A Plan of Action Under LTSP III

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Executive Summary

The approach of the next solar maximum and the accompanying increase in geomagnetic activity are spurring a renewed interest in "space weather" phenomena and a growing awareness of its impact on technological systems. New scientific knowledge about the space environment is finding application in improving space weather predictions and in helping find engineering solutions to space weather related problems. Canada's unique location for space weather observations and its expertise in investigating the space environment means that it has a significant role to play in emerging international space weather programs, particularly those in the US, Europe, and Japan.

This report describes the processes involved in space weather and the effects it can have on technological systems and infrastructures. A review is made of existing Canadian programs and areas of Canadian expertise, showing how these programs can be complemented through international collaborations. A plan of work is proposed that involves research to improve the understanding of the space environment, the development of new forecasting techniques, and implementation studies of space weather impacts.

Space weather disturbances near the Earth originate from eruptions of high energy particles from the Sun, which flow through space and interact with the Earth's magnetic field. The enhanced transfer of energy from the solar wind into the magnetosphere results in a corresponding onset of space weather. For example, magnetic disturbances observed on the ground induce electric currents in power systems and pipelines, and can interfere with system operation. In the magnetosphere, energization of particles can lead to spacecraft charging and damage to spacecraft components. Increased ionization of the upper atmosphere causes scintillation of satellite communication signals and disruption of HF (high frequency) radio communication. The changes in ionospheric conditions can also cause position errors for radio navigation systems such as GPS (global positioning system).

To improve understanding of the near Earth space environment, scientific work is needed on three key areas: 1) energy storage and release in the space environment, 2) magnetosphere-ionosphere coupling, and 3) the electromagnetic response of the Earth. In each focal area is embedded some of the most intensely researched space science problems, such as the triggering mechanism for space weather storms, and the origin of auroral arcs and ionospheric disturbances. The combination of Canadian geography, existing ground based observing infrastructures, and scientific expertise, have given Canada a solid foundation to build an internationally significant space environment program. This report proposes a wide range of global space environment characteristics that can be monitored by an enhanced Canadian ground-based instrument array, and describes how modeling and forecasting techniques can be used to extract maximum benefits from Canadian space weather data.

The impact of space weather on technological systems is an important area of concern in the space environment. For example, in power grids, modeling studies are required to determine

the GIC (geomagnetically induced current) distribution across the system, and examination of factors affecting transformer saturation, harmonics that are produced and where they flow in the system. Satellite designers need more precise information about charged particle fluxes for different spacecraft orbits and studies of the long-term effects of particle irradiation on spacecraft materials. For HF radio communications links, better specification of the extent of scattering, blackout, and frequency spreading is required. GPS users need to know what are the position errors introduced by ionospheric disturbances and how they can be removed by post-processing.

The requirements for the proposed space weather program, in terms of manpower and facilities, can partly be met by existing resources in industry, universities and government agencies. It is anticipated that funding for work on technological effects will come from industry, while forecast operations will continue to be supported by NRCan (Natural Resources Canada). Traditional support for university researchers is provided through NSERC (Natural Sciences and Engineering Research Council) grants, while major funding of facilities for use by Canadian scientists is presently provided by the Canadian Space Agency. It is proposed that new funding from the CSA Long Term Space Plan III (LTSP III) should be used to expand the current international opportunities and small payloads programs. Simultaneously, the remote sensing facilities in Canada should be integrated into an enhanced ground based Canadian super array. It is also proposed that additional funding be committed to a new national facility for data assimilation and modeling (FDAM). This will fill a significant gap in Canadian resources in global modeling and modern techniques in data processing and information theory.

Because of the diverse nature of space weather causes and effects, the proposed space weather program has a strong interdisciplinary flavor and an equally strong international component. The success of the program will be measured not only by advances in understanding of the space environment, but also by how effectively new knowledge is used to improve space weather forecasts and to develop engineering solutions for space weather problems. The scope of the proposed space science program is such that it will be able to assist Canadian industries that are directly impacted by the very harsh plasma space environment surrounding the Earth.

Chapter 1

Introduction

The investigation of the aurora borealis has led to discoveries of phenomena such as magnetic storms and substorms, natural particle accelerators, and a host of related processes affected by the solar wind interaction with the Earth's magnetosphere. With this has come the growing realization that at times of enhanced solar activity, there can be adverse effects on man-made systems, both on the ground and in space. In recent years, international efforts to understand the space environment have intensified. The primary objective has been to develop models and forecasts of space disturbances that impact on technological systems such as satellites, power utilities systems, pipelines, and undersea cables.

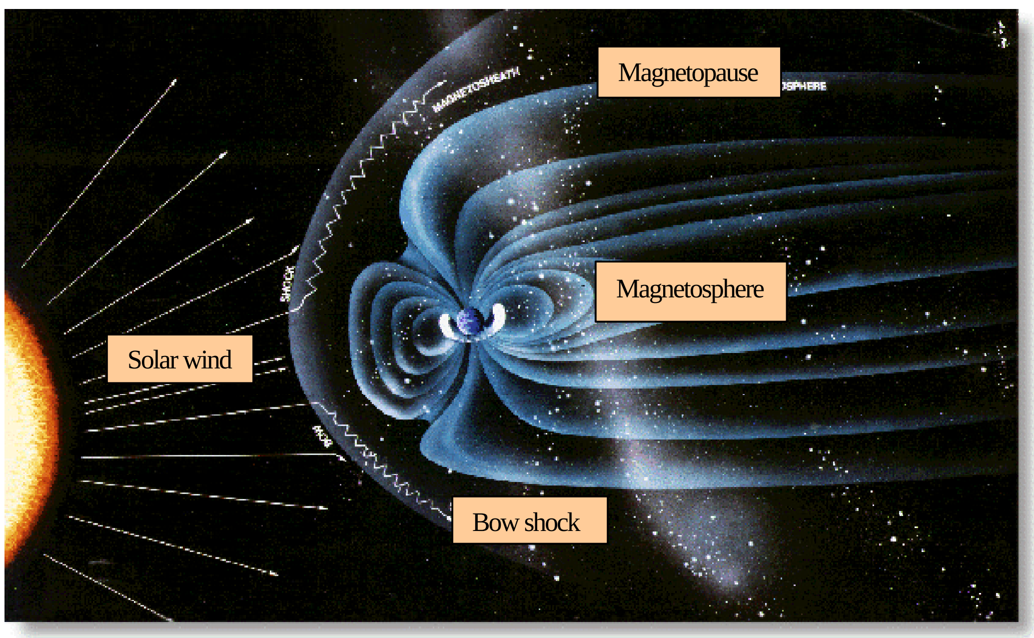

Figure 1. Space weather results from the assault on the Earth's protective magnetic layer by solar particles, producing, among other things, the natural wonder of the Northern Lights.

The space environment extends outwards from the Sun and throughout the solar system. The near-Earth space environment begins at an altitude of roughly 100 km, at the footprint of auroral activity. Violent changes of the constituent plasma and in the configuration of the space environment are referred to as "space weather". Space weather originates from eruptions in the Sun, which reach the Earth through shock waves carried by the solar wind, a plasma boiling from the surface of the Sun. Traveling at high speed (250-1000 km/s), the solar wind interacts with the Earth's intrinsic magnetic field, stretching it into a cigar shaped magnetic cavity called the magnetosphere.

The magnetosphere is populated by plasma and other charged particles of wide energy range, varying from cold ionospheric plasma produced by UV/EUV ionization to cosmic-ray particles of intergalactic origin. When the highly variable solar wind intensifies, and the interplanetary magnetic field turns southward (storm conditions), large currents flow in the magnetosphere, and large numbers of particles are injected into the ionosphere and at geostationary orbit. These conditions are the main cause of space weather effects on technological systems. In essence, space weather is determined by energy transport processes in the magnetosphere and how they respond to changes in solar wind speed, density, and orientation of the interplanetary magnetic field. This transport of energy, under active solar wind conditions, causes global energy releases known as magnetic storms and substorms.

On average, about 10 TW (terawatts) of solar wind energy is incident continuously on the Earth's magnetosphere. Under storm conditions, the energy flux can increase one hundred-fold over several hours. The energy dissipation rate averages 200 GW (gigawatts) in parts of the space environment where many technological systems are deployed, namely within and under the polar ionosphere and inner magnetosphere. During large magnetic storms, the energy dissipation rate can increase to the TW range. In comparison, the total electricity consumption by Canadians was 550 billion kilowatt-hours in 1995, for an average power of 60 GW (gigawatts).

During severe space weather, satellite and HF radio communications are disrupted by activation of the ionosphere, while communications satellites at geostationary orbit can suffer damage from enhanced fluxes of high-energy electrons. Magnetic storms also increase currents and particle flows in the magnetosphere, and the associated ionospheric currents give rise to three effects which pose potential hazards: 1) increased Joule heating of the atmosphere, 2) drastic changes in the properties of the ionosphere and increased occurrences of electron density irregularities, 3) significant inductive electric fields in ground conductors.

Atmospheric Joule heating leads to a vertical expansion of the mesosphere and thermosphere, and the resulting increased frictional drag causes abrupt changes in altitude and loss of positioning of low orbit satellites. The premature loss of Sky Lab in the seventies has been attributed to this effect. Ionospheric disturbances severely disrupt satellite and HF radio communications, and affect the performance of global positioning systems. Inductive electric fields lead to electric currents in large-scale conductors such as pipelines and power lines, and can cause problems with system operations. While many space weather effects are chronic and long-term, others can be spectacular and exact significant short-term costs, as manifested in a number of recent anomalies and failures of low-orbit and geostationary satellites, and significant power outages experienced by major utilities companies.

The arrival of solar maximum 23 around the turn of century will increase the number and severity of magnetic storms, leading to an increase in adverse space weather effects on technological systems. The solar maximum also coincides with significant new investments of hardware (GPS and low Earth orbit satellites) estimated at around $30 billion. Most of these systems are susceptible to space weather effects. The International Space Station is also vulnerable to low-altitude atmospheric drag effects. Furthermore, with increased human activity in space, prediction of the radiation environment will likely become an issue of health concern. On the ground, power grids have become more and more interdependent, and the possibility of a local space weather effect being cascaded or amplified in the wider network has become a serious concern that requires systematic study through space environment modeling and power system simulation.

Space weather impacts differently on countries of different geography, with Canada among the most severely affected owing to its high-latitude location and extensive land mass. The Canadian geography also affords unique opportunities owing to its proximity to the primary space weather system. Canada therefore has a clear advantage in conducting comprehensive ground-based monitoring and research, and is strategically important to international endeavors in space exploration, monitoring, and commercial use. In this report, a comprehensive strategic plan is presented to define scientific, operational and technological goals of a Canadian Space Environment Program (CSEP). Recommendations are also made on a broad spectrum of issues considered critical to the success of this program.

In Chapter 2, an overview is presented of the physical processes involved in space weather and the attendant technological effects. In Chapter 3 a review is presented of the current state of the space environment community in Canada. In Chapter 4, the proposed scientific program is presented, identifying problems which can be effectively addressed by Canadian capabilities, expertise, and concerns. Chapter 5 discusses the approach to the application of new scientific developments to improve modeling and forecasting services. Chapter 6 describes the work on space weather effects that is required for different industry sectors. Chapter 7 identifies the requirements for the space environment program, including new facilities for which funding is anticipated as part of the Canadian Space Agency LTSP III. Chapter 8 outlines the blueprint for the implementation of the Canadian space environment program.

Chapter 2

Space Weather Processes and Effects

2.1 Physical Processes

Space weather processes consist of a chain of events that propagate disruptive solar events to the Earth. The major links in the chain have been identified through half a century of space exploration and research. An overview of space weather processes is given, both as general information and as a frame of reference which will indicate Canada's position in the international space weather effort. In later chapters, areas will be identified in which Canada should focus resources and develop international leadership.

Space weather effects are transmitted through four major regions of the space environment: the solar corona and interplanetary space, the magnetosphere, ionosphere and upper atmosphere, and the Earth's surface. The space environment is governed by the laws of electrodynamics, magnetohydrodynamics, and space plasma physics. In the following, the major processes involved in each region is described.

2.1.1 Solar Corona and Interplanetary Space

The Sun is the origin of space weather disturbances. The solar corona is the region where the solar wind is accelerated; interplanetary space is the region where the solar wind travels at full speed. Embedded in the solar wind is the solar magnetic field which extends outward to form the interplanetary magnetic field (IMF).

The solar wind is accelerated by heating in the stratified solar atmosphere and represents a steady particle outflow from the Sun. The solar variability follows the well-known 11-year solar cycle. There are also periodic effects associated with the 27-day solar rotation. The more disruptive episodes follow less predictable patterns, and typically manifest as short bursts of much increased energy release, as dynamo and convective processes create regions of intense magnetic field and unstable plasma configurations. The collapse of unstable regimes at the Sun gives rise to such powerful events as coronal mass ejection (CME) in which large quantities of mass are ejected into interplanetary space at abnormally high speed, density, and magnetic field strength. In propagating through the background solar wind, CME streams form interplanetary shocks which accelerate particles to very high energy, and accelerate solar protons that can enter the Earth's polar region. When the impulse of a CME reaches the Earth, it drastically changes the configuration of the magnetosphere and energy of the near-Earth particle populations. In many cases, CMEs trigger geomagnetic storms in which particles and energy break the static confinement by the Earth's geomagnetic field and penetrate into geostationary orbit and the polar ionosphere. Understanding of the solar corona will identify the unstable regions conducive to

CME, and understanding of the solar wind will lead to predictions of the arrival time and intensity of disturbances at the Earth.

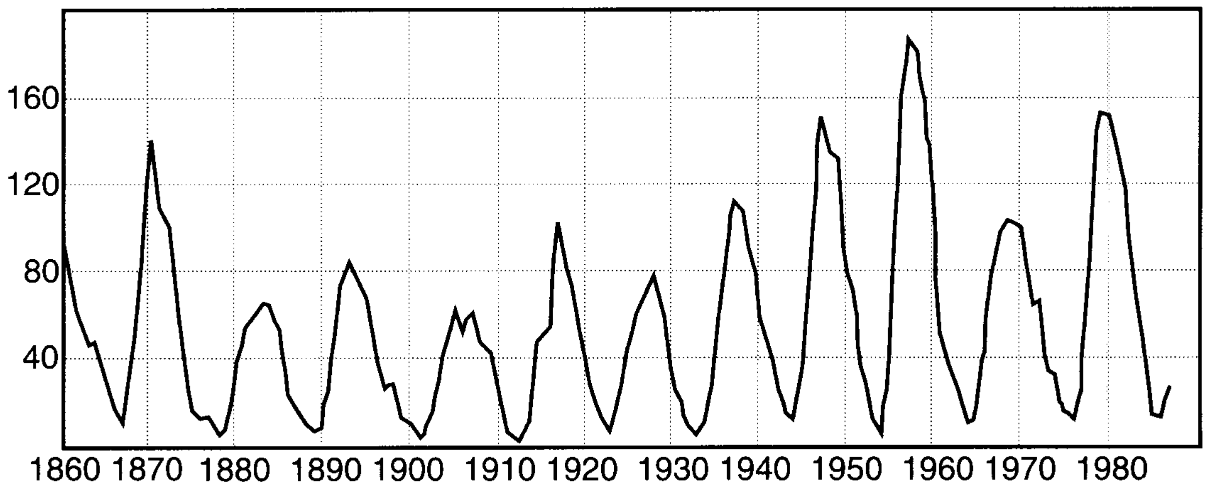

Figure 2. The solar activity follows 11-year sunspot cycle. The peak counts correspond to the solar maximum condition under which the space environment around the Earth becomes more active.

Solar flares represent another class of high-intensity space weather events. As the solar atmosphere is heated by energy converted from the intense magnetic field upwelling from the solar interior, the solar electromagnetic radiation in the radio, optical and x-ray range is enhanced. This enhancement can exert direct impact on the condition of the Earth's ionosphere and upper atmosphere, affecting communications over the poles.

2.1.2 Magnetosphere

The magnetosphere owes its existence to the intrinsic magnetic field of the Earth, which repels impinging solar wind particles. The boundary between the solar wind and magnetosphere is known as the magnetopause. Upstream of the magnetopause is the so-called bow shock which is similar to the shock wave around an aircraft traveling at supersonic speed. The solar wind plasma heated by the bow shock can gain entry into the magnetopause, particularly when the IMF turns southward and becomes connected with the Earth's geomagnetic field. The magnetic interconnection, coupled with the solar wind flow, acts as an electric dynamo which drives currents and particle motions in the magnetosphere and ionosphere, resulting in enhanced energy storage, transport, and dissipation. Solar wind energy can also enter the magnetosphere through viscous drag at the magnetopause, and through the onset of global compressional waves. A major magnetic storm typically results when these energy-entry mechanisms have been active for a significant length of time (several hours).

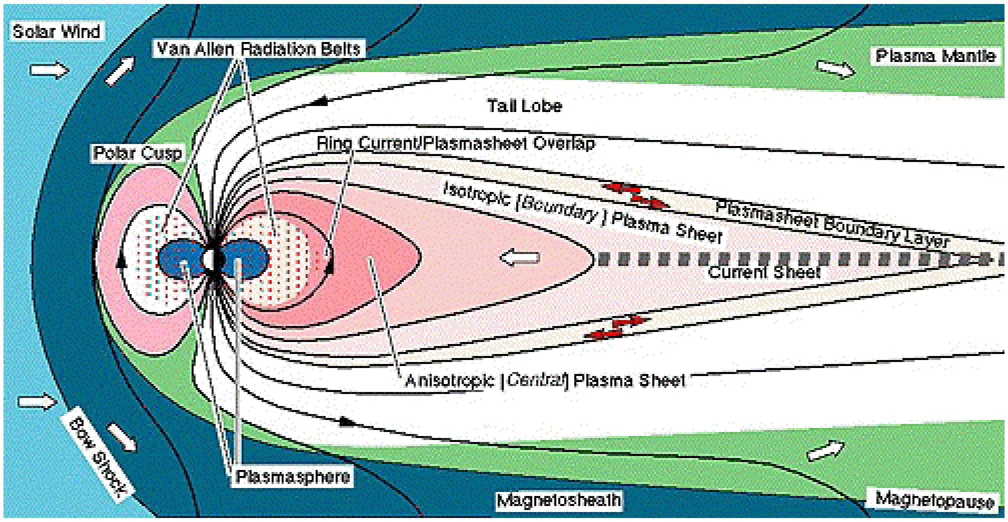

Figure 3. A noon-midnight cross sectional view of the Earth's magnetosphere .

