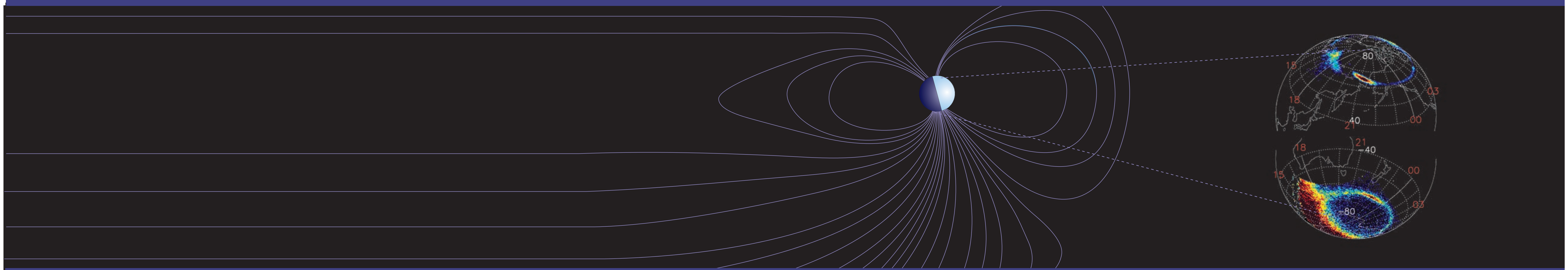
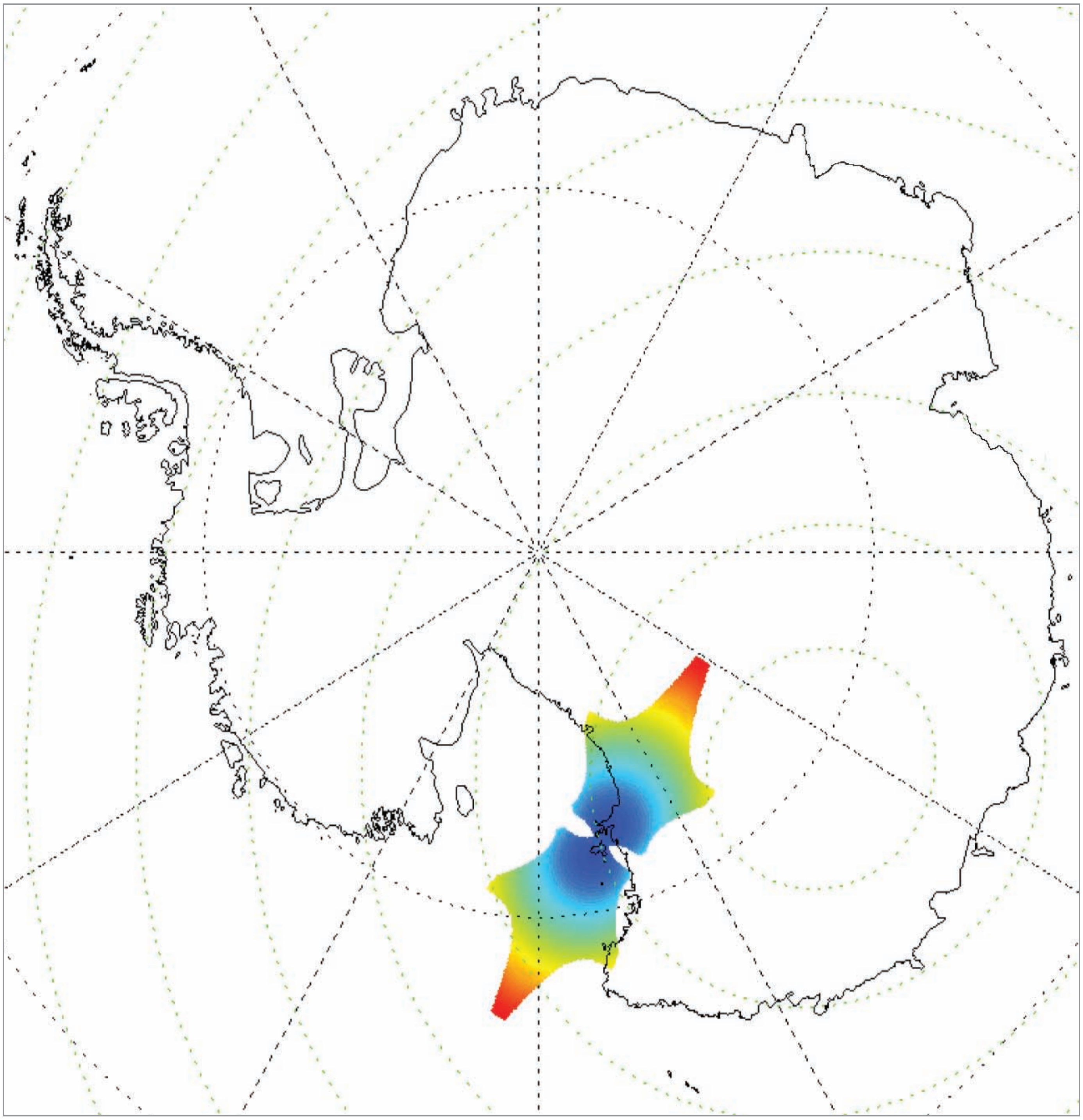
THE Antarctic Incoherent Scatter Radar Facility

Transformational Solar-Terrestrial Research In the High South



Antarctic ISR Workshop 8–9 AUGUST 2008

AISR 2009 v1.3



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Front piece: Simultaneous auroral images from the northern and southern hemispheres illustrating very different responses to the same solar wind drivers resulting from difference in the magnetic and geographic topologies as indicated in the schematic (N. Østgaard).

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Executive Summary

Almost 10 years into a new millennium, on the rise of the 24th solar cycle, our society is facing a number of challenges related to the energy exchange between our planet and the solar wind. There are signs of changes in the overall energy budget of our planet seen as temperature and possible longer term climate variability or changes. We are also becoming increasingly dependent on satellite-borne technology for, among other things, transportation and communication. Our oil and power grids are stretching for thousands of kilometers in northern areas, exposed to induced currents from geospace. We have an urgent need to understand and predict the complex interactions between our planet and the surrounding geospace, and in order to do so we need a more global approach in our quest to describe and model these processes.

The high-latitude southern hemisphere represents a crucially important resource in the drive to understand the solar-terrestrial system by providing a second set of fiducial points. The high southern latitude is fundamentally different from the high north, and is still not adequately used in terms of observational capabilities

On the road to a full understanding of the energy budget between the Sun and Earth, a number of outstanding science questions remains to be solved—science questions that can only be answered by adding an instrument with incoherent scatter radar (ISR) capabilities in Antarctica. ISR, and AMISR (Advanced Modular ISR) in particular, has the track record of transformational contributions to upper atmosphere science and in filling the gaps in the understanding of atmospheric boundary layers from both above and below.

Summarized here, and discussed in more detail in this report, are some of the critical science topics.

Large-scale inter-hemispheric asymmetry in magnetosphere-ionosphere coupling

Without understanding the different ionospheric responses in the two hemispheres and the resulting differential magnetosphere-ionosphere coupling, a full understanding of the geospace system will continue to elude us. Departures from nominal conjugacy at auroral oval latitudes have been clearly shown in simultaneous data from satellite imagers in either hemisphere. The combination of simultaneous density (particle energy), temperature (electron energy dissipation and ion heating) and flow (elucidating reconnection dynamics and magnetic tension) makes an ISR an essential addition to the array of southern hemisphere instruments, allowing for systematic studies which have not so far been possible.

Differences in inter-hemispheric potential

Global MHD (magnetohydrodynamics) models are the building blocks of all general circulation models in the Earth's magnetosphere-ionosphere system. Simultaneous north-south measurements will have great impact on improving global models by facilitating direct tests of specific models' predictions of north-south asymmetries. Only a pair of nominally conjugate ISR facilities is capable of delivering the detailed simultaneous observations necessary to achieve this confirmation.

Inter-hemispheric asymmetry on intermediate and small scales

There is considerable observational evidence that auroral conjugacy breaks down on small- and meso-scales in the ionosphere. Observations of inter-hemispheric auroral asymmetry are fundamental diagnostics of magnetospheric asymmetries, since auroral activity images large regions of the magnetosphere into much smaller areas of the ionosphere. Once again, only a pair of ISRs would allow inter-hemispheric differences between auroras to be measured in terms of multiple parameters such as particle energy and associated electric fields, as well as the correct interpretation of the differences in terms of their relationship to the background ionosphere.

Plasma sources for the magnetosphere

There are few, if any, conjugate observations of ion outflow events. If polar cap convection is asymmetric, then the impact of outflow drivers will be different in each hemisphere, thus affecting the rate of mass loading of the magnetosphere. Simultaneous measurements of convection, conductivity and outflow (all measured by ISRs) in each hemisphere will provide the appropriate observational test of model predictions of auroral arc intensification, drift motion and fading that are a consequence of the finite Alfvén wave propagation between the two hemispheres.

Inter-hemispheric asymmetry in the mesosphere and thermosphere

The northern and southern upper mesospheres are dynamically connected through a longitudinal summer-to-winter flow driven by gravity wave forcing. Simultaneous observations of the polar mesosphere and thermosphere at similar latitudes in both hemispheres will enable new understanding of the fundamental coupling between the neutral and charged parts of the atmosphere.

Neutral dynamics

The Drake Passage/Antarctic Peninsula is one of the most active regions on the planet in terms of neutral dynamics. An AMISR-like instrument has the ability to make routine measurements of the dynamics of the neutral atmosphere extending as low as 60 km, yielding data that cannot be obtained routinely with any other instrument.

TECHNICAL ADVANCES: REMOTELY OPERATED – POWER FLEXIBILITY

Modern AMISR-like ISRs are—in addition to being the perfect scientific tool for a location like Antarctica—also technically ideal for remote and extreme locations. Phased arrays with no moving parts, distributed transmit power for gentle degradation, and the capability to fully operate it remotely have not only been designed, but also tested in locations like Poker Flat, Alaska, (since 2006) and Resolute Bay, Canada, with enormous success. Additionally, the way the power consumption of an AMISR-like ISR scales with the duty cycle of the system makes it preferable in a location like Antarctica where the availability of instant power, and also of the oil for generating it, is limited.

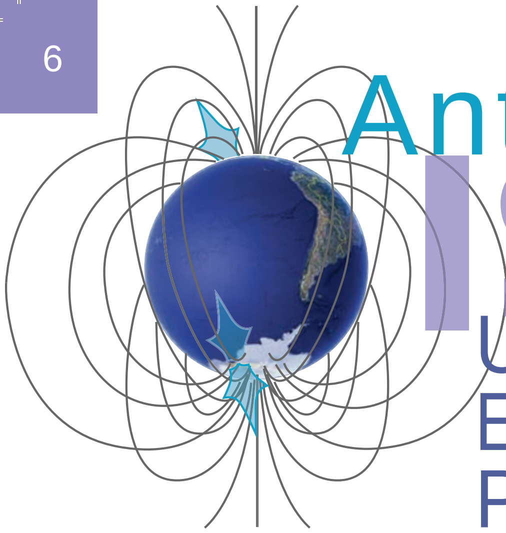
DIFFERENT GEOMAGNETIC LOCATIONS

The Antarctic continent is quite large–it encircles both the geographic and the geomagnetic poles and has a logistical accessible coastline that covers a multitude of geophysical regions, from the polar cap (i.e., McMurdo Station) to sub-auroral latitudes (i.e., the peninsula). Unlike the northern hemisphere with a number of disparate national interests and regulations, the Antarctic continent is international by nature and by definition, and hence provides more freedom in terms of choice of location.

INTERNATIONAL COLLABORATION

The international nature of the Antarctic continent also encourages strong collaboration in establishing and managing an instrument of this scale, as well as its use in both research and education. ■

T *is report is a synthesis of the contributions and discussions from the Chicago Antarctic ISR workshop in August 2008, and valuable and important contributions have been provided by all the participants.*



Antarctic ISR

UNDERSTANDING THE ENERGY BUDGET OF OUR PLANET

Photo: Craig Heinselman

The high-latitude southern hemisphere represents a crucially important resource in the quest to understand the solar-terrestrial system.

Our society urgently needs to understand both the energy balance of planet Earth's upper atmosphere and ionosphere and the impact of space weather-induced events on ground- and space-based technological systems.

The world's attention is also increasingly focused on issues related to matters of perceived, or actual, climate change and it is by now widely recognized amongst the public that our existence on this planet depends entirely on the energy flowing from the Sun. Less widely understood, but crucially important nonetheless, is that the Earth orbits within the outer reaches of the solar atmosphere and that the energy budget and equilibrium of the Earth and its climate depend not only on the heat and light emitted by the Sun, but also on the highly variable levels of energetic particles, magnetic fields and momentum transferred into the Earth's environment by the solar wind.

A recent workshop report, *Severe Space Weather Events—Understanding Societal and Economic Impacts*, issued by the National Academies (2008), estimates the societal and economic costs following a "severe geomagnetic storm scenario" to be at least $1 trillion, and maybe as much as $2 trillion, in the first year alone. Fully understanding the process can provide ways to mitigate, maybe even to avoid, such potential costs.

An essential requirement is a full understanding of the physics and chemistry of the coupling processes between the energy received from the Sun through its radiation emissions (at all wavelengths), particles, magnetic fields, and solar wind and the magnetosphere, ionosphere, and atmosphere. With our society becoming increasingly more dependent on vulnerable technological systems, in a time when the Sun's activity is once more on the rise toward a new solar maximum, this understanding needs to be developed as quickly and effectively as possible.

The high-latitude southern hemisphere represents a crucially important resource in the quest to understand the solar-terrestrial system because it provides access to a second set of fiducial points, as far removed in solar-terrestrial response space as possible from the existing set in the northern hemisphere, where the geographic and magnetic topologies are very different.

