals from non-dedicated transmitters (FM, e.g.)
- Magnetospheric monitors: global, high-time-resolution magnetometers, riometers
- Active Radio: Digisonde, Small Radar
- Optics: All-Sky Imagers, Interferometers (neutral atmosphere dynamics)
- Riometers and Neutron Monitors for Particle Fluxes
- Solar Monitors
- Enhanced Real-Time Communications and Analysis

Plan The Space Studies Board Committee on Solar and Space Physics will organize a 2-day workshop to explore the scientific rationale for such arrays, the infrastructure needed to support and utilize them, and proposals for an implementation plan for their deployment. The committee will summarize workshop discussions in a short report. This report will not make any recommendations.

B **Workshop Agenda and Participants**

AGENDA

Tuesday, June 8, 2004

8:30 am	Session I: Scientific Drivers for DASI	Chair: Jan Sojka
	DASI Overview and Plan of Meeting	John Foster
9:00	Science Drivers	
	Ionosphere/Magnetosphere	John Foster/Michael Kelley
	Thermosphere	Maura Hagan
	Solar	Jack Harvey
	Space Weather	Louis Lanzerotti/Odile de la Beaujardiere
	IHY Connections	Barbara Thomson/Justin Kasper
	Review of Community Input	John Foster
10:45	Workshop Open Discussion	
11:45	Chair's Summary of Session	
12:00 pm	Lunch	
1:00	Session II	Chair: Mark Moldwin
	NSF Perspective	Richard Behnke
1:15	Instrumentation	
	Magnetometers	Mark Moldwin
	Distributed Radar Arrays	Ray Greenwald
	Next-Generation Radio Instruments	John Sahr/Frank Lind
	Optical Instruments	John Meriwether
2:15	Workshop Open Discussion	
3:00	Chair's Summary of Session	

3:30	Logistics and Infrastructure Needed to Support DASI IT Considerations Remote Siting/Severe Climates Communications	Chair: Mike Kelley John Holt Alan Weatherwax Bob McCoy
4:30	Workshop Open Discussion	
5:15	Chair's Summary of Session	
5:30	Summary of Day 1 Activities Writing Assignments	John Foster/Bob Schunk
5:45	End Session	

Wednesday, June 9, 2004

8:30 am	Session III: Discussion/Writing Breakout sessions (compilation of written material) Science Facilitated by DASI Instrumentation Considerations Infrastructure and Logistics	Jan Sojka John Sahr Mike Kelley
10:45	Review of Workshop Findings	Subgroup Chairs
11:00	Working Group Discussion Outline of DASI Report Follow-On Writing Assignments	John Foster
12:00 pm	End of Formal Working Group Meeting	
12:15	Lunch	
1:00	Small Group Writing Sessions Working Group members invited to participate in afternoon writing session	

PARTICIPANTS

Claudia Alexander, CSSP, NASA Jet Propulsion Laboratory
Richard Behnke, National Science Foundation
Jim Burch, CSSP, Southwest Research Institute
Joan Burkpile, High Altitude Observatory, National Center for Atmospheric Research
Odile de la Beaujardiere, Air Force Research Laboratory

John Foster, CSSP, Massachusetts Institute of Technology
Ray Greenwald, Johns Hopkins University Applied Research Laboratory
Maura Hagan, High Altitude Observatory
Jack Harvey, National Solar Observatory
John Holt, Massachusetts Institute of Technology
Justin Kasper, Massachusetts Institute of Technology
Mike Kelley, Cornell University
Paul Kintner, Cornell University
Lou Lanzerotti, New Jersey Institute of Technology
Frank Lind, Massachusetts Institute of Technology
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John Sahr, University of Washington
Bob Schunk, CSSP, Utah State University
Jan Sojka, Utah State University
Barbara Thomson, National Aeronautics and Space Administration
Alan Weatherwax, Sienna College

C

Biographies of Committee Members and Staff

JAMES L. BURCH, *Chair*, is vice president of the Southwest Research Institute Instrumentation and Space Research Division. Before joining the institute in 1977, he was a NASA space physicist for 6 years. As an investigator in a number of spaceflight experiments, Dr. Burch has achieved a prominent reputation in the fields of upper atmosphere geophysics and space plasma physics. In 1996 he was selected as the principal investigator for the NASA Imager for Magnetopause-to-Aurora Global Exploration investigation, which provided the first-ever global images of key regions of Earth's magnetosphere as they respond to variations in the solar wind. SwRI led the team of researchers from eight U.S. and five foreign institutions selected to participate in the IMAGE project. Dr. Burch was elected a fellow of the American Geophysical Union in recognition of his work in the field of space physics aeronomy, including research on the interaction of solar winds on Earth's magnetosphere and the physics of the aurora.