Plasma inside the magnetosphere is in constant motion. Driven by the electromotive force from the magnetopause dynamo, magnetospheric convection transports energy and particles to the inner magnetosphere that is not in direct contact with the solar wind. Convection is a key factor in: a) distributing energy throughout the space weather system, b) producing the electromotive force that drives currents linking with the ionosphere, and c) causing the heating of plasma in the inner magnetosphere and ionosphere. Under storm conditions, all these effects attain particularly high intensity and are liable to sudden and unstable changes. While a magnetic storm represents a general elevation of the energy state of the magnetosphere as a whole, a magnetospheric substorm is more localized in that it impacts primarily the polar ionosphere. In either case, unstable conditions occur when energy storage proceeds at a faster rate than can be disposed of by relatively slow convection.

A major storm can excite a series of substorms during its course. The substorm drastically changes the configuration of the magnetosphere and releases the free energy driving space weather dynamics. The substorm is responsible for a) much intensified field-aligned currents, electrojets and auroral surge structures, b) brightening of discrete auroral arcs, c) heating and elevation of the thermosphere and intensification of the polar wind, and d) injection of energetic particles into geostationary orbit and surrounding regions. The much enhanced wave activities under storm conditions can accelerate injected particles to high energy and give rise to elevated energetic particle fluxes which pose significant dangers to satellites in geostationary orbit. The 1998 failure of the US Galaxy IV satellite (affecting some 10 million customers) occurred during a prolonged period of elevated electron energies.

2.1.3 Ionosphere and Upper Atmosphere

The ionosphere and thermosphere provides the inner boundary condition that controls energy transport and release in the magnetosphere, and they are key regions of space weather in their own right. Ionization in these layers is determined jointly by solar electromagnetic radiation in the UV and EUV range and particle precipitation from the magnetosphere. The dynamics of the ionosphere is driven from above by magnetospheric processes such as convection and substorms, and influenced from below by gravity waves, tropospheric circulation, and by ambient middle atmospheric tides. Magnetospheric energy input also heats the atmosphere and leads to changes in the electron density with altitude. Currents of magnetospheric origin can trigger ionospheric instabilities which produce irregularities with scale sizes down to centimeters. These processes lead to changes in the total electron content (TEC) of the ionosphere, scintillation, HF absorption, and density gradients which reflect HF communication signals. In the case of satellites, ionospheric irregularities produce scintillation and rapid fluctuations of the amplitude and phase of transionospheric signals. An important effect of the vertical expansion of the upper atmosphere (mesosphere and thermosphere) is increased drag on low-orbit satellites. Enhanced ion drifts in the ionosphere also create a frictional drag that leads to the neutral wind. Further downward propagation of magnetospheric energy excites gravity waves and may have climatological ramifications.

2.1.4 Earth's Surface

The chief space weather effect experienced at the surface of the Earth is geomagnetically induced currents (GIC). The origin of GIC is large temporal variations of electric currents in the ionosphere (the auroral electrojet) which generate inductive electric fields on the ground. Conductors such as power grids, pipelines, and transoceanic cables are vulnerable to currents produced by these inductive fields.

The electromagnetic properties of the ground play an important role in the use of magnetometers as a monitoring instrument of the space environment. Magnetospheric current systems generate magnetic field variations that penetrate hundreds of kilometers into the Earth. These magnetic field variations induce electric currents in the Earth that create a secondary magnetic field that contributes to the disturbance observed at the Earth’s surface. The size of the electric fields and currents induced in the Earth depends on the permeability and resistivity of host rock layers. Local changes in resistivity, such as at a coastline, also have a strong influence on the electric fields produced during geomagnetic disturbances.

2.2 Space Environment Hazards

Space environment hazards are natural effects of space weather processes on exposed technological systems. Many of the hazards are associated with sudden and large changes in the Earth’s magnetic field during storm conditions and with injections of energized charged particles into the inner magnetosphere and ionosphere. There is a need to understand how these hazards affect technological systems and economic activities, and for finding effective ways to avoid unnecessary losses of production through protective procedures derived from scientific modeling and prediction.

Canada's sensitivity to the space environment is particularly notable among developed countries. Canada's large land mass and relatively sparse population makes reliable and efficient telecommunications an essential factor in our economic and social life. The same geographical characteristic has also made it necessary that long-haul power grids and pipelines be constructed to service widely-separated population and production centers, and meet demands for power export. Compounding Canada's vulnerability to space weather is the fact that the most volatile region of space is threaded by the Earth's magnetic field onto Canadian territory. This coincidence of factors explains why Canada has been disproportionately represented in recent high-profile system failures associated with adverse space weather.

There are four major industrial groups that are exposed to significant space-environment hazards in North America:

2.2.1 Ground-Based Energy Sector

Over $600 billion is invested in ground-based energy delivery systems in North America, including power grids and oil and gas pipelines. Almost every facet of industrial and social activities depends on reliable delivery of power. Therefore, the impact of a major shutdown of these delivery systems can be very significant. The chief space environment hazards to power systems and pipelines are geomagnetically induced currents produced by magnetic storms. These quasi-dc currents cause transformer half cycle saturation, increased inductive-reactive requirements, over-heating and mechanical vibration of transformer cores. In the worst case this can lead to problems with system stability and power blackouts, as in the 1989 Hydro-Quebec outage. Power utilities in Canada experience larger GIC because their location is close to the auroral zone and because of the high resistivity of host rocks.

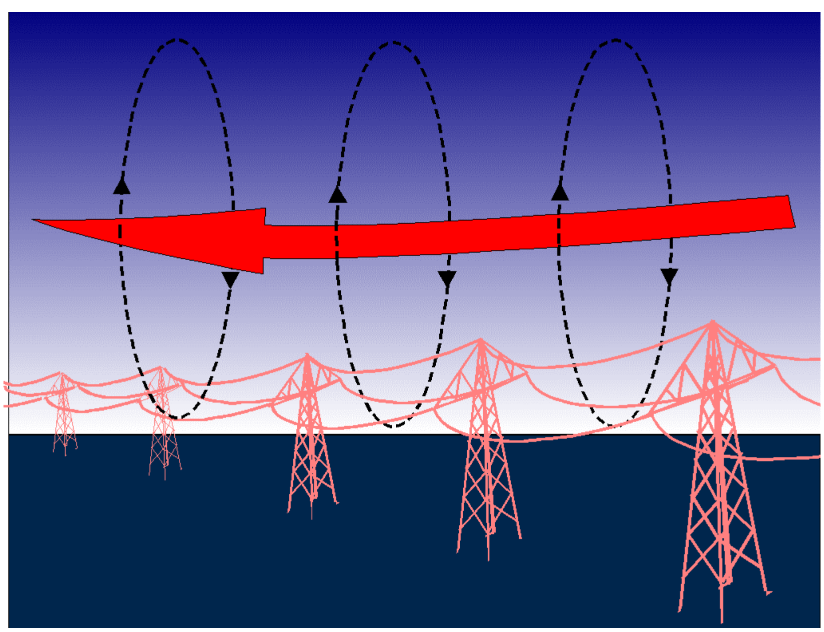

Figure 4. Schematic illustration of the production of Geomagnetically Induced Currents.

2.2.2 Satellites

In geostationary orbit alone, over $10 billion is invested in telecommunications satellites. At lower orbits, Earth-resources, weather monitoring, navigation, surveillance, and mobile communications satellites are being launched at an increasing rate. Some 700 satellites will be launched within the next 5 years, with many of the young engineers involved in their designs not having experienced a solar cycle and hence unaware of the potential space weather hazards. Satellite design is evolving such that the space environment is becoming of higher concern. This is largely because payloads are becoming smaller and lighter, with less shielding, higher output, less redundancy and higher densities of components through miniaturization. Satellites suffer problems and possible failures through surface and deep dielectric charging, single event upsets (SEU) caused by Galactic cosmic rays and solar protons from CME, solar radio interference, and material degradation by atomic oxygen. Additionally, sudden loss of altitude (10's of km) and decreased orbit lifetimes can occur as a result of ionospheric drag on satellites in low orbits. This can also result in loss of positioning by tracking systems on the Earth.

2.2.3 Navigation Systems

The Global Positioning System (GPS) is rapidly becoming the norm for establishing position with aircraft, and ships at sea. Aircraft, in particular, will increasingly rely on GPS for altitude information during landing. Traditional ground based LORAN systems, which rely on a ground wave and a sky wave reflected from the ionosphere, are being superseded by GPS systems, which rely on direct propagation of signals through the ionosphere. Both systems are affected by variable space weather, primarily due to disturbances of the ionosphere. These are associated with geomagnetic storms and solar proton events, which can cause increased ionospheric absorption, irregularities, and changes in the altitude of the ionosphere. In LORAN, HF communication is often not possible over the poles, while in GPS, scintillation effects arising from km-scale ionospheric irregularities can result in interference of transionospheric signals on the ground.

2.2.4 Radio Communication

HF radio communications rely on reflection from the ionosphere for transmission of the signal to distant sites so that the performance of a HF link is closely related to ionospheric conditions. Polar cap absorption (PCA) events are the most catastrophic events affecting high latitude circuits and attenuation in excess of 100 dB can be produced. Increased absorption associated with auroral precipitation can also interfere with high latitude radio propagation. Disruption of HF links on the dayside of the Earth can occur because of short wave fades (SWF) which follow x-ray flares. Changes in the reflecting ionospheric layers during geomagnetic storms also interfere with HF links and ionization reductions can result in the effective loss of the reflecting layer.

Chapter 3

Canadian and International Space Environment Programs

Canada has a long history of research into the space environment. The first magnetic observatory in Canada was established in 1839 at a site that is now part of the University of Toronto campus. Data from the Toronto observatory were used in the discovery that geomagnetic activity follows the eleven year solar cycle. Since then Canada has distinguished itself in many investigations of auroral and geomagnetic activity, making important discoveries in many areas of current space weather concern. Canada was also an early leader in the first wave of scientific exploration of space. In the 1960's, the Alouette and ISIS satellites made outstanding contributions to our understanding of auroral processes and to the early exploration of the Van Allen radiation belts. In the 1970's, Canada built the extensive infrastructure and expertise in ground magnetic observatories that have resulted in the current CANOPUS and CANMOS operations. In the 1980's, Canada broke new ground in collaborative space research and instrumentation through innovative payloads in a series of international missions, such as Viking, Freja, and Akebono. In the 1990's, CANOPUS, as Canada's contribution to GGS/ISTP, became fully operational and has been a much valued data source for research and space weather forecasting around the world. As a major partner in SuperDARN, Canada has also established a strong position in HF radar mapping of the ionosphere and energy circulation within the space environment. The implementation of the Small Payloads Program under CSA Long Term Space Plan II in the mid 1990's has created a new dimension to the Canadian space program, allowing innovative, versatile, and cost-effective instruments to be flown on balloons, sounding rockets, and microsatellites.

Figure 5. Antenna of the Saskatoon SuperDARN HF radar collect signals from the space environment and help scientists understand the energy circulation driving space weather.

The continued growth of Canada's instrument and observational capabilities was mirrored by significant strides made in the scientific understanding and modeling of the space environment, and the acquisition of state-of-the-art computational facilities and expertise. The Canadian Network for Space Research (CNSR) provided the initial impetus to Canada's expanded presence in space plasma physics and space weather modeling. In less than five years, Canadian space scientists had developed a substantial body of theoretical and computational expertise, which promised to elevate Canada's outstanding observational capabilities to a point where Canadian data would drive space weather models and forecasting. The discontinuation of CNSR in 1995 temporarily disrupted the pace of this progress, but the Canadian Space Agency has managed to retain the key elements through transitional support.

As space weather concerns are put into a sharper focus, it has become evident that a broad, coherent Canadian Space Environment Program must be in place to integrate existing programs and new initiatives to achieve clear, long-term objectives. It is instructive to begin by reviewing Canada's current position in space science, where the strengths are, and what can be accomplished in the next ten years.

3.1 Canadian Geography

Canada's achievements in space environment research have benefited considerably from its geography. The Canadian landmass is directly under the zone of auroral activity, thus affording an ideal ground-based view of the effects of the solar-terrestrial relationship and space weather. Figure 6 is a snapshot of the inferred position of the auroral oval (reconstructed through CANOPUS magnetometer data) over Canada. The Canadian landmass encompasses the latitudinal range of the auroral oval and extends well into the polar cap. The east-west extent of Canadian territory also gives the much needed longitudinal range required for the determination of local time dependencies of auroral processes. Figure 6 suggests that the auroral oval gives a 'TV screen' view of the polar ionosphere and magnetosphere: By viewing ionospheric features, scientists and engineers can infer, through theoretical investigation and modeling, magnetospheric processes and space environment conditions. This natural advantage has by and large defined the basic orientation of Canadian space environment research, namely, understanding the space environment using ground-based observation, in-situ probe, remote-sensing, and computation and modeling of the ionosphere. The Viking UV imager and CANOPUS photometer are two recent examples of the value of ionospheric observations to theoretical thinking on magnetospheric physics, and of the considerable potential of diagnostic use of ground-based instruments.

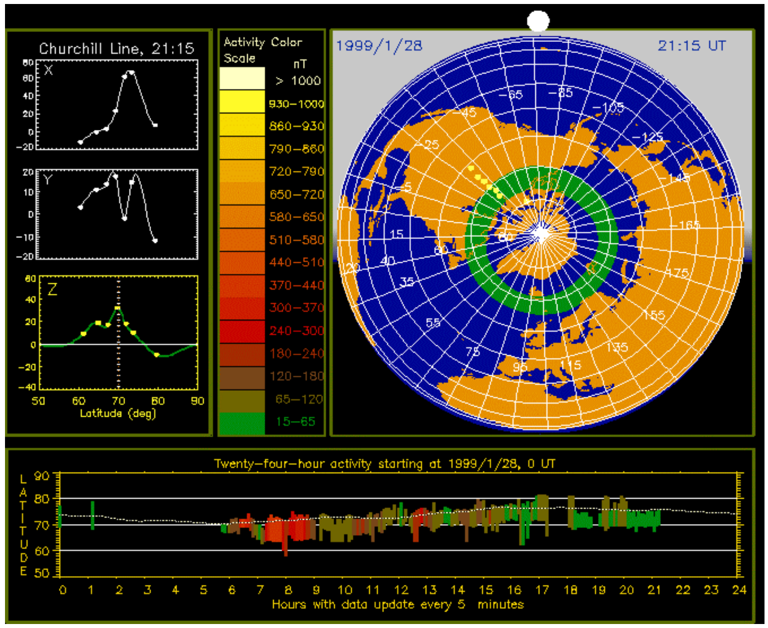

Figure 6. Space environment condition can be specified and predicted by using ground-based observation of the polar ionosphere. The figure shows the real-time location of the auroral oval constructed from the CANOPUS data.

3.2 Canadian Space Environment Capabilities

Canadian space environment expertise is distributed across various universities, government agencies and industries. The universities provide basic scientific knowledge and expertise in instrumentation, modeling, and computation. The government agencies, most notably the Canadian Space Agency and Natural Resources Canada, provide programmatic direction, financial resources, and forecasting facilities. Industry offers engineering know-how in finding practical solutions to space weather problems.

3.2.1 Expertise in Ground-Based Observation of the Space Environment

A number of ground-based space weather observation arrays have been built and operated successfully in Canada. These include

- The CSA-funded CANOPUS array consisting of magnetometers, riometers, photometers, and all-sky imagers
- The NRCan geomagnetic observatory network operated by the Geological Survey of Canada
- The Canadian component of the SuperDARN HF radar network funded by NSERC
- The Canadian Advanced Digital Ionosonde (CADI) array funded under the CNSR.

Through wide deployment across Canada, these instrument arrays give unparalleled monitoring capabilities for geomagnetic disturbances (magnetometers), energetic particle precipitation into the Earth's upper atmosphere (riometers), auroral emissions (meridianal scanning photometers), auroral morphology (all-sky auroral imagers), ionospheric electric field and plasma flow (high-frequency coherent radars), and ionospheric electron density (digital ionosondes). Canadian scientists and engineers are at the forefront of instrumentation technologies in the listed areas. In addition to instrument expertise, Canadian scientists have developed an excellent reputation in the collection of a wide variety of data for understanding the space environment.

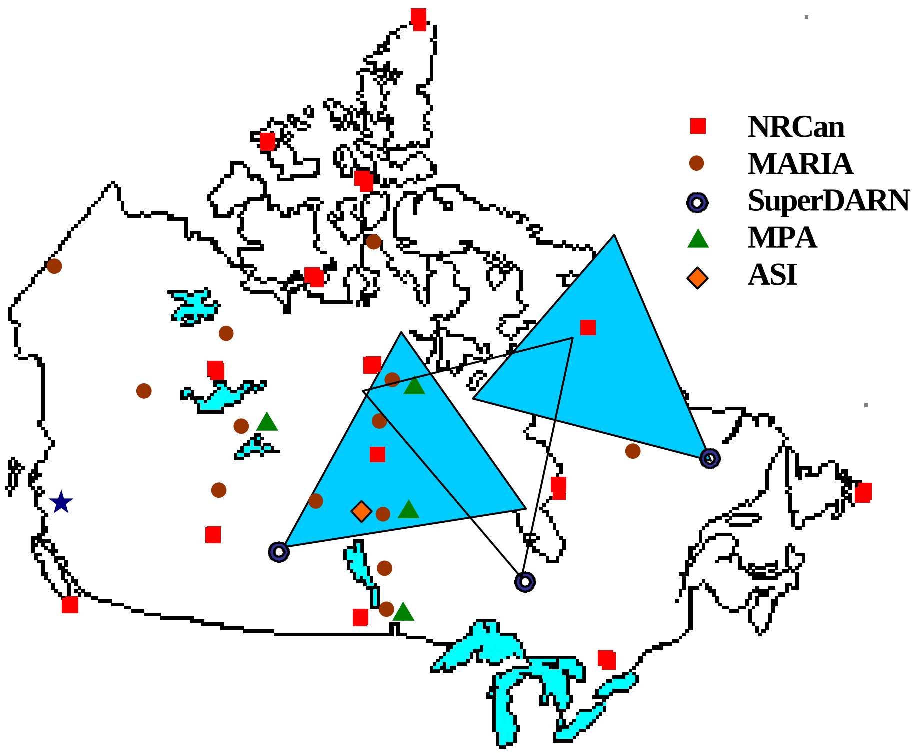

Figure 7. Distribution of ground-based space weather instruments in Canada. The star represents the proposed location of the Prince George SuperDARN radar.

3.2.2 Expertise in In-Situ Space Plasma Observation

Canada's presence in space has followed a balanced approach in payload flights, through active participation of international collaborative missions on the one hand, and the autonomous Small Payloads Program on the other. With the flexibility afforded by this strategy, Canada has been able to seize the most desirable flight opportunities, while keeping the continuity of the instrument flight program. Optical imagers, particle detectors, microsatellites, sounding rockets, and high-altitude balloons are among the areas where Canada has a significant technological interest. Expertise is distributed among a number of universities and government laboratories, such as the University of Calgary for imagers and particle detectors, York University and the

University of Toronto for microsat technology, and the Communication Research Centre (CRC) for radio science.