Besides their geographic and magnetic topologies, the northern and southern polar regions differ in many other ways including land-ocean relations, overall temperature (the south is colder than the north), biodiversity, pollution and dust levels, existence of indigenous people, and political constraints.

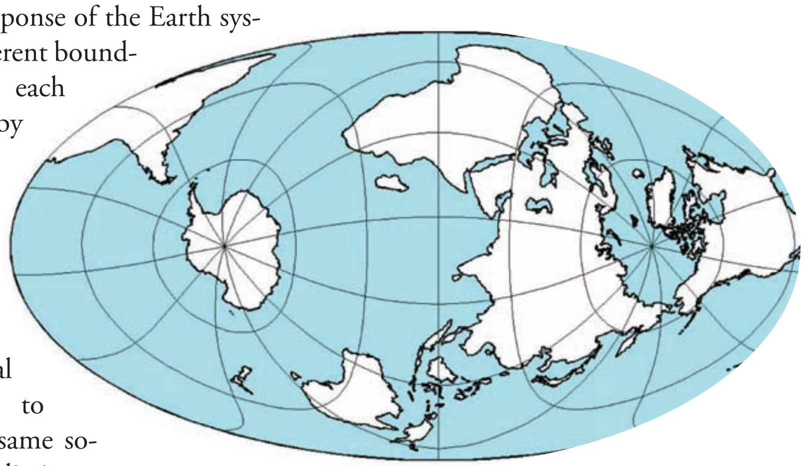
Twenty years ago, the atmospheric community assumed symmetry of the atmosphere in both hemispheres but that assumption was soon dispelled by observations, notably by the spectacular discovery of the now well known ozone hole (Farman, Gardiner and Shanklin, 1985) whose development in the southern hemisphere differs greatly from that of its much smaller northern counterpart—the latter being even unknown until the southern observations prompted similar observations in the north.

The heat and light from the Sun constitute the bulk of the energy transferred, but, even though the impact on the Earth is almost exclusively controlled by the geometry of the Sun-Earth orbital system, the interaction is still hugely complex and, at times, counter-intuitive. Most of the remaining energy delivered by the Sun comes through terrestrial interaction with the solar wind and is predominantly related to processes in the polar regions. Due to the paucity of measurements the general aeronomy of the high-latitude southern hemisphere is much less well observed or understood than the northern equivalent.

The Sun-Earth connection intimately involves interactions between the magnetic fields of the Earth and the solar wind which are not only asymmetric and variable between the two hemispheres, but also affect and feed back on each other in complex and seemingly unpredictable ways. In addition to such energy budget considerations, the swirling interdependence of the solar wind particles and fields, the ionized upper reaches of the atmosphere, the circulating atmospheric currents, and the bulk atmosphere itself are responsible for a whole slough of disturbances and processes which have far reaching, and almost exclusively deleterious, affects on both space- and ground-based technological systems.

A sophisticated observatory located at a high southern latitude is essential for continued progress in understanding the Sun's influence on the structure and dynamics of planet Earth's ionosphere and its coupling to the lower atmosphere.

Fortuitously, the asymmetries of the Earth's magnetic field, and its orientation with respect to the rotational axis provides a natural laboratory for the study of the response of the Earth system at two different boundary conditions, each characterized by very different magnetic field topologies, illumination regimes, and geographical and topological environments, to essentially the same solar wind and radiation source.



Large inter-hemispheric differences in terrain and ice-cover lead to important differences in wind circulation, and subsequently in atmospheric temperatures and composition since coupling of the Ionosphere-Thermosphere-Mesosphere systems occurs from below as well as from above.

The inter-hemisphere asymmetries in the variables that describe the state of the Earth's atmosphere must be

Because the necessary instrumental installations do not currently exist, fundamental questions remain unanswered.

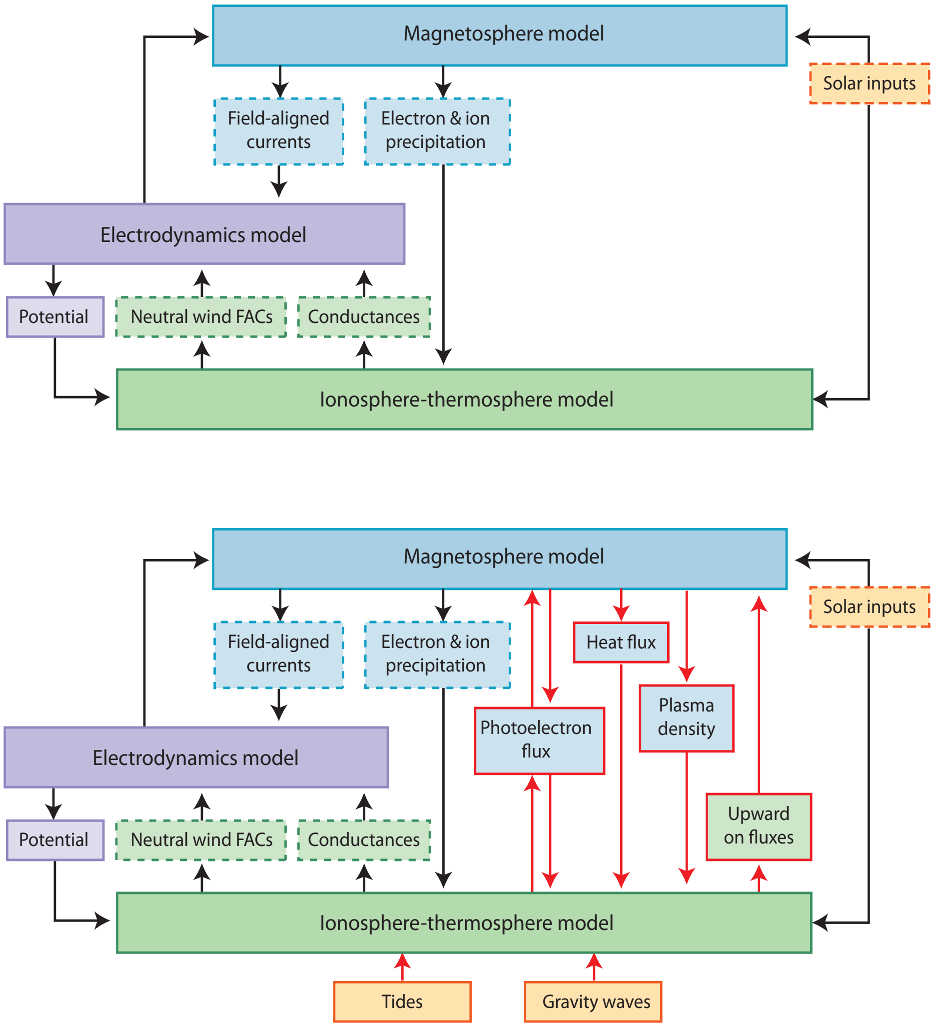


Figure 1. Comparison between what ionospheric and atmospheric models can currently describe (top) and what they should describe (bottom). Red lines show new capability afforded by an Antarctic ISR. Adapted from A. Glocer, (2008) presentation at Chicago meeting.

measured with the correct set of instruments deployed in both hemispheres. Because the necessary instrumental installations do not currently exist, fundamental questions remain. Figure 1 describes what current models are able to describe and the gaps in knowledge that must be filled before models are capable of predicting the response of the coupled atmosphere-magnetosphere-solar wind system to natural and man-made sources.

A sophisticated observatory located at a high southern latitude is essential for continued progress in understanding the Sun's influence on the structure and dynamics of planet Earth's ionosphere and its coupling to the lower atmosphere.

Incoherent scatter radar (ISR) technology has long represented the most effective ground-based monitoring capability in the upper atmosphere and ionosphere, but the logistical challenges in deploying such major infrastructure into the sometimes hostile and challenging environment of the Antarctic continent have made such deployments unimaginable until now.

Recent advances in radar technology, as represented by the Advanced Modular Incoherent Scatter Radar (AMISR) in Poker Flat, Alaska, coupled with wide ranging advantages in the modes and operating procedures of these radars over traditional technologies, as illustrated by the unprecedented data collection undertaken during the International Polar Year (the Poker Flat ISR has been running almost without interruptions since March of 2007), now make it entirely possible to imagine establishing an incoherent scatter radar in Antarctica. Long-term uninterrupted runs, necessary to unravel seasonal and solar cycle trends, will become the norm. Remote operation and low-maintenance, which allow the required measurements to be collected efficiently, are fundamental operational advantages over the previous generations of ISRs.

The reliability and effectiveness of the AMISR-class radars translates directly into reliable data streams of great utility, and to immediate scientific advances, student opportunities and higher degrees. All our experience in scientific measurements and elegant technological solutions comes together in these world-class instruments and the surest and most direct way to dramatically expand their application is to deploy further elements at locations where they can provide entirely new views of the geospace environment. Amongst those, Antarctica is overwhelmingly the most logical choice.

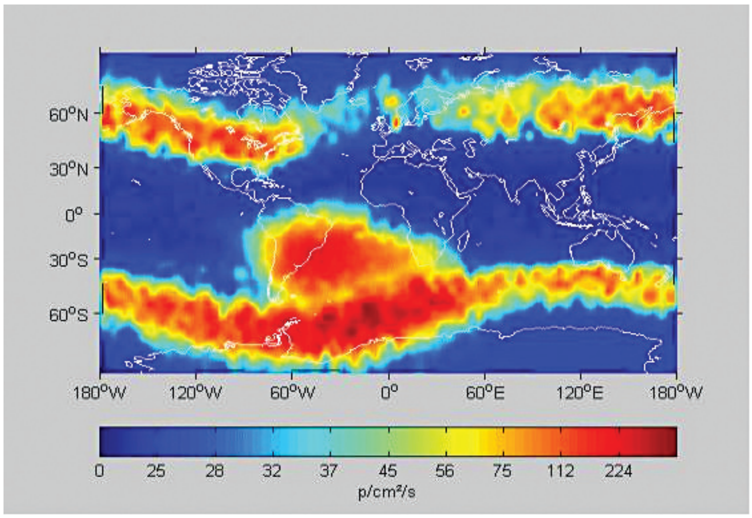
New and exciting science has always followed the introduction of powerful facilities into new areas (such as the move of the Chatanika radar to Greenland and the construction of the EISCAT Svalbard Radar at Longyearbyen) and the implementation of new and improved technology (such as the Poker Flat ISR (PFISR) recently installed close to the old Chatanika site in Alaska). While these developments have each been driven by clearly defined scientific requirements (Kelley 1990, Bjørnå 1991), much of their impact has been in unexpected areas and in fields that were little understood, or unknown, beforehand.

The ever increasing preoccupations with the actual and possible consequences of climate change, even those not of anthropogenic origin, make the project of expanded measurements in the high-latitude southern hemisphere both timely and urgent.

Incoherent scatter radar is the perfect tool to make the detailed measurements required to observe, quantify, and exploit the Antarctic data resource.

The transformational discoveries and insights guaranteed by a sophisticated Antarctic interdisciplinary facility, anchored by an AMISR-class radar and supporting science instruments, make the undertaking not only desirable but essential. Opportunity, requirement, and appropriate technical capabilities come together at this time.

While the utility of a southern high-latitude ISR and related instrumentation



Electron loss to the atmosphere during disturbed conditions showing dramatic differences between the northern and southern hemispheres.

is generally accepted, it is important to identify and evaluate the core issues and create a clear rationale for the project.

Later sections of this document identify the core outstanding science questions and describe how southern hemisphere measurements will address these by quantifying the differences in the state of the southern hemisphere relative to the northern hemisphere, will provide essential boundary conditions to state-of-the-art models, and will establish ground truth to model predictions. An interdisciplinary approach is the key to achieving the transformational gains which will follow from a proper understanding of the missing pieces.

EDUCATION & OUTREACH

Public outreach and the education and training of the next generations of scientists are important elements in the success of any major scientific project, and in the case of the Antarctic ISR, the opportunities and benefits are large. The timely and urgent focus on the Earth's climate and interaction with the Sun and the solar wind should, and will, not only concern today's scientists but also those of future generations and the establishment of a high latitude southern ISR will provide a great opportunity to educate both students and the general public about the complexity of the coupled Sun-Earth system and how processes, often only poorly understood today, affect both the Earth's climate itself and our own space- and ground-based technological infrastructure.

Since the inauguration of the first full AMISR face at Poker Flat at the end of 2006, there has been a real boost in a multitude of disciplines related to ISR technology and research, and the involvement of students at all levels has not only been encouraged, but also been important and productive. Students – from undergraduate summer students to PhD students – have already made extensive contributions and the new mind set of the next generation of young scientists is crucial to the developing field of space sciences, especially following the advances in technology and information systems associated with the new NSF AMISR systems.

During the first two years of the Poker Flat ISR operations, three Ph.D. dissertations have been completed using PFISR data and there are currently 17 further graduate students using the data in their work. There are also seven

Photo: Anja Strømme

During the first two years of operations, 3 Ph.D. dissertations have been completed using PFISR data, and 17 further graduate students are currently using the data in their work.

undergraduate students who have been heavily involved with the data, and five of these students have authored or co-authored five publications.

The international nature of the Antarctic continent encourages a strong international collaboration in establishing and managing an instrument of this scale, as well as its use in both research and education.

Within the first two years 72 researchers from 34 institutions were actively involved with measurements by the PFISR; 28 papers have been published (or accepted for publication) in peer-reviewed journals, including a special issue of the Journal of Atmospheric and Solar-Terrestrial Physics (2009) highlighting the first results from PFISR.

There is a rather stable user base associated with the classical ISRs with broadly constant numbers of students, involved institutions, and publications over many decades ensuring strong momentum on which to build and which will be carried through to an Antarctic incoherent scatter radar.