CLAUDIA ALEXANDER is a space plasma physicist at the Jet Propulsion Laboratory. She does research on comets and on the exosphere of Jupiter's moon Ganymede. She serves as both the project scientist and project manager of the NASA contribution to the International Rosetta mission and has recently served as the project manager of the Galileo mission (until its demise). She began her research career with a study of the thermal history of Ganymede while an undergraduate at the University of California, Berkeley. She continued research at the University of California, Los Angeles, on the solar wind and the solar wind interaction with Venus. She completed a Ph.D. in space plasma physics (gas kinetic theory) at the University of Michigan in 1993, where she wrote a numerical model of the process of expansion of gases from a comet nucleus. Dr. Alexander's community interests include contributing to a NASA-sponsored, Internet-based, public science learning tool entitled "Windows to the Universe."

VASSILIS ANGELOPOULOS is a research physicist at the Space Sciences Laboratory, University of California, Berkeley. In 1999, he was a member of the Science and Technology Definition Team for NASA's Magnetospheric Constellation; he has also served as a member of the Science Definition Team for NASA's Geospace Multiprobes. Dr. Angelopoulos's awards and honors include the 2001 Macelwane Medal, conferred by the American Geophysical Union in recognition of significant contributions to the geophysical sciences by young scientists; the 2000 Zeldovich Medal, conferred by the Russian Academy of Sciences and COSPAR to recent Ph.D. recipients for excellence and achievement; and the 1994 Fred Scarf Award, conferred by AGU's Space Physics and Aeronomy Section for the best Ph.D. thesis in that section.

ANTHONY CHAN is an associate professor in the Department of Physics and Astronomy and a member of the Rice Space Institute at Rice University in Houston, Texas. Dr. Chan received his Ph.D. from Princeton University in 1991. His area of expertise is in theoretical plasma physics with an emphasis on space and astrophysical plasmas. Dr. Chan's research involves the study of sources, losses, and acceleration mechanisms of relativistic electrons in Earth's magnetosphere as part of the National Space Weather Program and the NSF Geospace Environment Modeling (GEM) Program. He is also working in collaboration with NASA astronaut Dr. Franklin Chang-Diaz and his team in the Advanced Space Propulsion Laboratory at the Johnson Space Center to develop plasma rocket technology for NASA's

interplanetary mission. He is also performing medical research in collaboration with anesthesiology researchers. Other research that Dr. Chan is involved with covers the use of phase-space Lagrangian Lie transform methods to derive new relativistic kinetic transport equations.

JAMES F. DRAKE is currently a professor in the Department of Physics and the Institute for Physical Science and Technology at the University of Maryland. His work is currently focused on magnetic reconnection with space physics applications and turbulence and transport with applications to the magnetic fusion program. Dr. Drake is a fellow of the American Physical Society and was the recipient of a Humboldt Senior Scientist Research Award.

JOHN C. FOSTER, *Committee Writing Team Leader*, is a group leader with the Atmospheric Sciences Group at the Millstone Hill Observatory, and he is associate director of the Massachusetts Institute of Technology's Haystack Observatory and a principal research scientist. Dr. Foster's research interests are in the physics of the magnetosphere, ionosphere, and thermosphere. Topics of particular interest include magnetosphere/ionosphere/atmosphere coupling, incoherent scatter radar, plasma waves and instabilities, ionospheric convection electric fields, and cleft and high-latitude phenomena. Dr. Foster previously served as a member of the National Research Council's (NRC's) U.S. National Committee for the International Union of Radio Science (ex officio, 1999-2002) and the Committee on Solar and Space Physics: A Community Assessment and Strategy for the Future (2001-2002). He also served as a member of the Committee on Solar-Terrestrial Research (1988-1991).