Typically, in-situ measurements on suborbital and orbital platforms provide data that permit detailed quantitative tests of fundamental physics concepts. The physical scale sizes measured extend all the way from micro-scale plasma phenomena in kinetic plasma, as observed with particle detectors, to global scale phenomena as seen in images of the auroral oval. The detailed understanding thus obtained will lead to comprehensive theoretical models of the ionosphere-magnetosphere system.

3.2.3 Expertise in Space Plasma Physics Theory

As a practical concern to space weather initiatives, a strong theoretical knowledge base is crucial to the proper design of predictive models, to experimental efforts in probing space, and to the appropriate use of data in improving fundamental understanding. Theoretical capabilities in the Canadian space research communities have grown in close coordination with experimental strengths. At the Universities of Western Ontario and New Brunswick are concentrated theoretical expertise in ionospheric instabilities and anomalous transport processes that give rise to various active conditions in the ionosphere. At universities in Western Canada there exist a range of theoretical expertise in magnetosphere-ionosphere coupling, magnetospheric waves, convection, and substorms. At the University of Alberta in particular, theoretical expertise has been systematically integrated into a number of sophisticated models of key space weather processes. Examples include magnetic reconnection, substorm onset mechanisms, ULF (ultra-low frequency) kinetic and inertial Alfven waves, and relativistic electron acceleration.

3.2.4 Expertise in Space Environment Modeling

Canada's ability to exploit space environment data is increasingly dependent upon scientific expertise in space weather modeling and forecasting, and also upon the existence of state-of-the-art computational infrastructures for massive data-handling and modeling operations. Canada's modeling expertise is well matched to Canadian geography and instrument capabilities, and is positioned to address a number of practical concerns to Canadian industry sensitive to space weather, such as satellite, utilities and pipeline companies. One of Canada's foremost strengths is the modeling of meso-scale processes that are directly involved in the release of energy powering space weather. Canadian scientists are international leaders in the investigation of substorm physics, global MHD waves that guide energy flow throughout the space environment, acceleration of auroral electrons and ions, and generation of MeV electrons in geostationary orbit.

The most powerful computational facilities exist at the University of Alberta. The Alberta group has also developed 3D computer codes that are capable of simulating many important space weather processes. The computing facilities at the University of Alberta Space Physics Group are currently supported through an NSERC Major Equipment Grant and through large donations from Silicon Graphics Incorporated of Canada. The Space Physics Group also a substantial stake in MACI (Multimedia Advanced Computation Infrastructure) which has received significant funding from the Province of Alberta Intellectual Infrastructure Partnership Program (IIPP). MACI, which involves over 40 faculty at the Universities of Alberta, and currently has the fastest parallel computer in Canada (an SGI Origin 2000 with 100 processors), is particularly suited to computationally intensive tasks envisioned in this report. MACI is also designed for modern techniques of information theory, data processing, high-speed data network, and multi-media applications, all of which are becoming critical requirements for an information-based economy.

3.2.5 Expertise in Forecasting Geomagnetic Activity

Forecasting services in Canada commenced in 1974 with the provision of 27-day forecasts by the geomagnetism program within the Department of Energy, Mines and Resources (now Natural Resources Canada). Short-term forecasts started in 1976. In 1986 the Ottawa Forecasting Center became a regional warning center of the IUWDS, now the International Space Environment Service (ISES). Over the years there have been continued developments in forecast production and delivery. Three-zone geomagnetic forecasts were introduced in 1984 and the application of linear prediction filtering to production of the forecasts was implemented shortly afterwards. Originally, forecasts were delivered by telex and were distributed through Emergency Preparedness Canada and broadcast by local CBC radio stations. From 1979 short-term forecasts have been made available through an automatic telephone answering service. The distribution of magnetic storm warnings by fax started in 1987. Now extensive use is made of the internet for forecast delivery.

Short-term forecasts are based on observations of solar activity and conditions in the solar wind which are relayed from other ISES warning centers, notably Boulder. This information, combined with real-time data from the Canadian magnetic observatories then provides the input to the forecast process. Until 1995 forecasts were prepared manually, based on an understanding of the space environment, together with climatological information and empirical relations. With the retirement of key staff this knowledge base has been encoded in an expert system which now produces forecasts automatically. The move to a computerized system has allowed forecasts to be produced more frequently and provides the ability to produce unscheduled forecasts whenever there is a significant change in input conditions.

The Canadian geomagnetic forecasts now go to over 300 subscribers from industry and the public. Users range from survey companies, power utilities, satellite operators to GPS HF radio users. Magnetic survey companies are interested in magnetic activity itself, but for many other users the magnetic information is a proxy for the parameters that more directly affect their system. For power utilities the requirement is for knowledge of the geomagnetically induced currents (GIC) in their system, satellite operators want to know about particle radiation and GPS and radio users are concerned about ionospheric conditions. The Canadian forecasting center is working closely with a number of industry groups to develop forecasts of the specific space environment conditions that are of concern.

3.2.6 Expertise in Effects on Technological Systems

Industries in Canada have had to deal with the extreme space environment conditions that exist at high latitudes and have, in many cases, developed special expertise to cope with various space weather problems. Canadian pipeline operators were among the first to recognize that geomagnetic disturbances affected pipeline voltages and are world leaders in designing systems to mitigate these effects. Power engineers from a number of Canadian power utilities have been responsible for some key developments in understanding the interaction of magnetic disturbances with power systems.

The Communications Research Centre has played a significant role in the investigation of radio wave propagation and continues to be a major contributor on HF communications. Several Canadian universities are involved in work to understand how ionospheric disturbances affect the characteristics of GPS signals received in Canada. There are also several researchers involved in research on the effects of the space environment on satellites.

3.3 Long Term Space Plan III

Funding and infrastructure support to Canadian space environment projects is provided principally by federal agencies. In some cases, provinces have made substantial contributions, such as the support of CRESTech from Ontario, and the MACI project in Alberta. As a national concern, it is suggested in this report that Canada's space environment strategy is best coordinated at the federal level. The Canadian Space Agency has traditionally played the role of the lead federal agency for Canada's space program. NRCan, by its mandate, has also a strong interest and important role in the space environment, particularly in providing forecasting services to Canadian industry and society at large. The Communications Research Centre, a research institute of Industry Canada, houses expertise on space weather effects on ionospheric communications. NSERC is the primary source of funding for basic space environment research in Canada.

Beginning in 1996, the CSA has led the effort to formulate Canada's space science program, and this effort is now leading to closer cooperation amongst the various federal agencies, universities, and industry. In particular, the consultations have led to the drafting of Canada's Long Term Space Plan III (LTSP III). Under the Space Environment subprogram of the CSA, LTSP III proposes that Canada's space environment thrust in the next ten years be based on four major directions

- International Opportunities
- Small Payloads
- Acquisition and Enhancement of Space Weather Forecasting Capabilities
- Facility for Data Assimilation and Modeling (FDAM)

It is anticipated that LTSP III will enhance existing activities in the first three areas through additional resources directed towards meeting new challenges confronting the space weather program. The FDAM initiative was proposed under the LTSP III to address the pressing need for a more quantitative understanding of the space environment that can improve forecasting, modeling, and mitigation of space weather effects.

As a recommendation in this report, it is suggested that the Acquisition and Enhancement program be further divided into two sub-programs: Ground-based observation and data network for space weather, and forecasting and space weather services. This division not only represents a more rational organization of work to be performed, but also reflects the existing concentration of Canada's forecasting and space weather services at NRCan. With active interactions between the proposed FDAM and its user groups, an enhanced Canadian Space Environment Program promises to provide an extended set of forecast parameters and data/information products. The ground-based observation component would likely be managed through a community-wide mechanism, in a manner similar to the current CANOPUS science team.

The overall LTSP III programs strikes a balance between discovery, understanding, and applications. International Opportunities and the Small Payloads Programs are designed to maintain Canada's tradition of success in the discovery of fundamental processes in space. The goals of these programs, as set out by the LTSP III task force are to:

- Provide Canada with a continued presence in the active exploration of space.
- Provide an opportunity for Canadian space industry to maintain and enhance its technological know-how in manufacturing cutting-edge space hardware.
- Provide Canadian scientists with opportunities to develop innovative ideas and experiments to explore new domains of the space environment and make crucial measurements to enhance our scientific understanding.

The Observation, FDAM, and Forecasting programs are to provide Canada with a long-term, full-range capability in space weather monitoring, modeling, and information services. This initiative will be based on systematic use of our current understanding in the development of models and other prediction techniques, and requires additional expertise in efficient data handling, parallel computing, prototyping, and knowledge of affected systems. The adoption of this initiative, regarded as the space weather program under LTSP III, reflects the view that space weather is predictable, and represents a significant evolution in the way we approach space environment study through a systematic integration of expertise into a stream of continuous operations. The primary focus in this report will be on the three program components dealing directly with space weather.

3.3.1 International Opportunities Program

The space science community in Canada is small by international standards. However, this has not prevented Canadians from making important contributions in a number of international space missions. Because of the high cost of satellite missions, Canada has adopted a collaborative approach in space exploration and concentrated its efforts in building space instruments for which it has internationally leading expertise. For example, the Canadian UV imager experiment on the Viking satellite marked an important milestone in the interpretation of auroral dynamics, and contributed to current thinking about substorm physics. Equally significant, Canadian UV imager design has evolved into an international standard for auroral imaging in current and upcoming satellites missions such as Polar and IMAGE. Canadian particle detector technology has contributed to knowledge of ionospheric particle outflow. The success of Canadian instruments on international satellite missions has demonstrated not only the scientific ingenuity of Canadian scientists, but also the technological excellence and reliability of the Canadian space industry. The reputation and goodwill created by past Canadian successes are conducive to Canada's future participation in international missions. It is expected that Canada's future in space exploration through sophisticated orbital instruments will continue along its traditional collaborative path.

3.3.2 Small Payloads Program

The autonomous element of Canada's effort in space exploration and discovery hinges principally on the Small Payloads Program, which launches sub-orbital payloads such as high-altitude balloons and sounding rockets, and light-mass microsatellites. The current Small Payload Program (SPP) was reinstated under CSA LTSP II and has met with enthusiastic response from Canadian scientists. In connection with SPP, the CSA also administers a Concept Study program that supports efforts to develop innovative instruments and flight ideas.

SPP vehicles are distinguished by their economy of costs, flexibility, ability to resolve very small scales, and collection of information on vertical structures. For example, sounding rocket measurements can provide valuable information on auroral dynamics, wave-particle interactions, and polar wind acceleration, information which orbital observations are often unable to provide. They can also provide measurements on ambient ionospheric particle distributions that shed light on the physics of ionospheric irregularities, energy transport, and momentum coupling with the neutral atmosphere. The results of the ODEPIDUS experiment have shown that sounding rockets are very useful platforms for experiments on radio wave propagation in the ionosphere. As an educational tool, SPP projects also present training opportunities for graduate students who in turn will carry the skills into the workforce. From a scientific point of view, SPP bridges the gap between ground-based observations and in-situ orbital measurements.

Because of its unique scientific and economic character, the Small Payloads Program will allow Canadian scientists and the Canadian space industry to take an aggressive approach toward discovery and technological innovation. Through Canadian management, the program will be devoted to meet Canadian interests and concerns. Through the Announcements of Opportunities (AO) process currently used by the CSA to select small payload projects and concept studies, windows are created for non-directed, community-driven initiatives that lead to high productivity and novel and unanticipated results.

3.3.3 Ground-Based Observation Program

Ground-based observation of the auroral zone and polar cap provides a powerful means of monitoring and conducting research on the space environment. Canada already has an outstanding infrastructure in place for this purpose, with the CSA-funded CANOPUS network of magnetometers, photometers, and all-sky imagers, NRCan-operated CANMOS magnetometer array, and NSERC-funded Canadian component of SuperDARN. Combined, these instruments provide global monitoring of geomagnetic, electric, and optical signatures of auroral activity, and are actively used by the Canadian and international communities in scientific and applied research. It is expected that infrastructure maintenance of the current CANOPUS and CANMOS arrays will continue through the support from CSA and NRCan. Additional funds are being requested under LTSP III to enhance the ground-based observation program in strategic areas. One primary task facing Canadian scientists and space funding agencies is the development of a framework whereby all of the ground-based observation resources are coordinated to address a common set of questions, including observational parameters, data management, data analysis, and linkage with modeling and forecasting modules. Acquisition of new instruments, including high-power computers to handle the increased data volume, is another major issue needing attention.

3.3.4 Facility for Data Assimilation and Modeling

There has emerged a general consensus in the space environment community that the excellent space weather data collected in Canada is underused by Canadians. This, in part, is because Canadian expertise and resources in data management, modeling, and computation have not been set in a functional framework which puts more emphasis on extracting from data key information of the space. Modeling and scientific computation are two key components to obtaining a predictive capability for space weather. It was in this spirit that the Facility for Data Assimilation and Modeling (FDAM) was proposed as a distinct space weather component under LTSP III.

FDAM is envisioned to be a national facility open to use by scientists from across Canada. CSA will fund and direct the FDAM to fulfill a range of crucial tasks, which include

- Developing data assimilation methods and tools to integrate the data streams from the Canadian space weather superarray
- Carrying out scientific investigation into space weather processes monitored by Canadian instruments
- Developing models which use Canadian data to specify the condition of the space environment
- Developing models and algorithms to simulate space weather processes
- Providing computing power and expertise for data visualization and model prototyping
- Representing Canada in international modeling collaborations.

As a consolidated operation, FDAM would concentrate on extracting the maximum value from Canadian data. This is not restricted to better ways to represent data and the underlying space environment condition, but also aimed at predicting space environment behavior through simulation models. Modeling and its associated data and prototyping work will also contribute to the advancement of basic knowledge of the space plasma physics. Three-dimensional visualization of the space environment, rapid data handling and distribution, and a high-performance computing environment for validating theoretical ideas and forecasting routines are some of the benefits FDAM is expected to bring to the Canadian space environment program

(CSEP).

3.3.5 Forecasting and Space Weather Services

While data and models generated from the above programs have intrinsic scientific value, and are expected to establish a unique position for Canada among the world's leading countries in space environment research, the question of their practical utility needs to be addressed. The proposed Forecasting and Space Weather Services module would be the practical outlet for those elements of CSEP with application potential. This operation would principally be coordinated by the Geomagnetic Laboratory of NRCan, and expected to

- Maintain space weather information delivery systems to users
- Serve as a hub of public education information through upgraded web and other internet resources
- Develop refined climatological and empirical forecasting tools for certain long-term conditions of the space environment
- Prototype predictive models developed at FDAM or imported from abroad against Canadian data and industrial specification
- Facilitate joint research on mitigating space weather effects on technological systems.

3.4 International Space Environment Programs

In the early 1990's, the international space science community began to develop the concept of a space weather initiative that would integrate space research and modeling. This resulted in a general re-alignment of scientific priorities in major funding agencies for space science. In the US, in particular, the strategic and commercial importance of space weather applications was quickly realized, and in 1997 the US National Space Weather Plan (NSWP) was published. There are similar organizing efforts for European and Japanese space weather programs.

The US National Space Weather Program is a multi-agency program coordinated through the National Space Weather Program Council. The participants include NASA, the Department of Commerce through the National Oceanic and Atmospheric Administration (NOAA), the Department of Defense, the National Science Foundation (NSF), the Department of Interior, and the Department of Energy. NASA s involvement in the US NSWP is based on "its traditional role" of research into the physics of the solar-terrestrial system, and is oriented more towards scientific understanding. NOAA s responsibility is defined as "real time monitoring and forecasting of the near-Earth space environment for non-military applications" with emphasis on "satellite instrumentation, data assimilation, environmental forecasting, research, and numerical modeling."

The fundamental strengths in the US program arise from its long history of in-situ space exploration, extensive research infrastructures and manpower, heavy investment in space-borne platforms, and sustained funding of basic research. Ground-based observations have been relegated to secondary importance in profile and funding. This is largely because the US geography is not ideally suited to ground-based observations of the space environment (except in Alaska). It has been recognized that an over-emphasis of in-situ measurements is not necessarily an optimal strategy in space weather study; cost and technological limitations would set the resolution, continuity, and coverage of space-borne platforms much below the level ground-based instruments are capable of in some key problems. The growing number of CANOPUS data requests has shown that scientists in the US and other countries have recognized the value of Canadian data and are using them to address their lack of effective ground-based monitoring capabilities.

Space weather has also been on the agenda of various member countries of the European Space Agency. On November 11-13, 1998, ESA held a workshop on space weather, seeking to better organize “the extensive collaborative efforts with near real-time data from spacecraft, ground-based and theoretical simulations with the aim of establishing predictive systems relating the cause (solar activity) to the effect on technological systems and human activity.” For example, the ESA 4-satellite mission Cluster II, expected to be launched in mid-2000, will represent a notable advance in space environment research by providing true vector measurements of many key quantities in the magnetosphere. The European countries also maintain a large contingent of ground-based instruments in Scandinavia, the UK, and Greenland. Canada has a long history of successful collaborations with ESA countries in space instrument missions. Closer ties with the ground-based segments between the two continents should be pursued with renewed vigor, as they portend to give a near global ground-based view of the space environment, especially if means could be found to assist the Russian space environment efforts.

3.5 Canadian Opportunities

From the summary of the expertise that is available in universities, government agencies, and industry, it is clear that space science in Canada has a solid foundation from which to build a space environment program of international significance, and demonstrable benefits to Canadians. Canada’s fundamental strengths were identified in Section 3.2, namely, the capability to monitor and predict the auroral ionosphere using ground-based networks and small payloads. These strengths, coupled with Canada’s advantageous geography, will put it in the position of “collecting data everyone wants.”

What is necessary is a clear vision and commitment to build strengths in computational infrastructure and manpower, with skills in data manipulation, physical understanding, high-performance computing and forecasting. Such strengths do not have to be built from scratch, as key expertise in space weather modeling and forecasting already exist in Canada. The proper computational environment for space weather modeling can be established within five years following the start of CSEP, provided we act decisively.

Chapter 4

Scientific Program

The Canadian Space Environment Program will act as a vehicle for research on the polar ionosphere and magnetospheric regions that affect technological systems, and industries vulnerable to space weather. This will be accomplished through utilization of scientific data to predict space environment conditions and hazards. The ability to utilize scientific data sets is dependent upon the general health of Canadian scientific research. In particular, Canada has an existing infrastructure of scientific instruments that collect primary data, and a growing complement of computers and networks for processing data and developing models that can be used to support Canadian and international science projects. CSEP will strengthen the existing programs by bringing a new sense of focus, by adding technology and manpower to meet emerging challenges, and by coordinating resources and expertise. In this chapter, the scientific focus of CSEP is described. The basic approach of the scientific program is of a “ground-up” orientation (Figure 8), whereby inquiries are based mainly on the use of ground instruments and scientific models to infer conditions in more distant regions of the space environment. This approach benefits from the global view and continuity of observations characteristic of ground instrument networks. The sample problems, organized in distinct levels, represent the categories of ionospheric space environment specification (level 2), magnetospheric space environment specification (level 3), dynamical simulation of space weather processes (level 4), and applications (level 5).