The AMISR has caused a surge of interest among younger researchers, and an annual AMISR school is co-hosted between the Haystack Observatory and the SRI International staff in order to train them. The first school took place at Haystack Observatory in July 2008 with 20 students from US institutions together with one overseas student; the next, to be held at SRI International in Menlo Park, California, 13-17 July 2009, is already well subscribed. The annual AMISR school is an important addition to a range of sources of education in this field throughout the world. Specific graduate level courses in ISR related disciplines are available at a number of universities in the US, Europe and Japan, and the well established EISCAT summer school is hosted in conjunction with the bi-annual EISCAT workshop. In the coming years we are planning a closer collaboration between the US and European summer school as part of a stronger international collaboration.

As with the current ISRs, data from the Antarctic ISR will be readily available online through community databases (including the CEDAR and the MADRIGAL databases and the virtual observatories which map their metadata) for the benefit of the entire science community.

The international nature of the Antarctic continent also encourages a strong international collaboration in establishing and managing an instrument of this scale as well as its use in both research and education.

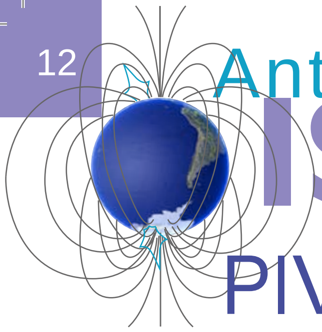
The Antarctic Radar will have high public visibility and will provide images and data likely to capture the interest of the public and particularly of young school children who may well subsequently become tomorrow's innovative scientists.

Photo: A. Strømme

Opposite page and above: Some next-generation ISR researchers at the first AMISR Summer school. Haystack Observatory, July 2008.

Photo: C. Heinselman

The AMISR radar at Poker Flat, Alaska.



PIVOTAL SCIENCE WITH AN Antarctic ISR

Photo: C. Heinselman

Several key questions in upper atmosphere and space physics can only be addressed by a multi-disciplinary program of simultaneous measurements from both hemispheres.

For many years, it has been clear that several key questions in upper atmosphere and space physics can only be addressed by a multi-disciplinary program of simultaneous measurements from both hemispheres, and that the required set of observations could best be secured by a facility centered around an instrument having the capabilities of an advanced ISR. Only now, with the advent of easily reproducible AMISR technology, with a proven track record and designed for unattended remote operation in extreme locations, does the possibility exist to make such an observing program a reality.

The asymmetry and differences between the northern and the southern hemispheres are much more significant than the similarities. The distribution of land masses relative to the oceans are nearly inverted, causing the atmospheric wind patterns to be significantly different. The combined effect of the different wind patterns and the distribution of high land masses causes the gravity wave activity, intensity and frequency – one of the fundamental ionospheric drivers from below - to differ significantly between the hemispheres. Furthermore, at high southern latitudes the continental structure of Antarctica results in a very strong winter polar vortex that isolates the air column above the continent preventing horizontal exchange of air masses. Chemical constituents are constrained to very different production and loss sources due to the much longer scale times resulting in a fundamentally different chemistry from northern polar latitudes. The atmospheric temperatures are steadily lower in the south than the north, which is a result of the differences in land mass and circulation patterns. The air is drier with less water vapor and with less locally produced man-made aerosols.

At high southern latitudes forcing from above also differs significantly from the north. The magnetic field strength is weaker in the high southern latitudes, and hence the high south experiences more intense auroral particle precipitation.

LARGE-SCALE INTER-HEMISPHERIC ASYMMETRY IN MAGNETOSPHERE-IONOSPHERE COUPLING

In recent years there has been an accelerated emphasis on viewing geospace in a multi-disciplinary systems framework. Examples of this include the Space Weather Modeling Framework (SWMF) at the University of Michigan and the Center for Integrated Space Weather Modeling (CISM) at Boston University as well as broad international programs such as International Living With a Star (ILWS). Yet without understanding the different ionospheric responses in the two hemispheres and the resulting differential magnetosphere-ionosphere coupling, a full understanding of the geospace system will continue to elude us. In fact, the influence of the polar asymmetry on magnetospheric processes is not even widely considered in the community models.

The concept of magnetic conjugacy, essentially the idea that identical processes occur at opposite ends of the same field line, is frequently taken as an automatic paradigm in describing the global response to any kind of magnetosphere-ionosphere phenomenon. Although genuine known conjugate observations are rare due to the shortage of observing instruments in Antarctica (and in many cases the need for simultaneous particular conditions, clear skies for optical work for example, in both hemispheres), those observations which do exist show that the true picture is much more complex than the simple-minded conception of a hemispherically symmetric response.

The most obvious reason for not expecting the conjugacy predicted by simple field models is that the Earth's magnetic field is far from being a symmetric dipole. Although every closed field line connects to the atmosphere of both hemispheres, the different effects of electric field, conductivity, magnetic tension and reconnection rate mean that even closed field lines do not necessarily display simple conjugacy. Departures from nominal conjugacy at auroral oval latitudes have been clearly shown in simultaneous data from satellite imagers in either hemisphere, e.g., by Østgaard et al. (2004) and Stubbs et al. (2005), among others. Figure 2, taken from Østgaard et al. (2004), compares an auroral oval image obtained in the southern hemisphere to a predicted oval obtained by mapping the simultaneous northern hemisphere observations with a standard field model. The discrepancies arise from a combination of magnetic field orientation, reconnection rate, conductivity and dipole tilt effects, but the understanding of which factors are most important at any given time requires a substantially larger data set.

The merging of the solar wind magnetic field with the dayside magnetospheric field is the major mechanism by which solar wind energy is transferred to the magnetosphere. However, only a fraction of the available solar wind energy actually enters the magnetosphere. One factor that controls this transfer is the length of the dayside merging region. Simulations have shown that the length of the merging line is controlled by ionospheric conductivity [Fedder and Lyon, (1987)]. But the two hemispheres have different conductivities and it is not clear how the two conductivities interact to establish the length of the merging region or regulate the rate of merging. The high time and spatial resolution of an Antarctic ISR in conjunction with a northern hemisphere ISR will allow for simultaneous studies of dayside merging and the transport of flux across the merging line.

At high latitudes, field lines can be open due to reconnection either on

Without understanding the different ionospheric responses in the two hemispheres and the resulting differential magnetosphere-ionosphere coupling, a full understanding of the geospace system will continue to elude us.

the dayside (for negative IMF Bz) or in the tail lobe (for positive IMF Bz). Field lines opened under these conditions are then convected anti-sunward or initially sunward, respectively, before being re-closed, most usually in the magnetotail. For these high-latitude open field lines, the concept of magnetic conjugacy has no meaning, and the symmetry or asymmetry of their positions and characteristic particle energies depends on factors such as the elapsed time since reconnection and the degree of magnetic tension to which the field lines are subjected. This in turn depends on factors such as the magnetospheric topology and the IMF orientation. Using observations derived from a single hemisphere only, it is impossible to make complete statements about the time history of motion and particle energy dispersion as the two ends of a field line evolve away from a reconnection site. Without inter-hemispheric observations, it is also impossible to distinguish the relative roles of the IMF Bx and By components in determining the location of reconnection regions. The importance of the IMF Bx component in reconnection is still very controversial because of the lack of appropriate observations. On one hand, studies such as Stubbs et al. (2005) have asserted that inter-hemispheric asymmetries in auroral oval size provide evidence of a Bx-dependent effect, adding magnetic flux to the tail lobe of one hemisphere rather than another, while other studies (e.g., Finch et al. 2008) based on the use of proxy indices to study the response of magnetic activity in the two hemispheres to different IMF conditions, find no evidence of a Bx-dependent effect on MI coupling.

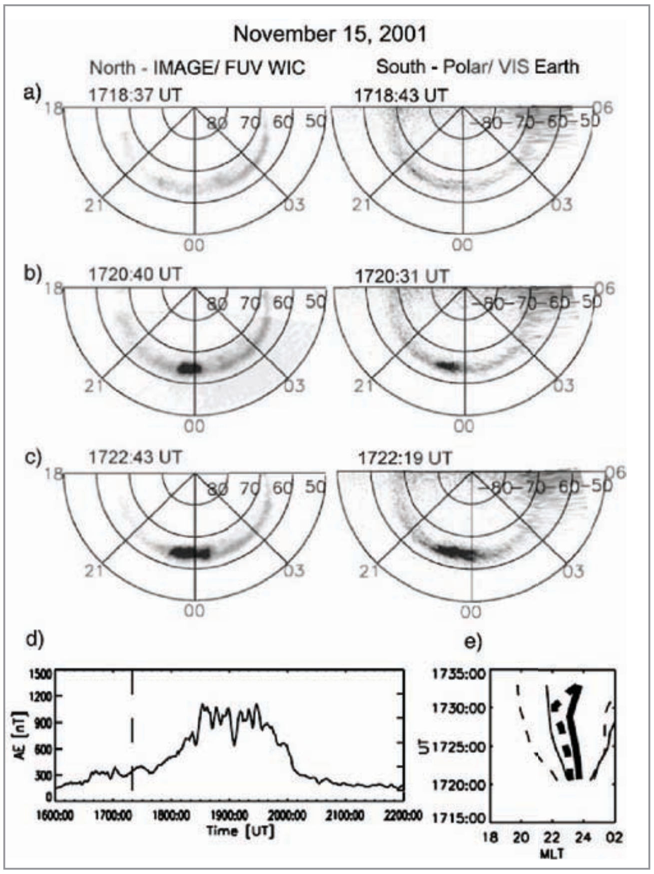


Figure 2. (a)–(c) Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) Wideband Imaging Camera (WIC) images from the Northern Hemisphere and Visible Imaging System (VIS) Earth images from the Southern Hemisphere mapped onto apex magnetic coordinates. (d) The quick-look AE index from Kyoto, Japan. (e) The peak (thick) and the 50% intensity contour (thin) local time location for the substorm onset in the southern (dashed) hemisphere and the northern (solid) hemisphere (Figure 2 from Østgaard et al., 2004).

An ISR is the only instrument that can measure convection, aurora and particle/dynamical boundaries simultaneously.

The role of IMF Bx in modulating reconnection is difficult to deconvolve from other factors such as conductivity and dipole tilt, but understanding which process dominates has profound implications for magnetospheric dynamics. Crooker and Rich (1993) have argued that, under conditions of IMF Bz north, the production of stirring cells by lobe reconnection should be a summer phenomenon only, because the Earth's dipole axis is tilted toward the Sun. On the other hand, authors such as Lockwood and Moen (1999) have argued that if the Bx component is sufficiently large, the resultant magnetic geometry can allow reconnection in either hemisphere, independent of the dipole tilt. Østgaard et al. (2003) found clear examples of non-conjugate theta aurora in the northern and southern hemispheres under IMF Bz north conditions, though the data did not necessarily imply that reconnection was ongoing in one hemisphere only.

Conductivity effects also need to be considered, and it is likely that auroral structures in the sunlit hemisphere can be suppressed because solar-produced ionization helps to supply the necessary current carriers. Distinguishing the relative roles of dipole tilt, conductivity and Bx will be one of the key benefits of a comprehensive program of simultaneous inter-hemispheric ISR observations.

Satellite-borne imagers and field/particle instruments can contribute to the resolution of this debate, supported by ground-based instruments such as coherent scatter radars, optical images and magnetometers. However, an ISR is the only instrument that can measure convection, aurora and particle/dynamical boundaries simultaneously, independently of conditions and without any temporal/spatial ambiguities. The simultaneous measurements of density (particle energy), temperature (electron energy dissipation and ion heating) and flow (elucidating reconnection dynamics and magnetic tension) make an ISR an essential addition to the array of southern hemisphere instruments, allowing systematic studies of a kind which have not so far been possible. ◊

DIFFERENCES IN INTER-HEMISPHERIC POTENTIAL

Global MHD models are the building blocks of all general circulation models in the Earth's magnetosphere-ionosphere system. Simultaneous north-south measurements will have great impact on improving global models by facilitating direct tests of specific models' predictions of north-south asymmetries.

For instance, during solstice conditions there is a strong asymmetry between the winter and summer ionospheric conductivities. This causes a feedback to the magnetosphere, in which the field-aligned currents are increased in the summer hemisphere and decreased in the winter hemisphere. However, even with this compensation there is still a statistical inter-hemispheric difference in the ionospheric potential, where the winter potential is typically larger than the summer potential. In global models of the magnetosphere, the same trends are observed, but the inter-hemispheric differences are much larger. Thus a detailed investigation of the impact of the polar asymmetry is likely to have a profound and transformational impact on the understanding of the geospace system as a whole.

Global MHD models are used to measure the role of bow shock dynamics

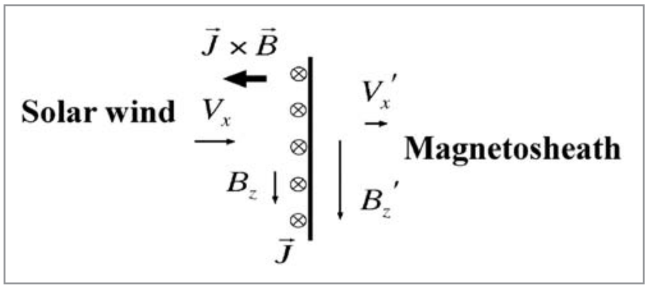


Figure 3. Compression of the solar wind across the subsolar bow shock (solid vertical line) and the resulting bow shock current and the JxB force exerted on the solar wind.

in governing polar cap potential saturation, the phenomenon in which the electric potential imprinted on the Earth's ionosphere grows in direct relationship to the solar wind input only to a certain threshold. As the solar wind magnetic field increases, the magnetic shear across the bow shock increases and the ratio of magnetic pressure to plasma pressure in the magnetosheath also increases. When that ratio becomes large, magnetic forces dominate the magnetosheath flow and control the rate of dayside merging by controlling the flow, and hence the electric field, at the magnetopause. The large magnetic shear at the shock means that there is a large electric current flowing across the shock, as shown in Figure 3 for southward IMF.

This current must close somewhere and Siscoe et al. (2002) concluded from tracing current streamlines that the bow shock current closes through the ionosphere as Region 1 current. Simulation results from the Lyon-Fedder-Mobarry code support this view, as illustrated in Figure 4. Across the entire volume of the sheath the magnetic shear indicates that current must be flowing towards Earth through the sheath in the dawnside polar caps and away from the Earth in the duskside

Even after compensating for known factors, there is still a statistical interhemispheric difference in the ionospheric potential.

