CANADIAN GEOSPACE MONITORING (CGSM) PROGRAM

EXCERPTS FROM THE SCIENCE PLAN

CGSM SCIENCE TEAM

SUBMITTED TO THE CSA AND UNDER REVIEW

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Executive Summary

Canadian GeoSpace Monitoring (CGSM) is motivated by the recognized need for greater fundamental understanding of planetary environments that are affected by short and long term variability of our star - the Sun. The Sun and Earth form a tightly coupled system, with solar variability driving effects on space weather and climate, the creation of harsh radiation environments and the generation of the aurora. The CGSM program seeks to understand this fundamental solar-terrestrial coupling and its influence on our planetary environment.

The overarching scientific goal of CGSM is to understand the transport of mass and energy across multiple scales throughout the entire solar-terrestrial system. CGSM will enable Canadian scientists to address *grand challenge* questions at the forefront of space physics research. The primary CGSM scientific objective is to elucidate the fundamental processes that cause and control

I. convection within and energy injection into the global magnetosphere.
II. magnetotail instabilities and flows.
III. auroral particle acceleration.
IV. energization, transport and loss of energetic magnetospheric particles.
V. injection, transport, and loss of low energy magnetospheric particles.

CGSM results will enable significant advances to be made in developing and improving space weather prediction and empirical space environment models, and will provide valuable deliverables for the Canadian space industry. CGSM science will be central to understanding the exogenic contribution to terrestrial climate change, particularly during the current period of rapid changes to the magnetic environments of both the Sun and the Earth.

CGSM is a coordinated observation, data assimilation, and modeling program. Our observational program employs an integrated continent-scale array of radio, magnetic, and optical instruments. Following a significant expansion utilizing state-of-the-art technology, CGSM instrumentation will represent an internationally unique facility with which to pursue fundamentally new solar-terrestrial science. Owing to Canada's geographic position of having the largest readily accessible landmass under the auroral and polar regions, and its history as a leader in solar-terrestrial science, CGSM will enable Canadian scientists to lead international efforts to answer fundamental questions in solar-terrestrial physics. In return, we will be afforded a leadership role in International Living With a Star (ILWS), a major multi-agency, multi-spacecraft, solar-terrestrial applied and fundamental science program. The CGSM program will also train highly qualified scientists, engineers, and information technologists, and will include an extensive outreach program promoting the public understanding of science and attracting the next generation of young Canadians to a career in science and technology.

Introduction

The solar-terrestrial environment begins at the sun with the solar wind expanding outward through interplanetary space. The solar wind, typically flowing at between ~300-1000 km/s, creates the heliosphere, which is the magnetic bubble carved out in inter-stellar space by the solar wind plasma and its embedded magnetic field. Within the heliosphere, planetary magnetic fields carve out cavities in the solar wind that are known as magnetospheres.

The Earth's magnetosphere is bounded at its base by the ionosphere (at around 100km) and in outer space by the magnetopause. The shape and size of the magnetopause is determined by pressure balance between the plasma environments in the magnetosphere and the flowing solar wind. This region constitutes the near-Earth space, and is populated by ionized gas (or plasma) of both solar wind and terrestrial origin. Significant electric currents are a ubiquitous feature of this environment, are powered by the solar wind, and continuously deposit energy in the form of heat in the Earth's upper atmosphere. Magnetospheric charged particles undergo acceleration due to a host of plasma-physical phenomena, one beautiful consequence of which is the aurora, an ever-present though highly variable feature of the terrestrial environment. The solar wind is inherently non-steady, with its magnetic field, density and flow speed varying on a range of time and length scales. Variations in the solar wind modulate the solar-terrestrial coupling processes which drive the transport of mass, energy and momentum into near-Earth space, leading to variations of the magnetospheric particle population, electric currents, and the aurora; such disturbances in the magnetosphere are commonly called "space weather". When the highly variable solar wind intensifies, and the interplanetary magnetic (IMF) field turns southward, the processes governing solar-terrestrial energy transport become more efficient. Significant energy is then injected into near-Earth space, and is subsequently released in global magnetospheric disturbances known as storms and substorms.

On average, the rate at which solar wind energy is incident on the magnetopause is about 10 TW (terawatts). Under storm conditions, this 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 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.

The injection of solar wind energy into the near-Earth space environment manifests itself through the development of intense electric currents, the acceleration of energetic particles, the generation of harsh radiation environments, and through the development of increased joule heating and the production of density irregularities in the ionosphere. These disturbances can cause a wide range of problems for ground- and space-based technological systems. Magnetic disturbances on the ground induce electric fields in power systems and pipelines, and interfere with control systems. For example, on 12/13 March 1989, geomagnetically induced currents (GICs) in the HydroQuebec grid caused a series of transformer trip-outs which resulted in a total blackout of the Quebec power system, leaving 6 millions residents without power for over 9 hours [*Boteler*, 1998]. Two transformers destroyed during the HydroQuebec incident cost $3M each, whilst the direct costs due to lack of service and replacement power ran to $10M's of dollars.

In near-Earth space, energetic particles can damage satellite components, circuitry, and systems via spacecraft surface charging, as well as deep dielectric charging caused by the penetration of MeV energy electrons. Famous examples attributed to deep dielectric charging include the failure of Galaxy 4 in May 1998 (carrying 90% of all US pager traffic and affecting 45 million customers) and Telstar 401 in January 1996 (carrying ABC, FOX and PBS signals to millions of homes in the US) [e.g., *Baker et al.*, 1998a, 1998b]. Large MeV energy electron fluxes are also of concern for radiation doses received by the International Space Station, by Shuttle astronauts undertaking space walks, and even for air crews who regularly fly high altitude polar routes. Increased ionization and disturbances in the upper atmosphere also cause scintillation of satellite communication signals and HF radio communication, and can introduce significant position errors in radio navigation systems such as GPS (global positioning system).

Solar terrestrial coupling is also responsible for the injection of mass from the solar wind into near-Earth space, for the injection of particles from the ionosphere into the magnetosphere, and for the circulation and loss of this material in the global system. Variations in the mass distribution in near-Earth space can have significant effects on satellite orbit decay rates. These mass re-distributions also influence the rate at which energy is transferred between waves and energetic particles in the magnetosphere, influencing the intensity of harsh radiation environments in near-Earth space.

There also exists a well-documented link between solar activity and terrestrial climate, on both the 11-year timescale of the cycle of solar activity and sunspot number as well as on longer centurial and millennial timescales. Centennial scale depressions in sunspot number are known to have coincided with periods of global climatic cold, such as the little ice-ages which occurred during periods of low solar activity such as during the Maunder minimum between 1645-1715 (The Thames in London regularly froze over during this interval; see *Shindell et al*. [2001] for an analysis of the global and regional temperature changes).

Theoretical explanations suggesting how exogenic climate change might be driven by solar cycle variability remain controversial. However, in spite of the constancy of the total visible flux emitted by the sun through the solar cycle, recent evidence has shown that variations in solar UV output influencing global atmospheric circulation patterns or the seeding of clouds by cosmic rays, themselves modulated by solar activity variations in heliospheric magnetic field, both provide plausible and convincing candidate mechanisms. Interestingly, the magnetic environments of both the sun and the Earth appear to be rapidly changing at the present time. The coronal field at the sun has doubled in the last 100 years, whilst the north pole of the Earth's magnetic field is currently moving faster than it would if the internal dynamo creating the Earth's magnetic field had been switched off [e.g., *Newitt et al.,* 2002]. It is unclear how these changes will affect the solar-terrestrial interaction and thus studying them is crucial to understanding how solar variations couple to the terrestrial system.

For the influence of the sun on the near-Earth environment to be fully explained, understanding and monitoring the fundamental processes responsible for solar-terrestrial coupling will be vital. Monitoring the spatial and temporal development of global current systems and flows, the energization and loss of energetic particles, and the transport of mass, energy and momentum throughout the global magnetosphere is essential to achieving this scientific goal, and is a primary focus of the Canadian Geospace Monitoring program (CGSM). CGSM, when fully implemented, will represent an internationally unique state-of-the-art multi-instrument facility for the global monitoring of meso-scale magnetospheric activity. By utilising the unique geographic location of the Canadian landmass for the deployment of continent-scale ground-based arrays of optical, radio, and magnetometer instrumentation, CGSM will provide a unique window on the geospace environment. This will enable Canadian scientists to address fundamental questions at the forefront of international solar-terrestrial science. The science objectives for the CGSM program are collected into target *grand challenge* themes (referred to throughout as "science themes"), and these scientific goals are discussed in more detail below.

The continent scale coverage afforded by the CGSM array will provide a detailed picture of the dynamical solar-terrestrial environment that is impossible to monitor with in-situ spacecraft. Data from the CGSM array will be collected in real-time using state-of-the-art satellite data retrieval systems, providing data for exciting opportunities for real-time space weather studies. Real-time data will also facilitate excellent outreach and public understanding of science activities, including real-time collages of global auroral imaging from the ground. Real time data will also enable the creation of a real-time “AuroraWatch alert” advance warning system, highlighting auroral viewing opportunities to the Canadian public, particularly in the more populated southern regions of Canada. The CGSM infrastructure will also enable the production of real-time value-added data products and geomagnetic indices that provide snapshots of the current levels of geomagnetic and space weather activity. Information of use to Canada’s space programs, whether astronautic, scientific, or commercial, such as a geomagnetically induced current (GIC) simulator for the power and pipeline industries, will also be provided through the Canadian Space Weather Forecasting service to be operated within the CGSM umbrella by Natural Resources Canada (NRCan).

CGSM data will be accessible through the Province of Alberta funded Space Sciences Data Portal. This state of the art Web-based data archival and distribution system will provide seamless data access to the Canadian and International communities, establishing a leadership role for Canada in the global space sciences community. Through integration and assimilation of data into physics based models via the CGSM Facility for Data Assimilation and modelling (FDAM) supercomputers, CGSM will also facilitate the development of improved solar-terrestrial models, particularly in the inner magnetosphere, as well as improving both radiation belt and other space weather specification models. CGSM will also train a new generation of highly qualified scientists and engineers with expertise in scientific instrument operation, deployment, and maintenance, data analysis, theory and modelling, satellite and network communications systems, as well as computer science and engineering.

Based principally on CANOPUS, Canada was afforded “instrument status” in ISTP. More recently, and in recognition of our intention to enhance and integrate our ground-based program through CGSM, the CSA has been given the role of lead agency responsible for ground-based science in ILWS, and a significant leadership role in that exciting new international program. Through CANOPUS, SuperDARN, and now CGSM, Canadian researchers have had the opportunity to be co-Is on at least three NASA MIDEX proposals (Auroral Multiscale MIDEX, Connections, and THEMIS), a significant role in the Cluster Ground-based Working Group and the Cluster Electric Fields and Waves Experiment, and finally direct involvement in major international space weather efforts.

To summarize, CGSM is the flagship mission in Canadian space science, facilitating exploration of near-Earth space and advances in science, technology, education, and public awareness. It has societal relevance, capitalizes on Canada’s strategic geographical and historical advantages, and enhances Canada’s international status. CGSM creates opportunities for Canadians, is a unique program on the world stage, and addresses exciting scientific questions of fundamental importance.

Science Objectives

The CGSM science program involves research into solar physics, space physics and geophysics, all of which form a system of tightly-connected phenomena, all driven by solar magnetic activity. These include: solar wind physics, solar wind-magnetosphere coupling, magnetospheric dynamics, magnetosphere-ionosphere coupling (including ion outflow), auroral physics, ionospheric physics, and the substorm and storm cycles. In this rich scientific area, classical mechanics, statistical physics, electrodynamics, fluid dynamics, nonlinear dynamics, information theory and sophisticated computational methods are all brought to bear on questions that are important not only to space science, but also to cosmology, magnetohydrodynamics, and plasma physics in general. The goal of the CGSM program is to understand the transport of mass and energy across multiple scales through the entire solar-terrestrial system [see also the “CANOPUS 2000” and “Space Weather in Canada” documents for more background to CGSM science]. Whilst the CGSM program will enable Canadian scientists to address a wide range of fundamental questions at the forefront of international space physics research, CGSM research will focus on a number of *grand challenge* themes (referred to throughout as “science themes”).

Dayside magnetic reconnection, as well as a shear-flow “viscous” interaction at the magnetopause resulting from the generation and propagation of magnetohydrodynamic waves, both drive the anti-sunwards flows of plasma within global magnetospheric convection. These processes are inherently time-dependent, solar wind magnetic field changes driving the dynamic motion of the dayside merging line and varying the spatial profile of the stresses which drive global convection. Understanding these processes is the focus of science theme I. Nightside reconnection, which often occurs explosively during the substorm, closes field lines driven into the magnetotail, and completes the cyclic global convection process. In the magnetotail energy is also transported Earthwards by intense Alfvén waves which propagate in the nightside magnetotail. These processes are not well understood either theoretically or experimentally, and their study forms the focus for CGSM grand challenge science theme II. Magnetosphere-Ionosphere coupling is achieved through numerous electrodynamic, particle, and plasma physical processes, some of the most interesting of which involve active feedback. Energy transport to the ionosphere and atmosphere below can manifests itself through auroral processes, specifically via field aligned currents, energetic particle precipitation, as well as through the propagation of a range of Alfvénic and magnetohydrodynamic waves. These auroral energy transport processes form the focus of CGSM grand challenge science theme III. Global and local wave modes in the magnetosphere provide a pathway for energizing energetic particle populations in the magnetosphere. They can also be used to monitor the fundamental processes governing the structuring and dynamics of cold plasma population in the magnetosphere, the dynamic evolution and structure of the plasmapause representing a particularly important scientific target. Understanding the energy and mass transfer associated with these processes represent the goals of CGSM grand challenge science themes IV and V, respectively. In summary these themes are

- *I* *Driving magnetospheric convection and controlling energy injection into the global magnetosphere.*
- *II* *The triggering and development of magnetotail instabilities and flows.*
- *III* *The generation, modulation, and multi-scale structure of auroral arcs and auroral particle acceleration.*
- *IV* *The role of wave-particle interactions in the acceleration and loss of energetic particles in the magnetosphere.*
- *V* *Cold plasma injection, transport, and loss in the global magnetosphere.*

Within CGSM we will adopt a fundamentally new methodology in order to address these questions. CGSM will involve the deployment and operation of an extensive multi-instrument network of state-of-the-art equipment, which will allow us to monitor the signatures of the fundamental processes responsible for these elements of magnetospheric dynamics in unprecedented detail. However, it is our approach to the analysis and interpretation of these complex multi-platform data sets which will be particularly innovative. Through the development of web-based Information Communication Technologies (ICT), incorporating active involvement from ICT industry partners, we will develop a suite of new web-based tools with which to manipulate and analyze multi-platform data. The multi-instrument data will also be incorporated and assimilated into physics based simulation models, revealing definitively the plasma-physical processes responsible for the observed signatures. This methodology will foster cross-collaborations between different CGSM instrument teams and promote cohesion between the scientific efforts of CGSM scientists. This approach will ensure that the rich data sets which will be collected by the world-class CGSM observational programs are mined efficiently and hence that the maximum scientific benefit is derived from CGSM.

In the sections below we first discuss in more detail the CGSM operational infrastructure, and highlight how it will be used to address these grand challenge science questions. We then address the science targets within each of the themes, highlighting specifically the current state of knowledge and outlining how the CGSM program will contribute solving outstanding questions.

CGSM Program Elements

The CGSM program consists of the synergized operation of extensive ground-based observational programs, together with data collection in real-time via state-of-the-art satellite communication, the serving of CGSM data on the WWW via the CGSM Space Science Data Portal, and the development of sophisticated physics-based numerical models by data assimilation. The observational infrastructure of CGSM is organized into 6 programs:

1) CANOPUS (magnetic);
2) NRCan (magnetic);
3) NORSTAR (optical/radio).
4) SuperDARN (radio);
5) CADI (radio);
6) F10.7 (radio).

These ground-based observational programs are supported by a state of the art data retrieval system, and the CGSM web portal:

7) VSAT (Real time satellite data retrieval system);
8) SSDP (Space Science Data Portal).