STEPHEN A. FUSELIER, a researcher at Lockheed Martin Advanced Technology Center, has been involved with the development of the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) spacecraft since its inception. He is currently a co-investigator on two instruments onboard IMAGE: Far Ultraviolet (FUV) imagers and the Low Energy Neutral Atom (LENA) imager. He is also the lead U.S. investigator on the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) on the joint European Space Agency/NASA Rosetta mission. Dr. Fuselier is an author or co-author of more than 60 scientific publications, is a fellow of the American Geophysical Union (AGU), and was the 1995 recipient of the AGU James B. Macelwane Award.

SARAH GIBSON is a scientist at the High Altitude Observatory of the National Center for Atmospheric Research. Dr. Gibson's interests are in the role of the large-scale solar coronal magnetic field in both stable and dynamic coronal structures, and in the connections between the multiple heights and scales on which these structures are observed. To that end, she has interpreted observations using theoretical models of coronal force balance. Dr. Gibson's current research focus is on coronal mass ejections—the eruptions of large amounts of matter from the Sun's outer atmosphere that can affect sensitive electronics systems on and orbiting Earth. Her recent work has focused on sigmoidal magnetic fields. These twisted, S-shaped fields may be precursors to coronal mass ejections and are under study to determine if they can be used as tools for forecasting severe geomagnetic storms. Dr. Gibson is the recipient of several awards and honors. She was a committee member for the Solar Physics Division of the American Astronomical Society.

CRAIG KLETZING is an associate professor in the Department of Physics and Astronomy at the University of Iowa. Prior to joining the University of Iowa in 1996, he was a research associate professor at the University of New Hampshire. He also held a visiting appointment at the Max-Planck-Institut fuer extraterrestrische Physik in Garching, Germany, in 1993 and 1994. Dr. Kletzing's research interests lie in the area of experimental space plasma physics, and he has been a principal or co-investigator on several sounding rocket and satellite projects. He is particularly interested in the particle acceleration processes in the auroral zone. As part of this research he is working on laboratory plasma experiments to verify theoretical space plasma models in a controlled setting. In addition he has worked on particle transport problems in the magnetosphere and on the effects of lightning on the lower ionosphere.

GANG LU is currently a scientist in the Terrestrial Impacts of Solar Output section of the High Altitude Observatory at the National Center for Atmospheric Research. Her primary research covers high-latitude ionospheric electrodynamics and ionosphere-magnetosphere interactions. Dr. Lu serves as the scientific discipline representative to the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). She is a member of NSF's Geospace Environment Modeling (GEM) Steering Committee and a member of the Auroral Plasma Physics Working Group at the International Space Science Institute. She is the associate editor for the *Journal of Geophysical Research*, was elected as the secretary for the aeronomy section of the AGU SPA, and is the author of more than 70 peer-reviewed research papers. Dr. Lu received her Ph.D. in space physics from Rice University in 1991.

BARRY H. MAUK is a physicist and section supervisor in the Applied Physics Laboratory at Johns Hopkins University. Dr. Mauk's professional service includes study scientist for NASA's Living with a Star Geospace Program; principal investigator for the Auroral Multiscale Midex mission, selected for Phase II consideration, January 1999; co-investigator with NASA's Voyager Low Energy Charged Particles Investigation and NASA's Cassini Magnetospheric Imaging Instrument Investigation; team member of the Galileo Energetic Particle Detector investigation; and instrument scientist on the Messenger Energetic Particle and Plasma Spectrometer investigation. Dr. Mauk has served on the NRC's Committee on Planetary and Lunar Exploration; NASA's Science Working Group Panel for the Inner Magnetospheric Imager; NASA's Multiprobes Mission Science Definition Team; and NASA's Sun-Earth Connections Roadmap Committee, 1999. He served as a member of NASA's Sun-Earth Connections Roadmap Committee in 2002.