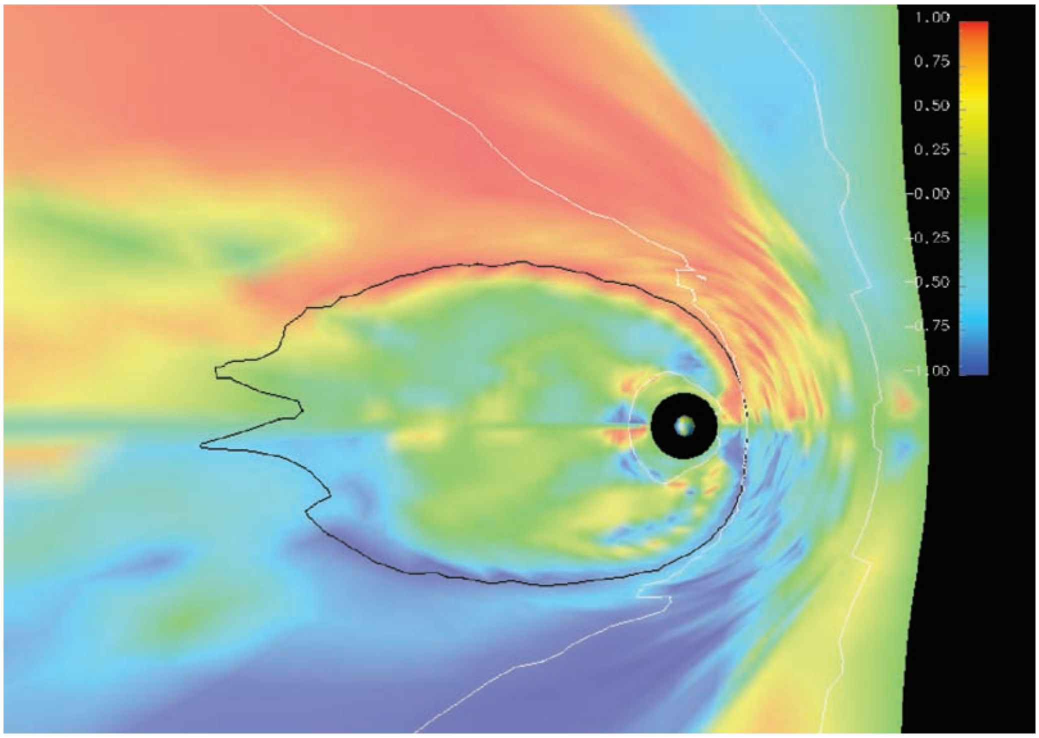


Figure 4. Direction of magnetic shear (or current) in the equatorial plane with the solar wind parameters Bz=-20 nT, V=400 km/s and n=5/cc . The black line is the Bz =0 contour and the white lines are contours of n=5/cc. The shear points toward the Earth for negative (blue) values and it points away for positive (red) values. (From R. Lopez presentation at Chicago meeting.)

polar caps (for southward IMF). The existence of these currents on open field lines was recently verified using DMSP observations (Lopez et al. 2008).

Observations of inter-hemispheric auroral asymmetry are fundamental diagnostics of magnetospheric asymmetries, since auroral activity images large regions of the magnetosphere into much smaller areas of the ionosphere.

It is important to note in Figure 4 that $\vec{J} \bullet \vec{E} < 0$ across the shock, thus the shock is a dynamo converting solar wind mechanical energy into electric energy. The closing of the bow shock current represents a third source of potential together with reconnection and viscous processes. This point was made by Siebert and Siscoe (2002), who identified the bow shock current as the dynamo that powers reconnection at the magnetopause. Thus the current flowing into the polar cap can directly deposit solar wind energy into the ionosphere, drive ionospheric convection, and produce a potential asymmetry between the hemispheres. The majority of the force from the solar wind can be exerted at the bow shock for low Mach number. The current at the bow shock opposing the solar wind must close somewhere. It may close at the boundary between the solar wind and the Earth's magnetic field, producing a system of electric currents with specific polarity.

The current in the shock is a generator. The associated currents have been measured in the polar cap and MHD models predict that the sunward hemisphere closes more field-aligned currents but develops lower potential than the dark hemisphere (Lopez et al. 2008). MHD models also predict that the convection reversal boundary should occur further poleward of the open-closed field line boundary in the winter hemisphere than in the summer hemisphere. It is proposed that this happens because the summer hemisphere can support higher field-aligned currents due to its greater density of charge carriers.

This gives the summer hemisphere a lower potential relative to the winter hemisphere, when the bow shock current is closed via the ionospheric load. All these predictions could be directly tested with simultaneous north-south measurements that involve conductivity, convection and field-aligned currents under conditions of low Mach number solar wind, when the bow shock current dominates the force balance with the solar wind flow. This requires latitudinal measurements of the convection pattern in each hemisphere, ideally supported by comparative measurements of the conjugate field-aligned currents and conductances. Only a pair of nominally conjugate ISR facilities is capable of delivering the detailed simultaneous observations necessary to achieve this confirmation. ◊

INTER-HEMISPHERIC ASYMMETRY AT INTERMEDIATE AND SMALL SCALES

The interchange of mass, momentum and energy within the atmosphere-magnetosphere-solar wind system occurs at various scales. In addition to the large-scale differences discussed above, there is considerable observational evidence that auroral conjugacy also breaks down on small- and meso-scales (100 m–10 km and 10 km–100 km in the ionosphere, respectively) which map to scales between the ion gyroradius in the magnetosphere and the thickness of magnetosphere boundary layers. For example, Sato et al. (1998) observed substorm onset signatures in which very dynamic auroral breakups occurred in one hemisphere, while the aurora in the other hemisphere remained quiescent, as shown in Figure 5. Sato et al. (1998) showed that, while large-scale structures can be accurately reproduced in nominally conjugate observations of optical aurora, small-scale auroral features can be very different. In one case, they found that the apparent southern hemisphere conjugate point of an auroral arc seen in the north moved by 200 km in latitude and 50 km in longitude in one hour. Also, one example of non-conjugate aurora can be seen in Figure 7.

The comparison between the motion of auroral arcs and the background plasma convection has profound consequences for understanding the origin of aurora and the electromagnetic coupling between the ionosphere and the magnetosphere. If arcs are an optical manifestation of the release of magnetic tension, then there should be a relative motion between the arc and the background plasma, which Haerendel et al. (1996) have termed as “proper motion.” If this proper motion is large, it indicates a decoupling between the atmosphere and magnetosphere, but if this motion is small or non-existent, then the aurora is better understood as a microphysical response rather than a breakdown in the current flow along equipotentials. There are examples that demonstrate reasonable conjugacy of meso-scale features but serious discrepancy on small scales (<1 km, curls, multi-arc systems). If the observed motions of optical forms are entrained in the ExB flow, this would suggest that aurora are a microphysical response and not indicative of a breakdown of current flow along equipotentials. However, large proper motion would indicate decoupling between the ionosphere and magnetosphere.

There is considerable observational evidence that auroral conjugacy breaks down on small- and meso-scales in the ionosphere.

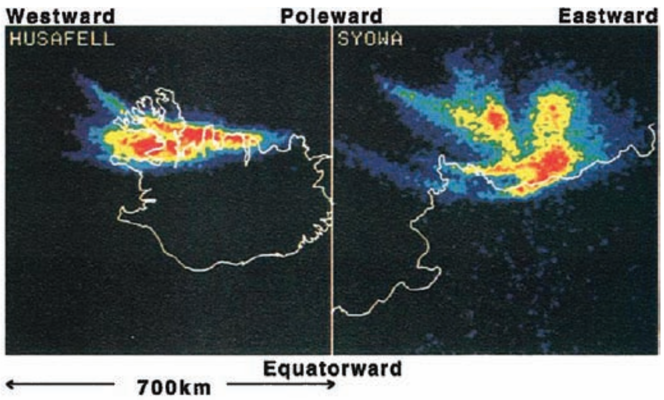


Figure 5. An example of non-conjugate aurora where an auroral breakup is observed in the southern hemisphere (Showa) and no breakup is apparent in the northern hemisphere (Husafell) (Plate 1c from Sato et al., 1998).

Systematic studies of auroral proper motion based on simultaneous observations from both hemispheres have not been possible up to now, and hence several important questions are unresolved, such as

1. Whether the proper motion is different in different hemispheres, and
2. The nature of the connections (if any) between auroral proper motion, arc brightness and energy flux.

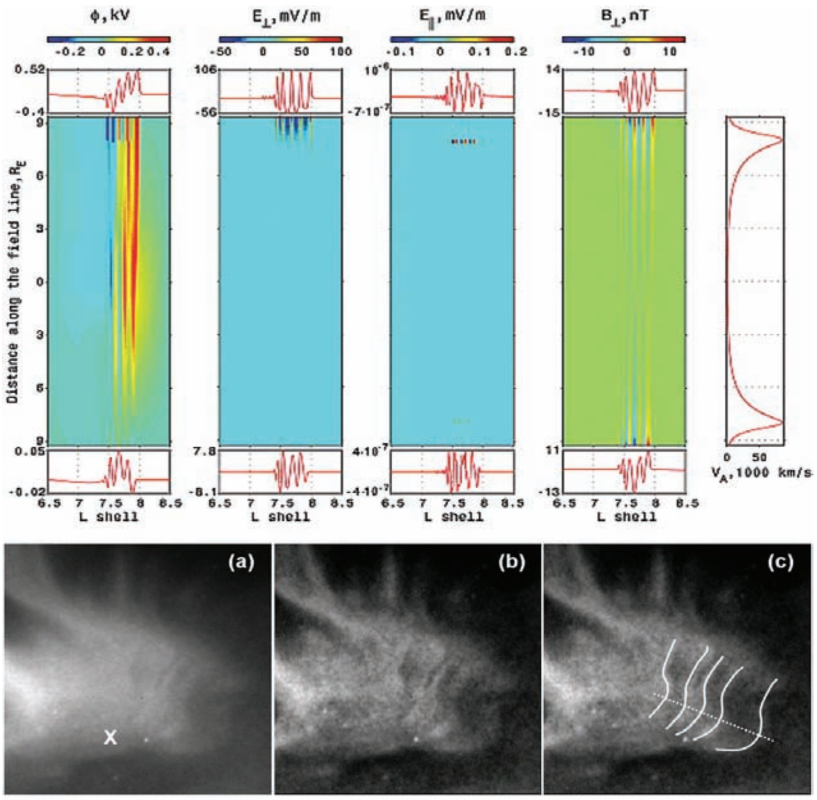


Figure 6. (Top) Field-aligned potential drop between winter and summer ionosphere versus inter-hemispheric distance and magnetic latitude (Figure 1 from Pokhotelov et al., 2002). (Bottom) (a) Example raw image, corresponding to a snapshot of a multiple arc system that evolved through Alfvén wave dispersion. (b) Image after adaptive histogram equalization. (c) Same as (b), but annotated to highlight faint periodic structures (Figure 1 from Semeter and Blixt, 2006).

Observations of inter-hemispheric auroral asymmetry are fundamental diagnostics of magnetospheric asymmetries, since auroral activity images large regions of the magnetosphere into much smaller areas of the ionosphere. This means that apparently small-scale breakdowns in ionospheric conjugacy can represent substantial asymmetries in the magnetosphere. A statistical investigation of the ionospheric footprint of the field lines where processes first begin in each hemisphere can provide major clues to their magnetospheric location, helping for example, to distinguish whether substorm signatures first appear on near-Earth or down-tail field lines. Simultaneous inter-hemispheric ionospheric observations thus have the potential to provide important information for magnetospheric physics, and ISRs are in many ways more appropriate to make such comparisons than optics alone.

There are two reasons for this. First, inter-hemispheric optical comparisons are possible for just a few months in each year around the equinoxes. Secondly, the optical signature of substorm initiation, the auroral breakup, is observed when the substorm is already in the nonlinear phase of M-I coupling. ISRs can observe the precursors to the optical aurora by observing Poynting flux. Indeed, the first response of the magnetosphere is an enhancement in Earthward Poynting flux. This would produce a localized increase in ionospheric electric field and, hence, ion temperature and ion convection velocity. Simultaneous ISR-THEMIS measurements will determine if these observations are the telltale ionospheric signatures of reconnection in the plasma sheet. These responses are invisible to optics. Also invisible to optics, but measurable with ISRs, is the ionospheric conductance. Measurements of inter-hemispheric differences in ionosphere conductance and convection are required to test predicted intensification, drift motion and fading of arcs which are a consequence of finite Alfvén wave propagation between the magnetosphere and the ionosphere and between the northern and southern ionosphere. Alfvén waves are the principal vehicle for communicating stress between the ionosphere and the magnetosphere. Figure 6 shows an example of models' predictions of inter-hemispheric phase shift in electromagnetic field and magnetic field-aligned potential. Combined ISR-optics measurements can test the scale size of the systems of multiple discrete arcs that are predicted by Alfvén wave instability models. The bottom panel of Figure 6 shows an example of high-speed optical measurements that can be used to resolve the small-scale structure of arcs and rapid arc breakup concomitant with Alfvén wave dispersion.

Departures from symmetry between the two hemispheres occur not only due to magnetospheric effects, but can also arise because of differences in the ionospheres at the two ends of the field line. For example, the possibility for different amounts of solar-produced ionization to carry currents can suppress aurora in one hemisphere relative to the other. Such non-conjugacy can also be a reflection of differences in the acceleration or scattering geometry of precipitating particles. Once again, only a pair of ISRs would allow inter-hemispheric differences between auroras to be measured in terms of multiple parameters such as particle energy and associated electric field, as well as the correct interpretation of the differences in terms of their relationship to the background ionosphere, to determine whether such differences arise from ionospheric or magnetospheric factors. ◊

PLASMA SOURCES FOR THE MAGNETOSPHERE

The coupling between the ionosphere, the magnetosphere and the solar wind does not occur only electrodynamically. The ionosphere also makes a substantial contribution to the mass content of the magnetosphere through the supply of ionospheric plasma, particularly heavy ions, by various extraction mechanisms. Ion outflow, as the process of extraction has been termed, has a variety of causes including thermal expansion of the upper atmosphere, enhanced ambipolar diffusion and wave-particle interactions.