CGSM scientific and space weather objectives necessitate the development of sophisticated techniques for the integration of data from the different instrument arrays, the assimilation of that data into physical models, and constraint of such models with the data. Two CGSM program elements are devoted to such efforts, and will lead the development of predictive capabilities based on CGSM data. These are:

9) FDAM (Facility for Data Assimilation and Modelling);
10) Canadian Space Weather Forecast Center (CSWFC).

These cornerstone elements of the CGSM program are discussed in more detail below.

The CGSM observational array is built on pre-existing world-class infrastructure, however, the CGSM program will facilitate the further expansion of this array to create an internationally unique observational capability with which to study fundamental questions in solar-terrestrial science. We will be undertaking extensive deployment of state-of-the-art magnetometer, optical and radar instrumentation which will provide a unique window on the complex magnetospheric dynamics in near-Earth space. We will utilize Canada's unique geographical advantage to monitor the ionospheric projection of global magnetospheric dynamics extending from the polar cap, through the auroral oval, and into the mid-latitude regions spanning the outer radiation belts plasmapause. We will also instigate a complete overhaul of our data retrieval, archiving, and distribution system, ulitizing state-of-the-art real-time satellite data collection architecture. Through FDAM and the SSDP, we will also complete the implementation of new techniques for data assimilation, analysis, and visualization. Technical details relating to the infrastructure in each of the elements of the CGSM program are provided in the Technical Proposal which accompanies this document.

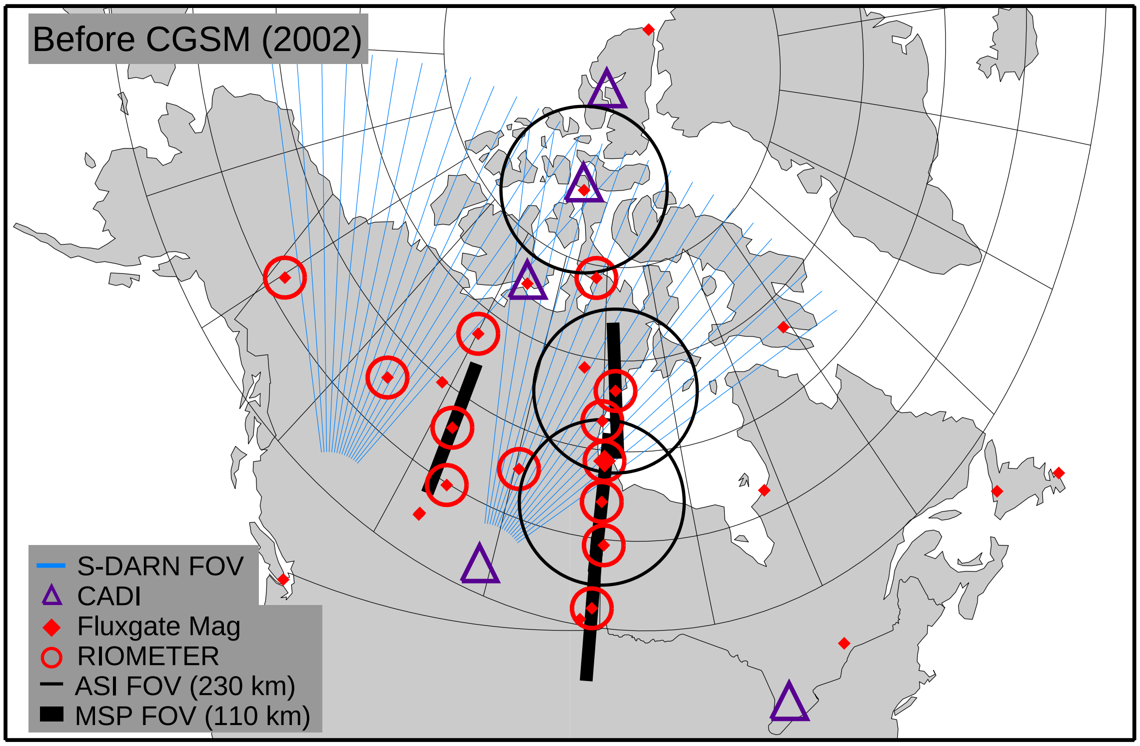


Figure 1: Present status of ground-based instruments operated by programs that will fall under the CGSM umbrella, prior to the enhancements to be undertaken within the CGSM program

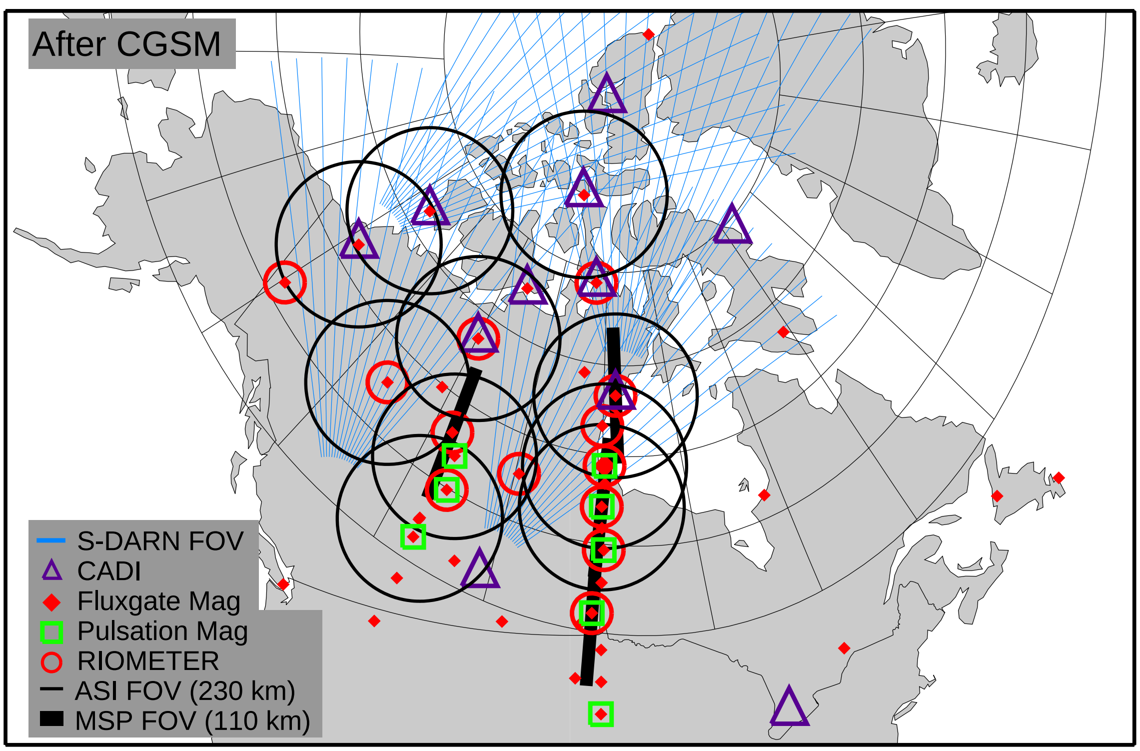


Figure 2: Enhanced CGSM ground-based instrument array.

Ground-based Observations

The CGSM observational program is built upon pre-existing extensive, world-class, and well-developed infrastructure. There are six observational program elements, each of which operate a specific type (or types) of instruments. These include the CANOPUS and CANMOS magnetometer networks spread across Canada, the CADI array of digital ionosondes, and the NORSTAR instruments of imagers, photometers, and riometers which remote-sense particle precipitation. The SuperDARN HF radars provide nearly global maps of ionospheric convection, and for more than 50 years the F10.7 cm solar monitor has provided measurements of the solar radio flux. The locations of instruments operated by these programs at the inception of CGSM (and where appropriate their FOVs) are shown in Figure 1. Contours indicate constants of geomagnetic latitude and longitude. The geomagnetic system used is AACGM [*Baker and Wing,* 1989] and the latitude contours shown are for 60° through 80° in 5° steps. Longitude contours are separated by 15° (ie, one hour of local time). For reference, geosynchronous orbit nominally maps to roughly 67° invariant (ie, Gillam), and the polar cap boundary is generally over, or poleward of, ~75° invariant (ie, Rankin Inlet) in the evening sector.

Prior to CGSM, the observational programs had evolved along separate lines. Space science is increasingly multidisciplinary in nature, and new research advances demand the integrated use of data from multiple instrument platforms together with sophisticated physics based models and simulations. Observations of electric currents, particle precipitation, and convection, provided by instruments viewing a large common volume, together with the capacity to utilize that data in an integrated fashion, will be of extremely high scientific value. Consequently, these operational programs will be merged into a coordinated and synergized scientific effort within CGSM.

Within CGSM we will also be deploying considerable new observational infrastructure. This will provide more extensive higher temporal and spatial resolution coverage of the ionospheric projection of the global magnetosphere. This new instrumentation will redress the inability of the pre-CGSM array to address some of the highest priority questions in near-Earth space plasma science. The instrument configuration in the expanded CGSM array shown in Figure 2 takes full advantage of our unique geographical position. In the subsections below, we discuss briefly describe each of the elements of CGSM.

Magnetic Observations (CANOPUS and NRCan)

The CANOPUS magnetometer array is widely regarded as the best ground-based array in the world, whilst the NRCan magnetometer array represents a founding and essential element of the international INTERMAGNET program. The existing 25 fluxgate magnetometers of the CANOPUS and NRCan arrays will be supplemented with the deployment of an additional 15 fluxgate magnetometers, together with the deployment of 8 higher frequency induction coil magnetometers, as a CGSM extension to the CANOPUS array. This will be the first enhancement to the CANOPUS magnetometry program since its inception in 1988, and will be funded by CFI as part of the CRC in Space Physics of Dr. Ian Mann at U. Alberta. We will increase the sampling rate of the vector magnetic field at all of the fluxgate magnetometers to 1Hz, the induction coil systems being configured to measure the vector field at 20 Hz. Collectively this enhanced instrumentation will provide the magnetic measurements necessary for core CGSM science objectives to be addressed.

Specifically, the new fluxgate magnetometer deployments will provide significantly extended coverage into mid-latitudes, as well as providing magnetometer coverage under the fields of view of the SuperDARN radars in western Canada. The new mid-latitude fluxgate magnetometers will be deployed along two meridians which extend the Churchill line south, and which will develop coverage along a new Alberta line meridian. In addition, mid-latitude coverage will be developed by the deployment of fluxgate magnetometers between the Alberta and Churchill lines. This will enable the spatial and temporal monitoring of the global magnetospheric current systems generated by convection and solar-terrestrial coupling to be monitored all the way from the polar cap to deep inside the plasmasphere.

Monitoring the magnetic signatures of the current systems associated with global magnetic convection, flux transfer events, and reconnection driven plasma motion will be essential for the tackling science theme I. The new mid-latitude coverage of the CGSM magnetometer array will also allow real-time Pi2 substorm onset timing [e.g., *Nose et al*., 1998; *Olson*, 1999 and references therein] as well as the meridians of the field aligned current elements of the substorm wedge to be located with respect to stations in the CGSM array [e.g., *Cramoysan et al.,* 1995] in real-time using the assimilation of magnetic bay data into a current wedge model. An example CANOPUS measurement of the X-component disturbances of a number of pseudobreakups, followed by a substorm, is shown in Figure 3. This Figure shows clearly the Pi2 and magnetic bay signatures at the mid-latitude stations. The new mid-latitude magnetic monitoring provided by CGSM will be crucial for addressing science theme II. Note also that the CGSM mid-latitude grid will be further improved when the CANMOS Glenlea station is relocated west of its current position to Brandon.

The global coverage of the CGSM expanded magnetometer network will also enable the study of the magnetic signatures of convection [science theme I], global oscillations in the magnetotail [science theme II], field line resonances, and auroral structures [science theme III] to be studied on a continent scale. Mid-latitude coverage also allows the monitoring of ultra-low frequency waves from the plasmapause and outer radiation belt regions, which can be used to monitor the density structures in plasmapause region [e.g., *Waters et al.,* 1995, 1996; science theme V], and are believed to strongly influence energetic particle populations in the magnetosphere [e.g., *Mathie and Mann*, 2000; science theme IV]. The expanded CGSM fluxgate magnetometer array will provide global coverage which will allow the signatures of the physical processes to be studied within CGSM to be monitored with unprecedented accuracy.

The totally new network of induction coil magnetometers to be deployed with CGSM will also create an internationally unique observational capability for monitoring high frequency magnetospheric waves at geosynchronous orbit, and spanning the outer radiation belt and ring current. This new capability will allow the monitoring of PiB signatures which can be used to time the local onset of a substorm with an accuracy of ~1s, and will allow the spatial and temporal evolution of electromagnetic ion cyclotron (EMIC) waves in the magnetosphere to be studied in unprecedented detail.

EMIC waves are believed to represent a dominant loss process for the outer electron radiation belt, the EMIC waves themselves being excited by a cyclotron resonance with ring current particles ions. The collective CGSM monitoring of the ULF waves implicated in radiation belt acceleration [e.g., *Mathie and Mann*, 2000; *Elkington et al.*, 1999; *Lui et al*., 1999] and the EMIC waves implicated in loss [e.g., *Horne and Thorne*, 1998], will facilitate the development and improvement of space weather specification models and will contribute significantly to studies within science theme IV. The higher temporal resolution induction coil magnetic monitoring, when taken in combination with optical and riometer monitoring of particle precipitation, will also enable the study of the properties of the ionospheric Alfvén resonator (IAR) and its role in structuring auroral precipitation to be determined [science theme IV]. Indeed, the structuring of ionospheric emissions by the IAR will form an important science focus for the forthcoming NASA GEC mission, and these CGSM observations will form an important ground-based input to this program.

The collective coverage of the CGSM magnetometer array will also enable the spatial characteristics of the magnetic field changes responsible for driving geomagnetically induced currents (GICs) in power grids and pipelines to be monitored in unprecedented detail. The expanded CGSM magnetic field data will provide crucial data input into the GIC modeling work to be completed within the Canadian Space Weather Forecast Center to be operated by NRCan, the new mid-latitude coverage being of particular significance for the monitoring and modeling of GICs in the regions of Canada's highest population density.