EUGENE N. PARKER is the S. Chandrasekhar Distinguished Service Professor Emeritus in the Departments of Astronomy and Astrophysics and Physics at the University of Chicago. He is one of the nation's most distinguished theoretical astrophysicists. A recipient of numerous prizes from his peers, he also has extensive NRC service on committees and task groups related to solar physics and astronomy. Dr. Parker is a member of the National Academy of Sciences (NAS) and chaired the NAS Astronomy Section from 1983 to 1986. His current research interests include theoretical plasma physics; magnetohydrodynamics; solar and terrestrial physics; basic physics of the active star; application and extension of classical physics to the active conditions found in the astronomical universe (for example, the stellar x-ray corona); and the solar wind and the origin of stellar and galactic magnetic fields. Dr. Parker served as chair of the NRC Task Group on Ground-based Solar Research (1997-1998).

ROBERT W. SCHUNK is a professor and the director of the Center for Atmospheric and Space Science at Utah State University. His expertise lies in the general areas of plasma physics, fluid mechanics, aeronomy, space physics, electricity and magnetism, and data analysis. Dr. Schunk has developed numerous computer models of space physics phenomena, regions, and spacecraft-environment interactions. With colleagues, he developed unique three-dimensional time-dependent models of the ionosphere, polar wind, plasmasphere, thermosphere, plasma cloud expansions, and ionosphere/high voltage sphere interactions. Dr. Schunk has published numerous papers comparing model predictions with measurements, using data from several coherent and incoherent scatter radars, ionosondes, rockets, satellites, and the space shuttle. He is vice chair of Commission C of COSPAR, a scientific committee of the International Council of Scientific Unions, and is a member of Commissions G and H of the International Union of Radio Science.

GARY P. ZANK is a professor of physics and the director of the Institute of Geophysics and Planetary Physics at the University of California, Riverside. He was formerly with the Bartol Research Institute, University of Delaware. His research interests are wide-ranging, encompassing the physics of the outer heliosphere, the interaction of the solar wind with the local interstellar medium, compressible and incompressible turbulence, shock wave theory, particle acceleration at both interplanetary and galactic

shocks, cosmic rays, solar energetic particles, coronal heating, general linear and nonlinear wave theory, the interaction of comets with the solar wind, and general magnetohydrodynamic theory. Dr. Zank is the recipient of an NSF Presidential Young Investigator Award and the Zeldovich Medal, which is awarded jointly by the Russian Academy of Sciences and COSPAR, and he is a fellow of the American Association for the Advancement of Science.

Staff

ARTHUR CHARO, Study Director, received his Ph.D. in physics from Duke University in 1981 and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. Dr. Charo then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a fellow from 1985 to 1988. From 1988 to 1995, he worked in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment (OTA). Dr. Charo has been a senior program officer at the Space Studies Board (SSB) of the NRC since OTA's closure in 1995. His principal responsibilities at the SSB are to direct the activities of the NRC Committee on Earth Studies and the NRC Committee on Solar and Space Physics. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and was the American Institute of Physics' 1988-1989 Congressional Science Fellow. In addition to directing studies that have resulted in some 28 reports from the NRC, he is the author of research papers in the field of molecular spectroscopy; reports to Congress on arms control and space policy; and the monograph *Continental Air Defense: A Neglected Dimension of Strategic Defense* (University Press of America, 1990).

ANGELA BABER, a research assistant with the Space Studies Board from October 10 through December 16, 2005, graduated in December 2004 from the University of Colorado at Boulder with a B.A. in astrophysics and a minor in mathematics. As an undergraduate, Ms. Baber was involved in the NSF-funded Science, Technology, Engineering and Mathematics Teacher Preparation (STEM-TP) program as a teaching assistant. She is now the assistant project coordinator for the STEM-TP program. In addition, she is a professional researcher for the Education Commission of the States, an organization that researches and reports on key education policy issues in the nation. Ms. Baber recently published a 50-state database that houses information on paraprofessional requirements across the states.

THERESA M. FISHER is a senior program assistant with the Space Studies Board. During her 25 years with the NRC she has held positions in the executive, editorial, and contract offices of the National Academy of Engineering. She has also held positions with several NRC boards, including the Energy Engineering Board, the Aeronautics and Space Engineering Board, the Board on Atmospheric Sciences and Climate, and the Marine Board.