Although it has been measured by radars, rockets and satellites, most ion outflow observations have been carried out in the northern hemisphere, and there are few, if any, conjugate observations of outflow events. The same measurements have shown that the mass loading can be of such magnitude as to be capable of modifying the growth rate and threshold of instabilities in the magnetosphere, of changing the location and magnitude of the acceleration of relativistic electrons in the radiation belts, or hindering reconnection in the dayside and/or nightside magnetosphere.

There are few, if any, conjugate observations of ion outflow events.

Some of the most striking observations of ion outflow have been made during periods of high magnetic activity, in which a sub-auroral polarization stream causes Storm-Enhanced Densities (SED) to be transported from the auroral zones through the cusp as so-called "tongues of ionization" (TOIs) as shown in Figure 8. Recent observations using both ground and space-based thermal plasma imaging techniques have revealed such an ionospheric SED event to be the low altitude signature of the plasmaspheric drainage plume that resulted from the erosion of the polar boundary layer (Foster et al. 2005). Large ionospheric density enhancements subsequently become entrained in the cross-polar cap convection as tongues of ionization, and cross the polar cap to emerge into the return flow region of the midnight sector. Throughout its transit through the cusp, polar cap and nightside auroral regions, cold plasma can be accelerated by outflow processes to be injected into the plasma sheet and ring current. This storm-time redistribution of ionospheric material has mainly been observed in the northern hemisphere, although there are sufficient observations (e.g., from GPS techniques that measure total electron

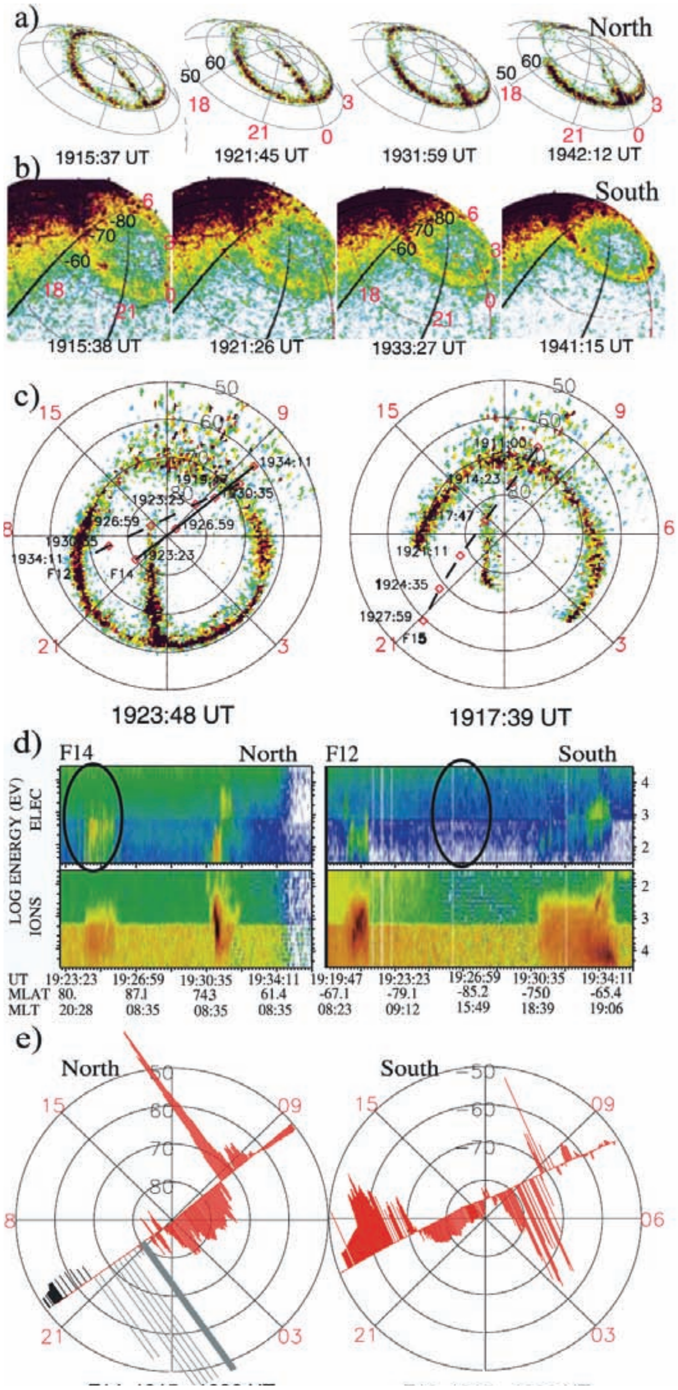


Figure 7. November 5, 2001. (a) SI13 images from the NH. (b) VIS Earth images from the SH. (c) Trajectories of DMSP passes (solid: NH, dashed: SH) mapped onto simultaneous SI13 images from the NH. (d) Spectrograms from DMSP, electrons and ions, where the ovals signify the expected location of the theta auroral precipitation (if any). (e) Cross track plasma drift data from DMSP. Grey color indicate data where the amplitude is not correct. All images are presented in apex magnetic coordinates (Østgaard et at. 2003).

content in the ionosphere) to confirm that it also occurs in the southern polar regions. However, there has been no systematic attempt to investigate the conjugate nature of this phenomenon and how this depends on factors such as IMF orientation, season, conductance and dipole tilt. It is known that the most intense SED plumes are observed in the American longitude sector, making the study of its conjugate signatures particularly interesting because of the presence of the South Atlantic Anomaly in this sector.

Despite the importance of the problem and three decades of research, the development of models to describe ion outflow from first principles has been slow. One of the main reasons is that outflow operates over a vast range of altitudes, from the F region in the ionosphere to several thousand kilometers in the magnetosphere, and over all scale lengths, from small to large scale. Furthermore, the processes that push the ions upward are different at different altitudes. Therefore the adequate description of outflow requires simultaneous measurements of multiple parameters at various altitudes. A complete set of measurements requires a facility with the array of instruments that can measure the initial stage of the extraction process at different scale sizes and spatial coverage. The combination of ground-based measurements and space-borne remote sensing of the outflow region provides the best approach for achieving the necessary space-time coverage.

Global MHD models are in a state of development where ion outflow is introduced by ad-hoc methods that include pressure gradient effects or empirical relationships between Poynting flux and ion outflow. Description of ion outflows from first principles is in an early stage. As models progress, it will be of critical importance to have the right measurements to test the models' predictions of ion outflows as they are traced from their source into

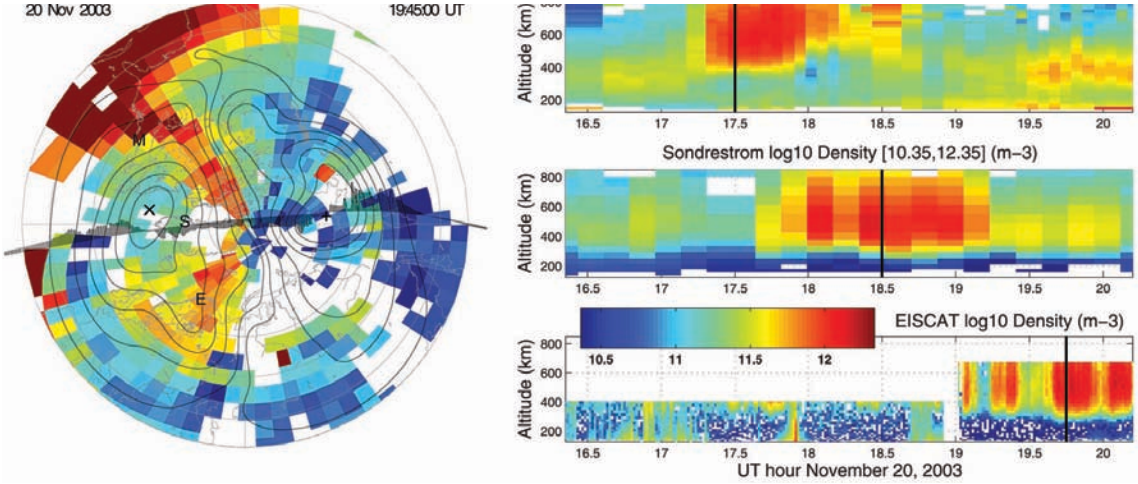


Figure 8. (Left) Polar projection of a TEC plume during a geomagnetic storm. The SED/TOI plume is seen to extend continuously from its low-latitude source in the prenoon sector, through the dayside cusp and across the polar cap to the midnight sector over the EISCAT facility (E). (Right) Vertical profiles of F region plasma density above the three high-latitude ISR facilities. Vertical black lines indicate times when the SED/TOI plume was sampled by each vertical radar beam. Millstone Hill observations at 1730 UT sampled the SED as it entered the dayside cusp. Sondrestrom (1830 UT) observed the TOI in the central polar cap. EISCAT Tromso observed the TOI (1945 UT) as it exited the polar cap near midnight. (Left panel is Figure 6 and right panel is Figure 7 taken from Foster et al., 2005.)

the magnetosphere. Convection has significant impact in creating Joule heating and moving outflows across field lines. If polar cap convection is asymmetric, then the impact of outflow drivers will be different in each hemisphere, thus affecting the rate of mass loading of the magnetosphere. Conductivity in the ionosphere also regulates the rate of outflow through its influence on the propagation of Alfvén waves that accelerate ions. Simultaneous measurements of convection, conductivity and outflow (all measured by ISRs) in each hemisphere will provide the appropriate observational test of model predictions of auroral arc intensification, drift motion and fading that are a consequence of the finite Alfvén wave propagation between the two hemispheres. ◊

INTER-HEMISPHERIC ASYMMETRY IN THE MESOSPHERE AND THERMOSPHERE

The mesosphere is the region between the stratosphere and the thermosphere, and is often referred to as the boundary between Earth's atmosphere and space. The upper mesosphere is a very important boundary region within which lower atmospheric and ionospheric processes compete. Unraveling the competing processes is particularly challenging at high latitudes where the ionospheric drivers are strongly influenced by magnetospheric inputs. The polar mesosphere is therefore a multi-dimensional boundary layer with neutral air gravity waves, planetary waves, and tides forcing it from below, and ionospheric plasma processes and particle precipitation driving it from above. The northern and southern upper mesospheres are dynamically connected through a longitudinal summer-to-winter flow driven by gravity wave forcing. Mass conservation causes the air to rise at the summer pole with the associated adiabatic cooling driving the summer mesopause down to below 130°, making it the coldest place in the Earth's vicinity. Noctilucent clouds and Polar Mesospheric Summer Echoes (PMSEs)—strong radar backscatter at HF, VHF, and even UHF frequencies—in the ~82–85 km altitude summer mesopause are manifestations of the complex coupling processes taking place in this region, although the causes of noctilucent clouds and PMSE are far from being understood. An example of NLC/PMSE measurements from Poker Flat can be seen in Figure 9.

PMSE occurrence and intensity are believed to depend strongly on factors such as temperatures at ~87 km, the existence of available water vapor in the mesopause region for ice formation, the density and size of aerosols acting as nucleation kernels, gravity wave activity acting as a mesopause refrigerator pump, and charged particle precipitation charging the ice crystals. PMSE intensity and occurrence are hence also North-South asymmetric. Although ISRs do not measure temperatures in the *D* region (there is a relationship between temperature and the width of the ISR-measured spectra but the ion composition at those altitudes is not well determined), ISRs do measure atmospheric winds, tidal modes and long-period waves. These waves are important in driving circulation that in turn influences atmospheric temperature. ISRs can also measure the size of the aerosol particles.

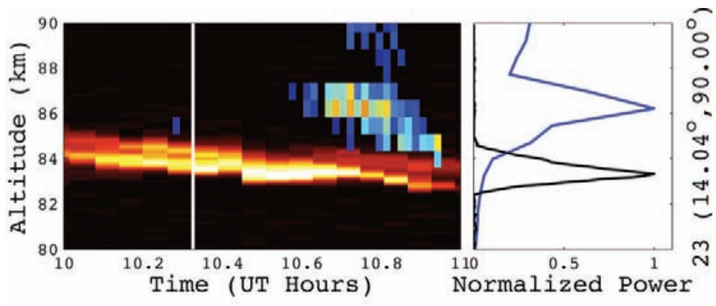


Figure 9. PMSE layer above lidar NLC layer (Taylor et al., JASTP, 2009).

Simultaneous observations of the polar mesosphere and thermosphere at similar latitudes in both hemispheres will enable new understanding of the fundamental coupling between the neutral and the charged parts of the atmosphere. Long time series can reveal differences in trends in the Earth's climate. Over the last two decades, signs of global changes have been seen over the entire planet, and the changes have been most noticeable in the polar regions. Near the Earth's surface some of the changes rrepresent global warming. However, "greenhouse cooling" is expected in response to increasing amounts of radiatively active gases, mainly carbon dioxide, in the middle (stratosphere and mesosphere) and upper (thermosphere) atmosphere (e.g., Roble and Dickinson, 1989; Akmaev and Fomichev, 2000; Bremer and Berger, 2002; Akmaev, 2002, 2003; Akmaev et al., 2006).