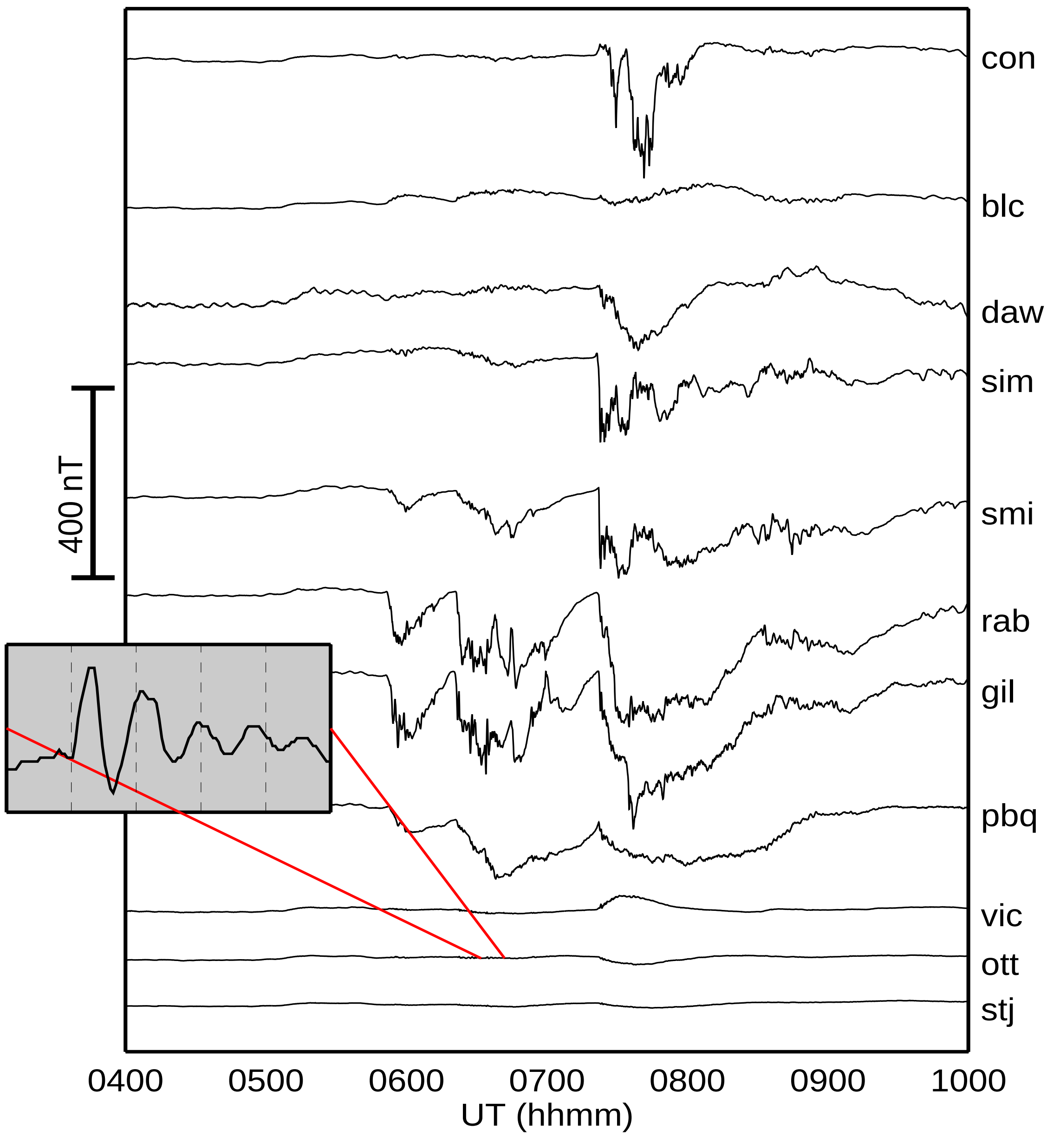


Figure 3: Example of data from the existing Canadian magnetometer array. This is a stack plot of X-component magnetometer data from the stations indicated. The top, middle, and bottom stations are at high, auroral, and subauroral latitudes, respectively. There is a sequence of pseudobreakups, followed by a substorm [*science theme II*]. *Spatial coverage afforded by our continent wide array allows exploration of the spatial extent and structure, and temporal evolution of such events. Not visible at this scale are the Pi2s at lower latitude and auroral stations (cutout of Ottawa data shows one Pi2 - full scale 2 nT; dashed lines 2 minutes apart).*

NORSTAR (Optical/Riometer)

NORSTAR is the imaging component of CGSM, and has three programmatic elements consisting of observations with CCD-based all-sky-imagers (ASIs), meridian scanning photometers (MSPs), and single beam zenith pointing riometers. The current NORSTAR program comprises ASIs at Resolute Bay, Rankin Inlet, Gillam, Fort Churchill and Athabasca which collect data at four auroral wavelengths (471, 558, 630, 486 nm), MSPs at Rankin Inlet, Gillam, Pinawa, and Fort Smith (which operate at the same four the wavelengths listed above, plus three for background), and 13 riometers, one located at each of the 13 existing CANOPUS sites. The MSPs and riometers are described briefly in *Rostoker et al.* [1995], and a description of the NORSTAR ASI program is given by *Donovan et al.* [2003c]. The details of the optical FOVs and riometer locations of the existing NORSTAR instrumentation are shown in Figure 1 and sample keogram constructed from merdional slices through the field of view of the ASI during a field line resonance is shown in Figure 4.

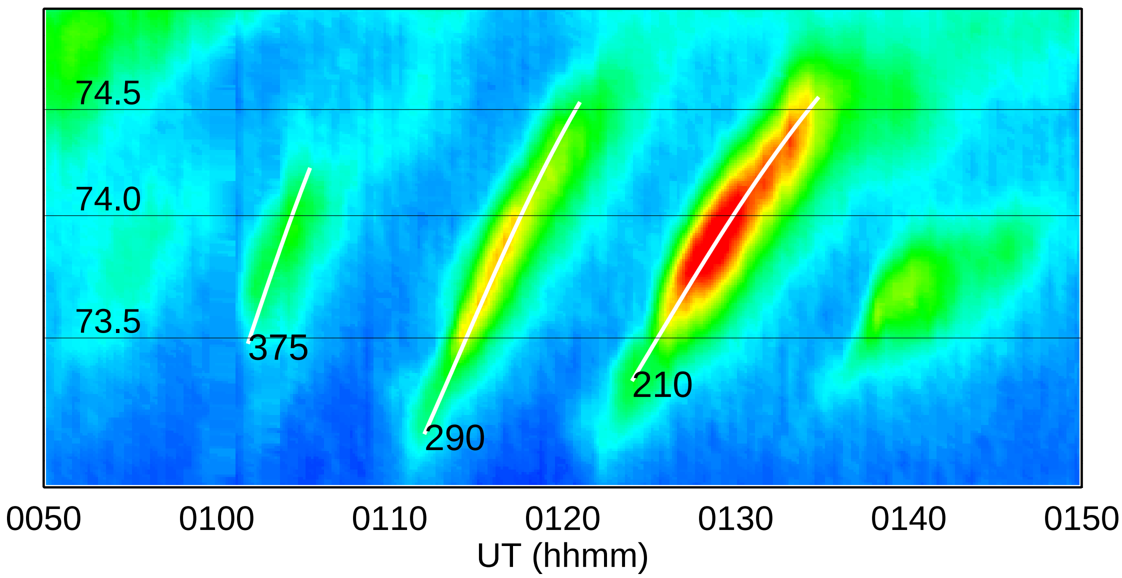


Figure 4: Example of NORSTAR ASI keogram data. Intensity of 630 nm emissions from Rankin Inlet ASI, with ionospheric speeds (in meters/second), and invariant latitudes (degrees) indicated.

Under CGSM, the NORSTAR capabilities will be significantly extended with the deployment of five additional ASIs, to be funded from a CFI proposal tied to the nomination of Dr. Eric Donovan for a Canada Research Chair at the University of Calgary. These enhancements will extend the NORSTAR instrument coverage into the FOVs of the Kodiak-Prince George SuperDARN radar pair (see below), will provide extended coverage at auroral and polar-cap boundary latitudes to span over five hours of MLT, as well as increasing the global optical coverage along the Churchill line (see Figure 2). One of these new ASI deployments (POCA) will be placed at the Churchill Auroral Observatory, the Churchill CGSM site being developed into an Auroral Observatory so that it can be used for high temporal and spatial resolution special observing campaigns, for supporting instrument testing, and as well as providing facilities for the important activity of field training of students and post-doctoral fellows. Observatory costs will be absorbed by operating grants, and infrastructure will be provided through the Churchill Northern Studies Center (http://mail.churchillmb.net/~cnsc/).

Collectively, NORSTAR provides quantitative high time and space resolution mesoscale measurements of particle precipitation. The unique contribution of NORSTAR to CGSM is to map characteristic energy and energy flux of precipitating protons (diffuse) and electrons (diffuse and discrete). The riometers form a thirteen-pixel imager, providing mesoscale maps of high energy (>30 keV) electron precipitation observed indirectly through the attenuation of cosmic radio noise. MeV solar proton events can also be monitored since these cause blanketing polar cap absorption (PCA) events in the polar cap. The MSPs provide measurements of the intensities of auroral emissions and reasonable estimates of relevant background emissions, from which quantitative estimates of proton energy flux, as well as the characteristic energy and energy flux of electrons, are possible. The MSPs have a proven capability of identifying the open-closed field line boundary (at least in the evening sector), the b2i/IB, and the equatorward/earthward edge of the electron central plasmasheet (CPS).

The expanded ASI array will provide an internationally unique two-dimensional high temporal and spatial resolution mesoscale imaging capability from the polar cap to the plasmasphere along the Churchill meridian, and across three hours of local time on field lines typically threading the inner CPS. The ASI images provide mesoscale maps of diffuse and discrete electron aurora, and the proton aurora (though the capacity to do so has only been demonstrated during quiet times when background subtraction issues are minimized). The ASIs deliver all of the information that the MSPs do (save for proton aurora intensities when there is significant discrete electron aurora), although due to technical limitations (cannot operate when the moon is up nor simultaneously image at two wavelengths) the current generation of all-sky imagers will be unable to match the capabilities of the MSP. This will require the continued operation of both the ASI and the MSP instruments during CGSM.

The CGSM expanded NORSTAR array will collectively provide a magnetospheric imaging capability which is unrivalled in its spatial and temporal coverage. When NORSTAR images are integrated with both SuperDARN convection maps (see below) and the continent wide Canadian magnetic field measurements, CGSM scientists will have a unique capability to study magnetospheric dynamics. Specifically, this will enable the exploration of core science topics which are central to the CGSM grand challenge (science) themes. These include the spatial and temporal development of: CPS convection, polar cap convection, and its relation to CPS dynamics as monitored by precipitation [science theme I]; the auroral arc precipitation at substorm onset, auroral signatures of near-Earth plasmasheet instabilities at substorm expansion phase onset, and the two-dimensional structure of auroral poleward boundary intensifications [science theme II]; the properties of discrete auroral arc precipitation, and the role of the ionospheric Alfvén resonator and field line resonances in structuring discrete arc precipitation, and in producing pulsating aurora [science theme III]; and the electron precipitation associated with the development of the ring current (particularly from riometer data) and pulsating precipitation observed in conjunction with the ultra-low frequency waves believed to drive and influence ring current and radiation belt particle acceleration [science theme IV]. Consequently, the imaging capability of the expanded NORSTAR program will be essential to the achieving the science goals of CGSM.

NORSTAR technical activities have led to, and continue to lead to, the retention and enhancement of optical imaging expertise in the Canadian community. This has enabled the continuation of developments along the Portable Auroral Imager path (see http://www.phys.ucalgary.ca/~trondsen/pai/) with continued development involving newer and more sensitive CCD-based imagers, evolving optics, and innovative new uses for such devices. The NORSTAR program will also precipitate technological advances through the design and development of the next generation of ASI, with a very real possibility of the formation of a spinoff imaging company. This will provide engineering and design expertise to Canadian scientists and students, and the solution will provide a prototype for the eventual replacement of the MSP array with next generation ASI instruments.

SuperDARN (Radio)

SuperDARN (SD) is an international project that has deployed 15 HF ionospheric radars [*Greenwald et al.,* 1995; *Sofko et al.,* 1998]. The fields of view of these radars cover a significant fraction of both the northern and southern auroral zones. Six of the SuperDARN radars have fields of view with total (Saskatoon, Kapuskasing) or partial coverage (Kodiak, Prince George, Goose Bay, Stokkseyri) over northern Canada. The Canadian SuperDARN team is distributed over four universities (Alberta, Calgary, Western Ontario and Saskatchewan) and the Communications Research Center in Ottawa, with headquarters at the Univ. of Saskatchewan. The radars at Saskatoon and Prince George are operated by the Canadian SD team.

SuperDARN data has been widely utilized for scientific and space weather purposes. The SuperDARN radars measure the autocorrelation function, or equivalently the power spectrum of: 1) ionospheric backscatter from the F-region; 2) ionospheric backscatter from the E-region; 3) meteor scatter; 4) ground scatter. Since the irregularities in the F-region are moving at very nearly the ExB convection velocity, the F-region velocity measurements can be used to produce a large-scale (each pair of SuperDARN radars covers a field of view of about 4 million km^2) convection map (equivalently a potential map). This is the ionospheric projection of the magnetospheric electric potential pattern generated by the interaction of the magnetosphere with the solar wind, and by processes internal to the magnetosphere. Such a pattern is the key to magnetospheric electrodynamics in all magnetic local time sectors, from the dayside, where the direct interaction of the solar wind at the cusp occurs, through the dawn and dusk flanks, to the nightside, where substorm activity occurs. Examples of global electric potential maps, inferred from the international array of SuperDARN radars are shown in Figure 5. Further examples can be found at http://superdarn.jhuapl.edu/timed/index.html.

Because, in addition to velocity, the power and spectral width of F- and E-region ionospheric scatter are both measured, various magnetospheric regions and boundaries can be mapped by the radars (for example, the cusp region can be delineated by the associated broad spectral widths). Each SuperDARN radar can also be used as a meteor radar to determine neutral atmospheric dynamics at meteor heights. Through the comparison of neutral winds with the plasma flows inferred from backscatter at different altitudes, SuperDARN can be used to examine the coupling between the neutral and ionized elements of the lower thermosphere. Ground scatter signals can also be used to monitor gravity waves and their and their relationship to Joule heating resulting from bursts of current in the auroral zone. The influence of gravity waves upon the meteor-derived neutral winds can also be used in neutral atmosphere studies at the base of the thermosphere. The SD ground scatter measurements also can be used to monitor the ionospheric density because these HF radars effectively act as ionosondes operating at oblique incidence.

The SuperDARN radars provide an important space weather product, namely nearly global, real-time convection maps of the high-latitude ionosphere. However, there are holes in this coverage, most notably in the polar cap. Plans are underway for a significant enhancement of the Canadian SuperDARN program with the installation of PolarDARN. This project will constitute a pair of additional HF radars, one at Inuvik and the other at Rankin Inlet. The PolarDARN field of view (see Figure 2) will cover the polar cap region in the Canadian Arctic, with coverage extending over the north magnetic pole towards Scandinavia, where the radar beams would intersect with those of the CUTLASS HF-radars. The deployment of PolarDARN will also increase the reliability of SuperDARN map potentials and all SuperDARN derived space weather products and geophysical indices (e.g., the cross polar cap potential), providing an important Canadian contribution to international SuperDARN data products as well as to the international space weather program. The PolarDARN project has been approved in principle by the CGSM SVG. The majority of the funding is expected to come from other sources, with

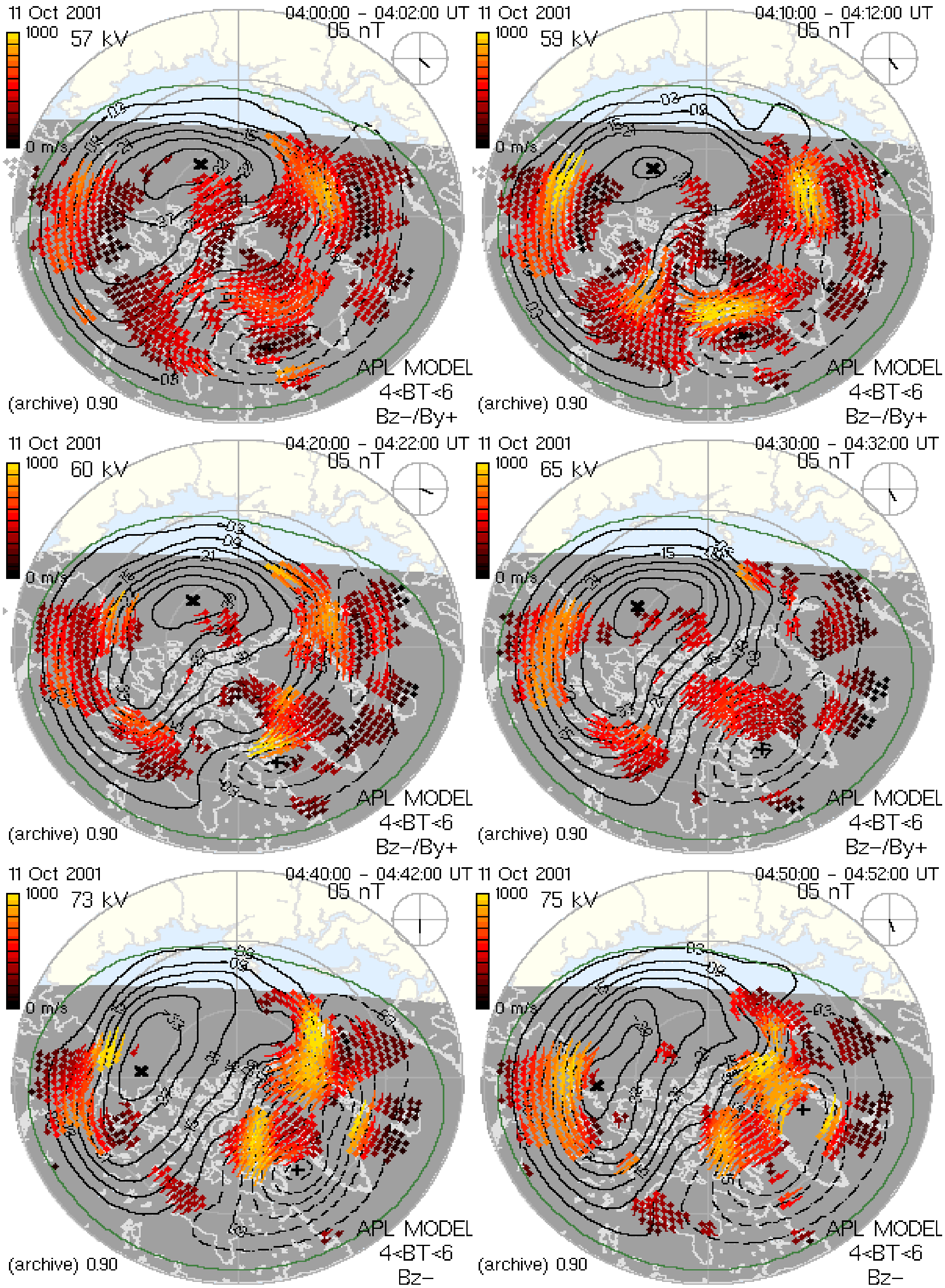


Figure 5: SuperDARN convections patterns - see text previous page. Figure taken from the Convection Map Archive on the SuperDARN APL Website (http://superdarn.jhuapl.edu/).

partial funding support from the CGSM and/or the Canadian portion of the ILWS project. With the PolarDARN expansion, Canada would have four HF-radars, giving it a high profile in the international SuperDARN community.