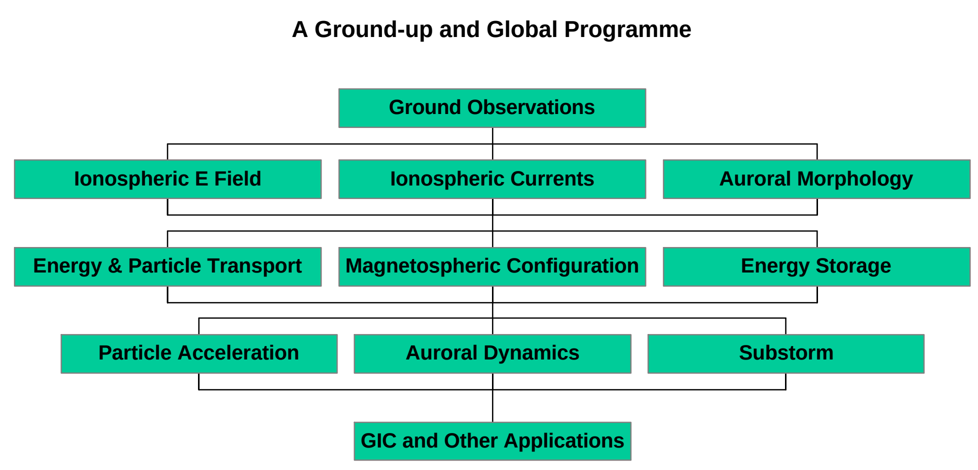

Figure 8. Organizational chart of major science components of CSEP.

The scientific program of CSEP recognizes the logical relationship that exists between space environment energy and transport processes, namely processes that cascade energy from large magnetospheric scales (hundreds of thousand km) to very small scales (1 km or less, characteristic of space weather effects within the ionosphere). Considerations have also been made regarding how the existing instrument capabilities in Canada can be enhanced to provide data support to modeling efforts. Data support will be provided through chains of magnetometers, optical imagers, radars, other ground-based instruments and through deployment of small payloads such as balloons and rockets.

It is recommended that CSEP concentrate scientific investigations on the three major scientific areas:

- Energy storage and release in the space environment
- Magnetosphere-ionosphere coupling
- Electromagnetic response of the Earth

These inter-connected processes determine the state of Earth's space environment as it couples to the impinging solar wind. Each of the major categories further contains specific problems for detailed study and modeling: Energy storage and release contains the sub-categories of magnetic storms and substorms, and energetic particle populations that present hazards to spacecraft devices and instruments. Magnetosphere-ionosphere coupling includes the formation of electrojets, ionospheric disturbances produced by energetic particles and by waves and instabilities generated during magnetic storms. ULF (ultra-low-frequency) disturbances at the Earth's surface includes the detection and measurement of time-varying magnetic and electric fields at the ground, and induced currents in power grids, pipelines, and other large conductors. Although it is convenient to divide space environment processes into the major categories described above, the central thrust of this plan is the recognition that space environment processes and effects are often inter-dependent and need to be tackled in a systematic approach.

A detailed outline of the scientific areas of inquiry that will form the basis of CSEP is described in the sections below.

4.1 Energy Storage and Release in the Space Environment

The broad concern here includes how solar wind energy penetrates the magnetopause; how energy in the form of fields and particles is distributed throughout the magnetosphere; how energy circulation drives the currents connecting to the ionosphere; how excessive energy storage causes substorm explosions; and how energetic particles are produced under storm conditions.

There are two fundamental processes that couple energy from the solar wind into the Earth's magnetosphere. The first process involves the merging of interplanetary and terrestrial magnetic fields. This causes enhanced magnetospheric convection and the opening of high latitude magnetic flux and its subsequent storage in the magnetotail. The second major process involves direct entry of energy into the magnetosphere in the form of the propagation of compressional magnetohydrodynamic (MHD) waves, and through viscous interactions at the flanks of the magnetopause such as the Kelvin-Helmholtz (KH) instability.

Canada’s unique geography and instrument arrays are invaluable for addressing the problems listed above. From Canada, magnetic field lines threading the auroral oval extend into the distant portion of the magnetosphere. Processes in the outer magnetosphere produce distinct ionospheric features, and through monitoring of these features, scientists can infer the state of the space environment, in much the same way that astronomers deduce properties of distant objects. Examples of the diagnostic use of ground data include the characterization of energy storage in the magnetotail, energy dissipation in the ionosphere, and sources of currents and energetic particles in the magnetosphere. This “ground-up” approach distinguishes CSEP in the international arena and will provide a crucial complement to satellite-based programs of other countries. Further major advantages to operating ground based facilities are their modest cost, and ease of serviceability.

Satellite and other in-situ observations will continue to be a valuable tool for measurements on fields and particles. Fiscal constraints in Canada do not easily afford long-term in-situ platforms that can provide continuous data streams. Cost factors also make it impossible to deploy many in-situ vehicles to achieve spatial coverage comparable to the ground-based instruments. Therefore Canada’s efforts in in-situ space environment objectives will mainly be in the improvement of scientific understanding of certain key regions of the space environment.

4.1.1 Energy Storage

The bulk of Canada's ground-based instruments cover the magnetic footprints of the near-Earth magnetosphere, which can be defined approximately as a region extending out to 10 Earth radii in the equatorial plane. The region of dayside merging, and processes along the flanks of the magnetopause can also be viewed from Canada using radars, optical, and other instruments. Understanding of these regions is critical to the success of space weather prediction, as they encompass the location of magnetospheric energy storage, and processes causing substorm eruptions, ring-current and radiation belt energization, generation of field-aligned currents, acceleration of auroral electrons, and excitation of large-amplitude waves that induce currents in large ground conductors.

A CSEP array will be able to monitor the storage of energy that occurs prior to the onset of magnetic storms and substorms, delineate various magnetospheric plasma regimes through meridian scanning photometers (MPA) and all-sky camera (ASI) data, and estimate quantities such as the polar cap electric potential from measurements made using radars. Measurements of the size of the polar cap (which magnetically connects to interplanetary space), the latitudinal extent of the auroral oval, and the strength and location of electrojets can also be used as an indicator of magnetospheric energy storage and geomagnetic activity. For example, using the Churchill line of CANOPUS magnetometers, and electric field measurements from the SuperDARN HF radars, Canadian scientists are developing different methods to investigate high latitude space weather phenomena.

The investigation of energy storage processes may further be divided into polar cap science and near-Earth magnetosphere diagnostic.

In polar cap science, it is recommended that Canada should endeavor to make maximum use of the advantage afforded by its geography. Canada encompasses the magnetic north pole, a distinction that allows unique scientific studies to be made of the polar cap. Under the CNSR (Canadian Network for Space Research), the Eureka observatory was constructed close to the magnetic north pole and served as a model upon which the US Polar Cap Observatory was based. Due to unfortunate diplomatic friction associated with the fishery dispute on the West Coast of Canada, the US polar cap observatory was not implemented. The situation and timing provide opportunities for Canada to play a more active role in polar cap science.

It has been realized that tracking the size and shape of the polar cap can be a useful primary indicator of impending geomagnetic activity. It is recommended that CSEP seek to improve the current polar cap boundary specification procedures by

- Systematically integrating the CANOPUS, NRCan, and other international circumpolar magnetometers data to achieve true 2D real-time specification
- Using complementary data sets, such MPA data, ASI and UV images, radar and other maps to augment and refine the procedure
- Finding correlations between the polar cap size and potential, and between energy storage mechanisms in the magnetotail and specific geomagnetic activity.

Additionally, polar cap science will address several important questions which are indicative of distant solar wind and magnetospheric conditions, such as

- Transpolar auroral arcs
- Particle precipitation from interplanetary space (the polar rain)
- Ionosonde sounding of transpolar ionosphere

Finally, it has been noted that a properly stationed pair of SuperDARN-type HF radars would complete coverage of the polar cap and provide key measurements of transpolar plasma flow which is a known measure of the solar wind-magnetosphere interaction.

In near-Earth magnetosphere diagnostic, it is recognized that many ionospheric features are signatures of magnetospheric processes. Through global data modeling, theoretical formulation, and use of computers, scientists can infer magnetospheric conditions not amenable to direct and continuous measurements. Examples include:

- Field-aligned currents from the magnetosphere
- Magnetospheric configurations from physical models and 3D computer simulations that use observed data or properties as inputs
- Magnetospheric electric fields and plasma convection from the mapping of the ionospheric electric fields determined by SuperDARN radars
- Reconstruction of the plasma pressure in the near-Earth plasma sheet using the inferred

magnetospheric electric and magnetic fields.

The above information provides a detailed quantitative characterization of the state of the magnetosphere during slowly time-varying periods, including the growth phase of the magnetic substorm. The specification of the near Earth space environment can be used in two ways in advance warnings of space weather hazards. First, the current condition can be processed through empirical techniques such as neural networks to give probable space environment conditions in the near future. Second, the information can be used as initial conditions that drive physics-based dynamical models that advance the current space environment condition into the future.

4.1.2 Energy Release by Magnetohydrodynamical Processes

Fundamental magnetospheric energy release mechanisms include magnetic storms and substorms, and their dissipation into the auroral ionosphere. Other important energy release processes involve the transport of MHD (magnetohydrodynamic) waves, magnetospheric field line resonances, MHD instabilities and ionospheric turbulence.

The specification of magnetospheric condition in section 4.1.1 is the first step to predicting geomagnetic activity and other effects of space weather. This knowledge does not by itself lead to reliable quantitative predictions concerning the severity and timing of magnetic storms and substorms. Empirical and statistical models can provide useful measures of the likelihood that 'something significant' may be about to happen. However, the precision of such forecasts can be improved only through physics-based models that evolve the system according to magnetohydrodynamic equations in time. Physical models must, however, rely on real-time data inputs provided by instruments on the one hand, and be integrated into the overall system of space weather information delivery. The linkage between physics-based modeling and forecasting is described in Chapter 6. Considerations of the data pipeline driving physics-based modeling is given in Chapter 7.

It is anticipated that the physics of magnetospheric energy release, or substorm onset, is one problem that will ultimately be solved with high-performance computers playing an indispensable role. Similarly, the configuration of the magnetosphere, which affects the mapping of ionospheric features, requires extensive computation for its solution and visualization. Internationally, predictive modeling of space weather is accomplished through 3D global MHD simulations, and by semi-empirical models such as the Rice University Magnetospheric Specification Model (MSM), which is based on calculations of particle drifts in prescribed magnetic and electric fields (provided either empirically or by global MHD models). There exist significant gaps in these modeling efforts that present opportunities for Canadian scientists. Specifically, Canada's strengths in physics-based modeling lie in its expertise in substorm theory and simulation (especially on the scales of energy release) and in tracking the flow of energy that is released into the space environment at meso-scales (hundreds of km). Concentration on meso-scale phenomena of energy release and transport during active periods will place Canada in a strong distinct position internationally, especially if this effort is closely integrated with Canada′s extensive ground-based instrument arrays. The research focus on meso-scale mechanisms of magnetospheric energy releases include:

- The triggering of magnetospheric substorm onsets
- The location and intensity of substorm energy release
- Energy flow into the ionosphere
- Particle injection into the ring current
- Acceleration of particles in the near-Earth space environment.

4.1.3 Energetic Particle Populations

The energization and transport of charged particles is a major aspect of space weather processes. There are three major regions where particle energization is of major concern: The ring current/outer radiation belt region, the near-Earth plasma sheet region, and the topside ionosphere. Strong energization events in these regions are transient occurrences typically associated with enhanced solar wind activities. In each case, there are unresolved issues regarding the physics of particle acceleration, and their understanding will enhance significantly the ability to predict space weather effects of specific concerns to satellite and communications industry.

The Ring Current/Radiation Belt Region. This region encompasses geostationary orbit. Particles from the solar wind are normally excluded from this region owing to the strong local geomagnetic field that deflects particles. However, during dynamic episodes such as substorms, this wall can be breached, resulting in particles being injected into closed orbits around the Earth. These injections are often accompanied by large increases in particle energies which can persist for several days. Of particular interest is the energization of electrons to several MeV, since they are a concern for the operation of geostationary satellites and low-orbit satellites traversing the foot-print of radiation-belt field lines. Although Canada does not have in-situ capabilities to monitor the flux of energetic particles in this region, it has been established, through Canadian data and investigative efforts, that drastic increases in energetic particle fluxes are often preceded by large-amplitude ULF geomagnetic pulsations that are ideally monitored by Canadian ground-based instruments. This correlation gives Canada the opportunity to play a leading role in monitoring energetic particle condition in this region, and in parallel, developing quantitative models to predict the level of the relativistic electron flux using both Canadian ground data and in-situ observations of the solar wind and geostationary orbit.

The Near-Earth Plasma Sheet. Aurora-producing particles originate principally from the plasma sheet, a region lying above the ring current/radiation belt. It is understood that the onset of substorm expansion is triggered deep within the plasma sheet. In particular, the brightening of discrete auroral arcs during substorms is attributed to the onset of an electric field parallel to the local magnetic field, resulting in enhanced precipitation of electrons into the ionosphere. While the global relationship between the electric potential and current in the parallel direction has been elucidated, the physical mechanisms that generate the parallel electric field have been less clear. A major challenge is to track the propagation of energy released in the equatorial plane along magnetic field lines, and construct quantitative models that describe the formation of parallel electric fields through plasma "imperfections" and nonlinear processes that manifest on small scales. Canadian scientists have established an international leadership in observing and modeling these processes, and this research fits well with Canadian instrument capabilities. It is recommended that modeling of auroral particle acceleration should continue under CSEP through more sophisticated models that incorporate expanded capabilities for observing structures on sub-km scales, and through more complete 3D computer models.

Ionospheric Particles and the Polar Wind. The polar wind is driven by an ambipolar electric field sustained by photo-ionization on the dayside. Ion outflow, of which the polar wind is a contributing factor, is partially driven by wave-particle interactions near the polar ionosphere. The polar wind is the dominant source of the plasmasphere and a significant source for the plasma sheet farther downtail. Through international satellite missions such as Akebono and Freja, Canada has acquired a large dataset concerning the characteristics of ionospheric outflow, and analysis of the particle-detector data has yielded new insight on the polar wind process. It is recommended that future studies in this area should be carried out on the theory and modeling front. Canada has the capability to model ionospheric outflow based on electromagnetic particle in cell (PIC) and hybrid computer simulation. Modeling of ion outflow through the ponderomotive force of ULF waves is also being done in Canada, and can be compared with more detailed PIC, hybrid code and test particle calculations.

4.2 Magnetosphere-Ionosphere Coupling

The ionosphere is a key part of the space environment. As a conducting boundary, the ionosphere regulates the flow of energy in the magnetosphere and influences the onset and course of storms and substorms. The ionosphere is also a region that is crucially linked with modern communications systems, including ground and satellite based systems. The link in magnetosphere-ionosphere (M-I) coupling is Alfven waves, an oscillation of magnetic field lines that is analogous to the vibration of piano wires. The general principles of M-I coupling are well-known, but much remains to be done by way of understanding the processes which cascade energy from global scales down some of the smallest (1km, the electron inertial) scales found within the ionosphere.

Experimentally, the ground-based instruments at Canada’s disposal represent by far the most useful monitor of Alfven waves in the ULF frequency range. The incorporation of new instruments such as CADI, IRIS (imaging riometers), and small payloads instruments such as the upcoming GEODESIC rocket mission will give CSEP an enhanced capability to track a range of ionospheric features. These capabilities will allow Canadian scientists to define the ionospheric state on a large scale, understand and model fine scale auroral structures associated with enhanced energy input. They can also feed into programs on upper atmospheric heating and circulation. Until recently, computer modeling of M-I coupling has been difficult, because of the vast changes in spatial scales between the magnetosphere and ionosphere. However, the acquisition of supercomputing facilities in Canada gives the expectation that many relevant questions can be computationally addressed by CSEP. New developments in high-performance computing will also allow sophisticated computer models to be developed, and run in real or near real time. Studies of M-I coupling will also ensure that Canadians can continue to collaborate with scientists undertaking similar studies in Alaska, Scandinavia, and Greenland. Together, these efforts will result in near global coverage of the ionosphere.

4.2.1 Global Ionospheric Electrodynamic State

A number of key parameters of the ionospheric state can be inferred from measurements made by a proposed CSEP array and will involve both data collection and data assimilation methods. These include:

- The ionospheric currents from magnetometer measurements
- The ionospheric electric field from HF radar measurements and the pattern of global ionospheric convection.
- Auroral morphology from MPA and ASI measurements.
- Inference of ionospheric conductivity from the combination of HF radar, magnetometer and optical measurements.
- Characterization of resonant wave interactions from measurements of ULF geomagnetic pulsations.

All of these measurements are necessary steps to providing data and inputs that can feed into Canadian and international space weather programs.

4.2.2 Discrete Auroral Arcs and Fine Scale Auroral Processes

Large-scale energy transport ultimately feeds into the very small scales (1 km or less) found in discrete auroral arcs and related processes. Discrete arcs intensify during enhanced geomagnetic activity, and they are intrinsically connected with magnetic storms and substorms. An auroral substorm is initiated by the brightening of one or more auroral arcs, usually the most equatorward one. Thereafter follows a dramatic succession of brightening and expansion of aurora, and an explosive release of a large amount of magnetospheric energy that has been accumulated during the growth phase (see section 4.1 above). Much of the released energy is dissipated in the ionosphere, with additional amounts injected into the ring current and radiation belt region. The study of discrete arcs is therefore intimately linked to the overall understanding of the substorm processes. For many years, scientists have attempted to explain discrete arcs using a range of theories and computer models, although no consensus has yet emerged. However, observations have revealed that discrete arcs are associated with very strong field aligned currents that flow down magnetic field lines and close through Hall and Pedersen currents in the ionosphere. Discrete arcs are also associated with intense parallel electric fields that energize auroral electrons to energies of several keV. They can also energize ions through wave particle interactions and modify ionospheric conductivities. Some of these effects have been described in section 4.1 above.