Compositional redistributions in the upper atmosphere also are expected in association with changes in the temperature profile. Since radiative greenhouse cooling extends well into the thermosphere as in the case of CO_2 radiation (Akmaev et al., 2006), density reduction is expected to be a monotonically increasing function of height. Satellite drag measurements (Keating et al., 2000; Emmert et al., 2004; Marcos et al., 2005) show the density reduction trend, although with a ~50% smaller magnitude. Long-term series from ISR facilities in both hemispheres are needed to measure the wind circulation patterns that connect the northern and southern thermospheres and to measure the impact of the reduction in temperature and density in the polar upper atmosphere. Among the multiple long-term effects of the reduction is the impact that a depleted reservoir of oxygen may have on the population of the magnetosphere and the processes that have been mentioned in the previous section. ◊

NEUTRAL DYNAMICS

There are a number of unresolved neutral atmosphere scientific topics to be addressed at high southern latitudes. These could be addressed well with an ISR in Antarctica given the capabilities already demonstrated with PFISR. Some of these are strictly issues of neutral dynamics, and several involve neutral-ionosphere interactions. Among these are

- Gravity wave/mountain wave penetration and energy transport at a site having maximum response and offering an ideal laboratory for such studies;
- Large-scale dynamics (tides, planetary waves, and mean motions), and their inter-hemispheric comparisons;
- Gravity wave interactions with the mean and tidal structures.

The Drake Passage/Antarctic Peninsula is one of the most active regions on the planet in terms of neutral dynamics. Figures 10 and 11 illustrate the large gravity wave momentum fluxes and potential energy variances inferred from satellite measurements in the stratosphere suggesting this is a strong source region.

The highly dynamic activity over this region is probably a result of extremely active sources of various waves at lower altitudes. These include:

- Very large mountain waves arising from the southern Andes and the Antarctic Peninsula;
- Apparently very strong gravity waves arising from jet stream sources; and
- Large semidiurnal tidal responses at these latitudes in the MLT.

Figure 12 shows evidence of the large mountain waves that must contribute to these enhanced variances over the southern Andes and the Antarctic Peninsula. These mountain waves, and the more general gravity waves contributing variances at lower altitudes over the Drake Passage, will clearly have significant responses in the MLTI. Figure 13

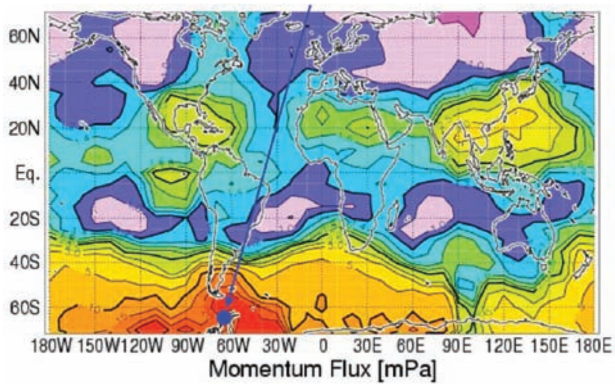


Figure 10. Estimates of GW momentum flux magnitudes at 25 km altitude by the CRISTA satellite suggesting that the southern Andes and AP region is the most active on Earth at small GW scales (Ern et al. 2004). Shown as the blue dot is Palmer Station, which is almost directly conjugate to the Millstone Hill ISR. Palmer Station is a well-provisioned, year-round U.S. base with easy sea access.

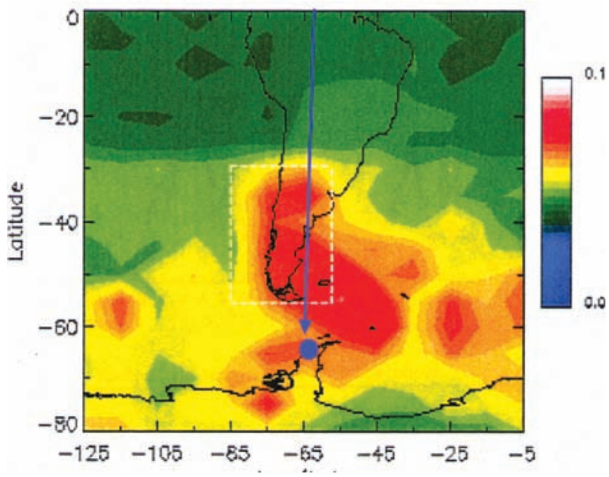


Figure 11. GW brightness temperature variance (K2) estimates averaged from 30 to 55 km from MLS limb radiance measurements (Jiang et al. 2002, Wu and Jiang 2002).

shows semidiurnal tidal structures observed between 75 and 100 km with the SAAMER meteor radar at 54°S on Tierra del Fuego, Argentina. These structures are likewise significantly larger than expected from tidal modelling with the GSWM. These waves are expected to result in dramatic neutral and ionospheric responses to which AMISR has already demonstrated sensitivity at Poker Flat, Alaska.

PFISR has the ability to make routine measurements of the dynamics of the neutral atmosphere extending as low as 60 km, yielding data that cannot be obtained routinely with any other instrument (i.e., Janches et al., 2009). Examples of the Doppler velocity spectra obtained with a 4-beam PFISR configuration are shown in Figure 14. The winds inferred from these spectra are shown in Figure 15 and exhibit both gravity waves and tidal structures; such structures are expected to be even larger at southern locations where the source regions are much stronger. ◊

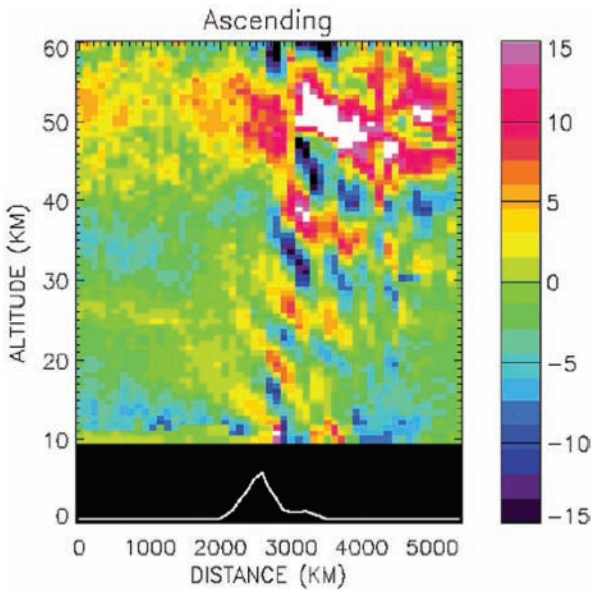


Figure 12. Temperature perturbations (K) measured by HIRDLS suggesting a large-amplitude MW arising due to flow over the SA (Alexander et al., 2008).

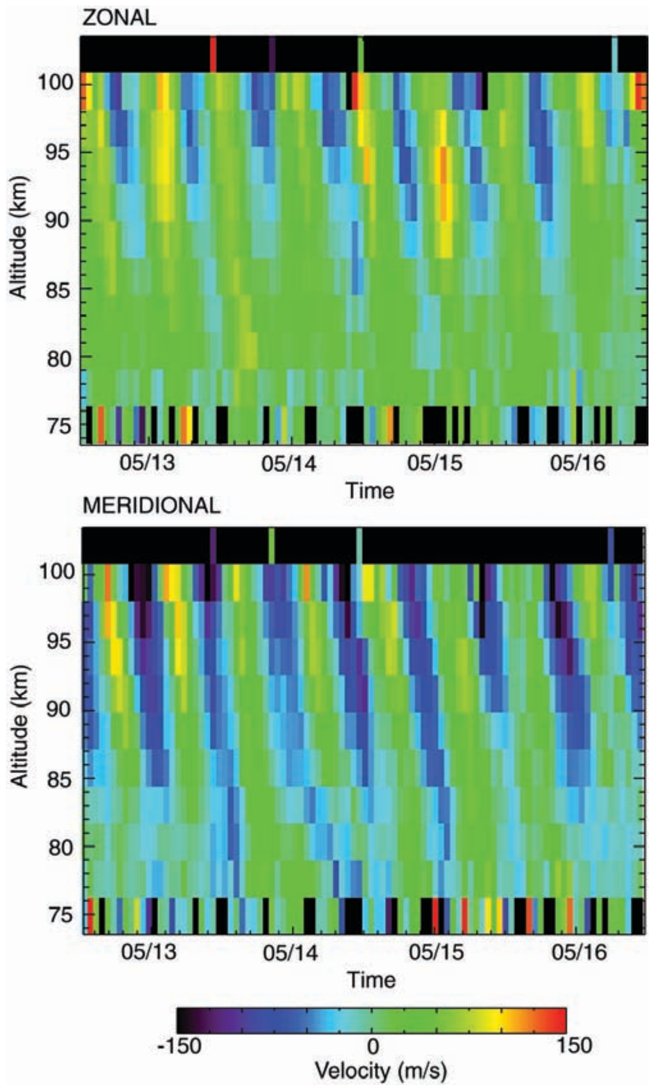


Figure 13. Semidiurnal zonal and meridional tidal winds (upper and lower) observed with SAAMER on Tierra del Fuego at 54oS. Note that amplitudes at the higher altitudes are typically 50 to 100 m/s. Courtesy of D. Fritts and D. Janches..

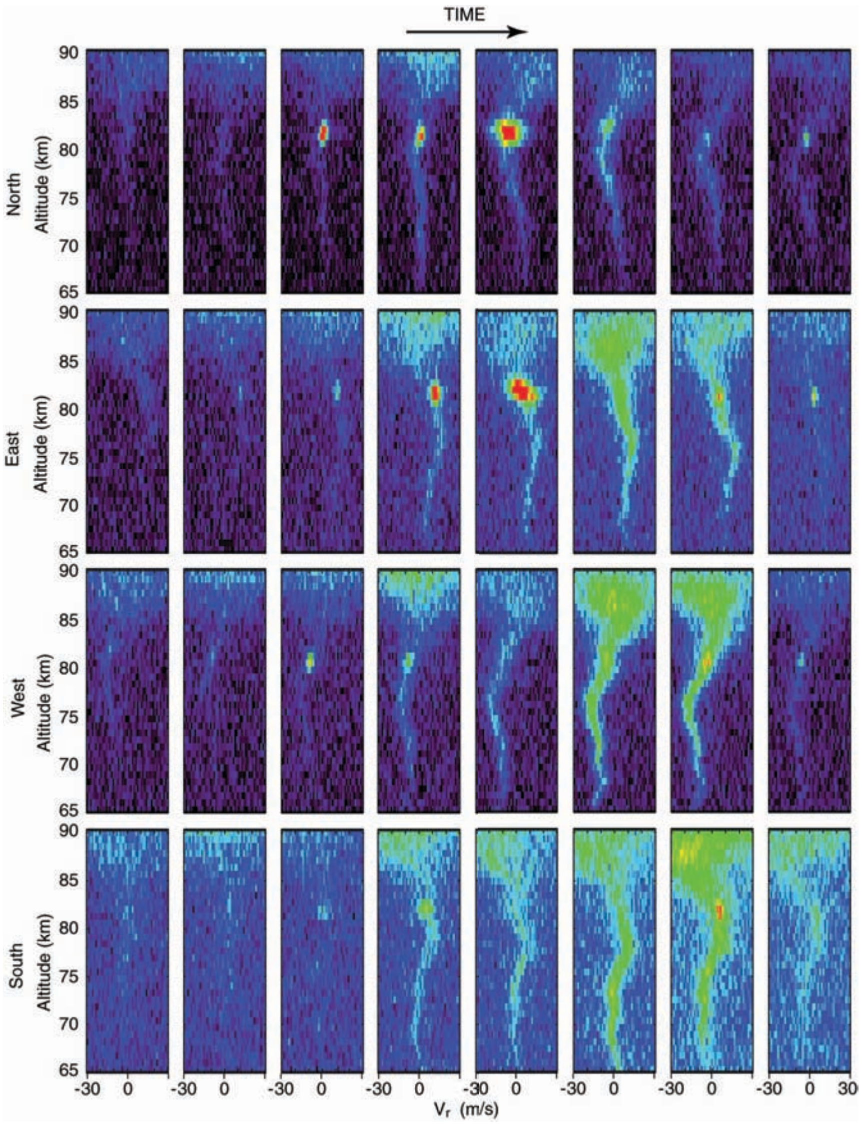


Figure 14. Hourly spectra for three beams with PFISR during normal auroral conditions in summer. Note the PMSE signatures at ~85 km at various times. Note especially that the spectra typically yield velocities as low as 60 km. (Janches et al., 2009)

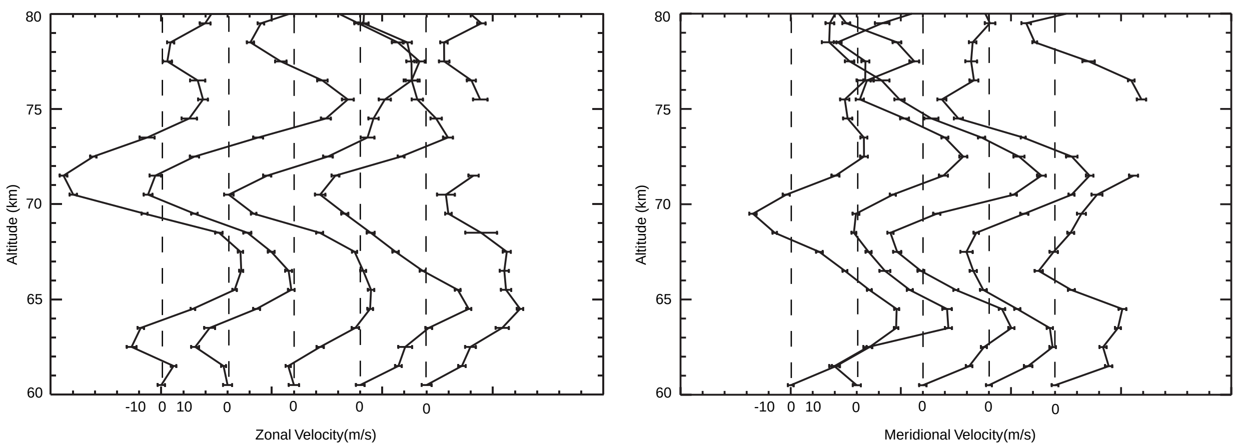
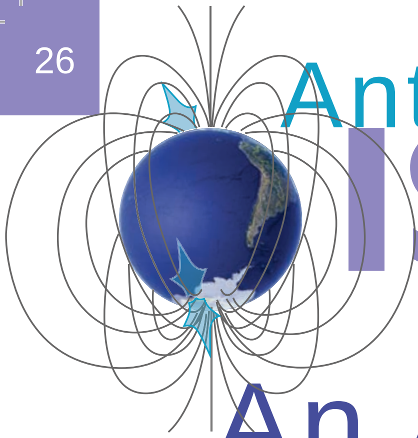


Figure 15. Zonal and meridional winds obtained from the spectra in Figure 14. These demonstrate the unique capabilities of AMISR for neutral studies at these altitudes.