Coverage from the SuperDARN network provides the capacity to monitor global processes such as: dayside reconnection, flux transfer events and global current systems [science theme I]; substorm associated flow changes that precede and follow substorm expansive phase onset [science theme II]; the ionospheric electric fields which accompany auroral polewards boundary intensifications, themselves driven by magnetotail processes [science theme II]; as well as the electric fields associated with field line resonances and auroral arcs [science theme III]. The SuperDARN radars provide the global radar coverage necessary for the science goals of CGSM to be addressed, and the addition of PolarDARN will significantly enhance those capabilities.

CADI (Radio)

Prior to CGSM, the CADI array operated as an array of five digital ionosondes. Of these, three are operating in polar regions: the CADIs at Resolute Bay and Eureka provide unique monitoring of open field line regions, whilst the third at Cambridge Bay often lies under the ionospheric projection of the boundary between open and closed magnetic field lines (i.e., the polar cap boundary). The existing CADI array will continue operations under CGSM, and will be enhanced with the addition of six new CADI instruments (see Figure 2). These instruments will be deployed both east and west of the existing three polar stations, at geomagnetic latitudes that are typical of the polar cap boundary between open and closed magnetic field lines.

Each CADI instrument provides two basic types of ionospheric measurements: i) ionograms which give information about ionospheric electron densities and vertical ionospheric structuring; and ii) fixed frequency measurements which measure the Doppler shifts of the reflections and from which ionospheric flows can be calculated. CADI convection measurements have been truthed against both SuperDARN convection measurements, and velocities inferred from optical measurements of drifting auroral polar cap patches [*Grant et al.,* 1995]. An example of measurements of CADI convection speed is given in Figure 6. A significant advantage of the digital ionosonde is that it gives virtually continuous high time resolution measurements, even during dynamic times. The CGSM coverage provided by the CADI array thus facilitates the monitoring of reconnection events, including FTEs, as well as the continuous monitoring of convection local to the CADI location which will provide crucial input to science theme I. The CADI array will also permit the study of transient ionospheric and magnetospheric phenomena such as substorms [science theme II], as well as remote-sensing the characteristics of drifting ionospheric patches [science theme V].

Transport of magnetic flux and plasma across the open-closed field line boundary is also one of the most important processes in the magnetospheric system, and plays a central role in both the supply of plasma to the central plasma sheet, and the supply of energy to the overall convection process. The new CADI instrumentation deployed in the expanded CADI array will provide an internationally unique capability for continuously monitoring convection and ionospheric characterization in the important polar cap boundary region across ~7 hours of magnetic local time. This monitoring will be particularly crucial for addressing science theme I.

In summary, the temporally continuous CADI data set will provide an excellent complement to the SuperDARN dataset. CADI ionospheric density and flow measurements, particularly at the polar cap boundary, will providing important monitors of the global solar-terrestrial coupling related to science themes I and II. CADI data will also provide monitoring of the dynamics of the mass density profiles in the coupled ionosphere-magnetosphere system which will be important for studies related to science theme V. An additional benefit of operating the

CADI program within CGSM will be its capability for mesoscale characterization of the ionosphere and convection in the region surrounding the FOV of the NSF funded incoherent scatter facility at Resolute Bay [the discussion related to the Relocatable Auroral Observatory in *Other Programs* later in this proposal].

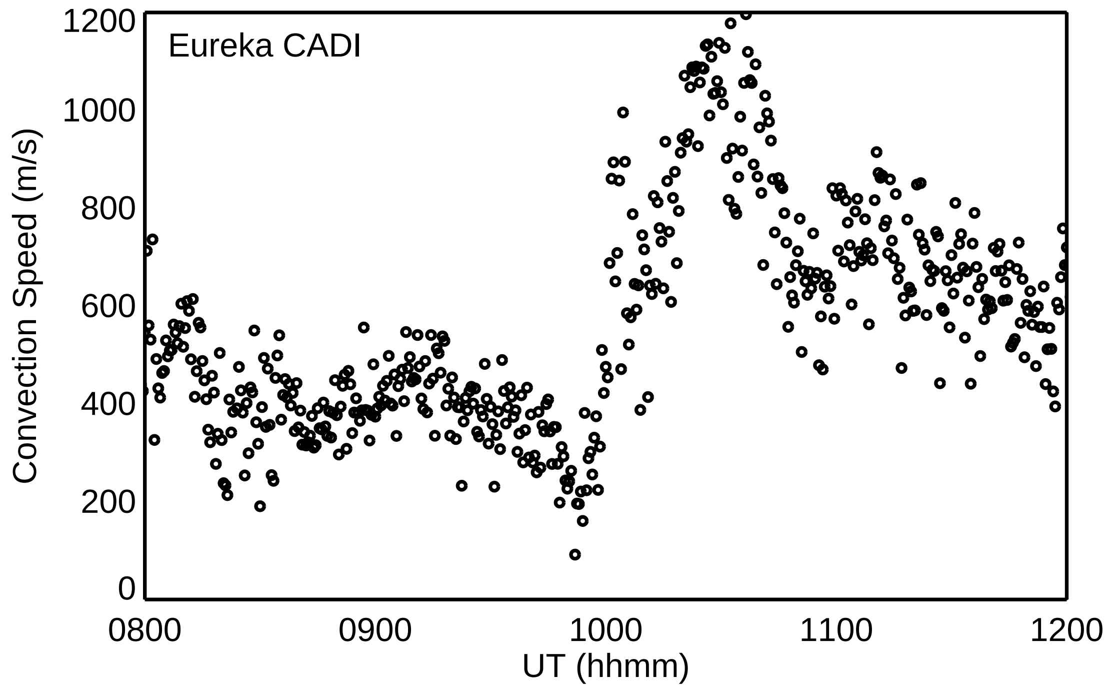


Figure 6: Example of CADI convection speed measurements from the Eureka instrument. There is a substorm onset at 0950 UT (seen separately in Dawson magnetometer measurements), which is preceded by a rapid decrease in convection speed, and followed by a significant increase [*Jayachandran et al., 2003*].

F10.7 (Radio*)*

The NRC Solar Radio Monitoring Program has produced the 10.7cm Solar Flux activity index for more than 50 years. The length of this consistent record of solar activity is exceeded only by that of the sunspot number index, which has a strong empirical component. The 10.7cm Solar Flux is recognized worldwide as one of the best indices of solar activity. Furthermore, this program has an outstanding reputation for accuracy and consistency. What has become known as the F10.7 index is almost certainly the most highly used single piece of space information in the world, see Figure 7.

The discovery that the 10.7cm Solar Flux is a useful proxy for solar ultraviolet and soft X-ray emission, and even for solar irradiance, led to an increasing use of the ground-based 10.7cm Solar Flux as a proxy for quantities that would otherwise have to be measured from space. Its industrial/commercial applications extend from the ground to space, in power utilities, terrestrial wire (and rail) networks, airborne transportation, and in space-based navigation and communications systems. For example, it is used to calculate heating levels in the upper atmosphere, in order to model the effects of changing air drag on satellites in low Earth orbit [see science theme V], and NASA and ESA both incorporate the Solar Flux data into their atmospheric density models that communications companies use for orbit management. The

F10.7 measurement hence represents an essential input into the space weather program which will be conducted within CGSM.

Under CGSM, the monitoring of the 10.7cm flux will continue, and upgrades will be undertaken to the antennas and to the web based data provision and services provided in support of the F10.7 data at DRAO. This will ensure that the existing high data quality is maintained, and that the Canadian contribution to international efforts in long-term space weather monitoring continues.

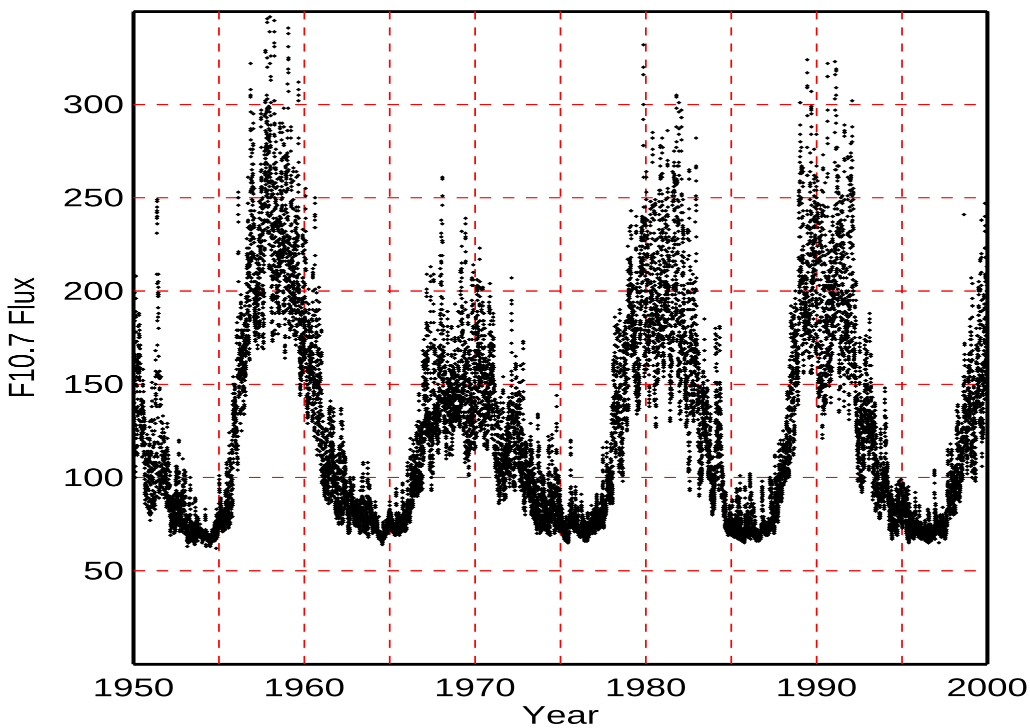


Figure 7: 50 years of F10.7 cm solar radio flux measurements

Data Assimilation, Modeling, and Space Weather

The six observational elements of CGSM will be complemented by scientific activity in data assimilation, modelling, and space weather. This will be carried out under the auspices of the Facility for Data Assimilation and Modeling (FDAM), the Space Sciences Data Portal (SSDP), and the Canadian Space Weather Forecast Center (CSWFC). These programs are described in the following two subsections.

FDAM and SSDP – Scientific Infrastructure

FDAM has a key strategic role in CGSM in providing computer infrastructure for housing operational data from all of the instrument arrays, as well as developing physics models and software tools through which integrated use of the data will be possible. FDAM will also support the development of a CGSM Space Sciences Data Portal (SSDP) that will allow Canadian and partner international researchers and industry, as well as the general public, to access CGSM data and knowledge. The SSDP will incorporate the provision of CGSM data and value-added derived solar-terrestrial data products, and host web pages devoted to public outreach (details of the value-added CGSM data products, and the CGSM Public Outreach program, are discussed in more detail in separate sections below).

One of the most important and innovative elements of FDAM operations will be the creation, maintenance, and development of physics-based models into which CGSM data will eventually be assimilated. CGSM observational programs generally observe the ionospheric projection of magnetospheric phenomena, and the interpretation of such ground-based data has traditionally relied on empirical magnetic [e.g., *Tsyganenko* 1987, 1989, 1996; *Kubyshkina*, 1999, 2002] and electric [e.g., *Weimer*, 1996] field models. Further empirical relations are then used to interpret this data for space weather purposes. However, empirical models generally break down during the most dynamic (and most interesting) phases of magnetospheric phenomena. A natural strategic goal is to replace empirical models with self-consistent physics-based models, and this is the objective of the data assimilation aspect of FDAM. To exploit the full scientific capabilities of the CGSM data set for magnetospheric and space weather purposes, and for CGSM data to be successfully incorporated into *in-situ* satellite data studies, including the use of ground data to provide context for satellite measurements, the development of global physics-based models is essential. FDAM is hence dedicated to the development and implementation of global and meso scale physical models that give added scientific value to CGSM data.

FDAM benefits from computer infrastructure and technical support that is nationally and internationally unrivalled in the University sector. This includes full integration into the MACI (www.maci.ca) and WestGrid (www.westgrid.ca) high-end computer facilities that are funded by the Provinces of Alberta and British Columbia, and the federal government through the Canada Foundation for Innovation. FDAM has access to 4 SGI Origin-class parallel computers in MACI, as well as dedicated cycles on Corona, a 32-way SGI Origin 3800 parallel computer. The grid-computing project WestGrid has allocated FDAM 5 TB of storage on its hierarchical file system, and will provide access to a new 256-way shared memory parallel supercomputer to be housed at the University of Alberta. In Alberta, provincial funding from ASRA has led to the purchase of a 2TB array of SUN T3 StorEdge, an 8-way SUN Fire V880 server, a SUN 280 Web Server, and SUN Grid Engine and Technical Compute Portal software. These elements are critical to the development of the SSDP and its associated Web Services. FDAM also operates a local network of dual processor SGI Octane and Linux workstations, an 8-way SGI Power Challenge server, and mid-range mass storage RAID arrays. All of this computing power will be essential for meeting the goals of FDAM within the CGSM program, being particularly important for global MHD modeling in the coupled solar wind-magnetosphere-ionosphere system.

FDAM has developed a formal relationship with one of the foremost global modeling efforts in the US. The memorandum signed by the University of Michigan Ann Arbor and the UofA provides the CGSM program with access to the global MHD BATS-R-US code that is a core model in the US National Space Weather Program, and which will contribute significantly to the success of the CGSM FDAM program. Plans are also in place to implement a version of BATS-R-US that includes the Rice Convection Model during CGSM, which would allow a ring current module to be implemented into the global MHD code. In providing access to BATS-R-US, FDAM will use Canadian ground-based data to validate and/or constrain BATS-R-US. This is an essential step toward operational space-weather forecasting in Canada. Global MHD models will be essential for understanding the global and plasmaphysical context of both the ground-based observations made within the CGSM program and those made *in-situ* by partner CGSM satellite missions such as THEMIS and CLUSTER.