CATHERINE A. GRUBER is an assistant editor with the Space Studies Board. She joined SSB as a senior program assistant in 1995. Ms. Gruber came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and has also worked as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

D

Acronyms and Glossary

AE index	Auroral electrojet index—designed to provide a global, quantitative measure of auroral zone magnetic activity produced by enhanced ionospheric currents flowing below and within the auroral oval. Ideally, it is the total range of deviation, at an instant of time, from quiet day values of the horizontal magnetic field around the auroral oval.
Aeronomy	Study of the physics and chemistry of the upper atmosphere, concerned especially with upper-atmospheric composition (for example, nature of constituents, density, and temperature) and chemical reactions.
AMISR	Advanced Modular Incoherent Scatter Radar—combines a powerful, state-of-the-art incoherent scatter radar with supporting optical and radio instrumentation in a transportable format.
anthropogenic radio emission	Emission of radio-frequency electromagnetic radiation caused or produced by human activity.
ARGOS	Advanced Research and Global Observation Satellite
atmospheric tide	Periodic global motion of Earth’s atmosphere; also called atmospheric oscillation.
aurora	Band of light caused by fast charged particles following Earth’s magnetic lines of force to impinge on the upper atmosphere.
BAS	British Antarctic Survey
CADI	Canadian Advanced Digital Ionosonde
CANOPUS	Canadian Auroral Network for the OPEN (Origins of Plasmas in Earth’s Neighborhood) Program Unified Study
CARISMA	Canadian Array for Real-time Investigations of Magnetic Activity
charge-coupled device	A device that converts light into electrical current; the digital camera equivalent of film.
CIR	co-rotating interaction region in the solar wind
CME	coronal mass ejection
corona	The outermost region of the Sun’s atmosphere, visible as a white halo during a solar eclipse.
coronagraph	A telescope, or an attachment for a telescope, equipped with a disk that blocks out most of the Sun to enable photographing of the Sun’s corona.
DASI	distributed arrays of small instruments

D, E, F region	Ionospheric ionization appears in a number of regions or layers, with the D layer situated mainly below 80 km altitude, the E layer centered near 110 km, and the F layer having a peak density near 250 km and extending to above 1000 km.
diffraction pattern	Pattern produced when waves interfere with each other after having been spread or bent as they pass round the edge of an object or through an opening that is close to the wavelength of the waves.
dipolar ion	An ion carrying both a positive and a negative charge.
DOD	Department of Defense
DOE	Department of Energy
Doppler broadening	Frequency spreading that occurs in single-frequency radiation when the radiating atoms, molecules, or nuclei do not all have the same velocity and may each give rise to a different Doppler shift.
Doppler shift	The amount of the change in the observed frequency of a wave due to the relative motion of the source and the observer.
D _{st} index	An index of magnetic activity derived from a network of near-equatorial geomagnetic observatories that measures the intensity of the globally symmetrical equatorial electrojet (the ring current).
dynamo effect	A process in the ionosphere in which winds and the resultant movement of ionization in the geomagnetic field give rise to induced current.
ecliptic plane	The intersection plane of Earth's orbit with the celestial sphere, along which the Sun appears to move as viewed from Earth.
electromagnetic field	An electric or magnetic field, or a combination of the two, as in an electromagnetic wave.
electromagnetic wave	An electric field spreading in wavelike-fashion through space at a speed of about 300,000 km/s.
equatorial anomaly	A region of high electron concentration in the tropical ionosphere on either side of the equator at magnetic latitudes of about 10 to 20 degrees.
Fabry-Perot interferometer	An optical instrument used to make extremely fine spectral resolution measurements.
Faraday rotation	Rotation of polarization of a beam of linearly polarized light when it passes through matter in the direction of an applied magnetic field.
GCR	Galactic cosmic ray—high-energy protons, anti-protons, electrons, positrons, and charged atomic nuclei that originate outside our solar system, most likely (although their origin is unknown) in supernova explosions and/or stellar fusion processes.
geocorona	The outermost part of Earth's atmosphere that emits Lyman-alpha radiation under the action of sunlight.
geodesy	The geologic science of the size and shape of Earth.
geomagnetic storm	A large-scale manifestation of solar wind-magnetosphere-ionosphere coupling that develops when the coupling is intensified by solar wind disturbances such as co-rotating interaction regions (CIRs) or coronal mass ejections (CMEs).