Antarctic ISR

An Antarctic Facility

Photo by Arne Oddvar Bergdal

Modern ISR design allows realistic consideration of deployments to previously impractical locations

As discussed in the previous section, there are science reasons of overwhelming importance for establishing an observatory of ISR quality at high southern latitudes. The ability to make extended, semi-continuous, high resolution observations and inputs to global models of the upper atmosphere and ionosphere should be leveraged. The upper atmosphere and space science communities are in great need of the information that an ISR in the high south can provide. After a general description of ISRs, and the AMISR in particular, the following sections address some of the site considerations.

The Incoherent Scatter Technique

The use of incoherent scatter radars as a powerful ground based diagnostic tool for studying the near-Earth space environment began with the first theoretical predictions by Gordon (1958) and the first observations by Bowles (1958) a few months later. An overview and updated description of the theory, instrument and signal processing can be found in Farley (1996).

The term Incoherent Scatter (IS) from an ionized gas refers to the extremely weak scatter from fluctuations in plasma density caused by the random thermal motion of the ions and electrons. When the radar frequency, ω_{radar}, is much higher than the plasma frequency, ω_p, the radar wave travels almost unperturbed through the very diluted ionospheric plasma, but a small fraction of the wave energy is deposited into the acceleration of the electrons, which re-radiate back as small dipoles.

Due to the very low radar scattering cross section of an individual electron, only about 10^{-28} m^2, the total cross section of all the electrons in 10 km^3—a typical volume probed in an IS experiment—of the ionosphere with a maximum electron density of the order of 10^{12} m^{-3}, is only about 10^6 m^2. To detect signals from this weak source, we need a radar capable of detecting a coin at 300 km distance!

Incoherent scatter radars therefore consist of large aperture antennas, powerful transmitters, and sensitive and sophisticated receiver systems. In addition to measuring the signal and its power, ISRs also measure the full Doppler power spectrum or equivalently, the auto-correlation function (ACF) of the back-scattered signal.

The scattered signal contains information about the profiles (in altitude, latitude and longitude) of plasma density, electron and ion temperatures, ion composition, bulk plasma motion, and various other parameters and properties of the observed plasma at altitudes ~60–1000 km.

Utilizing modern technology

Modern ISR design allows realistic consideration of deployments to previously impractical locations. The National Science Foundation's AMISR, and the proposed new EISCAT 3D system currently being designed in Europe, take advantage of phased array antennas and new technologies, including distributed solid state transmitters, which have moved ISRs into a new era where it becomes feasible, for the first time, to construct and operate ISRs at truly remote locations - such as the northern polar cap and the Antarctic continent. The construction and successful first years of operation of the AMISR at Poker Flat, Alaska, provides a graphic demonstration of the technical progress of ISR technology, the overall health of the field of space and upper atmosphere research as a multi-disciplinary endeavor, and the relative ease with which such facilities can now be established and operated remotely. In order to make a transformational contribution to the understanding of the energy and momentum transfer budget in the Sun-Earth system, a permanent deployment of an ISR in the high southern hemisphere will be a key element. ISRs have the ability to provide continuous and uninterrupted altitude profiles and local 3D maps of the key parameters through the varying ionospheric regions, from the complex and strongly neutral driven mesosphere up to the much more dilute and magnetospherically driven upper thermosphere and ionosphere. This makes incoherent scatter radar the most powerful ground based instrument for upper atmosphere and ionosphere research.

In Poker Flat, Alaska , the first full realization of AMISR, the Poker Flat Incoherent Scatter Radar (PFISR) finished engineering tests in December 2006, became available for use by the community, and began operations for specific user-requested measurements. The PFISR supported six rocket campaigns during the winters of 2007 and 2009. Additionally, PFISR has been operating in a low-duty cycle mode whenever not running other experiments. This 24/7 coverage that began in support of the International Polar Years (2007–2008) continues and has provided a wealth of data to the modelling community.

Within the first two years: 72 researchers from 34 institutions were actively involved with measurements of the PFISR, 28 papers have been published (or accepted for publication) in peer-reviewed journals, including a special issue of the *Journal of Atmospheric and Solar-Terrestrial Physics* (2009) highlighting the first results from PFISR. We see the establishment of an Antarctic ISR as a way to carry the momentum of high quality aeronomy and space science to a new era.

Phil Moran at Ffab Productions

Artist's concept of EISCAT 3D.

Photo: C. Heinselman

Close-up view of the first of two AMISR-class radars at Resolute Bay, Canada.

AFFILIATIONS OF RESEARCHERS THAT HAVE USED PFISR DATA SINCE JANUARY 2007:

Aerospace Corporation
Boston University
Clemson University
Cornell University
Dartmouth College
EISCAT Scientific Association
Geophysical Institute of Peru
Haystack Observatory, MIT
HIPAS Observatory, Alaska
Johns Hopkins University
Lancaster University, UK
Massachusetts Institute of Technology
Nagoya University, Japan
Naval Research Laboratory
Northwest Research Associates
Pennsylvania State University
Rutherford-Appleton Laboratories, UK
Southwest Research Institute
SRI International
Stanford University
Tohoku University, Japan
University Centre in Svalbard, Norway
University of Alaska, Fairbanks
University of California, Berkeley
University of California, Los Angeles
University of Colorado, Boulder
University of Iowa
University of Leeds, UK
University of New Hampshire
University of Washington
University of Wisconsin
University of Tromsø, Norway
Utah State University
US Air Force Research Laboratory

Power Flexibility

The lowest power consumption for an AMISR-class radar occurs when the radar is inactive and drawing only "house power" to maintain computers and utility distribution units, heat enclosures, etc. In this state the local power demand is ~20–40 kW.

During active operation the power consumption depends on the so-called duty cycle of the transmitted pulse code, which, for an AMISR, can be between ~1% and 10%. The power consumption, in addition to the ~20-40 kW house-power, scales with duty cycle. Experiment operation at 1% duty cycle (like the very successful IPY/climate change mode used at Poker Flat, Alaska) implies a total local power demand of ~100 kW, while experiments taking advantage of the full 10% duty cycle will demand ~700 kW. For PFISR, most of the common observations operate between 3%-7% duty (~240–520 kW).

The long-term average power consumption (over a month or a year) will

PFISR operational parameters	
Max RF Duty	10%
Pulse length	1µs-2 msec
TX Frequency	430-450 MHz
Antenna Gain	~43 dBi
Antenna Aperture	~715 m^2
Beam width	~1.1°
System Temperature	~120 K
Steering	Pulse-to-pulse ~±25°
Max system power consumption	100–700 kW* (op.) <30 kW (house power)
Max operation	Continuous (depends on available power)
Minimum measurable Ne	~$10^9 m^{-3}$
Typical time resolution	E-region <~20 sec F-region <~5 sec (per beam** for typical ionospheric conditions)
Typical range resolution	600 m to 72 km (mode dependent, can be extended)
Plasma parameters	N_e T_e T_i $\mathbf{V}_i$ ν_{in} Composition
Derived parameters	**E** **J** **J·E** **J·E'** **Un** σ_p σ_h
Unattended operation	
Data volume	~6 TB/year (PFISR)
No moving parts on the antenna	
Environment	-40 C to +35 C

* Typical experiments currently use up to ten essentially simultaneous look directions (beams)

** Figure is for radar operation at maximum (10%) duty cycle. The system can be run at reduced duty cycle, with consequently lower power requirements. For example, the very successful 1% 'IPY' mode requires ~100 kW only.

depend on how much of the total time the radar is transmitting and the mix of different experiments run.

The opportunity to adjust the duty cycle of experiments according to the power available is another strength of the AMISR concept. The overall number of hours of operation can be adjusted easily (and remotely) to match the available power/fuel. If more power becomes available, higher duty cycle experiments – and hence higher time resolution data - can be introduced by simply uploading new experiment files to the system.

An AMISR can be deployed with one or more dedicated generators to provide power for radar operations. A full AMISR face consumes just less than 30 liters of diesel fuel per hour at 1% duty cycle, rising to 200 liters per hour at 10% duty cycle. For a typical annual target of 2000 hours of operation, the fuel requirement will therefore be between 57,000 liters (all 1% duty cycle) and 400,000 liters (all 10% duty cycle) plus 30-70,000 liters needed for house-power for the remaining 8000 hours of the year.

Site Considerations

The Antarctic continent is large, and a number of different sites for placing an Incoherent Scatter Radar would be of great relevance and importance. Due to the added logistical challenges of constructing, managing and operating an ISR in Antarctica, two considerations have to be met:

1. The location should be coastal or near-coastal due to the fuel needed to operate the radar, and
2. The location should be at or close to an existing Antarctic station to take advantage of pre-existing, or shared, infrastructure. The radar could be deployed with up to a ~1 MW dedicated generation capacity but the local availability of 24/7 'house' power would be a great benefit.

With the large number of stations spread around the coast of Antarctica these requirements need not significantly constrain

Photo by Arne Oddvar Bergdal

The opportunity to adjust the duty cycle of the experiment according to the power available makes an AMISR class radar uniquely suited for Antarctica.

the geomagnetic locations and the science issues one could address.

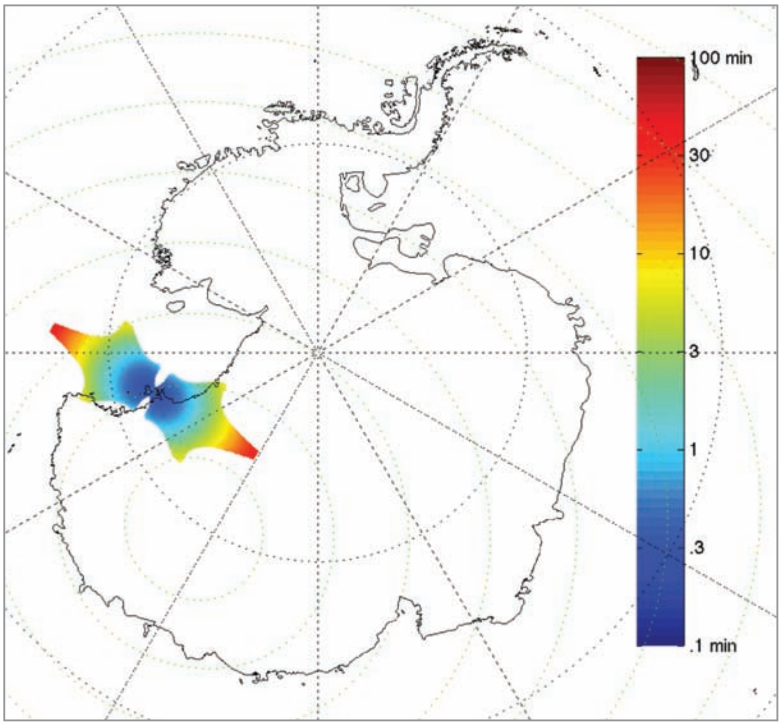


Figure 16. Example showing two 45° tilted AMISR faces in McMurdo.

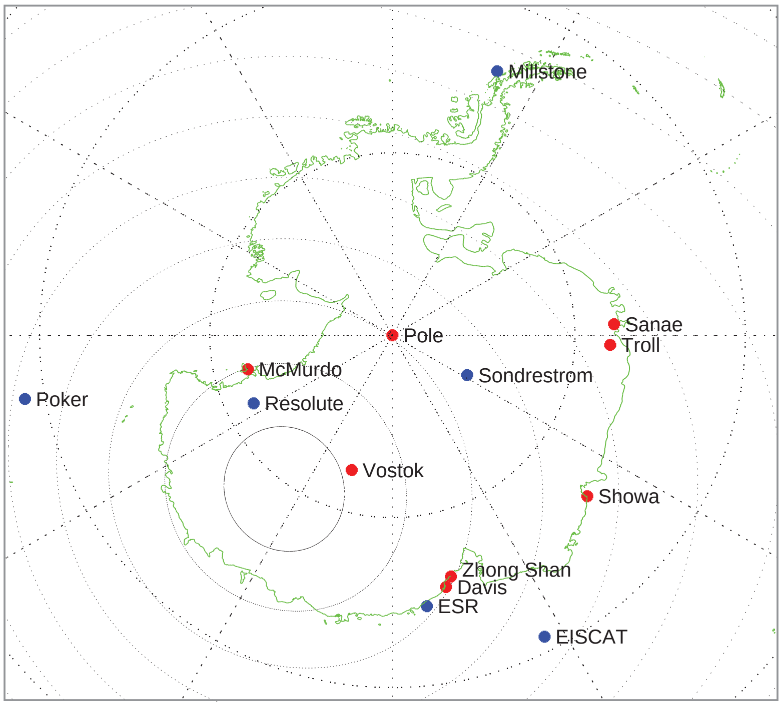


Figure 17. Antarctic stations (in red) and mapped conjugate points of selected northern stations.

MAGNETIC LATITUDE

The main considerations in determining the location of an Antarctic incoherent scatter radar are the science problems to be addressed. These are strongly dependent on the magnetic latitude of the station, which will determine the areas of geospace the system will be capable of observing. The Earth's high latitudes are very dynamic, and a few degrees change in geomagnetic latitude can make an enormous difference in which ionospheric regions one can probe. Figure 16 shows the F-region (300 km) coverage of two AMISR faces tilted at 45° at McMurdo. To accomplish many of the scientific goals outlined in this document (including the measurement of currents, winds, Joule heating and auroral precipitation), the Antarctic ISR must be able to also observe the E region. The latitudinal coverage of the E region is much more limited and could be a deciding factor in where to place the radar.