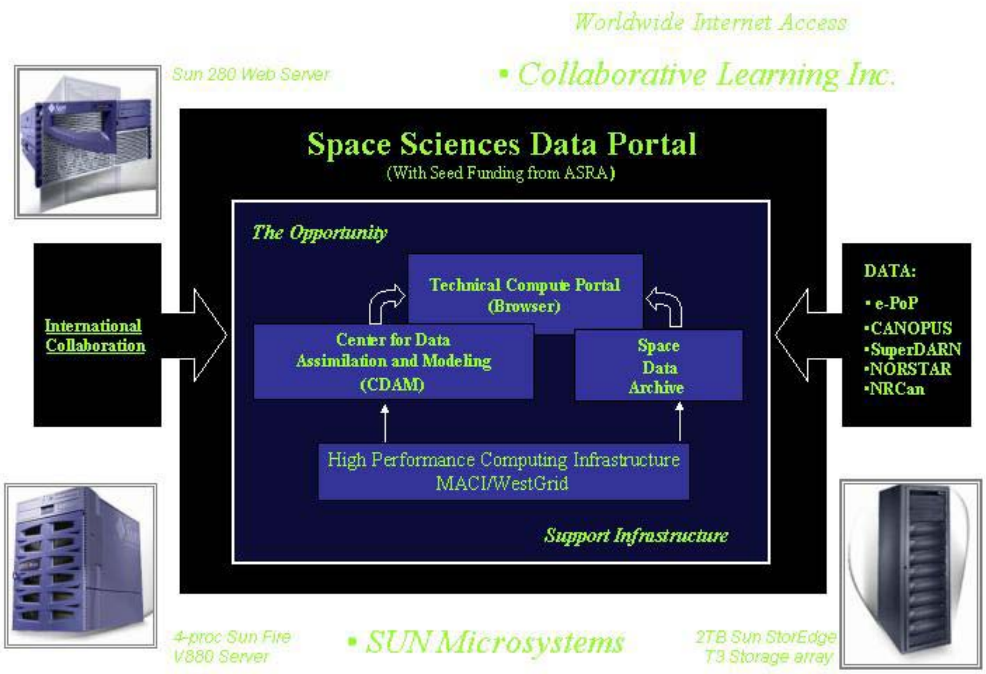


Figure 8: structure of FDAM – including the Space Sciences Data Portal and Center for Data Assimilation and Modeling (global MHD and other models)

Recent publications document the progress in both the application of FDAM physical models to space physics questions, and the assimilation of data into these models [e.g., *Wanliss et al.,* 2000, 2002; *Rankin et al.,* 1999, 2000; *Tikhonchuk and Rankin*, 2002; *Kabin et al.,* 2003]. Figure 8 shows the logical relationship between the components of FDAM and the CGSM. In what follows, we discuss in more detail how the FDAM infrastructure will contribute to CGSM science goals.

To understand the influence of the direction of the IMF on driving global magnetospheric convection [science theme I] requires the existence of global MHD models which include dynamically the time-dependent effects of the solar wind-magnetosphere interaction, as well as the coupling and feedback which occurs through the magnetosphere-ionosphere coupling driven by the propagation of Alfvén waves. The current controversy concerning the parallel-anti-parallel merging hypothesis can also be best addressed though the coordinated multi-instrument data assimilation and modeling efforts which will be possible within FDAM. Consequently, FDAM will be central to developing a complete understanding of the processes driving magnetospheric convection [science theme I]. Similarly, understanding the global instabilities which operate to produce plasma injections and flows in the magnetotail, produce explosive releases of energy during substorms, as well as their ground magnetic and electric field, and particle precipitation signatures [all essential elements of science theme II] will also require access to realistic modeling such as that provided by BATS-R-US.

Energetic particle dynamics in the ring current and outer radiation belt are strongly constrained by magnetic field topology. Currently, there are two competing theories for outer radiation belt acceleration, the first invokes enhanced radial diffusive transport and energization in ULF wave fields, the second invokes local VLF (lower band chorus) wave acceleration processes outside the plasmapause. Calculations of particle phase space density, and their local gradients, are essential for distinguishing inwards diffusive energization and transport from local

VLF acceleration processes. Unfortunately, the storm times when the acceleration processes are operative are also characterized by extreme magnetic field distortions that are very poorly represented by empirical magnetic field models. Using an improved BATS-R-US code that incorporates a realistic ring current would produce a next generation model that may be capable of delivering the required realistic storm-time magnetic field modeling capability. The ability to calculate these realistic storm-time magnetic fields will be crucial if the core scientific issues within science theme IV are to be fully understood.

Other FDAM models include a particle transport code that represents another important CGSM tool. The code utilizes a combination of the adiabatic equations of particle motion, as well as reverting to the full equations of motion when necessary. Using this transport code, particle trajectories can be traced through fields that are specified either by empirical or physical models. This code can be used to model and study, for instance, the effects of pitch-angle scattering on precipitation [science theme III], the characteristics of the interactions between energetic ring current and radiation belt particles [science theme IV], as well as the drivers of ion outflow [science theme V]. FDAM has also developed reduced MHD, Vlasov and 2D PIC kinetic models of auroral arcs [science theme III], nonlinear models of MHD shear-flow instabilities [science themes I, II and III], and most recently a 2D finite element MHD model of dispersive, nonlinear ULF waves [science theme III]. The latter model uses an arbitrary magnetic topology, and is useful for studying auroral electric and magnetic fields, and for studies of meso-scale magnetosphere-ionosphere coupling. Additionally, FDAM has developed graphical user interfaces to a number of models that are useful in mapping auroral phenomena which will also be of critical importance for understanding the magnetospheric dynamics which drive the aurora [science theme III].

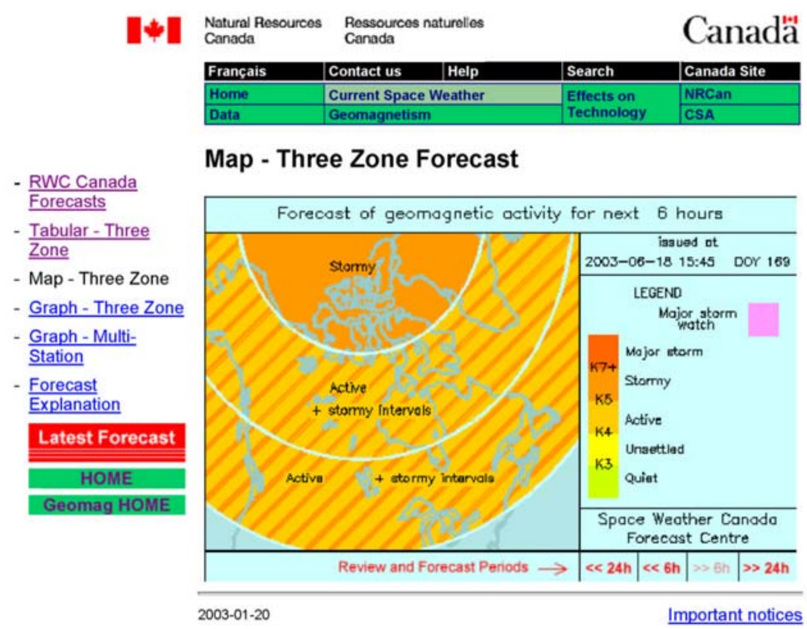
While work already completed at FDAM represents tremendous strides in data assimilation (see, for example, the constraining of models with optical data in the work of *Wanliss et al.* [2000, 2002]), there is clearly a great deal more to be done. Examples include the constraining of physical models with density profiles from magnetoseismology, auroral boundaries which in turn determine the open-closed, "trans-beta", and isotropy boundaries, as well as the inner edge of the electron and ion plasma sheets, the global convection and electric current circuits, and the solar wind conditions. These will all be possible with the infrastructure that will be available within the FDAM project.

In summary, FDAM will provide a new advanced data analysis, assimilation, archiving, and retrieval focus for Canadian ground-based research that will greatly enhance the visibility of the CGSM program on the world stage. Importantly, coordinated availability of data from all CGSM programs at the SSDP will enable CGSM and partner international scientists to easily gather, merge and analyze multi-platform CGSM data. When combined with the data assimilation capabilities, FDAM will promote the cross-fertilization of research ideas and will foster collaborative research programs involving CGSM scientists at multiple institutes working together to pursue CGSM science goals. This scientific cohesion will ensure that CGSM is more that the sum of its parts, maximizing the science output produced by scientists working on all of the CGSM projects.

CSWFC – Space Weather Infrastructure

The Canadian Space Weather Forecast Centre started as a forecast service operated by the Geomagnetism Division of the Earth Physics Branch of the federal Department of Energy, Mines and Resources. In those early days, the forecasts were long-term for up to 27 days in advance. Primary users included geophysical exploration companies, for scheduling aeromagnetic surveys and ground magnetic surveys. In 1976 regular short-term forecasts were introduced. In the following years the production and delivery of forecasts evolved to separate forecasts being produced for sub-auroral, auroral, and polar regions and made available via the web page, by ftp, and through an automated voice message system. Since the 1980s exchange of data has been facilitated through membership in the International Space Environment Service (ISES) and the Ottawa Forecast Centre is now one of ten ISES regional warning centers around the world.

In more recent years the Canadian Space Weather Forecast Centre (CSWFC) has evolved to become a complex, dynamic, largely automated facility. The primary products, geomagnetic forecasts and near-real-time reports, are produced entirely automatically, using expert system concepts in a UNIX/LINUX computer environment. Input data are acquired on a near-continuous basis from the adjacent QNX-based INTERMAGNET Geomagnetic Information Node (GIN), and from primary data suppliers including SEC (Boulder), NASA (LASCO), IPS (Sydney), DRAO (Penticton), CSA (CANOPUS), as well as other sporadic suppliers of information. All of these processes are automated. Outputs are disseminated to users primarily via the World Wide Web, through the www.spaceweather.gc.ca website. The subpage with the latest forecast is shown below. Operational staff and duty forecasters monitor the proper functioning of the large number of individual computer programs, and also carry out checks on the space weather conditions and the veracity of the forecast products.



Canada's geographic location has been a boon for the science community studying auroral and magnetospheric phenomena, but these same phenomena have been a source of problems for a wide range of Canadian industries. Auroral ionospheric disturbances have for a long time caused blackouts of HF radio communications and nowadays also affect systems using trans-ionospheric propagation such as GPS. Geomagnetic disturbances disrupt aeromagnetic and ground magnetic surveys and produce geomagnetically induced currents (GIC) in power systems and pipelines. In March 1989 these GIC were so severe they caused a power blackout of the Hydro-Quebec system and relay trips and other system disturbances on other power systems in Canada. On pipelines the GIC affect the pipe-to-soil potentials, changing the electrochemical conditions at the pipe surface and creating conditions where corrosion may occur. For technology in space, ie satellites, the situation is even worse with the electronic systems being exposed to the charged particles of the space environment. These and other system effects continue to create an expanding need for forecasts of space weather.

The CSWFC will work closely with other CGSM partners to utilise the new knowledge that will be generated over the lifetime of CGSM and turn this knowledge into new forecast services that will be valuable to clients. Solar radio flux measurements are an under-utilised resource for space weather forecasting so there is great potential for new developments in this area. The 10.7 cm flux and other radio flux measurements can provide indications of coronal mass ejections (CMEs) and, in combination with model of the solar atmosphere, radial velocities of the CME. More analysis and statistics is needed to distinguish the signatures for those events that have a significant effect at the Earth. Solar radio bursts are also correlated with the eruptions of solar protons that cause problems for satellites and are responsible for polar cap absorption events.

How the magnetosphere responds to changing solar wind conditions is a critical element in determining which solar disturbances are geo-effective. Substorms are the most frequent cause of magnetic field changes that produce geomagnetically induced currents (GIC) in conducting networks on the ground. However, CSWFC investigations have shown that some of the historical major power system disturbances have been associated with sudden jumps in magnetospheric convection. The new investigations carried out within CGSM will produce a better understanding of the current systems involved and the solar wind conditions that produce the largest effects. CSWFC will use this knowledge to forecast the rapid magnetic field changes that can cause problems to power systems.

The expanded CGSM measurements of magnetospheric disturbances will help to identify the conditions that have a significant impact on satellites. Energised radiation belt particles have damaged geostationary satellites causing permanent loss or severe disruption of service (eg Anik E2). CGSM researchers have made significant contributions to understanding the wave-particle interactions that produce high energy radiation belt particles. This work needs to be extended and resulting understanding of particle energization incorporated into improved warning services for satellite operators.

Auroral particles, as well as their visible manifestation, are a source of ionization which affects the propagation of radio waves. This affects both radio waves going through the ionosphere, such as those used in GPS, and radio waves reflected by the ionosphere, such as those used in HF communication. Improved knowledge of auroral dynamics can be used to improve forecasts of conditions that can affect users of both these services.

The above descriptions are just examples of areas where new knowledge generated by the CGSM science will be applied by the CSWFC to provide new or improved space weather services. In addition the increased monitoring of geospace and real-time transmission of data planned as part of CGSM will provide further opportunities for improving space weather services. The challenge will be to use the new knowledge and data in an effective way to produce services that will be of real use to the clients.

CGSM Real-time Data Collection Infrastructure

A key element in the Canadian Geo-Space Monitoring Program will be the capability for the reliable and rapid collection, assimilation and dissemination of data. The current CANOPUS project benefits from real-time magnetometer data collection via an Anik satellite via Skyswitch and a Telesat Canada contract. However, this connectivity only offers a low-bandwidth solution, and uses a radio band which will be discontinued by Telesat in 2005.

Within the CGSM project we retain the operational desire to be able to collect data reliably in real-time, but wish to rationalize the data collection infrastructure so that data from most of the experimental elements of CGSM can be relayed in real-time through the same data collection infrastructure. Such a move will require the adoption of a system which benefits from a considerable expansion in bandwidth as compared to the current CANOPUS Telesat solution. Scientifically, the program would benefit from the fact that data from the entire suite of CGSM instrumentation would be available in real-time. Operationally, real-time data provision also provides considerable benefits in that system faults can be identified quickly, minimizing undesirable data gaps. Perhaps more importantly, moving to a single common data collection infrastructure for the entire CGSM provides a strategic benefit in that it considerably simplifies the maintenance procedures for the CGSM array since all remote sites will operate the same hardware. Having the data collection for the entire array being handled through a single system will also allow CGSM system wide instrument status and data collection integrity to be monitored quickly and efficiently. For such an extensive array, this will be an extremely important operational consideration.

To satisfy these CGSM programmatic requirements, we are proposing a complete overhaul of existing CANOPUS communications with transition to the use of Very Small Aperture Terminal (VSAT) technology for real-time satellite data collection. We propose to use the VSAT solution offered by Nanometrics, since this solution has demonstrated reliability and field heritage in harsh Canadian environmental conditions, not least through its use for real-time data collection within the Polaris magnetotelluric program. The Nanometrics VSAT solution offers sufficient bandwidth for the solution to be used for the collection of almost all data streams from every CGSM site, with the exception of the SuperDARN radars. Data from sites with both fluxgate and pulsation magnetometers, with riometers, MSPs, as well as CADI, can all be brought back with this VSAT solution in real-time. Summary 1 minute 64x64 resolution ASI images will also be collected in real-time by the VSAT solution. SuperDARN data is already retrieved in real-time through a different infrastructure which will continue to operate under CGSM. The two way communication available through VSAT will also enable system repairs to be completed remotely. These could be as straightforward as a system reboot, or involve meaningful interaction with a site custodian who can, provided the instrument technician can "see" what is going on with the instrument, effect fairly significant repairs.

The majority of scientific use of the CGSM data will be event-based and statistical studies which are carried out in the months and years following the times at which the data was collected. However, there are four further compelling reasons to adopt a comprehensive real-time data retrieval strategy:

1. <u>Coordination of CGSM Programs</u>. An important facet of the CGSM is that operators of instruments in the network will have access to information from other instruments. This could be a key factor in observations of special occurrences, where as much prior notice as possible is needed. For example, the detection of a solar coronal mass ejection or flare will produce space weather and geophysical phenomena of both scientific and industrial interest. Appropriate notice would make it possible for other programs to bring on line the resources to get the maximum scientific information from the event, and if appropriate to give timely warning to those programs, services and activities that could be adversely affected. In some cases, the warning timescale could be as short as minutes or even seconds, so the data network must be designed to accommodate such timescales.
2. <u>Provision of Information to External Programs.</u> CGSM data will play a valuable role in support of rocket, satellite, and ground-based campaigns. Solar radio data give initial notice of solar phenomena that will have a terrestrial impact. The decision of when to launch and auroral sounding rocket from Poker Flat Rocket Range (AK) is always based on real-time information about the solar wind (e.g., from ACE), magnetospheric (e.g., from GOES), and ionospheric conditions. In particular, CANOPUS magnetometers and photometers are often used as the basis for such launches, as they show the onset of a global substorm which will expand across the path of the sounding rocket [*D. Knudsen,* private communication]. Present

and future satellite missions (e.g., Polar, Cluster, THEMIS, MMS, etc.) allow for the operation of instruments in burst modes. During conjunctions over Canada, we anticipate coordinated studies with the operators of these major missions. These operations will involve a combination of changing the spacecraft operating mode based on evolving conditions as seen from the ground, or the converse. During ground-based campaigns, the operators of high time and space resolution campaign-style instruments will base their operations on information from the CGSM array. Real-time, two-way communications are an essential component of such campaign observations.