The origin of discrete arcs and fine scale auroral features has been referred to by some as a holy grail for space plasma physics, and Canadian scientists have been at the forefront in this area. For example, Canadian observations and models have revealed that the substorm is initiated in the inner plasma sheet, well within the field of view of Canadian instruments such as magnetometers, scanning photometers and all-sky cameras. Data from these instruments are advancing our understanding of auroral arc physics, and can be used to derive inputs for computer models that attempt to describe the full dynamical evolution of auroral processes. During active periods, auroral arcs contain a hierarchy of structures which cannot be readily related to the more global magnetospheric source. Effects which manifest on scales smaller than 10's of km are mainly attributed to nonlinear plasma processes operating very close to the ionosphere at the electron inertial scale, while in the magnetosphere auroral arcs are regulated at the much larger scale of the ion gyroradius. Understanding how energy cascades across all spatial scales is a fundamental scientific challenge in auroral arc research, and also one that has direct practical implications since the energy cascade has a direct bearing on the characteristics of ionospheric turbulence and localized density irregularities. The energy process can also cause sharp local current intensifications that affect large conductors such as power lines.

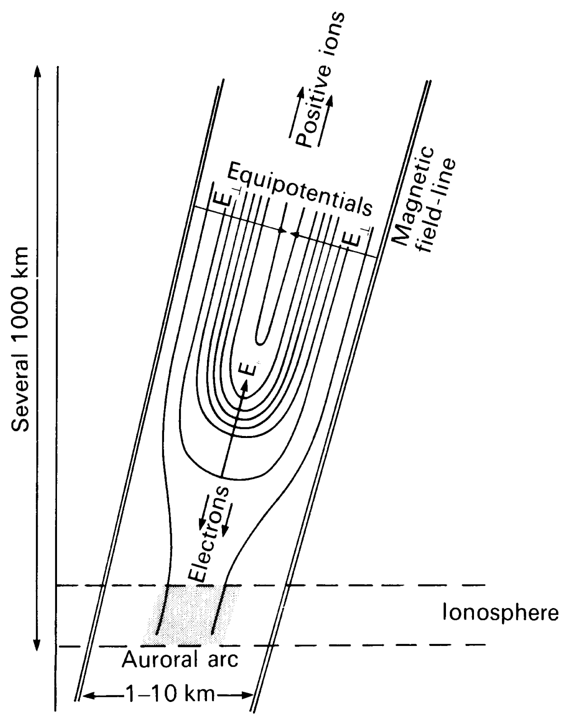

Figure 9. Auroral arcs form through the bombardment of accelerated magnetospheric electrons.

When the scale size of ionospheric structures falls under the km range, ground-based instruments begin to lose resolution. Flights of instruments onboard sounding rockets and microsatellites can then provide critical information on fine-scale structures, ambient microscopic processes, and their relationship to the encapsulating large-scale structures. These studies naturally fit small payload instruments, and future payloads on international satellite missions. Because of their lower costs and continuity of operation, ground-based measurements can fulfill the long-term needs of a space weather monitor. The advantage of in-situ instruments flown under CSEP can be maximized if close collaboration and calibration with ground-based observations is built into the scientific plan. Opportunities in this collaboration are numerous, particularly in auroral arc physics discussed in this section. With such collaborations, the disadvantage of the short life span of in-situ instruments can be further compensated by developing theoretical and computer simulation models that can provide predictions of fine-scale structures and dynamics from the meso- and large-scale features observable on the ground.

4.2.3 Discrete Auroral Arcs and Fine Scale Auroral Processes

A rich variety of auroral forms are present within the auroral ionosphere. To predict the spatial distribution and progression of space weather effects in the ionosphere and on the ground, one must know how these forms evolve. Many of the structures are associated with ULF wave processes coupling magnetospheric energy to the ionosphere. The most dynamic of these auroral forms is the westward travelling surge vortex that forms during the substorm expansive phase. The field aligned currents associated with vortex structures can present ground anomalies to power systems such as transformers. Many smaller scale auroral vortex structures are also present, ranging from the smallest scales of 1 km or so to a few tens of km. The mechanisms that form vortex structures are varied, but they generally involve both velocity and magnetic shearing. Both types of shear arise in ULF wave fields that are excited resonantly on geomagnetic field lines, whereas field aligned currents alone will normally support magnetic shear. Vortices form through nonlinear plasma instabilities such as Kelvin-Helmholtz or collisionless tearing instabilities. They may also materialize when sheared magnetic fields evolve towards a force free or minimum energy state.

Canadian instruments such as radar and all-sky cameras are capable of observing auroral vortex structures down to 1-km scales, and Canadian scientists have documented many such examples in the literature. Small scale vortex structures are not generally visible in magnetometer arrays because of limited spatial resolution, but can be more readily observed by SuperDARN radars, where they are found to evolve over periods of seconds to minutes within the large-scale convection near the dawn and dusk flanks of the lower latitude boundary layer. Vortices have also been attributed to magnetic cloud events in the solar wind which wind their way down geomagnetic field lines and propagate anti-sunward. It is remarkable that these distant events can be observed and interpreted from the ground, and mapping these transient flows has become an active endeavor in international space weather programs such as the GEM (geospace environment modeling) program in the US. At lower latitudes, smaller scale vortex structures may be associated with discrete arcs, and it has been speculated that the auroral substorm may evolve from the destabilization of such arcs. Possible destabilization mechanisms include a nonlinear interaction between shear flow (Kelvin-Helmholtz instability) and ballooning or interchange instabilities.

A planned enhancement of all-sky cameras in the CANOPUS chain will be very valuable in addressing the question of auroral dynamics. Advanced computing infrastructures and computer modeling programs are also equally imperative, so that observations can more easily be transformed into predictions. Under the CSEP time frame of 10 years, it is reasonable to expect that the questions separately discussed in sections 4.2.2 and 4.2.3 can be unified and addressed in a self-consistent model which describes the entire energy cascade and transport process. Ultimately, this may finally pin down the mechanisms driving or initiating the explosive energy releases associated with magnetic storms.

4.2.4 Ionospheric Turbulence

Most of the plasma involved in M-I coupling is located at ionospheric altitudes. Hence, the ionosphere has a major influence on auroral and polar cap phenomena. Ionospheric turbulence, a term used to describe highly variable small-scale (sub-kilometric) phenomena, not only alters the state of the ionosphere and impacts HF communications, but also influences the channel by which ionospheric ions flow out to the magnetosphere. The ionospheric conductivity is known to be susceptible to ionospheric turbulence, and this affects the important phenomena such as the formation of electrojets. Ionospheric conductivity exerts important influences on magnetic activity, especially during winter, and at night. The tremendous amount of waves and turbulence during active times can also change the local transport properties of the medium (from conductivity to electron density distribution).

Much of the energy in turbulence is associated with the auroral structures described in section 4.2.3. Numerous turbulent phenomena include ion acoustic turbulence, polar patches, ionospheric irregularities, solar proton polar cap absorption events, and fine-scale conductivity enhancements. Support of these investigations will ensure that connections can be established between complex magnetospheric phenomena and their auroral features. The CADI array operated by the University of Western Ontario can monitor multi-scale ionospheric structures and certain aspects of turbulence. The University of Calgary, in partnership with the University of Maryland, plans to develop an array of imaging riometers (IRIS) which can monitor electron density enhancements with fine time and spatial resolutions. Ionosondes use reflected radio waves to probe electron densities in the ionosphere, while riometers base their measurements on absorption of cosmic radio noise emitted by stellar objects. These instruments offer excellent opportunities for coordinated event studies with new (more short-lived) high resolution satellite missions such as FAST (currently in orbit), IMAGE (Imager for Magnetopause to Aurora Global Exploration), which has a planned launch in early 2000, and IMEX (Inner Magnetosphere Explorer), which is set for a launch date in mid 2001. This will ensure that Canadian scientists can compete in the international arena of space research.

4.2.5 Upper Atmospheric Heating and Winds

Enhanced flows of electromagnetic energy dissipate in the upper atmosphere by two major routes: Joule heating and momentum transfer to the neutral wind. A smaller fraction of the deposited energy is due to energetic electrons. Energy dissipation causes heating and vertical expansion of the atmosphere, factors that can produce increased drag on low orbit satellites such as weather satellites and larger objects such as the international space station. There may also be gravity waves consequent to magnetic storms. CSEP has an overlap of interests with the CSA Atmospheric Environment Program at this interface. Therefore, it is recommended that collaborations be explored at such community forums as DASP. For example, SuperDARN radars can provide fairly detailed information on the ionospheric electric field which controls the rate of Joule heating and the strength of ionospheric convection powering the neutral wind, as well as information on gravity waves, and meteor showers which are of interest to the atmospheric community. The interferometry technology used by WINDII, which has brought much valuable insight into atmospheric winds might be adapted for similar measurements at thermospheric altitudes.

4.3 Electromagnetic Response of the Earth

The previous sections have addressed the propagation of energy from the solar wind into the magnetosphere and ionosphere. In this section the flow of energy into the Earth itself is examined. During a geomagnetic disturbance, electric fields and electric currents are set up within the earth and act to reflect some of the incident energy and also partially shield the deeper regions of the Earth from the disturbance. The induced currents within the Earth also create a magnetic field that contributes to the total magnetic field observed at the Earth's surface. These surface observations are the principle measure of currents in the ionosphere, so an improved understanding of the induction effects will greatly contribute to accurate determination of the ionospheric currents.

The electric field produced by the magnetic disturbance propagating down from the ionosphere is the critical parameter that is responsible for geomagnetic effects on technological systems. In spite of this long-recognized role, there are still disputes about the nature of the electric fields involved. There is a need for new instruments that can provide suitable measurements of the electrical conditions at the Earth's surface. Traditional electric field measurements only record the total electric field. Priority should be given to the development of new instruments that can measure the component parts of the electric field. Such instruments would open up new possibilities for mapping the response of the Earth to geomagnetic disturbances.

4.3.1 Determination of Ionospheric Currents

A prerequisite for using surface magnetic field observations to determine ionospheric currents is the separation of the internal and external parts of the magnetic field variations. A number of mathematical tools have been developed that allow this separation. Assuming a flat earth the external and internal parts of the horizontal and vertical magnetic field variations are related by Hilbert transforms to the magnetic field components observed along a line of stations. If the curvature of the Earth is included the same separation can be achieved by fitting zonal harmonics to the observed magnetic field data. Spherical cap harmonic analysis (SCHA) generalizes this fitting technique to any surface on the sphere.

The spatial coverage of magnetic field observations has only rarely been sufficient for the above separation techniques to be used. However, the combination of the CANOPUS and NRCan magnetometer arrays, along with the addition of new magnetometers could provide the extensive coverage of the magnetic field variations that would allow these techniques to be used to great advantage to more accurately map the ionospheric current densities across Canada.

4.3.2 Electric Fields at the Earth's Surface

The electric fields produced at the Earth's surface during geomagnetic disturbances are dependent on the conductivity structure of the Earth and the frequency content and spatial extent of the incident disturbance. While the general principles are well known, we are still a long way from a quantitative understanding of the induction process. This is principally because of a lack of data on the critical parameters. The frequency content is easily measured but the spatial characteristics of the source fields have generally been ignored in electric field calculations. Now, with the extensive measurements planned as part of this program, sufficient information will be available to examine the effect of the source field dimensions on the production of electric fields.

The conductivity structure of the Earth is an important parameter in the induction process. However, only recently has information on the bulk conductivity values been collected in a form that can routinely be used for electric field calculations. Considerable further work is needed to extend the knowledge base to include the lateral variations in conductivity responsible for potential gradients that distort the electric field. This is obviously a necessary part of calculating the electric fields along the Earth's surface. Also, in some applications (such as determining pipe-to-soil potentials) the electrical potential at the Earth's surface is itself the parameter of interest.

Recent studies that have examined the earth response at higher frequencies (periods less than 1 minute) have shown that there is considerable natural electromagnetic noise in areas where there are shallow changes in the earth conductivity. The earth response at longer periods is dominated by the deeper large scale conductivity structure. Now, the finding of the effect of small scale structure has vastly increased the number of anomalous sites where earth surface potential changes will be produced. A more detailed mapping of the earth conductivity structure will be necessary to provide the information required for evaluating the effect of the above listed areas on technological systems.

4.3.3 Electric Fields at the Seafloor

The electric fields experienced by submarine cables depend on the response of the Earth looked at from outside (i.e. at the surface) and by how electromagnetic disturbance propagate within the Earth itself. For calculating the electric field at the seafloor this involves determining the attenuation of the electromagnetic disturbance by the conducting seawater. As with continental induction, induction in the sea is influenced by the spatial characteristics of the external disturbance, and this will be especially important at high latitudes.

To calculate accurately the total voltage produced in a submarine cable during a geomagnetic disturbance will require an improved understanding of the effect of the coast on the seafloor electric fields. For a uniform source field the currents perpendicular to the coast are deflected down into the Earth. However, for the more realistic case of a localized source, the currents impinging on the coast can also be deflected away from the source. When one considers the irregular shape of a real coastline the problems are further complicated. There is thus a need for sufficient resources to be provided for high resolution electromagnetic modeling of coastal boundaries.

Canadian scientists are at the forefront of work on modeling the electric fields at the seafloor. However, as yet, there are no Canadian measurements of the seafloor electric fields. To remedy this, every opportunity should be taken to obtain measurements on seafloor cables that have been taken out of service, or through collaborative work with cable operators. Access to seafloor measurements can also be provided through international collaborations with groups who are recording voltage fluctuations on both powered and unpowered submarine cables.

Chapter 5

Space Weather Forecasting

An important goal of the CSEP is to improve space weather forecasting. The CSEP will act to provide a bridge between scientific researchers and those involved in forecast operations so that there can be a speedy transition of new knowledge into operational tools that can be used for forecasting. Active participation of industry groups in CSEP will also help ensure that the forecast products developed meet the needs of users.

Forecasts of geomagnetic activity have been produced by NRCan (and its fore-runners) for over 20 years, and because of its experience, facilities and industrial connections, NRCan will continue to be the pipeline through which space environment information is distributed. Scientists at the NRCan forecasting center will continue to play an active role in forecast development. In the new environment of CSEP, Canadian scientists from other institutions will find a greater opportunity and incentive to become involved in developing new forecasting techniques. For instance, at the University of Alberta, an empirically based model of the location of the auroral oval has already been developed, with graphical output available over the internet.

Improvements to the forecasting operation can be expected through the use of additional data from CANOPUS and SuperDARN and through the extensive use of data processing, visualization, and model outputs from computational facilities at the FDAM. Services developed from techniques that exploit magnetic and optical data, and data from the SuperDARN array, will be used to provide information on ionospheric and magnetospheric conditions, and to give advance warnings of substorms, geomagnetic activity, and energetic particle populations. With the proposed CSEP, we expect forecasting operations to be significantly strengthened and the range of forecast parameters to be expanded.

Discussions with various industrial sources have led us to distinguish two types of forecast services that are needed.

<u>Long Term Forecasting.</u> The degradation of many technological systems is caused by the cumulative long-term behavior of the space environment. Examples of such climatological information are the cumulative dosage of irradiation a satellite is expected to receive over its expected operational life time, and the degree of corrosion of pipelines over many years. Satellite engineering and power grid design need information for the extreme conditions the system is expected to encounter. Although physics is important in clarifying how system effects are linked with space weather causes, long term forecasting can be done through statistical analyses of historical data, on the assumption that the space environment, in the long run and in the cumulative sense, is largely periodic over a solar cycle.

Short Term Forecasting. A number of technological systems are sensitive to transient (minutes to hours) and single extreme events. Examples include anomalies in satellites and disruptions in power grids. Short-term forecasting is needed for these events for the proper planning and implementation of emergency measures. The statistical approach often cannot facilitate such information, because the inherent statistical error would not meet the stringent accuracy requirements for such information. Instead, accurate event forecasting must rest on a true understanding of the physical processes involved, and the ability to model the space environment according to the cause-and-effect relationship revealed by scientific investigation.

The first requirement of short-term forecasting is to provide a warning of disturbances up to several days in advance. This means issuing a warning when a solar eruption is observed. The problem with this is that not every solar eruption produces disturbances on the Earth. Consequently there is a need for an improved understanding of how the disturbances propagate through the solar wind. When a disturbance reaches the Earth, a fundamental problem is knowing what fraction of the energy input is directly coupled into the ionosphere and how much is stored in the tail for subsequent release. Investigations should be carried out to examine whether more sophisticated models such as global MHD models, charged particle dynamical models, and artificial intelligence techniques such as neural networks, can be useful to short-term forecasting.

Our understanding of the forecasting requirements has led us to organize forecasting operations into four modules.

5.1 Climatology

Climatology often seems to be the "poor relation" in space weather studies, although it can still provide useful information. For setting technological design criteria the climatological information may be exactly what is required. Also climatological data are an essential part of "event driven" forecasting schemes as it provides a back-up source of information that can be used whenever there are disruptions to the normal data channels feeding into the forecasting process. Finally, climatological studies can be a productive way of stimulating new discoveries and understanding of fundamental physical processes, by revealing recurring patterns in an accumulated set of data.

There are many data sets both acquired from Canadian measurements and international sources that are worthy of climatological examination in light of recent advances in space physics and emergence of space weather concerns. Records of the occurrence of geomagnetic disturbances (based on the *aa* index) are being extended back to 1847 to provide a 150 year record covering the whole period during which long electrical conductors have been used in man-made systems. Most modern records of indices provide a more detailed record of the magnetic activity over a shorter time scale (*Kp* since 1932, and *Dst* since 1957). The classic study on geomagnetic activity statistics by Bartels (1964) only included *Kp* data from 3 solar cycles, but *Kp* values are now available for six complete solar cycles. A repeat study would have twice the data which alone would improve the reliability of the results, but a study done within the context of our improved knowledge of the solar wind - magnetosphere interaction could test for associations not considered in the earlier study, such as the IMF sector.

Magnetic disturbances are associated with an interplanetary magnetic field that has a southward component in the solar magnetospheric (GSM) coordinate system. While the interplanetary disturbances and their associated magnetic field orientation originate on the Sun the geometric mapping of the IMF orientation from the solar equatorial (GSEG) coordinate system to GSM coordinates provides a modulation of the magnetic field orientation seen by the magnetosphere. This produces the well-known Russell-McPherron effect generally considered to be the cause of the seasonal variation in geomagnetic activity. Although this has been known for many years, this information has not been exploited for forecasting.

The seasonal modulation is related to whether the Earth is in the “toward” or “away” sectors of the Sun’s magnetic field. Information on the IMF sector has been obtained by direct measurements from satellites such as IMP 8 and ISEE 3. Indirect measurements can also be obtained from ground magnetic observations. The interplanetary magnetic field By component influences magnetospheric convection and causes a shift in the foci of the ionospheric convection current loops. This is seen as a change in the diurnal variation of the magnetic field observed on the ground within the polar cap. Data from high latitude stations, such as Resolute Bay, can thus be used to identify the solar sector direction. These data can be used to fill in gaps in the satellite data (when the satellite is in the magnetosphere) and to extend the solar sector data back to earlier times (Resolute started operating in 1952).