geospace	The domain of Sun-Earth interactions, including the near-Earth interplanetary medium and Earth's magnetosphere, ionosphere, and thermosphere (also called the solar-terrestrial environment).
GONG	Global Oscillations Network Group
GPS	Global Positioning System
gravity wave	A wave in a fluid medium in which restoring forces are provided primarily by buoyancy (that is, gravity) rather than compression.
H- α line	The spectral line of neutral hydrogen that falls in the red part of the visible spectrum and is convenient for solar observations; universally used for patrol observations of solar flares.
helioseismology	The analysis of wave motions of the solar surface to determine the structure of the Sun's interior.
heliosphere	The region surrounding the Sun where the solar wind dominates the interstellar medium.
HF	high frequency
interference fringes	A series of light and dark bands produced by interference of light waves.
ion	An isolated electron or positron or an atom or molecule that by loss or gain of one or more electrons has acquired a net electric charge.
ionogram	A graph of the virtual height of the ionosphere plotted against frequency.
ionosonde	A radar system for determining the vertical height at which the ionosphere reflects signals back to Earth at various frequencies.
ionosphere	The region of the atmosphere from approximately 100 to 1000 km in altitude that contains a significant concentration of electrons and ions produced by the ionizing action of the Sun's radiation (ultraviolet and X rays) on atmospheric particles.
IPS	Interplanetary scintillation—rapid variation in apparent position, brightness, or color of a distant luminous object viewed through the atmosphere or ionosphere.
ISR	incoherent scatter radar
K _p index	A 3-hourly planetary index of geomagnetic activity calculated by the Institut für Geophysik der Universität Göttingen, Germany, from the K indices observed at 13 stations primarily in the Northern Hemisphere.
LPM	Low-power magnetometer—a single-battery, non-solar unit designed to last for 1 year (or more) of operation in a polar winter environment.
MACCS	Magnetometer Array for Cusp and Cleft Studies
magnetic flux	A measure of the quantity of magnetism, in terms of how densely packed are the magnetic lines of force passing through a specified area in a magnetic field.
magnetic storm	A disturbance or fluctuation in Earth's magnetic field, associated with solar flares; also called <i>geomagnetic storm</i> .

magnetic substorm	A descriptive term for the changes over typically 1 to 3 hours in the local magnetic field, at high latitudes, as a result of input from the solar wind and current flows in the magnetotail region of Earth's magnetosphere; can cause geomagnetic induced current at high latitudes.
magnetometer	An instrument for measuring the magnitude and sometimes also the direction of a magnetic field, such as Earth's magnetic field.
magnetopause	The boundary of the magnetosphere, separating plasma attached to Earth from the one flowing with the solar wind. The location of the magnetopause is determined by where Earth's magnetic field balances the pressure of the solar wind—about 63,000 km from Earth in the direction of the Sun, or about 1/6th the distance to the Moon's orbit.
magnetosphere	The region around Earth whose processes are dominated by the Earth's magnetic field, bounded by the magnetopause.
Maunder minimum	The period from roughly 1645 to 1715 A.D. when sunspots became exceedingly rare, as noted by solar observers of the time.
megahertz	Unit of frequency, equal to 1 million cycles per second
meridian	Great circle that passes through both the north and south poles; also called line of longitude.
mesopause	Top of the mesosphere situated at about 80 to 85 km.
mesosphere	A division of Earth's atmosphere extending from altitudes ranging from 30-50 km to 80-90 km.
MeV	One million electron volts
MHD wave	Wave in a compressible, electrically conducting fluid immersed in a magnetic field.
M-I-T	magnetosphere-ionosphere-thermosphere
NASA	National Aeronautics and Space Administration
neutral line	The line that separates longitudinal magnetic fields of opposite polarity.
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PENGUIn	Polar Experimental Network for Geophysical Upper-atmosphere Investigations
photometry	The measurement of light intensities.
photosphere	The visible surface of the Sun.
planar wave	A wave that is far enough from its source that its wavefront has no effective curvature, or is planar, over a short distance. Seismic and electromagnetic waves are treated as plane waves even though that assumption is not strictly correct.
planetary wave	Large-scale wave, generally associated with the jet stream, that propagates vertically, affecting circulation in the stratosphere. Four or five planetary waves are generally spanning the circumference of Earth at one time.
plasma	A gas containing freely moving ions and electrons, which is therefore capable of conducting electric currents. A "partially ionized plasma" such as Earth's ionosphere is one that also contains neutral atoms.