3. Space Weather Information and Forecasting. CGSM will be the basis of our national space weather program, and a significant element of the international space weather program. Our ability to monitor changing ionospheric currents in real-time will form the basis of the most valuable deliverables to our industrial partners in the electric utility, pipeline, and geophysical exploration industries. Furthermore, real time monitoring of auroral boundaries via the ASIs, photometers, and proxy data from SuperDARN will provide valuable input to and truthing for the global convection models upon which modern space weather predictions will be based. CGSM space weather contributions will not be credible without our proposed real-time data retrieval capabilities. Within ILWS, the international ground-based magnetometer community are proposing to build on the recent re-installation of real-time magnetometer data collection from the AE magnetometers in Siberia with an expanded global real-time magnetometer data collection program. Real-time data from magnetometers around the world will be used to construct real-time maps of magnetic disturbances, electrojet strength, field aligned current distributions, and other magnetometer derived real-time space weather products. The CGSM magnetometer array will form a vital element of this real-time magnetic monitoring program in the Canadian local time sector.
4. Community Outreach. Our plan is to have a significant public outreach program in CGSM. This program will be web-based, with possible linkages to major television and radio networks. The availability of real-time data will enable the creation of real-time data products aimed at promoting public interest and understanding of solar-terrestrial science. Specifically the real-time capability will allow for the continuation of the very successful real-time CANOPUS auroral oval monitor (see http://canott.dan.sp-agency.ca/www/rtoval.htm), and will allow the creation of an AuroraWatch Canada service within CGSM (see the section “Outreach and the Promotion of Public Understanding of Science” for more details).

Value Added Data Products

The objectives of a Canadian Space Weather program were elucidated in detail in the CSA sponsored report "Space Weather in Canada", submitted by W. Liu, R. Rankin, and D. Boteler, in 1999. The authors of that report proposed a Canadian approach to space weather, involving the development of data-driven, self-consistent, physical models of the solar wind-magnetosphere-ionosphere-thermosphere system, and large-scale continuous monitoring of the near-Earth space with a ground-based "super-array", working towards a capability of meaningful prediction of the dynamics of the near-Earth space that put technological systems at risk.

A Canadian Space Weather Program is impossible without CGSM. The F10.7 solar monitor is the most widely used space weather observation, worldwide. With F10.7, Canada has a valued monitor of the source of all geospace variability: the sun. Observations from our continent wide magnetometer, CADI, optical and riometer arrays, and global SuperDARN array, will provide real-time input to our empirical and physical models, from which quantities such as the density of magnetospheric plasma, parameters related to radial transport and loss of high energy electrons, the likelihood of substorm onset, geomagnetically induced currents (GICs), and more.

Developing the above mentioned predictive capabilities, as well as the ability to create relevant value added data products is a long term goal. Reaching that goal of course requires the operation of the CGSM instrument array. More importantly, though, we will need to carry out the basic research (such as that described above) that will allow us to create the *value added* data products, and meaningfully integrate our observations and models.

CGSM will continue and enhance our capability to collect high quality, long-term data sets from which useful (in practical and scientific terms) geophysical and solar physical parameters can be derived. Continuous knowledge of these parameters provides a straightforward means of monitoring the state of the magnetosphere-ionosphere system, the rate of energy input from the solar wind to the magnetosphere, solar activity, solar wind speed, and heating levels in the upper atmosphere. Since CGSM will ultilise state-of-the-art real-time satellite data collection, CGSM will be able to provide many of these data products in real-time. These data products will be distributed via the CGSM SSDP, operated within FDAM.

We will also offer a more limited set of these data products for mirroring and hosting at the web sites of other international web based data distribution programs. For example, the OVATION project, based at the Applied Physics Laboratory (APL) (http://sd-www.jhuapl.edu/Aurora/ovation/index.html), represents a clearing house of several proxies for auroral precipitation boundaries. Similarly, the World Data Center for Geomagnetism in Kyoto, Japan, (http://swdcdb.kugi.kyoto-u.ac.jp/wdc/Sec3.html) distributes the ring current indices DsT, SYM-H, SYM-D, ASYM-H, and ASYM-D, as well as the planetary index Kp. Sites such as NSSDC and CDAWeb also offer to accept external data products and distribute them to the international solar-terrestrial physics community. We will use CGSM data to infer *at least* the following geophysical quantities and geomagnetic indices (note: the data upon which the index will be based is listed in parenthesis in each case):

- Solar UV (F10.7);
- Solar soft X-ray (F10.7);
- Solar total irradience (F10.7);
- cross-polar cap potential (SuperDARN/CADI/Magnetometers);
- substorm likelihood (Optics/SuperDARN);
- invariant latitude of plasmapause boundary (Magnetometers);
- radial density profiles (Magnetometers);
- Pc5 index, and local *AE, Au, Al* (Magnetometers);

- electrojet strength and location (Magnetometers);
- electron energy flux and characteristic energy flux (Optics);
- proton energy flux (Optics);
- ionospheric conductivities (Optics);
- polar cap, dipole to tail-like transition, and trans-Beta boundaries (Optics);
- isotropy or b2i boundary (Optics/SuperDARN);
- HRX hourly activity index (magnetometers);
- DRX daily activity index (magnetometers);
- K 3-hourly activity index (magnetometers);
- fluence index (magnetometers).

All of these indices will be available from the central CGSM web site on a near-real time and historical basis. They are of enormous value in scientific studies, decision making in real-time space science experiments, space weather, and to industry. Through deriving and distributing these indices, Canada is fulfilling an important obligation to the national and international community.

As discussed above, within CGSM the combined operation of all of the observational cornerstones, together with FDAM, will enable a wide range of value-added data products to be provided to the international community. In this section, in order to provide examples of the use of CGSM data to provide value added geophysical indices, we discuss four ground-based quantities that can be used as proxies for four solar-terrestrial parameters. These are the F10.7 index, the spectral power in the Pc5 wave band, the magnetic latitude of the equatorward boundary of the proton aurora, and the latitudinal profile of local resonant standing Alfvén frequency. These provide proxies for solar coronal magnetic flux, the solar wind speed, the inclination of the geomagnetic field in the inner magnetosphere, and the radial profile of mass density in the magnetosphere.

Coronal Magnetic Flux: The 10.7 cm solar radio flux can be used to monitor variations of magnetic flux in the solar atmosphere. The F10.7 cm solar radio flux index measures the slowly-varying component of solar radio emission which is generated by thermal emission originating in plasmas trapped in the magnetic fields overlying active regions. The F10.7 index is related to the product B•dB/dt, which is itself proportional to dW/dt, the rate of energy dumping in the active region magnetic fields. The F10.7 index can hence to be used to provide a proxy for the UV emissions from the solar corona, this proxy measure being used widely in NASA and ESA atmospheric models.

ULF Pulsation (UP) Index: ULF wave power in the Pc5 band can be used to develop a proxy for upstream solar wind speed, with the excellent correlations which exist between 1-10 mHz power in the morning sector providing a particularly useful proxy [*Vennerstrom*, 1999; *Mathie and Mann*, 2000a; 2001, *Baker et al*., 2003]. Such an index is useful for providing proxy solar wind speed during periods when upstream solar wind monitoring is not available (e.g., during the CRRES mission in 1990-91). ULF waves are also recognized as an important component of radiation belt dynamics, approval has already been granted by the International Association of Geomagnetism and Aeronomy (IAGA) ULF Waves Working Group for a Sub-Group to given the task of creating a meaningful ULF wave power (Up) index. Moreover, a proposal to the U.S. NSF funded GEM program has already been submitted to fund the U.S. work required within this Canadian-US-Japanese partnership; Mann is the co-PI on this proposal.

The Isotropy (or b2i) Boundary: The correspondence between the equatorward boundary of the proton aurora and the DMSP b2i boundary has been established by *Donovan et al*. [2003]. The b2i is the equatorward termination of strong pitch angle scattering of ~1-~50 keV CPS protons [*Sergeev et al,* 1995; *Newell et al,* 1996, 1998; *Donovan et al*, 2003]. The scattering is thought to be caused by breaking of the first adiabatic invariant due to highly curved field lines in the vicinity of the current sheet. It follows that the latitude of the IB is controlled, to a significant extent, by the inclination of the magnetic field in the inner magnetosphere. Hence the latitude of the equatorward boundary of the proton aurora can be used to remote sense that inclination [*Donovan et al*, 2003]. In Figure 16, the equatorward boundary is superposed on a keogram of several hours of 486 nm data obtained by the Gillam MSP. The top panel shows magnetic field inclination at GOES 8, ~2 hours MLT east of Gillam. The ability to remote-sense magnetospheric topology on a semi-continuous basis, across many hours of MLT is an important space weather and space science tool, facilitating studies of substorms, auroral arcs, and more.

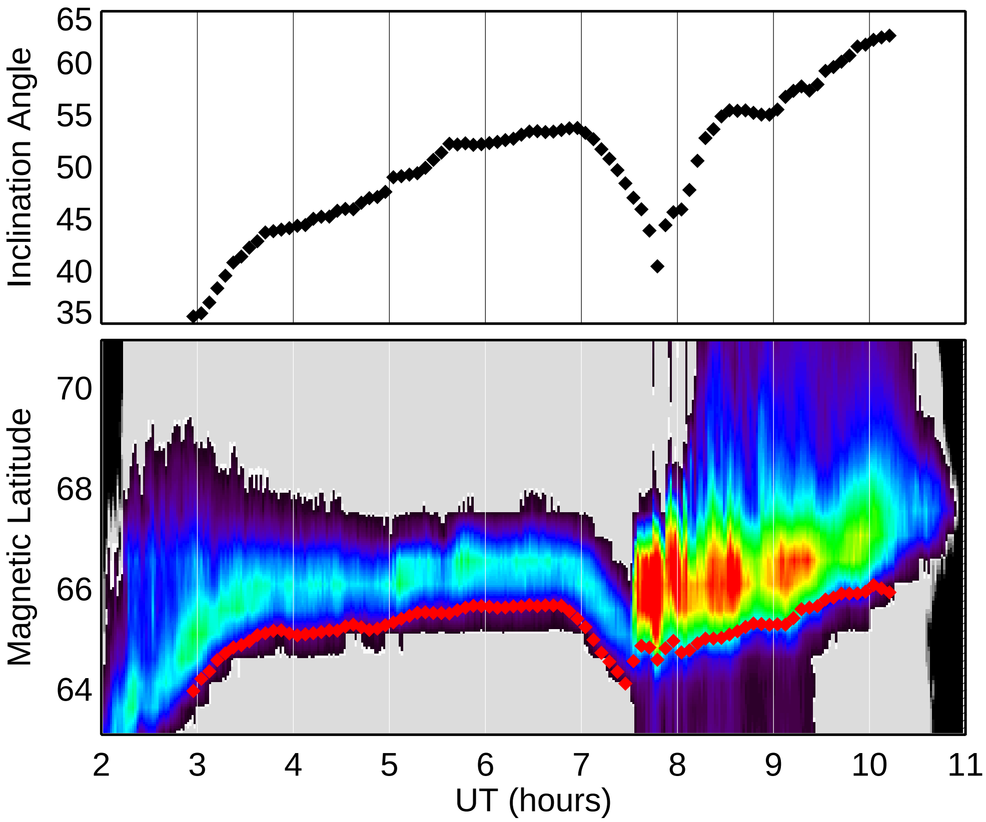


Figure 16: Magnetic field inclination at GOES 8 (top), and a keogram (bottom) of 486 nm (proton auroral) emissions from the Gillam photometer (~2 hours local time west of GOES 8). The overlaid red diamonds indicate the latitude of the "optical b2i", which is an excellent proxy for the inclination at geosynchronous orbit (see text above).

Magnetospheric Cold Plasma Radial Density Profiles: As discussed under science theme V, the cross-phase technique can be used to monitor the L-dependent profile of the local Alfvén eignefrequency in the magnetosphere, and through inversion with a suitable model magnetic field to infer the properties of the density profiles in the magnetosphere [e.g., *Waters et al*., 1995,1996]. By developing an automated algorithm for the detection of the local cross-phase peak, we will be able to deliver a real-time monitor of the dayside density profiles on a quasi-continuous and on-going basis.

International Partnership Programs

The international scientific community supports an exciting broad-based program involving major satellite and ground-based programs, as well as modeling and simulation efforts. Canada is afforded a unique geographical advantage by having the largest readily accessible landmass under the auroral and polar regions. We have capitalized on this advantage through world-class ground-based observations and cutting-edge science activities, and as a result have historically been and continue to be significant contributors to the international space science effort.

Our observations complement those made in space, providing essential context, allowing for the separation of temporal and spatial variation, and quantifying coupling between the ionosphere and the magnetospheric/solar wind regions in which the observations are mode. This has increased Canada’s status within space agencies, the international scientific community, and the public. Such international programs are presently increasing in scope, as we zero in on the crucial in situ and remote sensing measurements that will bring closure to the central questions in our field. Examples of such present and future missions are Cluster, Magnetospheric Multiscale, Magnetospheric Constellation, and the Radiation Belt Explorers.

The importance of coordinated ground-based and space-based observations for advancing our scientific understanding of solar-terrestrial processes has been clearly established and widely recognized [e.g., *Rostoker,* 1982; *Opgenoorth and Kirkwood,* 1989; *Opgenoorth and Lockwood,* 1997; *Opgenoorth,* 1997, *Cowley and Lockwood,* 1997; *Mann et al,.* 2002; *Cully et al.,* 2003c; and the contents of “First Cluster Results”, Special Issue of *Annales Geophysicae*: Vol. 19, No. 6, 2002]. In fact, a satisfactory, end-to-end understanding of solar-terrestrial processes is impossible without cooperative studies involving both ground-based and space-based observations. One example (of many) of this is the hypothesized IMF northward turning substorm trigger [*Lyons et al.,* 1997]. The northward turning of the IMF can only be observed by instruments on a solar wind probe. On the other hand, the changes in the global convection that follow the northward turning, and likely lead to the sequence of events culminating in an onset, are most readily observed by the SuperDARN radars and CADI array. Furthermore, identifying the location and time of substorm onset with sufficient temporal resolution requires ground-based magnetometers and optical instruments. Closure of questions related to substorm onset, the nature of auroral precipitation, the role of waves in acceleration, transport and loss of ring current particles, and the convection cycle demands coordinated ground-based space-based observations.

Our ground-based observational program has been the most meaningful and widely recognized Canadian contribution to the international solar-terrestrial science program. With this contribution, and the value the international community places on it, Canadian researchers have virtually unrestricted access to data from all important international solar wind, magnetospheric, and ionospheric missions. These include, but are certainly not limited to, Polar, Geotail, Cluster, DMSP, GOES, FAST, WIND, IMP, ACE, CRESS, AMPTE, and Equator-S. With this data, scientists working in Canada can carry out front line research on literally any aspect of space science. Furthermore, having our data and the relevant scientific expertise, Canadian researchers have had the opportunity to enter into innumerable exciting collaborations with international researchers. On some missions, Canadian ground-based capabilities are deemed centrally important to the meeting of scientific objectives, and hence to the fundability of those missions. This has led to co-I status for several Canadian researchers on a number of major proposals. Examples include three proposed MIDEX missions, Connections, Auroral MultiScale MIDEX (AMM), and THEMIS. AMM was funded for Phase A but not for flight, and THEMIS was recently approved for launch in 2006. On a more local front, Canadian SuperDARN, CADI, and FDAM all have formal roles in the upcoming ePoP Canadian micro-satellite.