Magnetic indices can provide a look at the global response to solar wind conditions. However, for more detailed forecasting of the magnetic activity levels within Canada it is necessary to examine the morphology of the magnetic disturbances actually observed in Canada. For example a study has been made of the occurrence of *dB/dt* values that may be critical for power system operation. At the time of that study digital data were available from the Canadian magnetic observatory network for just over one solar cycle (1977 to 1989). A subsequent study made a detailed examination of magnetic disturbances occurring during 1991. With the continued accumulation of data in the following years there is now digital data available for two complete solar cycles.

Statistics of geomagnetic activity can provide a guide to the levels of activity that a system, such as a satellite or a pipeline, will be exposed to over its expected lifetime. However, the statistical information required depends on the type of system. Power system operators are concerned about the few extreme events that would produce large geomagnetically induced currents in the system. Hence the need was for statistics of the peak *dB/dt* to be expected in different parts of the country. For pipelines the impact of geomagnetic activity is a cumulative effect so the need is for information, not on the few extreme events, but on the more frequent events that, although smaller, are still large enough to take pipe-to-soil potentials outside the safe range. For other systems, such as satellites, the magnetic activity levels, such as range values, are used as a proxy for the actual conditions that will cause problems. As described above, extensive data sets are now available; it is only a matter of finding the personnel resources to turn these into useful climatological statistics.

5.2 Empirical Forecasting

Empirical forecasting uses various data processing techniques to search for patterns that may be used to predict the occurrence of an event based on precursors which do not have to be the physical cause of the event. These methods do not have physical relations as their first order of concern, but rather concentrate on discovering and exploiting patterns in the system behavior. This approach may lead to the determination of simple correlations or more sophisticated forecasting methods involving time series techniques such as Fourier transforms which represent the response of the physical system in terms of linear or nonlinear filters. A new class of methods involves artificial intelligence techniques such as neural networks that can be used to “train” a computer to respond to data inputs through auto-corrective feedbacks.

Neural network applications related to space weather have almost exclusively focused on prediction of geomagnetic indices. This is because of the ready availability of geomagnetic index values as a training set for the neural network. At least one neural network routine is now in continuous operation, using Advanced Composition Explorer (ACE) satellite data to predict *Kp* values. This is not an area where the Canadian space physics community has been in active pursuit, although there is experience with neural networks in some engineering departments. There are however opportunities for international collaborations with those groups specializing in artificial intelligence techniques.

On a more detailed level, we often need to predict is the parameter that actually has an impact on a particular technological system. However, to do this directly is unlikely to be practical for technological measurements because the datasets are too small for determining empirical relations or training a neural network. Also any changes to the system configuration alter the system response and would require determination of new empirical relations or retraining of the neural network. Instead it is better to determine a geophysical parameter from which the system response can be calculated.

Consider, for example, the procedure involved in predicting the level of geomagnetically induced currents (GIC) in different parts of a power system (similar issues will apply to other technologies). If a transmission line is taken out of service, the flow of GIC across the system will be altered. Therefore it is inadvisable to use empirical relations involving GIC directly. Instead, if the electric field is known, GIC can be calculated for any system configuration. Previous Canadian studies of geomagnetic hazard to power systems have established empirical relations between *Kp* and the electric fields experienced by power systems. Combining this with neural network predictions of *Kp* could provide an estimate of the electric field for input into power system models that would calculate the GIC.

Global indices cannot give the best indication of local conditions; so an improvement would be to use the abundance of data we have in Canada for training neural networks to predict the local conditions directly. For example, great strides have been made in determining the inductive coupling between the auroral electrojet and power systems on the ground; therefore predictions of the auroral electrojet location and amplitude could be used to predict the GIC expected in power systems. As described in Chapter 4, ground magnetic observations from the CANOPUS array can be used to determine the current density profile of the auroral electrojet. Combining this with ACE data provides the training set that could be utilized for setting up a neural network prediction of the electrojet location and amplitude and from that the GIC in Canadian power systems.

5.3 Physical Forecasting

Physical forecasting bases its prediction on the dynamical solution to equations that represent cause-and-effect relationships underlying the real system. The computational requirements for physical forecasting are very high, as many regions and modes of interaction have to be accounted for to represent the complex space environment. The data demand is also much heavier than for empirical forecasting, because the representation is global and three dimensional. Compounding the difficulty of physical forecasting is the uncertainty in some key scientific issues, such as the substorm onset mechanism. However, in spite of these difficulties, and largely due to progress in computing and scientific visualization, space science has advanced rapidly in the development and use of physics based models of the space environment. For example, global MHD simulation codes (with inputs based on optical and geomagnetic data) can describe the growth phase characteristics of substorms remarkably well, in spite of a lack of detailed information on the nature of the solar wind interaction at the magnetopause. Convection models relating the energies and spatial distribution of particles have been developed to give important information to operators of satellites. Many advanced and novel techniques are possible, such as combining test particles with global MHD codes, and studying the transport and energization of these particles through the magnetosphere. Reduced MHD models can use data inputs from more global models to investigate trigger mechanisms for substorms. This could lead to models of the electrojet current systems that would provide predictions of variations in activity levels.

Physical forecasting is a major objective of the Canadian space environment program, and offers exciting possibilities for producing accurate and refined space weather forecast information. During the course of LTSP III, we see the value of physical modeling to be manifest principally through its use in the hybrid forecasting operations described below. Efforts at developing physical forecasting capabilities will be concentrated in the FDAM, with close collaboration with forecast services operations at NRCan.

5.4 Hybrid Forecasting

Our review has shown that there exists a great wealth of space environment data from various satellite, suborbital, and ground-based instruments. These data sets are not independent, but are linked by various physical relationships. For example, the solar wind condition is responsible for geomagnetic disturbances. If we understand the physical relationship that is involved, we can work toward improvements in the accuracy and reliability of forecasts. As a possible example of one particular CSEP operation, the characterization of the condition of the auroral oval might lead us to predict through an empirical procedure the state of the magnetosphere-ionosphere system in the region of substorm onset. This information can be used as an initial condition that drives a physical model simulating the process of substorm onset and the consequent energy and currents flows that appear in the ionosphere. This example demonstrates that a physical model does not have to represent the whole chain of space weather processes to be useful in an operational sense.

Empirical models do not operate effectively out of their range of average conditions, i.e., for the extreme variations that present the most interesting (destructive) forms of space weather. Physical forecasting is faced with difficulties of its own, and requires a development stage before physics based forecast services can become operational. Currently all space weather forecasting systems in the world face the practical difficulties in using full-fledged physical models for space weather prediction, because of scientific and computational limitations. Therefore, forecasting success, in the intermediate term, will depend on how well the theoretical and simulation expertise is integrated into the forecasting operation. Within the timeframe of this initiative, the most likely scenario for improvements in forecasting is a hybrid approach whereby physical knowledge, data visualization, and physical model outputs are gradually injected into empirical forecasting schemes and services to improve performance. In comparison with space weather programs in other countries, CSEP is distinguished, among other things, by the importance it places on the collaboration between scientific works in the physical simulation and empirical forecasting areas. The hybrid forecasting operations described above highlight the degree of collaboration that is required to enhance both empirical and physically based forecasting operations. In particular, close interactions between forecasting services at NRCan and modeling activities at the FDAM will be critical.

Chapter 6

Technological Effects

To be useful for technological applications, the space weather program needs clear objectives related to the requirements of different industries. Four groups are considered: ground electrical systems, satellites, radio communication systems, and navigation systems. For each of these work is needed on understanding the reaction of the system to the space environment and on predicting the occurrence of disturbances, both in a statistical sense and as a design tool, and forecasting of events so that preventive action can be taken.

6.1 Ground Systems

Canada's efforts in understanding geomagnetic effects on ground electrical systems are made by different industry groups, often in collaboration with NRCan scientists at the Geomagnetic Laboratory, Geological Survey of Canada. The systems affected include power systems, pipelines and submarine phone cables. A common requirement of all these systems is knowledge of the electric fields that these systems will experience. Beyond this there are research requirements related to the particular response of each system to magnetic disturbances.

6.1.1 Power Systems

Geomagnetically induced currents (GIC) are known to occur at times of geomagnetic activity, but there is a lot of work to be done to establish a quantitative relationship between the two. The structure of the source fields and lateral variations in earth conductivity can seriously affect the electric fields produced during geomagnetic disturbances. Calculations of these effects cannot be made in isolation but must be accompanied by recordings of GIC on power systems to provide the data that will allow verification of the modeling routines developed.

The main impact of geomagnetic disturbances on power systems arises because of transformer saturation produced by GIC. However, the inductance of large power transformers may be large enough to limit the growth of GIC. Also, currents induced in tertiary windings create magnetic flux in the transformer core that tends to cancel the GIC flux and slow transformer saturation. Knowledge of the frequency response of transformers coupled with information on the frequency spectra of the geo-electric field is needed to determine when transformer saturation will occur.

All of the above work is needed in order for a utility to make an informed assessment of the threat of magnetic disturbances to their system. There are two strategies for utilities whose systems are considered to be vulnerable: engineering solutions to make the system less vulnerable or the use of operating procedures to reduce system vulnerability at times of geomagnetic disturbances. The choice of a particular approach will depend on economic considerations. A combination of strategies may be used with inexpensive solutions such as adding harmonic filters to the most sensitive relays being augmented by operating strategies to cope with the most serious disturbances.

6.1.2 Pipelines

Prevention of pipeline corrosion requires that the electrical potential of the pipeline, relative to the surrounding soil, is maintained within a narrow range. Periodic surveys of the pipeline are carried out to ensure that the pipeline potentials are correct. However, on occasions, telluric currents produced by magnetic field variations, can cause the pipeline potential to fluctuate wildly. These telluric currents are of greatest concern for pipelines at higher latitudes where the magnetic disturbances are most intense. As well as interfering with pipeline potential surveys, telluric currents are of concern to pipeline engineers because of the possibility that they may be contributing to pipeline corrosion.

Telluric current effects vary considerably over the extent of a pipeline network. A key factor in understanding telluric current effects is knowing where the largest potential variations occur. Observations have proven difficult to obtain because of the sporadic nature of telluric currents and because of their variation with position along the pipeline. A few studies have been made using multiple recordings of pipeline potentials to determine the telluric current profile along particular pipelines. An extension of such work, as part of the CSEP, would help to build up a comprehensive picture of how different pipeline characteristics, such as coating resistivity, affect their response to telluric currents.

When the pipeline potential changes, there is a lag before corrosion commences. This introduces a frequency dependence into the pipeline response to telluric currents. The nature of this frequency response is unknown and requires investigation. When cathodic protection is removed (or interrupted) the pipeline takes some time to depolarize. It is open to question whether, during a magnetic disturbance the telluric currents drive the pipe into a depolarized state or whether the normal depolarization times still apply. This is an important factor in determining the conditions at the pipe - soil interface where corrosion occurs.

The above systems have their own research requirements related to the response of each system to a geomagnetic disturbance. However, all have similar requirements in terms of geophysical inputs. These are:

1) Reliable statistics on geomagnetic activity, tailored to the location of the system, for use as design criteria.

2) Improved determination of the electric fields produced during geomagnetic disturbances by including the effect of the structured source fields produced by the

auroral electrojet.

3) Further investigation of the ground conductivity structure within Canada and the inclusion of conductivity variations, particularly at the coast, in the calculation of electric fields.

4) More extensive observations of GIC in ground systems for comparison with and validation of the GIC modeling results.

In addition, power utilities have specific forecast requirements:

a) Delivery of advance (1 to 2 days) warnings of geomagnetic disturbances to power system operators to allow re-scheduling of equipment maintenance and other preventive action.

b) Delivery of short-term (30 minute) warnings of geomagnetic disturbances to power system operators to allow GIC response procedures to be implemented.

c) Continual updating of geo-alert status so that power system operations can return to normal as soon as possible.

Development of computer models that can accurately simulate geomagnetic induction in realistic pipeline networks is needed. The model should include the effects of pipeline discontinuities and the influence of geological boundaries.

6.2 Satellites

While the primary intent of satellite manufacturers is to construct satellites that are immune to space weather effects, the industry as a whole continues to experience a variety of anomalies that have been attributed to the space environment. The focus in this direction is to identify the correlation with the particular environmental phenomenon, understand the anomaly mechanism, and develop design improvements which can be introduced to future models to eliminate or reduce the susceptibility. From the satellite operator s perspective, space weather forecasting is useful, but their options are necessarily limited to avoidance measures, in contrast to, for example, power system operators.

Major concerns that we will address are the spacecraft interactions with the plasma environment: this causes spacecraft charging, deep dielectric charging and damage due to particle radiation. The drag and surface erosion produced by the neutral atmosphere is also a concern to spacecraft designers but is beyond the scope of major foci of the CSEP.

The plasma component of the environment represents a current flow to the spacecraft skin causing charge build-up. Differential charge build-up can cause potential differences between parts of the spacecraft which can cause destructive arc discharges. This can destroy solar cells, generate electromagnetic noise, and erode surfaces. The charging environment is severe at geostationary orbit and can lead to potential differences of several thousand volts. This has led to arcing that is believed responsible for anomalous operations and the failure of several satellites.

Radiation of high energy electrons can also cause deep dielectric charging and radiation damage to satellites. Charge deposited into electronic circuitry can cause a change in state (a single event upset, SEU) which may be temporary and just require resetting the electronics or may cause permanent damage. Passage of high-energy particles also leads to power loss in solar cells, degradation and failure of microelectronics and darkening of optical components. The radiation damage to solar cells is one of the most important life-limiting factors in spacecraft power system design.

The research areas above mainly relate to the objective of achieving a better definition of the space environment for application to satellite design, in particular communications satellites in geosynchronous orbit. Many extant industry standard guidelines, although they have served well enough over the last decade or so, should be updated to reflect new data accumulated since their publication. Also it is widely acknowledged that some models in general use contain gaps and discontinuities which, if better defined, may reveal hitherto unsuspected variations to which new designs are more sensitive.

Short-term variations in some environments may have more influence than has previously been thought, especially in relation to the phenomenon of internal charging/discharging. Even though in many cases the average environment is well characterized, there is a lack of information on the short term, both as to instantaneous magnitude and rate of change.

A major concern is the lack of any facility available to commercial operators that will reproduce the space weather environment accurately enough to permit system level satellite testing. The fact that, notwithstanding their being designed to all current guidelines, satellites continue to experience space weather-related failures illustrates a pressing need to develop some method of relativistically subjecting satellites to the actual in-orbit environment to demonstrate their immunity.

Specific areas requiring further research are:

1) Investigation of low-energy electrons in the <100 keV range, short term variation of flux at various energies, and refinement of a worst case substorm model for surface-charging phenomena evaluation.

2) Further investigation of electrons in the 500 keV - 10 MeV range, short-term variation of flux at various energies, and refinement of worst case peak flux and flux gradient models for internal-charging phenomena evaluation.

3) Improved determination of long-term average dose for radiation hardness evaluation of

semiconductor devices and integrated circuits, particularly low-current field-effect devices. Re-examine equivalency of current lab testing methods to actual environment.

4) Investigation of long-term radiation effects on insulators, dielectrics, and thermal control materials, particularly new materials introduced since 1995.

5) Improved solar activity forecasting and solar proton integral dose predictions for solar cycle 23 and subsequent; update Jet Propulsion Laboratory ’91 model to include complete cycle 22 data, and modify to work for AD2000+ epochs.

6) Update of NASA AE8, AP8 trapped particle models, more data for geostationary and medium earth orbits, improved modelling of orbital location dependency, redefinition of magnetospheric model to correlate with current epoch.

7) Reconciliation of various standards for solar irradiation, spectral distribution and solar constant at 1 AU.

8) Improvement of galactic cosmic ray model, evaluation of effects on linear devices, and upset rate.

9) Development of environmental signatures correlating to observed satellite anomalies, e.g. specific combinations of local geomagnetic field, plasma, low energy electron flux, short-term flux integral (moving-point average), short-term flux gradient/reversals, X-ray flux, EUV, understand dependencies in different satellites and different categories of anomaly.

6.3 Radio Communication Systems

From a communications perspective, space weather research is likely to be more beneficial in real time for satellite communications than for HF. In particular, real-time characterization of ionospheric scintillation effects as a function of geographic location, magnetic index, time of day and elevation angle could be feasible. Here, signals of opportunity, such as GPS signals, could be utilized.

Improvement to HF prediction programs could be achieved by incorporating real-time HF digisound data, magnetic indices, and solar wind data. Improved HF prediction programs for high-latitude regions are required. However, given the wide expanse of the Canadian Arctic, an array of these sounders that would be sufficiently dense to give an accurate picture of the Arctic ionosphere could not be achieved without considerable expense.

Current HF prediction programs provide only an indication of the expected received signal level and delay spread as a function of frequency. They do not provide any indication of Doppler spread, which provides an indication of the time variability of the fading, and this is a critical parameter for assessing the performance of HF data communications systems. Research should be focussed on ways of trying to estimate Doppler spread from measured space weather parameters, although this could prove difficult. One area which could be explored is whether mapping of the polar cap convection patterns (direction and velocity) could be related to the severity of Doppler spread. A further challenge would be to scale this for oblique paths.

What is the relation of the space weather collaboration as a research initiative to current engineering practices in HF communications? Adaptive frequency management systems (commonly referred to as automatic link establishment systems) are becoming common-place in modern HF communications systems. By employing some overhead to perform channel assessments on a periodic basis or prior to establishing communications, the optimum frequency (or the first frequency capable of supporting communications) is chosen to establish the link. Often communications signals themselves can be used as sounding signals. Further many link protocols have features which permit on-line monitoring of performance, which can result in link parameters being altered to maintain a link in dynamic conditions.

Such modern HF communications equipment incorporating adaptive techniques to handle or manage the dynamics of HF links represents an engineering solution that reduces the effect of space weather on HF communications performance. It must be recognized, however, that engineering solutions of this sort are based on a physical understanding of the system. Space weather models can be used to guide engineering design. How many channels are required in a given setting? What are their bandwidths? How will requirements vary next month or next year? Basic science in the service of engineering improvement is a fundamental principle of this space weather plan.

6.4 Navigation Systems

Many earlier radio navigation systems, e.g., LORAN, have been affected by variations in ionospheric conditions. However, the increasingly ubiquitous use of the Global Positioning System (GPS) has extended the potential impact of ionospheric disturbances to a greater number of users. These effects are greater in the auroral regions and so will have proportionally larger impact on Canadian GPS users. Groups at the University of New Brunswick and University of Calgary are involved in studying the effect of ionospheric conditions on the GPS signals and the Geomatics sector within NRCan operates the Canadian Active Control System (CACS) for correcting GPS measurements.