plasmopause	Outer periphery of the plasmasphere.
plasmasphere	Inside Earth's magnetosphere, a donut-shaped region that is basically an extension of the ionosphere, or the topmost part of Earth's atmosphere.
polarization	Orientation of the vibration pattern of light waves in a singular plane.
prominence eruption	An eruption of gas from the lower atmosphere (chromosphere) of a star and visible as part of the inner corona during a total solar eclipse. These eruptions occur above the Sun's surface (photosphere), where gases are suspended in a loop, apparently by magnetic forces that arch upward into the solar corona and then return to the surface.
quasar	Quasi-stellar object, believed to be among the most distant objects in the observable universe, emitting more energy than some of the most powerful galaxies.
radio Luxembourg effect	Powerful transmitters, such as the medium-wave (208 m) 1.2-gigawatt transmitter of Radio-Tele Luxembourg, can heat the ionosphere, causing two effects: first, weaker radio signals that also reflect from the ionosphere become modulated with the stronger signal; second, the ionosphere reflects the radio waves differently, causing the received signal to fade in and out. Also known as ionospheric cross-modulation.
rarefied density region	The upper atmosphere, sometimes defined as the region above the mesosphere, which extends to approximately 50 miles.
Rayleigh lidar	An optical radar that can probe the upper atmosphere by collecting light from the bulk medium.
ring current	An electric current carried by charged particles trapped in a planet's magnetosphere. It is caused by the longitudinal drift of energetic (10-200 keV) particles. Earth's ring current is responsible for geomagnetic storms.
riometer	A specially designed radio receiver for continuous monitoring of the intensity of cosmic noise. (Derived from <i>relative ionospheric opacity meter</i> .)
RISE	Radiative Inputs from the Sun to Earth
SAPS	Subauroral polarization streams—an inclusive name for phenomena that play critical roles in energizing and transporting ring current ions as well as convecting thermal plasma in the inner magnetosphere and in the mid- to low-latitude ionosphere.
solar cycle	The approximately 11-year quasi-periodic variation in frequency or number of solar active events.
solar energetic particles	Electrons and atomic nuclei produced in association with solar flares and other dynamic processes tied to the Sun.
solar flare	A sudden brightening in some part of the Sun, followed by the emission of jets of gas and a flood of ultraviolet radiation. The gale of protons that accompanies a flare can be very dangerous to astronauts.
solar limb	The edge of the solar disk.
solar wind	The outward flux of solar particles and magnetic fields from the Sun, typically with velocities close to 350 km/s.

spectrograph	A device that separates light by wavelengths to produce a spectrum.
sunspots	Any of the relatively cool dark spots appearing periodically in groups on the surface of the Sun that are associated with strong magnetic fields.
SuperDARN	A coherent HF radar network of nearly identical, largely automated HF radars that observes scatter of plasma irregularities in the E and F regions.
TEC	total electron content
telemetry	The system for radioing information, including instrument readings and recordings, from a space vehicle to the ground.
THEMIS	Time History of Events and Macroscale Interactions during Substorms. Themis is also the Goddess of Justice, and her blindfolded impartiality is needed in the discussion of substorm theories. Thus this program name has a double meaning, as the goal of the THEMIS mission is to impartially distinguish between two disparate phenomenological and plasma-physical models of the substorm onset mechanism.
thermosphere	The Earth atmosphere between 120 and 250 to 400 km (depending on the solar and geomagnetic activity levels), where temperature increases exponentially up to a limiting value T_{∞} at the thermopause. The temperature T_{∞} is called the exospheric temperature.
TIMED	Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics
tomographic restoration techniques	Mathematical transforms that combine two-dimensional images and create a three-dimensional composite image.
UHF	ultrahigh frequency
ULF	ultralow frequency
undershielded (penetration)	Temporary penetration of dawn-dusk electric field in times of increasing convection.
VHF	very high frequency