Though CGSM instrumentation will be a facility unique in the world, there are significant ground-based initiatives in other geographical regions. Our effort fits into a broader international program. Within this context, CGSM instrumentation is our contribution to a number of international programs. As in the case of international space missions, the Canadian ground-based effort provides collaborative opportunities with and access to data from international ground-based programs. Important examples are MIRACLE, EISCAT, RAO, MACCS, SAMNET, and SuperDARN.

On the programmatic level, CANOPUS was recognized within ISTP with *instrument status*, providing Canadian researchers with valuable access to ISTP mission data, and opportunities for collaboration. Canada has a leadership role in ILWS, as established by the CSA's role as the lead agency responsible for ground-based research, Canadian representation on the ILWS Steering Committee (with only four other agency level representatives, from NASA, ESA, ISAS, and RSA), and the chairing of both the ILWS Magnetosphere-Ionosphere-Thermosphere Coupling and Ground-Based Solar Observations Task Groups, and membership in the ILWS Modeling Task Group. This will provide Canadian researchers with an opportunity to play an important role in shaping the development of ILWS. Through the Geomagnetism program of the GSC (Geological Survey of Canada), we were founding members of INTERMAGNET. Presently, the Chairs of three INTERMAGNET committees (Executive Council, Technical Manual Committee, and WWW/GINS Committee) are GSC personnel. Finally, there is Canadian representation on both the Core Cluster Ground-based Working Group, and the GEM steering committee.

In the remainder of this section, we describe in some detail ILWS, and two US programs, the NSF sponsored GEM (Geospace Environment Modelling) and multi-agency NSW (National Space Weather) Programs. In Appendix I, we provide a list of international satellite and ground-based programs that provide data that is often, or can be expected to be, used in a coordinated fashion with CGSM data.

International Living With a Star (ILWS)

The ultimate goal of International Living With a Star (ILWS) is to increase our understanding of how the variability of the sun affects the terrestrial and other planetary environments both in the short and long term, and in particular how society may be affected by Solar variability and its consequences. To that end, ILWS aims to stimulate, strengthen and coordinate space research in order to understand the governing processes of the connected Sun-Earth System as an integrated entity. ILWS will involve a wide range of solar and solar-terrestrial missions of both applied and fundamental scientific character.

The ILWS program will build on the successful cooperation during ISTP (International Solar Terrestrial Physics) program, which was a coordinated space effort involving Europe, Japan, Russia/Soviet Union, and the United States. Beyond numerous new scientific discoveries, ISTP provided insight into the Sun-Earth space environment as a coupled physical system, mainly through the ad hoc coordination of simultaneous satellite observations within important regions and boundaries of geospace. The primary science aim is to elucidate the wealth of microphysical plasma processes in the Sun-Earth system, identifying those which have planetary-scale effects, in so doing clarifying the geoefficiency of the governing coupling processes. The ILWS approach of studying the "Sun-Earth system as a coupled entity" is an enterprise than cannot be undertaken by a single space agency, although even smaller national-scale space programs can provide missions capable of providing key parameters in certain regions. ILWS will be organized with a steering committee, a working group and various topical task groups.

ILWS Missions come from both NASA SEC funding lines, i.e. the fundamental science STP (Solar Terrestrial Probe) and applied science LWS programs. These are more specifically from the STP program Stereo, MMS, the Magnetospheric Constellation and the Geospace Electrodynamic Connection Missions, and eventually possibly the Solar Probe and from the LWS program SDO, the Radiation Belt Storm Probes, the Ionosphere-Thermosphere Storm probes, the Solar Sentinels and possibly a global imager mission. ESA expects to contribute ILWS extensions of Cluster, SOHO, and possibly even the Ulysses mission. New ESA missions in the ILWS framework include the China-ESA collaboration Double Star, and the Japan-ESA collaboration BepiColombo - where the Mercury Magnetospheric Orbiter (MMO) will study solar wind interactions with a magnetosphere in absence of an ionosphere, and also serve as an inner heliospheric sentinel, when in the Solar wind. ESA's ILWS flagship will undoubtedly become Solar Orbiter, which aims at observing the Sun close-up from a co-rotation orbit (0.21 AU), and in the later phase of the mission from outside the ecliptic plane at an elevation of 38 degrees. ESA also plans to make contributions to MMS, Stereo and Solar B, in order to improve either their science performance or data coverage. Japan aims to contribute Solar-B and possibly Geotail-2, while Russia will provide Koronas-Photon and possibly a new L1 Solar wind monitor mission. Apart from these missions, which are already in the IACG program, several smaller national space agencies and other US agencies, like NOAA, have expressed intentions of providing missions to the ILWS program.

Global-scale coordinated ground-based observations, and data assimilation and modeling programs will play a fundamental role in ILWS. Solar-wind, magnetospheric, radiation belt and ionospheric observations provide only part of the picture. Ground-based observations provide global context, the capacity to separate spatial from temporal variation, important timing information, and a crucial ability to quantify ionospheric and atmospheric effects of dynamic space processes. Global and local physics-based models provide the capacity to extrapolate contextual information from ground-based observations to the magnetosphere, and to help quantify the effects of magnetosphere-ionosphere coupling. CGSM will be Canada's flagship contribution to ILWS. On the basis of that expected contribution, we have been given the role of lead agency responsible for the ground-based component of ILWS. Further, CGSM will be afforded the status of a mission in the ILWS program. Through CGSM, Canada will play a leadership role in this exciting, international, multi-agency space program.

Geospace Environment Modeling (GEM)

The Geospace Environment Modeling (GEM) program is a National Science Foundation (NSF) Division of Atmospheric Sciences initiative to coordinate and focus research on the near-earth portion of geospace from the ionosphere to where the earth system interacts with the solar wind. The purpose of GEM program is to support basic research into the dynamical and structural properties of this portion of geospace, eventually leading to the construction of a global geospace general circulation (GGCM) model with predictive capability. Of particular importance to GEM is the dynamical behavior of disturbances of the magnetosphere-ionosphere system. A critical part of the strategy for achieving GEM goals is the incorporation of high-quality ground-based observations. These ground-based observations are required for deciphering the mesoscale properties of magnetosphere-ionosphere disturbances and for incorporation with other observations (from the ground and from space) to evaluate the large-scale structure of the disturbances. GEM is of particular relevance to CGSM research for two reasons: 1) As the world-leading ground-based observational program, we provide data that is key to characterizing the temporal evolution of the solar-magnetosphere-ionosphere system during GEM "Challenge Events" and Campaigns; 2) The focus of GEM on end-to-end understanding of dynamics in geospace, with strong emphasis on convection, the substorm, the plasmasphere, and source and loss of radiation belt and ring current particles provides an international stage for highlighting, testing, and advancing our own data assimilation and modeling program component.

The US National Space Weather Program

Space Weather has been identified by the US federal government as an area of strategic importance, due to the ever-increasing importance of satellite-borne technological systems for economic, military, and scientific reasons, and the increasing realization that space weather affects ground-based technological systems and the atmosphere. A number of agencies have together developed the US National Space Weather Program (NSWP) [see National Space Weather Program Strategic Plan, *government document*, 1995]. Through activities that now fall under the CGSM program envelope, Canada has significant involvement in several major US NSWP initiatives. Probably the most significant of these is the University of Michigan Space Physics Research Laboratory Space Weather modelling and simulation program, led by T. Gombosi and C. Clauer [see, for example, *Clauer et al.,* 2000], a significant component of which is the ongoing development of the BATS-R-US global MHD code that is being used to simulate complete end-to-end space weather events, from the corona to the Earth's atmosphere. The University of Michigan group (in particular A. Ridley) are attempting to integrate data from various platforms into the BATS-R-US implementation for the dual purposes of testing and constraining. One ultimate objective is to develop the ability to run such models in near-real time using them to fill in gaps in observations and as a basis for physically rather than empirically based space weather prediction.

The University of Michigan group entered into an agreement with FDAM, involving a memorandum of understanding that outlines an exchange of Canadian ground-based data for the BATS-R-US code. Through this exchange, the Canadian community now has access to, and is contributing to the development of, the BATS-R-US code, which will almost certainly play a central role in much of CGSM scientific activity. More than that, this arrangement has led to collaboration between the Michigan and U. Alberta groups, and the recruitment of C. Kabin as a research associate at FDAM. Canadian data is showcased in this high profile American program. Finally, the collaboration is growing, now formally involving NORSTAR, and hopefully other Canadian groups in the long run. This is but one example of numerous and highly productive international collaborative opportunities that the Canadian ground-based program has afforded Canadian scientists. Through the enhanced, integrated CGSM program, this will continue for years to come.

DMSP: This ongoing US Department of Defense (in particular the Air Force Space and Missile Systems Center) satellite program typically maintains as many as five spacecraft in highly inclined nearly circular (~830 km altitude) orbits. The spacecraft all carry geographic zenith pointing 30 eV to 30 KeV electron and ion detectors, as well as ion drift meters. Transits of the auroral oval, cusp, cleft, and polar cap are frequent. For example, an auroral zone transit is available usually within ten minutes of any specific time. The resulting data set is invaluable for characterizing the location of the auroral oval and all relevant precipitation boundaries, determining the characteristic energy, energy flux, and latitude profiles of precipitating particles, and remote sensing the ion and electron CPS. The DMSP spacecraft have provided literally thousands of overflights of the Canadian ground based instruments, and certainly hundreds of nearly direct overflights of our optical instruments when viewing conditions were excellent. Overflights will of course continue for years to come.

ePOP: The science objectives of the e-POP project are to quantify the micro-scale characteristics of plasma outflow in the polar ionosphere and to probe related micro- and meso-scale plasma and wave processes at unprecedented resolution. The e-POP project is highly synergistic with CGSM: it comprises a polar-orbiting micro-satellite for in-situ particle and wave measurements, and a program of coordinated ground observations using the CGSM SuperDARN, NORSTAR, and CADI facilities. The in-situ measurements will be combined with theoretical modeling to quantify the micro-scale characteristics of plasma and neutral outflows in the polar ionosphere, and the coordinated ground observation data will be assimilated to explore the effects of the aurora on these flows and those of related plasma microstructures on radio propagation.

GEC: Global Electrodynamic Connection is a NASA mission consisting of 4 (though the number may change) spacecraft circling the Earth in a petal constellation formation. This mission will be an ionospheric equivalent to CLUSTER, with changing inter- spacecraft separation to enable three-dimensional studies. The satellites will dip into the dense thermospheric regions overlapping the F-region ionosphere (~300 km) later in the mission to study *in-situ* the thermosphere/ionosphere/thermosphere coupling process.

GLORIA: Global Riometer Array is a proposed international project, involving riometer teams from the UK, Finland, Denmark, and Canada. The project objective is to develop a common data format for riometers operated worldwide, and a data product which would be riometer absorption maps on a global scale. This would provide insight into the temporal and spatial evolution of precipitation of high energy electrons and protons, allow for remote sensing of magnetospheric particle populations, and provide important space weather information related to PCA events. The CGSM contribution to Gloria will be to maintain and operate the existing 13 riometer array, and deliver calibrated absolute absorption data in a timely fashion to the GLORIA PI institute in Lancaster, England.

GPS: Global Positioning System signals can be used to infer TEC and tomographically reconstruct the ionospheric electron density profile. This information is valuable for space science research, and for space weather applications [see e.g., *Foster et al.,* 2002]. Furthermore, the fact that GPS technology is susceptible to ionospheric disturbances makes the GPS community a potentially important client for space weather services. At present, there is not a close link between the CGSM program and Canadian GPS researchers, however centers of expertise in this area are located at UNB and UofC, and it is reasonable to expect an expansion of university based GPS activity over the next years. In the future, CGSM should incorporate some GPS data products, and the CGSM community should build a working relationship with these two groups. An initial step for which discussions are presently underway is the possible installation of GPS scintillation detectors at several CGSM sites by Susan Skone of the University of Calgary. The objective of this effort would be to explore the effect of ionospheric structure (as identified by either NORSTAR imagers or the SuperDARN radars) on the accuracy of GPS position determination, something that could be of enormous importance to the utilization of GPS in air aviation.

GOES: Typically two of these meteorological spacecraft are in geosynchronous orbit on an ongoing basis, one over the eastern part of North America and the other over the western part. GOES East (presently GOES 12) is located magnetically conjugate to (roughly) Poste-de-la-Baleine, while the magnetic footpoint of GOES West (presently GOES 10) is (roughly) Fort Simpson. These NOAA spacecraft carry X-ray (λ~10 nm), and high energy particle (spin averaged fluxes of high pitch angle ~1 MeV electrons and tens of MeV protons), and magnetometer data. The X-ray and particle detectors are invaluable for monitoring evolving solar conditions (ie solar flares, etc), and outer radiation belt high energy charged particles. The magnetometers deliver three component vectors at slightly greater than 1 Hz. The essentially continuous time series of magnetic field data obtained in the vicinity of the inner edge of the cross-tail current sheet has proved to be extremely valuable in studies of the general topology of the magnetospheric magnetic field and the inner magnetospheric dynamics associated with substorms. From the perspective of our program (CGSM), the fact that these spacecraft are essentially conjugate to Canadian ground magnetometer stations makes them a natural extension of our ground-based monitoring program Interestingly, the GOES East and West spacecraft will be upgraded with the launch of the new replacement GOES NO/PQ series satellites to the same orbital locations in 2004. The GOES NO/PQ series satellites will carry additional instruments which will measure ring current ion and electron populations with energies between 80-800 keV and 30-600 keV, respectively [H. Singer, Personal Comm., 2002]. Consequently, the new GOES East and West satellites will be able to monitor the injected particle populations on either side of the CGSM search coil systems on the ground, resulting in the ideal complementary ground-satellite instrument coverage with which to monitor the physical processes producing EMIC emissions.

INTERMAGNET: global network of cooperating digital magnetic observatories. It promotes the adoption of modern standard specifications for measuring and recording equipment, in order to facilitate data exchanges and the production of geomagnetic products in close to real time. Where local support is lacking it is a further goal of INTERMAGNET to aid in the establishment of new observatories or to provide assistance with the upgrade and maintenance of existing facilities. Supplemental to this aim is the promotion of modern standards for measuring and recording the Earth's magnetic field. INTERMAGNET is represented in Canada by the NRCan magnetometry group.

International SuperDARN: This international consortium of research groups from Canada, Finland, France, Japan, South Africa, Australia, the UK, and the US operates 9 HF radars in the northern hemisphere and another 6 in the southern hemisphere. These radars utilize ionospheric refraction and coherent scatter from F-region irregularities to create global maps of ionospheric convection in near real-time. They facilitate studies of dynamic magnetospheric processes, solar wind magnetosphere coupling, and ionospheric phenomena, and play an important role in the evolving international space weather initiative. They frequently provide near real time monitoring of the cross polar cap potential, the b2i/IB, and the location of the cusp. See the map in the SuperDARN Enhancement section of the technical proposal: it highlights the importance of the Canadian SuperDARN program which is part of CGSM, the CGSM imaging, magnetometric, and ionosonde programs, as well as the importance of the proposed PolarDARN radars in terms of filling the gap in coverage over the polar cap.

MC: Magnetospheric Constellation mission will consist of 50-100 nanosatellites and will be the penultimate ILWS space project. The mission objective is to identify and map the linkages between small scale and global magnetospheric processes. On a grand scale, temporal and spatial ambiguities will be completely resolved. MC will provide quantitative detailed information on the timing and spatial evolution of global magnetospheric processes. It will bring closure on numerous scientific questions with profound implications for our understanding of astrophysical plasmas. All aspects of magnetospheric dynamics will be addressed by MC. The time frame of the mission will be at least ten years from now. Much of our understanding of global magnetospheric processes has been built up with large scale ground-based observations. A global ground-based initiative will play a fundamental role in MC – so much so that, without exaggeration, it is safe to say that in the absence of this global ground-based initiative, MC would not make scientific sense. A strong Canadian ground-based observational program, as well as active theoretical, simulation, modelling, and data analysis activities, will ensure a significant Canadian involvement in MC.