CACS is designed to provide improved GPS positioning capability for the Canadian surveying and geophysical community as well as for other spatial referencing needs. The system consists of unattended tracking stations which continuously record carrier phase and pseudorange measurements for all GPS satellites within station view. Presently, tracking stations are located in Algonquin Park, Ont., Yellowknife, N.W.T., Penticton, Victoria, Williams Lake and Holberg, B.C., St. John's, Nfld., Schefferville, Qué., and Churchill, Man. Each ACP is equipped with a high precision dual frequency GPS receiver and an atomic frequency standard. The recordings at the CACS tracking stations provide an extensive set of data that can be combined with the other monitoring functions within CESP to provide further information on the effect of magnetospheric disturbances on the ionosphere and on GPS signals.

Chapter 7

Program Requirements

The tasks described in the previous chapters entail not only a great deal of scientific and organizational work, but also investments in capital and human resources. Ground-based instruments need to be enhanced and integrated into a new infrastructure including modern networks, data archiving, and computing facilities. Scientific needs and technological advances require that additional instruments be built to extend the existing observational capabilities. Planning for the proposed facility for data assimilation and modeling (FDAM) needs to proceed apace in order to optimize the development of space weather models and the effective utilization and analysis of the new data sets, both nationally and internationally. Forecasting operations at NRCan need to be strengthened to handle an expected increased flow of data and modeling information. To progress in an orderly fashion, the requirements for each task must also fit the overall framework and expected budget of the space weather operation of CSEP.

Many requisite capabilities for an effective space weather program are to be found in existing facilities, such as CANOPUS and CANMOS. The maintenance costs for such ongoing operations are well established, and planning for the next generation of CANOPUS infrastructure is well underway. In this chapter, an overview is presented of CSEP space weather requirements, such as the FDAM. A brief summary of the current International Opportunities and Small Payloads Program of the CSA is given for completeness.

7.1 International Opportunities

By design, International Opportunities are normally responses to invitations from international partners to participate in suitable flights. LTSP III allows Canada to take part in 1 or 2 flights with a major instrument payload, with a total ten-year funding from LTSP III at $10-15 million.

While the long-term horizon of International Opportunities is not clear, it is profitable to give some preliminary consideration of the scientific profile of future International Opportunities projects, so that technical merits of a particular mission can be measured against a set of scientific goals.

It is evident that any Canadian instrument flown on-board a satellite attains added scientific value if it is complemented by Canadian ground-based observations. It seems useful that CSEP, in the early phase, consult with experimentalists, modelers and forecasters to arrive at a set of scientific problems which satellite instruments might contribute to solving. Another important issue of long-standing general concern is the use of data collected by space-borne instruments. Because of limited life spans, such instruments may not be relied upon as continuous data sources for space weather models. This underscores the importance of the post-analysis of instrument data, which, when done in close coordination with ground-based activities, can play an important role in “truthing” the models based on ground observations. Traditionally, there has been a dichotomy where the analytical works are assumed to be the responsibility of NSERC. As CSEP becomes a multi-agency program, this line of division no longer makes sense, and there should be a common strategy and support structure to ensure that space instrument data are adequately analyzed and find their way into space weather models.

7.2 Small Payloads Program

The Small Payloads Program (SPP) gives Canadian scientists a way to launch small, low-cost instruments into space in a timely fashion. Currently, the total CSA SPP program has an annual budget of $3.5 million, with an additional $1.5 million per year to come from the LTSP III.

While the scientific direction of SPP is community-driven, its financial management is designated with specific cost controls for each instrument category. Under LTSP II, cost guidelines are $0.5 million per project for high-altitude balloons, $2.5 million for sounding rockets, and $4.0 million for microsatellites. In the November 1998 Small Payloads Workshop in Toronto, there were discussions about a more flexible cost control scheme, but the general cost schedule is expected to be effective.

From the experience of completed SPP projects and discussions at the Toronto workshop, there is a general agreement that the current management approach of the SPP is a sound and efficient one. By implementing cost control management, the program not only gives scientists and engineers an increased chance to fly instruments, but also encourages technological innovations in placing sophisticated instruments on space-restricted vehicles. From the first-round SPP proposals, one can expect new technologies involving high-sensitivity particle spectrometers, rocket-mounted imagers, tethering technology, high-volume data transmission, and (potentially) on-board counter measures that can mitigate some space environment effects. The issue of proper analysis of scientific data collected by SPP experiments needs to be addressed as in the International Opportunities Program.

7.3 Ground-Based Observation Network

Ground-based observations of the auroral ionosphere and polar cap provide a powerful means of monitoring the space environment. As shown in Figure 7 of Chapter 3, Canada possesses an extensive ground-based network of magnetometers, riometers, photometers, all-sky imagers, ionosondes and HF auroral radars. While each instrument is a valuable scientific tool in its own right, and can provide important insight into fundamental processes, it is only through integration of all instruments, and in some cases acquisition of new ones, that one can expect the network to function as an effective space weather monitor. One of the most urgent tasks facing

CSEP is incorporation of these instruments under a set of scientific and operational goals. In order to accomplish this task, close coordination among CSA, NRCan, NSERC, and university scientists must take place. Currently, the CSA is conducting a round of consultations concerning the next phase of CANOPUS, in which NRCan has participated as a full partner. The CSA has further made a significant contribution to the University of Saskatchewan's NSERC Major Installation Grant application for the Prince George SuperDARN radar, with a view of full incorporation of HF radar capability into the next phase of CANOPUS.

Much of the technical details concerning instrument locations, compatibility, data protocol, and management approach are currently under review, and the planning process has started with Dr. John Samson of the University of Alberta and Dr. Eric Donovan of the University of Calgary coordinating the effort. In this report, the focus is on the general justification for possible new instrument acquisitions that are considered critical to a successful space environment monitoring capability.

A survey of Figure 7 in chapter 3 shows a collection of 27 magnetometers, 13 riometers, 4 meridianal scanning photometers, 1 all-sky auroral imager, 3 HF radars (2 are foreign-operated but with full Canadian access), and 6 CADI ionosondes. Such an extensive and versatile ground-based instrument array is without parallel internationally and gives an excellent base from which to build the observational component of Canada's space environment program. A careful examination of the instrument configuration indicates a few areas of need. First, it is clear that the coverage of Western Canada is sparse in comparison with other regions. Second, the ASI component needs to be enhanced to take advantage of this instrument's demonstrated capability in space weather monitoring. Third, CADI ionosondes, which were developed under CNSR support, can potentially be of significant value to space weather observations, and their inclusion in the proposed space weather super-array outlined in this report is important. Consideration should also be given to such CNSR technologies as SAPPHIRE VHF radars that are useful for monitoring ionospheric irregularities in the E region. There is also a need for some reconfiguration of the magnetometer array, in anticipation of the CANOPUS-CANMOS coordination. Finally, it is noted that global real-time specification of the space environment using the data from ground-based arrays requires adequate networking and computing power, a concern common to all members of CSEP.

In total, the maintenance and operation of the ground-based space weather instrument array will entail a cost in the $2.5 million per annum range. The detailed costing will be provided by the CANOPUS II planning team. In the following a description is provided of several new requirements for space weather observation, emphasizing the scientific justification for each new requirement.

7.3.1 SuperDARN HF Radar

The international radar network known as SuperDARN (Super Dual Auroral Radar Network), with radars in both hemispheres, is a significant development in space weather and fundamental space science research. Each radar measures the line of sight Doppler shift of backscattered signals reflected by ionospheric irregularities. Operating in pairs, the radars give information about electric fields and field-aligned currents over a wide region of the high-latitude ionosphere, including the auroral zone and the equatorward portion of the polar cap. These measurements can be used to infer the strength and pattern of large-scale energy circulation in the magnetosphere. The radars are effective in monitoring the growth phase of substorms, in providing details about mesocale phenomena such as ULF waves and gravity waves. The SuperDARN network will give important data which can be used in computer models of large-scale convection and in applications that will lead to forecasting and global specification of the near-Earth space environment.

Technologically, the manufacturing of the coherent HF radar is fairly straightforward and can be accomplished in a short time (within a year). Currently, there are six SuperDARN radars operating in the Northern Hemisphere, three of which are in Canadian territory. NSERC is the funding agency for the Saskatoon radar, while the Applied Physics Laboratory, Johns Hopkins University, funds the radars in Kapuskasing and Goose Bay. The Canadian SuperDARN science team includes members from the Universities of Saskatchewan, Alberta, Western Ontario, and New Brunswick, and at the Communications Research Centre (CRC) in Ottawa. The world data copy center for all SuperDARN nodes is at the University of Saskatchewan. That, and the consideration of scientific and technical contributions from the Canadian team, give Canada a high visibility and strong influence internationally.

The Western Canadian coverage gap noted earlier can be filled by the proposed installation of a new SuperDARN radar pair stationed in Kodiak, Alaska and Prince George, BC. Supported by a CSA contribution, a request for funding the Prince George radar has recently been funded by NSERC through a Major Installation Grant. The funding for the Kiosk radar has already received approval from the US. Over the long term, it has been suggested that an additional pair of SuperDARN-type radars on Canadian territory could provide complete coverage of the polar cap. As indicated in the discussion about polar cap science, such a pair, coupled with an array of CADI, would make Canada the international leader in polar cap monitoring

The scientific and operational value of SuperDARN radars justifies their full incorporation into the Canadian space environment program. CSEP can take advantage of the successful funding of the Prince George radar, and other positive developments in the SuperDARN community, by injecting resources to support the exploitation of the HF radar data and the enhancement of a network linkage of the SuperDARN data system with FDAM.

7.3.2 Optical Instruments

Canada is a world-leader in designing and using the new generation of all-sky auroral imagers (ASI) based on CCD (charge-coupled device) technology. An ASI gives a wide-angle view of the spatial structure of the auroral oval (down to 1 km latitudinal scales) and visible aurora over extended regions of local and universal time. ASI data have been used to yield important insight into ionospheric and magnetospheric processes, such as the role of ULF pulsation in the onset of auroral substorms. The capabilities of ASI also complement the CANOPUS meridianal-scanning photometer (MPA) array that monitors emission strengths as a function of latitude and time in several key visible wavelengths. As noted above, the single ASI currently operating in CANOPUS is not sufficient for the full value of the instrument to be realized. Ideally, there should be enough ASIs to cover the full latitudinal width of the auroral region and also give adequate longitudinal coverage. Deployed in a proper configuration, the ASI and MPA array will provide high-resolution measurements on auroral morphology and dynamics. Another important use of optical instruments is the identification of plasma regimes in the magnetosphere. For example, the poleward border of the 6300 A emissions demarcates the plasma sheet boundary layer, and the Hb (4861 A) emission has been used by Canadian scientists to indicate the distribution of energetic ions (~10 keV) which are responsible for the onset of substorms. The current MPA array cannot give the full geometry of these important regions and boundaries, a shortcoming that will be addressed by the implementation of a suitable ASI array.

Currently, there are 4 CANOPUS photometers based in Fort Smith, Rankin Inlet, Gillam, and Pinawa, but only 1 CANOPUS ASI in Gillam (with one additional in the Eureka Observatory). Under the CNSR, an ASI was placed in the Eureka observatory and has provided valuable information about transpolar arcs. In order to make ASI a tool of operational value, its spatial coverage of the space environment should be enlarged, and its configuration should allow a fuller viewing range of the auroral oval, and by projection, the source of substorm onset and the outer radiation belt encompassing geostationary orbit. It is proposed that 4-5 new ASIs be added to the current CANOPUS array. The configuration of ASI's will be determined by the CANOPUS science team, and its deployment completed within the first few years of the LTSP III time frame. The future of MPA is another issue that needs attention. Age and environmental interference have affected the performance of some MPA instruments in recent years. Whether the next phase of CANOPUS will continue to operate MPA, or to incorporate MPA and ASI into a consolidated array, is a question that will be addressed by the CANOPUS II planning team through consultation with the community.

7.3.3 Magnetometers

With CANOPUS and CANMOS magnetometers, Canada has a solid infrastructure for the monitoring of geomagnetic disturbances. It has been noted that there are coverage gaps, particularly in western Canada, which need to be closed to allow a more optimal spacing for the inversion of magnetometer data to determine ionospheric currents and fields. There should be at least one component of the array which has latitudinal spacings of instruments on the order of 200 km to allow the estimation of magnetospheric plasma densities from measurements of the ULF magnetic fields associated with plasma waves in the magnetosphere. These details will be worked out in the design for the next generation CANOPUS array. The fluxgate technology used for the existing magnetometers should be more than adequate for monitoring processes up to time scales as short as one second. Some consideration might also be given to the possible use of induction coil magnetometers to monitor magnetic disturbances above 1 Hz. Considerable effort should also be made to ensure that the magnetometer array give near optimal input for modeling GICs in power grids and other ground based technological systems in Canada.

Inversion of magnetometer measurements has been used by scientists to infer the current and electric field distributions in the ionosphere; AMIE (Assimilative Model of Ionospheric

Electrodynamics) developed by US scientists at the National Center for Atmospheric Research (NCAR) is one such example. The existing models are sub-optimal in certain areas, as some key ionospheric properties (e.g., the conductivity distribution) need to be specified beforehand. In many cases, the specification is based on statistical data. CSEP is expected to make important contributions to the improvement of the inversion method, as it will bring to the problems combinations of magnetometer, SuperDARN and optical instrument data, and will significantly increase the robustness and accuracy of the estimation procedures for real-time ionospheric conditions on the large- and meso-scales.

7.3.4 CADI

A legacy of the CNSR, CADI (Canadian Advanced Digital Ionosonde) measures the electron density in the ionosphere, as well the convection velocity. It has operational value, both of its own and in complement to SuperDARN electron drift measurements. Given the current SuperDARN coverage gap in the polar cap, an enhanced CADI array in the polar cap is potentially of use since it can possibly provide measurements of ionospheric disturbances affecting transpolar communications.

7.3.5 New Instruments

During the course of consultation with the community, suggestions have been made that new types of instrument might be useful for space weather monitoring. The CSA might consider a Concept Study program directed towards ground-based instruments, in order to study the feasibility of new instrument ideas in accordance with the scientific and technical parameters of the space weather instrument array. Instrument proposals such as an imaging photometer array and SAPHIRE VHF radars could be funded initially as Concept Study programs before they are fully implemented. Other instruments with mature technology and proven scientific value, such as H *b* imagers, can be implemented directly.

7.3.6 Space Weather Data System

When fully implemented, the combined operations of the ground based observational array, FDAM, and NRCan forecasting center will generate very large volumes of data. This condition will place an increased demand for adequate computer resources to implement the forecasting and modeling programs that employ this data in an operational setting. There are frequent requests from scientists around the world for Canadian space weather data. Conversely, the Canadian space weather program will draw increasing amounts of data, both in real-time and after the fact, from international collaborators. A systematic approach to Canadian space weather data will be helpful to collaborations with space weather programs in other countries. An integrated information system including high-performance computers, data archive, retrieval and visualization is required for real time data processing and large scale computer modeling. This infrastructure, while located primarily at a central location, will be available to the wider community involved in space weather research. The computational facilities can also be used to maintain the integrity of a Canadian Space Weather Data System that will serve scientific and operational needs.

Massive data processing and computer modeling in the space weather program can be handled by parallel supercomputers. Such facilities naturally lead to a centralized location, with smaller systems being deployed at data collection and analysis nodes. While the up-front cost of acquiring a large scale computing infrastructure is significant, the cost can be significantly reduced by taking advantage of existing infrastructures within Universities. For example, the MACI (Multimedia Advanced Computer Initiative) project involving the Province of Alberta, and the Universities of Alberta, Calgary and Lethbridge is conveniently located within two partners identified as major participants in CSEP. The University of Alberta space physics group has a significant stake in the current MACI. This stake can be leveraged to achieve objectives set for CSEP. A recommendation is then that CSEP become a full partner in MACI and contribute funds toward enhancing computational power for space weather operations.

On the national level, there are large-scale initiatives in information technology through the Canadian Foundation for Innovation (CFI) and C3.CA. It is advisable that CSEP actively participate in such initiatives and work to extend the space weather information network anchored by MACI to other key nodes of CSEP, and to bring as many instrument sites online as possible.

A proposed committee with community wide representation would supervise the Canadian Space Environment Program's (CSEP) computational resources, while the FDAM will be charged with the responsibility of day to day maintenance of the system and resources. With new technological developments in high-speed networking, and increased bandwidth across the internet, the proposed mechanism for gaining adequate Canada wide CSEP computer resources will maximize efficiency, and will free most users from the overhead of technical maintenance.

Figure 10 summarizes the envisaged flow of instrument data to the modeling and forecast modules, pipelined through the Space Weather Data System. The proposed installation of this system is intended to ensure that data inputs into models and predictive routines meet a high standard of quality and compatibility. Furthermore, the data system would serve as the outlet for international data requests. A data manager will be required to carry out this task, with responsibilities in data archival, retrieval, visualization, and servicing data requests. Given the critical importance of data quality to modeling works, the data manager would be a member of the FDAM.

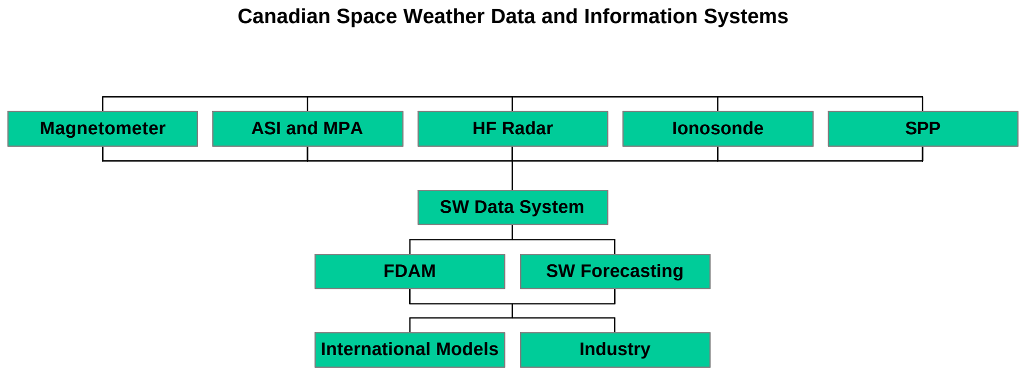

Figure 10. Operational linkage among major CSEP components

7.4 Facility for Data Assimilation and Modeling

Data Assimilation is a broad term that refers to the critical task of rendering useful representations of space weather phenomena based on data provided by instruments and models. Modeling refers to predictions concerning the state of the space environment, utilizing physics-based algorithms that evolve systems of governing equations, or identify recurring trends, in real or near real time. There is an almost indistinguishable link between these two tasks, and their fundamental importance to space weather programs has been demonstrated in the US national space weather program, which devotes 2/3 of its resources to modeling, and in similar programs in Europe and in Japan. Over the long term, physics-based modeling can be expected to achieve maximum benefits in space weather prediction, because of the impracticality of monitoring space weather phenomena across all space and time scales. It is for this reason that the FDAM has been proposed as an important element of CSEP.