MIRACLE: This Finnish project is a state of the art integrated radar, magnetometer, and all-sky imager network that operates in the Fenno-Scandinavian peninsula and on Svalbard. The MIRACLE network includes eight digital ASIs, six of them on the peninsula. These six imagers have highly overlapping fields of view, and coverage of the region is virtually continuous (the chances of clear sky at at least two of the sites is relatively high), and at times good data from multiple imagers with overlapping FOVs provides an excellent opportunity for tomographic reconstruction of the auroral emissions. The 27 magnetometer array is spread over a relatively small geographical area, and the data thus facilitates detailed studies of the ionospheric currents using sophisticated techniques developed at FMI. The radar component of MIRACLE includes the original STARE system, and the FOVs of the CUTLASS SuperDARN pair are at least partially over the MIRACLE array. MIRACLE provides world-class observations of ionospheric electric fields, magnetic fields due to ionospheric currents, and auroral luminosity with better spatial resolution than is available anywhere else on Earth. The spatial extent of MIRACLE coverage allows for studies of auroral arcs, cusp processes, pseudobreakups, vortices, pulsations, but not larger mesoscale processes. The CGSM array is contraposed (ie, at similar magnetic latitudes but separated by roughly 12 hours of MLT) to MIRACLE, the combined capabilities facilitating studies of truly global scale disturbances, and provides less dense spatial coverage of a significantly larger geographical area. The arrays are complementary in terms of location, and the scale of disturbance that they are optimally able to study.

MMS: The five spacecraft mission is targeted at understanding small-scale magnetospheric plasma physical processes on a fundamental level. Targeted questions are related to reconnection across collisionless boundaries, energy conversion and related particle acceleration at those boundaries, micro to meso scale coupling, and the spatial and temporal structure of collisionless shocks. The spacecraft will be closer together than the four CLUSTER spacecraft, and with superior attitude control, instrumentation, and telemetry, will open up new frontiers in plasma observations in the magnetosphere, affording for the first time a three dimensional picture of the electromagnetic fields and plasma properties in key magnetospheric regions. This mission is complementary to THEMIS in terms of spatial scale of the structures and temporal scale of the processes that are to be probed. (ie “microscope” rather than “telescope”). Though MMS is a multispacecraft mission, like Cluster it will deliver point measurements of gradients of densities, pressures ,bulk flows, and electric and magnetic fields. Consequently, MMS science will demand world-class ground-based observations on a global scale for characterizing the temporal evolution of the state of the magnetosphere, the nature of magnetosphere-ionosphere coupling.

NPOES: The POES and DMSP programs will be merged together to form the NPOES (National Polar Operational Environmental Satellite) program. The mission specifications, number of spacecraft, and time frame are evolving, though it is safe to say that NPOES will be an impressive enhancement to the international space science observing capabilities. Plans are in place for ion and electron detectors with some pitch angle resolution, operating at energies spanning those measured by DMSP and POES, and the incorporation of electric and magnetic field instruments, as well as imagers. The NPOES program, operating concurrently with CGSM, will provide Canadian researchers with valuable in situ observations that will complement our own ground-based observations.

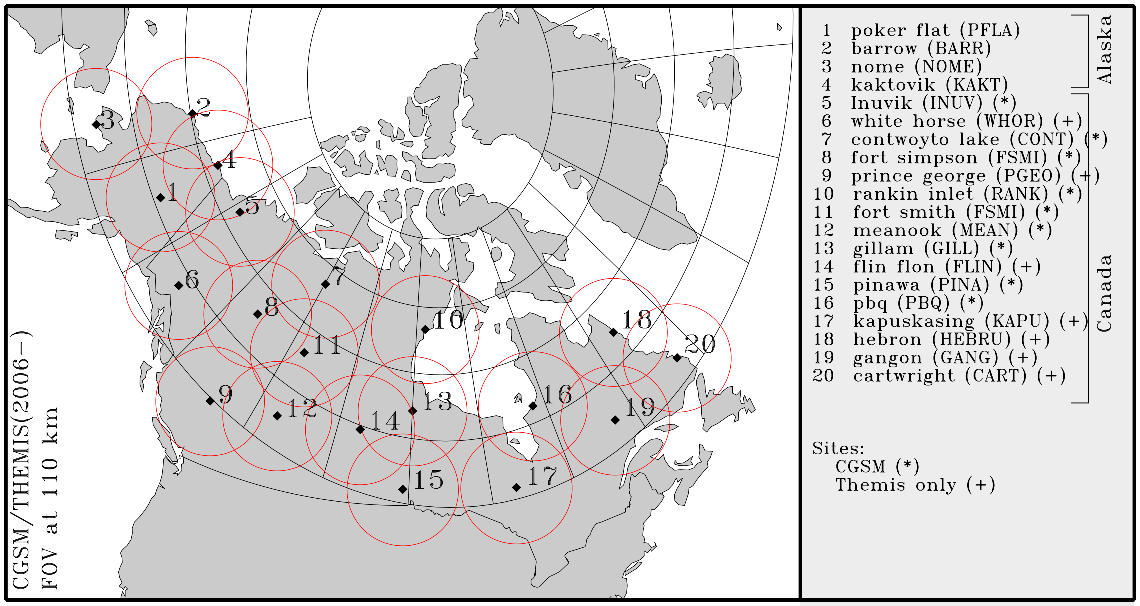
PFRR: Poker Flat Research Range is operated by the University of Alaska (Fairbanks) Geophysical Institute. Sounding rockets carrying scientific payloads are frequently launched there. Particularly in the case of rocket missions with ionospheric physics objectives (eg., GEODESIC) , the launch decision often rests on a detailed understanding of the real time auroral distribution. Many of these rockets, for example, are meant to fly through an expanding substorm surge. Consequently, Canadian ground-based instrumentation with real-time capability is of strategic importance to the PFRR rocket program.

POES: Polar-orbiting Operational Environmental Satellite program (formerly TIROS spacecraft, also operated by NOAA). The POES program has built up an impressive data base of *in situ* electron and ion differential energy flux measurements, both orthogonal to, and (downward) parallel to the magnetic field at ~850 km altitude. Of particular relevance to CGSM are measurements at energies ranging from 30 keV to 1000 keV for electron, and 30 keV to 6900 keV for ions, which complement lower energy measurements from the SSJ-4 and ESA instruments on DMSP. POES data is routinely utilized to determine precipitation boundaries, and snapshots of the precipitating energy flux at these higher, though still auroral, energies.

RAO: Plans are in place for an incoherent scatter radar at Resolute Bay, funded by the NSF, and operated by the University of Alaska. The advance facility for the Relocatable Atmospheric Observatory (a building with power, phone lines, and a dome), is presently housing a CADI, a NORSTAR imager, and a mesospheric radar. If the incoherent scatter facility is ultimately funded and constructed at Resolute Bay, this would be an enormous boon for Canadian space science. CGSM should commit to long term operation of magnetmeters, imagers, and ionosondes in support of this project, and hence secure a meaningful role for Canadian space scientists in the RAO.

RBM: The fleet of Radiation Belt Mappers will be part of NASA's LWS. The mission will consist of up two spacecraft in low inclination orbits, with a launch date in early 2008. The orbits will have 550 km perigees, and apogee for these spacecraft will be ~6.5 Re. The objective is to provide time-dependent mapping of particles and fields in the Earth's inner magnetosphere and plasmasphere, and the radiation belts. The instrument complement will include flux-gate and search-coil magnetometers, electric field probes, and relevant particle detectors. The scientific objectives of RBSP is to discover the origin and dynamics of high-energy particle populations, and trace the development and evolution of penetrating radiation during magnetic storms. This mission has an important role in the US National Space Weather Program.

THEMIS: This is a MIDEX mission which has recently been selected for launch in 2006, and a nominal two year mission, which would almost certainly be extended provided certain objectives are met. THEMIS will elucidate which magnetotail process is responsible for substorm onset at the region where substorm auroras map (~10Re): (i) a local disruption of the plasma sheet current or (ii) that current's interaction with the rapid influx of plasma emanating from lobe flux annihilation at ~25Re. Correlative observations from long-baseline (2-25 Re) probe conjunctions, will delineate the causal relationship and macroscale interaction between the substorm components. THEMIS's five identical probes measure particles and fields on orbits which optimize tail-aligned conjunctions over North America. Ground observatories time auroral breakup onset. Three inner probes at ~10Re monitor current disruption onset, while two outer probes, at 20 and 30Re respectively, remotely monitor plasma acceleration due to lobe flux dissipation. In addition to addressing its primary objective, THEMIS answers critical questions in radiation belt physics and solar wind - magnetosphere energy coupling. THEMIS's probes use flight-proven instruments and subsystems, yet demonstrate spacecraft design strategies ideal for Constellation class missions. THEMIS is complementary to MMS and a science and a technology pathfinder for future STP missions. The Canadian contribution to THEMIS will be to temporarily deploy and operate up to 16 (see map below) imagers in Canada, which will operate alongside another four imagers in Alaska. From the perspective of CGSM, the key issue in the THEMIS program is that the orbits will be designed so that conjunctions are always over Canada. This will lead to exciting science related to substorms when the apogees are on the nightside, and equally exciting science related to cusp dynamics, solar wind pressure pulses, and ULF wave generation in the magnetosheath and at the magnetopause when the apogees are on the dayside.



Science Team

The science team will consist of members of the Canadian space science community. Membership will be restricted to faculty members, research associates, and project scientists. Science team members will have unrestricted access to CGSM data, but will not be free to distribute that data to third parties. Science team members, subject to the approval of the SVG, will be able to use CGSM involvement as a basis for seeking research funding and entering into international collaborations. With the agreement of the SVG, researchers at foreign institutions will be eligible for science team membership. The CGSM science team is listed in the table below. Members of the SVG are indicated.

Samson, John	U. Alberta	samson@space.ualberta.ca
Rankin, Robert (SVG)	U. Alberta	rankin@space.ualberta.ca
Mann, Ian (SVG)	U. Alberta	imann@space.ualberta.ca
Milling, David	U. Alberta	dmilling@space.ualberta.ca
Fenrich, Frances	U. Alberta	frances@space.ualberta.ca
Voronkov, Igor	U. Alberta	igor@space.ualberta.ca
Rostoker, Gordon	U. Alberta	rostoker@space.ualberta.ca
Donovan, Eric (SVG)	U. Calgary	eric@phys.ucalgary.ca
Jackel, Brian	U. Calgary	bjackel@phys.ucalgary.ca
Trondsen, Trond	U. Calgary	trondsen@phys.ucalgary.ca
Knudsen, David	U. Calgary	knudsn@phys.ucalgary.ca
Cogger, Leroy	U. Calgary	cogger@phys.ucalgary.ca
Hamza, Abdelhaq	UNB	ahamza at unb.ca
Sofko, George (SVG)	U. Sask	sofko@skisas.usask.ca
Andre', Dieter	U. Sask	andre@skisas.usask.ca
Kustov, Sasha	U. Sask	kustov@skisas.usask.ca
Hussey, Glen	U. Sask	Glenn.Hussey@usask.ca
St.-Maurice, Jean-Pierre	UWO	jstmauri@uwo.ca
MacDougall, John (SVG)	UWO	jmacdoug@uwo.ca
Jayachandran, P.T.	UWO	jaya@uwo.ca
Moorcroft, Donald	UWO	moorcrof@uwo.ca
Prikryl, Paul	CRC	prikryl@cancrc.dgrc.doc.ca
Creutzberg, Fokke	Photometrics	CREUTZBERG@sp-agency.ca
Wallis, Donald	Magnametrics	Donald.Wallis@sp-agency.ca
Boteler, David (SVG)	NRCan	boteler@geolab.NRCan.gc.ca
Lam, Hing-Lan	NRCan	lam@geolab.NRCan.gc.ca
Newitt, Larry	NRCan	Newitt@geolab.NRCan.gc.ca
Coles, Richard	NRCan	coles@geolab.NRCan.gc.ca
Trichtchenko, Larisa	NRCan	larisa@geolab.NRCan.gc.ca
Connors, Martin	U. Athabasca	martinc@athabascau.ca
Landecker, Tom	NRC-DRAO	tom.landecker@nrc-cnrc.gc.ca
Tapping, Ken (SVG)	NRC-DRAO	ken.tapping@nrc-cnrc.gc.ca

List of Acronyms

AACGM	Altitude Adjusted Corrected Geomagnetic Coordinate System
AE	Auroral Electrojet (index)
APL	Applied Physics Laboratory (Johns Hopkins University)
ASI	All-Sky Imager
ASRA	Alberta Science and Research Authority
BATS-R-US	Block Adaptive-Tree Solar-wind Roe-type Upwind Scheme (UMich/Gombosi)
BBF	Bursty Bulk Flow
CADI	Canadian Advanced Digital Ionosonde
CANMOS	CANadian Magnetic Observatory System
CANOPUS	CANadian Open Unified Study
CCD	Charge Coupled Device
CD	Current Disruption
CDAWeb	Coordinated Data Analysis Web
CFI	Canada Foundation for Innovation
CGSM	Canadian GeoSpace Monitoring
CME	Coronal Mass Ejection
CNSR	Canadian Network for Space Research (NSERC Network of Centers of Excellence)
CRC	Canada Research Chair
CSA	Canadian Space Agency
CSWFC	Canadian Space Weather Forecast Center (NRCan)
DRAO	Dominion Radio Astrophysical Observatory
DsT	Disturbance storm Time
EMIC	Electromagnetic Ion Cyclotron
ePOP	Enhanced Polar Outflow Probe (CSA sponsored micro-satellite).
ESA	European Space Agency
FCE	Flow Channel Event
FDAM	Facility for Data Assimilation and Modeling
FLR	Field Line Resonance
FTE	Flux Transfer Event
GEM	Geospace Environment Modeling
GICs	Geomagnetically Induced Currents
HF (VLF)	High Frequency (Very Low Frequency)
IACG	InterAgency Consultative Group
IAR	Ionosphere Alfvén Resonator
ICT	Information and Communications Technology
ILWS	International Living With a Star (ESA/NASA/RSA/ISAS/CSA)
IMF	Interplanetary Magnetic Field
IPS	Inner Plasma Sheet
ISES	International Space Environment Service
KH[I]	Kelvin Helmholtz [Instability]
LAPS	Low Altitude Plasma Sheet
LAPSBL	Low Altitude Plasma Sheet Boundary Layer
LT	Local Time
LWS	Living With a Star (US/NASA)
MACCS	Magnetometer Array for Cusp and Cleft Studies (Boston U/Ausburg College)
MACI	Multimedia Advanced Computational Infrastructure (Alberta)
MAGIC	Magnetometer Array on the Greenland Ice Cap (UMichigan)
MARIA	Magnetometer And RIOMETER Array

MC	Magnetospheric Constellation (Proposed NASA Constellation)
MHD	MagnetoHydroDynamics
MIRACLE	Magnetometers – Ionospheric Radars – All-sky Cameras Large Experiment
MLT	Magnetic Local Time
MMO	Mercury Magnetospheric Orbiter
MMS	Magnetospheric Multiscale (NASA Explorer Class Mission)
MSP	Meridian Scanning Photometer
NASA	National Aeronautics and Space Administration
NENL	Near-Earth Neutral Line
NOAA	National Oceans and Atmospheres Administration
NORSTAR	NORthern Solar Terrestrial Array
NSF	National Science Foundation (USA)
NSSDC	National Space Science Data Center
OVATION	Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting (APL)
PBI	Poleward Boundary Intensification
PCA	Polar Cap Absorption
PIC	Particle In Cell
POCA	Polar Camera (CNSR)
PolarDARN	Polar Dual Auroral Radar Network
PSBL	Plasma Sheet Boundary Layer
RE	Earth Radii
Riometers	Relative Ionospheric Opacity METER
SAMNET	U. K. Sub-Auroral Magnetometer Network (Lancaster, UK)
SSC	Storm Sudden Commencement
SSDP	Space Science Data Portal
SuperDARN	Super Dual Auroral Radar Network
SWDS	Space Weather Data Service (now the CGSM Web Portal)
TB (GB)	TeraByte (GigaByte)
UofA/UofC	University of Alberta/University of Calgary
USask/UWO	University of Saskatchewan/University of Western Ontario
UT	Universal Time
VHF	Very High Frequency
VSAT	Very Small Aperture Terminal