The two key requirements to accomplish data assimilation and modeling are dedicated computer resources, and expert personnel. The operations in the FDAM are expected to include predictive algorithm development, investigative research, and model prototyping for forecast services. The expected outputs from the FDAM include data assimilation products and models of space weather phenomena. Although this report is not intended to work out detailed costs for specific programs, the anticipated amounts to operate the FDAM at its full capacity are on the order of $700,000 per annum. Of this, about $400,000 per year will be required to support 4 scientific and technical personnel; $2 million over 10 years (with $500,000 startup in year 1 for parallel computing infrastructure) is needed as a suggested contribution to the MACI project described below, and $100,000 for essential operations of the facility such as travel, networking, supplies, student training, and office support. These amounts are significant, but the FDAM will serve as a community resource for major computation and networking needs and for the coordination of the major program elements of CSEP into a functional operation for space weather prediction.

Supercomputing resources have been identified at the University of Calgary and the

University of Alberta in Edmonton. The Edmonton facilities have grown out of the efforts of the local space science group, who acted as the center for numerically intensive parallel computing in the former Canadian Network for Space Research (CNSR). Three-dimensional modeling and expertise on parallel and parallel-vector supercomputing and advanced visualization resides primarily at the Edmonton facilities. Infrastructure has been maintained there through NSERC major equipment grants, and CSA transitional support. More recently, Province of Alberta IIPP infrastructure support for parallel supercomputing has resulted in the purchase of an SGI Origin 2000 parallel supercomputer (configured with 48 processors), currently the fastest supercomputer in Canada. At the writing of this report, substantial new money has been injected into supercomputing facilities in Alberta through the MACI (see section 7.3.6 above) initiative, and from the Canada Foundation for Innovation. The total present funding to MACI is estimated at $21M over 4 years. During the second phase of MACI, the SGI Origin at the University of Alberta will be upgraded to 100 new generation processors. Part of MACI includes connecting facilities across Canada through a high-speed data link, and will interact closely with future initiatives under C3.CA.

It is recommended that the FDAM be organized in a project-oriented structure led by two Project Scientists. Project 1 will focus principally on tasks at level 2 and 3 in Figure 8 (Chapter 3). Project 2 will focus primarily on level-3 and -4 tasks. Application-oriented tasks in level 5 will be centered at the NRCan Geomagnetic Lab, and through collaboration with the FDAM. The Canadian Space Agency has issued a contract to develop fully the concept, problems, approaches, funding, and computational requirements of the two principal FDAM projects.

The FDAM will also entail a range of technical tasks that require skills in modern data base techniques and high-performance computing. There is an identified need for 2 data and programming specialists to perform a range of technical works involving enhanced/specialized database tools, multimedia visualization, and composition and optimization of parallel computer codes. Moreover, the technical specialists will also work to ensure the FDAM computing and networking environment is robust and linked efficiently with Canadian scientists who use FDAM facilities for their research and data analysis tasks.

7.5 Forecasting and Space Weather Services

As noted in section 3.2.4, space weather forecasts and related services have traditionally been centered at the Geomagnetic Laboratory of NRCan, a role that is expected to continue under CSEP. Given the expanded scientific and operational objectives, additional resources need to be allocated to strengthen the NRCan operation. Key requirements include personnel dedicated to the maintenance, upgrade, and extension of the forecast and information delivery system. Much of the climatological and empirical modeling tasks described in Chapter 5 would be carried out at NRCan. Through many years working with industry, NRCan has developed a close understanding of many space weather problems facing the power, pipeline, and satellite industry. In order to make space weather forecasting useful to industry, CSEP needs to dedicate a certain level of assistance towards the development of specific measures against space weather effects within affected industries. An example is the simulation of power system responses to space weather disturbances of specific type, intensity, and location, so as to identify points of vulnerability. Two FTE staff are needed to meet the additional works in the areas of forecasting and space weather services, at an anticipated cost of $200,000 per year from LTSP III funding. Combined with existing NRCan funding to the GSC Geomagnetic program, the enhancement will bring Canada's space weather forecasting and services operation to a level close to $1 million a year.

7.6 Other

With the above facilities in place, there remains a need to support Canadian scientists to conduct research and make effective use of them. There are a number of key space weather problems that have not been solved scientifically. In other cases, practical ways to mitigate space weather effects remain to be explored. The CSEP should consider a support mechanism to enable research on problems of space weather concern. Traditional funding sources for basic research (e.g., NSERC) should be approached to consider space weather as a basic category in the funding of the Space Physics and Astronomy division. CSA and NRCan, on the other hand, could support works with applied orientations, by funding such initiatives as investigation of space weather effects on specific systems and their solutions. Projects in the latter category would contain a significant industrial contribution through direct funding or in-kind support, and be carried out by teams of scientists and engineers. Possible areas include effects on satellites, power grids, pipelines, and communications systems.

It is suggested that resources be made available under CSEP for the support of initiatives that are not specifically in this plan but nevertheless deemed important. One example is collaborations with industry to develop technologies to combat specific space weather hazards. Ideally such collaboration would contain a direct or in-kind industrial contribution which matches or exceeds direct CSEP funding. Such collaborative research opportunities would likely emerge in the later stages of the program. However, in the earlier phase, funds might be directed towards enhancing the CSA concept study program or financing a limited grant pool to support certain basic research in partnership with NSERC.

Chapter 8

Program Implementation

This chapter maps out an implementation strategy for the proposed Canadian Space Environment Program (CSEP). This involves general considerations concerning management, metrics for program evaluation, and the international linkages that can be expected. The report concludes with an approximate timetable for the implementation of various program tasks.

8.1 Funding and Management

Basic research in space plasma physics will continue to receive funding from NSERC, while the CSA and NRCan have agreed to continue to fund the operation of CANOPUS and CANMOS. The International Opportunities and SPP can expect to be funded from the CSA LTSP II and III. In specific regard to the space weather program described in Chapters 4-7, most of the funding is expected to come from the CSA LTSP III, and will be directed toward enhancements of space weather capabilities ranging from ground-based instruments to modeling and forecasting. Assistance to industry will mainly be in the form of development of predictive models, forecasts of space weather effects, and through joint efforts to develop practical measures to mitigate or monitor specific technological effects such as GICs, or elevated particle energies in the magnetosphere. When appropriate, LTSP III might consider support of the initial stage of this development through collaborative research contracts.

8.1.1 Supervisory Committee

CSEP is intended to accommodate the broad interests of Canadians in the investigation of the near Earth space environment. It is recommended that a supervisory committee be formed to oversee the implementation of the space environment program. The suggested committee membership should consist of representatives from universities, government agencies, and industry groups involved in space science in Canada. Various industry partners have been contacted, and letters of intent have been obtained. The Supervisory Committee will meet periodically to set policy guidelines for the program, devise and adjust program priorities, review program performance, and work to encourage linkages between the science, forecasting, and technological effects parts of the program. The current Solar-Terrestrial Relations Advisory Committee (STRAC) might serve as model for the proposed space weather supervisory committee, and some members might naturally be drawn from STRAC.

8.1.2 Program Sub-Committees

Given the diversity of scientific objectives and the operational requirements among different CSEP components, there is a need to form specific program sub-committees that can advise the broader supervisory committee on issues of a more detailed nature. The recommendation is to form committees that represent each broad concern of the program. The program committees will operate much like the current CANOPUS science team, but have representation from participants in the International Opportunities and Small Payloads Program, the CANOPUS science team, and from scientists and engineers undertaking work on modeling and forecast services. These sub-committees will be concerned with.

- Providing detailed scientific and operational plans for the proposed space weather super-array, including recommendations on instrument configurations, data formatting, and the development of a data management and distribution policy.

- Overseeing modeling and computing resources to ensure that appropriate space weather models are developed. Adopting policy and guidelines for the proper maintenance of computing resources managed by FDAM for community use.

- Developing appropriate metrics for the evaluation of space weather forecasting services. Overseeing the integration of new models into forecasting operations. Ensuring methods are in place for public access to space weather information. Facilitating exchanges of information between industry and scientists to promote potential applications.

8.1.3 Space Environment Workshop

It is recommended that an annual Space Environment Workshop be held during which scientists, forecasters, and engineers will convene to publicize research accomplishments, exchange information, facilitate interactions, and develop future plans. During the workshop, each program subcommittee would present a review of the activities and progress in their respective area of concern.

8.2. Program Metrics and Evaluation

The success of CSEP will be evaluated according to a set of broad metrics, or indices of performance which data, modeling, and forecasting works will strive to meet. There are quality metrics, namely how accurately a model or forecasting scheme specifies or predicts the behavior of the system. There are effectiveness metrics, namely how useful the information generated is to users and the international scientific community.

There is numerous quantitative information embedded in space weather operations, and theoretically, for each output can be defined an appropriate metric. A microscopic metric system is deemed to be inefficient, as the benefits of models and forecast services will eventually become transparent to users. Too many metrics will also result in the pursuit of isolated tasks, to the detriment of overall objectives. Therefore, it is proposed that CSEP use broadly defined metrics in the evaluation of progress.

A comprehensive study of the effectiveness of the existing space weather prediction procedures in Canada should be carried out early in the CSEP to determine current capabilities and develop a reasonable expectation for future improvements. The following areas should be reviewed and the performance, wherever possible, given in quantitative terms

- Frequency of data requests from international science and modeling centers
- Current forecast parameters
- Forecast quality
- Forecast range
- Forecast efficiency

From this review, and ongoing work within the space environment program, the subcommittee on space weather services and applications will be able to devise metrics for expanded forecast services. It is expected that a clear set of program metrics will be finalized in the initial years of the program and that these will guide model and forecasting operations in the later stages of LTSP III.

How effective space weather operations will be in addressing industrial concerns is more difficult to define at this time, but this situation should change as the program progresses. Significant interest has been expressed by different industry groups, including TransCanada pipelines, power utilities in BC and Manitoba, and by Telesat Canada, which has provided a list of problems concerning the radiation environment of satellites. The industrial partners will be surveyed periodically, and their inputs used as part of program evaluation.

8.3 International Linkage

A CSEP founded on Canadian strengths will boost Canada's position internationally, particularly as it involves extracting maximum benefits from the excellent data that is collected by Canadian ground based instruments. The coordinated facilities and programs provided under CSEP brings Canadian space science into sharp focus, and will allow for participation with international partners on a distinct but equal footing. How well CSEP fits internationally will, to a significant degree, determine how successful Canada’s efforts are in the end. Since Canada lacks long-term in-situ measurement capabilities, and cannot match the comprehensive modeling infrastructures in larger countries such as the US, it is imperative that what is done is unique, and significant not only to Canadians but also to the world at large. The proposed CSEP is designed with care to satisfy this mandate.

8.3.1 Data Exchange

Canadian data, acquired from ground and small-payload instruments (and expected from outputs generated by models and data processing routines), has become extremely valuable to the international space environment. A crucial issue in international collaboration is how available Canadian data should be to space environment operations in other countries. The question was considered by the Space Weather Steering Committee in its August 4, 1998 Calgary meeting and revisited during the 1999 DASP meeting. There is a growing realization that in order for Canada to play an important role in international space weather efforts, Canadian data should be made open and accessible to potential users. In order to prevent misuse or commercial exploitation of Canadian data by foreign sources, it is suggested that high-quality, high resolution data be supplied to international requests through special arrangements which might include an agreement allowing Canadian parties to participate in any development of a commercial product. Low-resolution and/or uncalibrated data can be made available through the internet. In short, Canada's data policy should encourage maximum penetration of Canadian data in international operations on the one hand, and seek to protect Canadian resources until modeling and data management capabilities have grown to take advantage of commercial opportunities on the other.

Since Canada has no major in-situ capabilities, CSEP will also generate demands for specific foreign data. Of particular importance is solar wind data, radiation belt/geostationary data, and polar satellite data. In those instances, closer data cooperation is necessary in order for Canadians to gain access to high-quality foreign data and international partners' resources and expertise. The US National Ocean and Atmospheric Administration (NOAA) possesses measurement capabilities in the above three regions through its ACE, GOES, and POES satellites. There has been a reciprocal interest from NOAA in using CANOPUS and other Canadian data. Thus, NOAA is seen as an important partner, and it is recommended that joint efforts be taken to make the two databases and systems maximally compatible.

8.3.2 Modeling Linkage

Canada's strengths in modeling are concentrated on energy transport and release processes, magnetospheric waves, energetic particles, and electrojet activity. Conversely, a presence in modeling processes such as CME and the solar wind is limited in comparison with international efforts. An open approach is suggested in international modeling collaborations so that Canadian models can achieve the highest visibility and widest use possible. Most of the international space weather modelers are based in the academic community, and it is expected that it will be relatively easy to gain access to their models provided that the products are not developed under proprietary constraints from industry. In particular, some Canadian scientists are already members of the GEM program in the US, and have close ties with European and Japanese space weather programs. In the US, the GEM community has the task of constructing mainly computer modules that simulate the space environment. These linkages will prove very constructive for Canadian modelers.

Another important aspect of modeling is prototyping, i.e., systematic evaluation of the operational readiness of models. Proofing of models would be done jointly through the FDAM and NRCan forecasting center. Where model outputs require comparisons with data not originating from Canadian instruments, prototyping can be done in collaboration with foreign facilities such as the NOAA Rapid Prototyping Center in the US. This collaboration would help Canadian models and products establish a strong position in the production and use of space weather information internationally.

8.4 Linkage with Atmospheric Environment Program

The effects of the solar-terrestrial relationship on the middle and lower atmosphere are addressed under the LTSP III Atmospheric Environment Program. Unlike the space environment, the atmospheric environment is controlled principally by solar electromagnetic radiation and anthropogenic causes that have led in particular to ozone depletion and the possible onset of global warming. However, despite these differences, there are significant physical processes that link the space and atmospheric environments. For example, gravity waves and middle-atmospheric tides can change the ionospheric condition, which in turn changes the pattern of energy transport in the magnetosphere. Effects of magnetic storms can also reach downward to alter the sensitive global circuit of atmospheric electricity, with attendant effects on weather and climate. Research at such interdisciplinary levels can be pursued jointly by CSEP and the atmospheric program. In addition to common scientific concerns, the two programs can also cooperate in the sharing of resources and joint software development. For example, the existing CANOPUS and CANMOS sites can be used to house atmospheric science instruments. The space instrumentation facilities at York University, the University of Toronto, and the University of Calgary can reach agreements that accommodate exchanges of basic expertise. The weather forecasting operations at Atmospheric Environment Service (AES) can likewise pass useful experience, tools, and resources to its space environment counterparts in the FDAM and NRCan forecasting center, and vice versa.

8.5 Stages of Implementation

It is envisaged that the implementation of the space weather program will progress in stages. Given that the LTSP III funding and management questions have not been finalized, the following presentation represents a best estimate at this point. The stages in the first five years of LTSP III are presented in some detail. The directions of the second five years will depend in large part on achievements made in the first five years, and should come as part of the proposed comprehensive program review at the end of year 5. Consequently are list only expected results of the LTSP III programs at the end of year 10, without specific milestones for the intervening years.

Years 1

- Start-up of FDAM, initial funding and hiring scientific personnel
- SuperDARN funding
- Consulting group for CANOPUS/CANMOS/SuperDARN coordination
- Decision on CADI feasibility
- Forecasting upgrade at NRCan
- ASI and MPA initial funding

Year 2

- Implementation plan for CANOPUS/CANMOS/SuperDARN coordination
- Full ASI/MPA funding and installation of optical array
- FDAM technical personnel
- Prince George radar completion
- SPP AO I
- Review of effectiveness of preliminary space weather forecasting routines

Year 3

- Funding for new data management resources with upgraded links from MACI to key nodes
- Possible CADI funding
- First metric proposal
- FDAM core models completing code development and entering prototyping phase
- Tests and prototyping of empirical forecasting models at NRCan center
- Performance review of the amalgamated space weather superarray

Year 4

- Space weather superarray fully functional
- SPP AO II
- Data-driven testing of FDAM core models
- Porting of FDAM models to NRCan forecasting center for trials

Year 5

- Comprehensive program review
- Determination of space weather metrics
- Space weather data products and software tools begin development phase through collaboration among instrument groups, FDAM, and NRCan forecasting center
- Review of International Opportunities Program (if no suitable opportunities have arisen)

Year 10 Outlook

- 4 SPP AOs and 10-15 instruments flown
- Ground-based space weather superarray operating at full capacity
- Full incorporation into data operations of data assimilation routines from FDAM, local groups, or international sources; global real-time specification of ionospheric condition
- Global model of near-Earth magnetospheric condition
- Full dynamic simulation capabilities of auroral structures, substorm process, particle acceleration in both the auroral and geostationary orbit regions
- Effective hybrid forecasting model for GIC and related geomagnetic activity
- Effective empirical forecasting for long-term and statistical conditions of geomagnetic

disturbances and radiation environments in geostationary and low-altitude orbits

- Simulation of space weather effects on power grids and formulation of appropriate mitigation strategy.

Chapter 9

Conclusion

During the course of developing the plan for a Canadian Space Environment program (CSEP), there has been steady progress in the implementation of national and international space weather programs in the US, Europe, and Japan. Most recently, Russia, in spite of severe economic difficulties, has realized the importance of space science and is developing its own space weather initiative. The SPARC (Space Physics & Aeronomy Research Co-laboratory) initiative in the US has also emerged, with part of its mandate being to develop integrated databases and modeling tools that can exploit or resolve challenging issues in space science. The SPARC program has overlapping interests and parallel objectives to CSEP, and it can be expected that Canadian data and models will have a role to play in this, and other programs around the world. Canada's unique geography, and exposure to the most dramatic influences of the space environment, suggests that the proposed ground based arrays of CSEP will play a critical role in global space science endeavors, and the current number of requests for Canadian space data points to an optimistic future for Canadian space science in general. In the February 1999 Federal budget, the Government of Canada made a long term funding commitment to the Canadian Space Agency, and this has provided further optimism for achieving the vision and goals articulated in this report.

Optimism for Canadian space science is based on the outstanding facilities, expertise, and technologies already present in Canada's space community. There is ample evidence supporting the ingenuity and talents of Canadian scientists and engineers, who have brought Canada recognition and accomplishments in experimentation and theory. The rapid expansion and commercialization of space activities over the last decade means that there must now be an integration of Canadian space science activities, with both short term and long term objectives clearly established. CSEP provides an operational framework for coordinating different activities in Canada and for establishing overlapping goals. In moving to a knowledge based society, countries must also be able to compete in modern data base management techniques, information theory, and multimedia approaches to representations of complex phenomena which evolve rapidly in both space and time. Rapid advances in modern techniques of parallel computing and scientific visualization have put the tools at the scientists disposal. From the funding approved for the CSA LTSP III, new facilities in computing, forecasting, data collection and data processing will revitalize Canadian space science, and move it forward into the new millennium.