MAGNETIC CONJUGACY

One of the main drivers in considering the location for an Antarctic ISR is the opportunity for conjugate measurement of ionospheric features and variability. Requiring the existence of an ISR at the conjugate point in the northern hemisphere constrains the number of potential sites rather dramatically. Figure 17 shows the northern hemisphere ISRs mapped down to the south (in blue dots) with some existing Antarctic stations (in red). For a conjugate ISR in the south, it is clear that two locations stand out: McMurdo station (at ~80S magnetic latitude), which is conjugate to the Resolute Bay ISRs (RISR), and Davis or Zhong Shan stations (at magnetic latitude ~75S), which are conjugate to the EISCAT Svalbard Radar. One can also turn the reasoning around, and locate the ultimate spot in the southern hemisphere and envision constructing another northern ISR at the conjugate point. Figure 18 shows some of the Antarctic stations mapped to the northern hemisphere (blue dots) with the existing northern ISRs (in red). It is clear that Showa station (at magnetic latitude 67.0S) is conjugate to points on the north coast of Iceland.

However, the most important requirement is not exact conjugacy (which anyway varies with solar wind pressure, orientation and field direction) but rather the field-line regimes of the stations.

POTENTIAL LOCATIONS

The magnetic latitudes of a few of the coastal Antarctic stations are shown in the table below, together with conjugate points of some selected northern hemisphere stations.

For the southern hemisphere, the choice of the geographic latitude is of considerable importance. In addition to the requirement of a high enough geographic latitude to ensure local darkness for long periods of time around winter solstice, the relative location of the ISR to both the geographic and the magnetic pole is important.

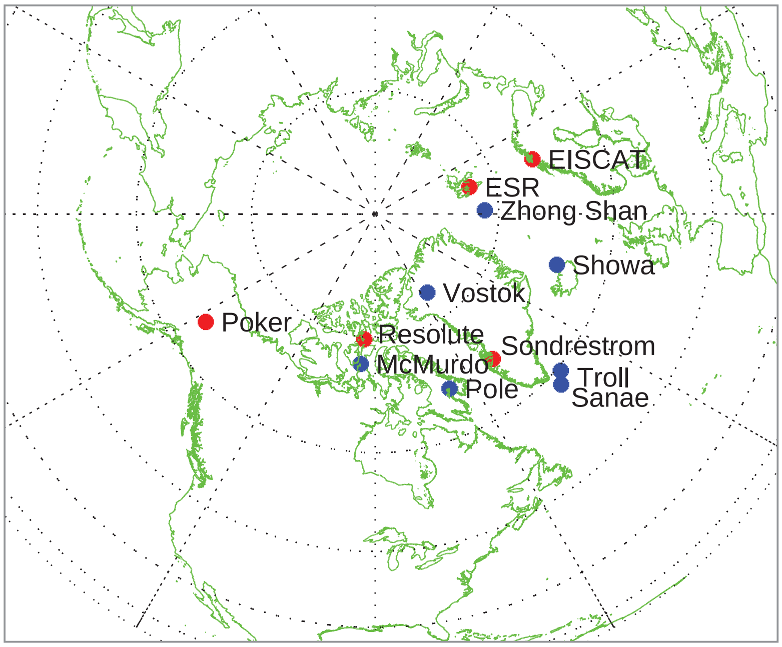


Figure 18. Arctic stations (in red) and mapped conjugate points of selected southern stations.

Magnetic coordinates of several Antarctic coastal stations together with those of near magnetically conjugate northern hemisphere sites.			
Conjugate pair	Geographic latitude & longitude	Geomagnetic latitude & longitude (CGM)*	L Value
Showa Leirvogur (Iceland)	69.0S 39.6E 64.2N 338.3E	66.5S 72.4E 64.8N 65.9E	6.4 5.6
McMurdo Resolute	77.9S 166.7E 74.7N 265.1E	80.0S 326.6E 82.7N 323.3E	- -
Davis Zhong Shan Longyearbyen	68.6S 78.0E 69.4S 76.4E 78.2N 15.8E	74.8S 101.2E 74.9S 97.5E 75.5N 110.9E	15 14 -
Troll	72.0S 2.5E	70.2S 73.3E	8.8
Palmer Millstone Hill	64.8S 295.5E 42.6N 288.5E	50.3S 8.8E 51.9N 7.0E	2.5 2.7
* Calculated for 2010 from http://omniweb.gsfc.nasa.gov/cgi/vitmo/vitmo_model.cgi			

POLAR CAP

The newest of the northern ISRs—the two AMISRs at Resolute Bay, Canada—will have a field of view that, if mapped to the south, will overlook the McMurdo station in Antarctica. A southern ISR at or close to McMurdo might be at too high geomagnetic latitude for dayside reconnection studies, but would be good for polar patch study and other polar cap and cross-cap phenomena. Comprehensive observations are available or will be possible.

CUSP

The polar cusp is a region of great interest because it is a boundary between open and closed field lines. The Davis/Zhong Shan stations are close to the conjugate point of the EISCAT Svalbard Radar and hence good for the studies of dayside reconnection and substorms during the recovery phase, with comprehensive instruments. Ground network/ chain geophysical data are available in the both regions.

Photo: C. Heinselman

AURORAL

In the northern hemisphere there are two auroral latitude ISR systems – The NSF PFISR in Poker Flat, Alaska, and the EISCAT mainland UHF and VHF systems (soon to be replaced by the EISCAT-3D system) in northern Scandinavia. Unfortunately the conjugate points of their field lines both fall in the Antarctic sea (Figure 17) and there are no possible conjugate pairs of north/ south auroral zone ISRs. For most cases discussed in the science sections above, the most crucial requirement is not having exact conjugacy, but rather having ISR measurements simultaneously at similar northern and southern invariant latitudes. By establishing an Antarctic ISR at Showa station, such similar latitude measurements can be achieved. Another auroral alternative is the Norwegian Troll station, which is closer to the South Atlantic Anomaly.

SUB-AURORAL

Palmer Station is an ideal site from which to address conjugate studies with Millstone Hill. In particular, PMSE processes would seem to be ideally addressed with an ISR at Palmer Station because of the greater sensitivity to variations in PMSE occurrence at the fringes of their distribution, and where we expect them to exhibit greater sensitivity to environmental factors such as mesopause temperature, water vapor, and wave forcing.

Initial Location

The initial choice of location (AMISR-class radars are transportable, so the initial location is not necessarily the only location which could be covered during the deployment) can only be determined after a more comprehensive evaluation of all the science goals and priorities than could be completed in the preparation of this initial report. This should be performed as part of a detailed feasibility study, which should also include specific practical and administrative site evaluations, both of which are beyond the scope of this report.

Photo: C. Heinselman

Management Planning for an International Antarctic ISR Consortium

High power radar facilities have been operated and managed under extreme conditions in the high Arctic for many years and there is considerable experience in the methods required and the problems likely to be encountered. This body of expertise has recently been considerably expanded both by the initiatives which led to the more or less continuous operation of several of the facilities during the International Polar Year and the construction, commissioning, and operation of the new class of phased array radars, notably at Poker Flat, Alaska, and more recently at Resolute Bay in northern Canada.

This experience is directly applicable to operations in the southern hemisphere and the present discussion illustrates this with regard to the deployment of a further phased array radar broadly identical to the two already mentioned.

All the potential Antarctic sites are considerably more remote and considerably more difficult and expensive to visit, particularly at short notice, and any radar deployed there must therefore be as nearly identical to an already deployed and operational instrument as possible. This is crucial and ensures that no unexpected new problems will occur related to a primary deployment under circumstances of access and operation that would make their resolution difficult, at best.

Notwithstanding that the proposed deployment should involve a fully tested and validated radar, there are important aspects which make this deployment different and more challenging than those already deployed in the northern hemisphere.

Deploying a radar to Antarctica almost certainly requires an international collaboration, discussed below, and again there is a developing body of experience available in this area since the second Resolute Bay radar face is being developed as a joint US-Canada project.

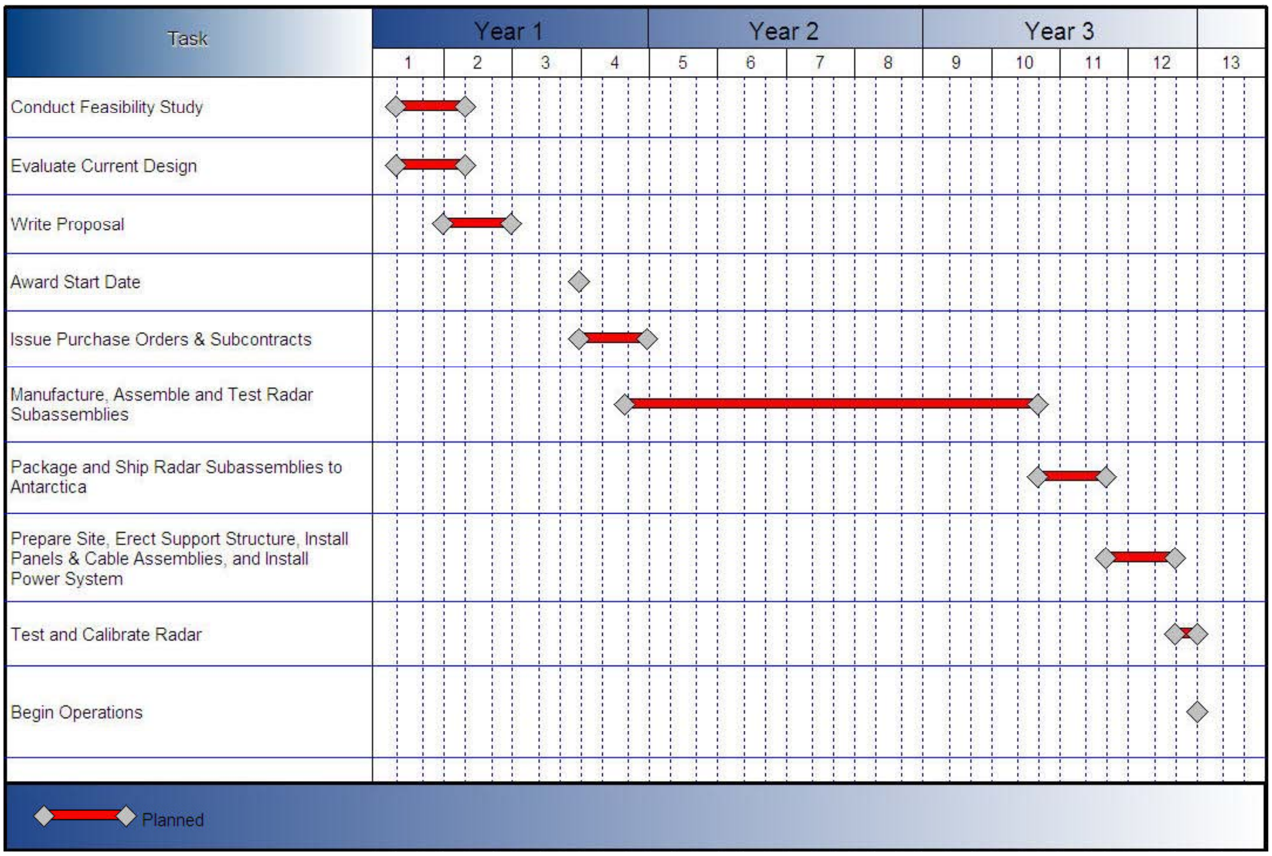
International considerations

The existing upper atmosphere facility incoherent scatter radars supported by the NSF have all been constructed as purely national facilities and, with the exception of Jicamarca, all continue to be operated and maintained in the same way.

Such an approach could also be applied to an Antarctic radar, but there are several reasons why it would be advantageous to widen the scope of the endeavor to include other international parties.

Adopting a trans-national approach echoes the overall attitude towards the Antarctic continent. Moreover, in general, involving international partners broadens the research base and enhances the effectiveness of scientific and technical collaborations in addressing

Adopting a trans-national approach echoes the overall attitude towards the Antarctic continent.



societally important research programs. However, there are also more immediate and specific reasons why international partners would be particularly appropriate in this case.

Establishing a large incoherent scatter radar at an entirely new location is unlikely to be practical or necessary; placing instrumentation in close proximity to an existing facility allows the sharing of logistics and supplies, as well as potentially resources, power, and skilled local expertise. Of the potential locations identified in this document (Figure 18), all but one lie close to existing operations maintained by countries other than the USA.

A bilateral arrangement with a suitable international partner will therefore be required, but widening the scope still further would also be beneficial in exploiting both available logistic and technical resources.

Timescales

The manufacture, installation, and commissioning of an Antarctic radar will all closely follow the corresponding steps at Resolute Bay and are expected to require broadly similar time and facilities, even if the deployed radar should include proven next-generation features.

However, the timing of access to sites in Antarctica allows a radar to be installed and commissioned within one season (as indicated in the Gantt chart above), rather than two as required in the northern hemisphere (in the high Arctic, the ice free shipping season is quite limited and only one ocean ship arrives very late each summer. After the ship's arrival, there is little time available for outside construction before the onset of winter).

Although the logistic and access requirements will depend heavily on the selected location, pre-deployment manufacturing and integration can be started quickly to ensure that the radar is deployed and operational in time for the next solar maximum.

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APPENDIX

Antarctic ISR Workshop 8–9 AUGUST 2008

During the URSI general assembly in Chicago in August of 2008, the Division of Antarctic Sciences in the Office of Polar Programs at the National Science Foundation and the Division of Atmospheric Sciences, Geosciences Directorate at the National Science Foundation co-hosted a workshop where the science rationale for an Antarctic incoherent scatter radar was discussed. Experts from the US and abroad were invited and a wide range of the science opportunities that can only be addressed by deploying an ISR in the high south was covered.

Names and affiliation of attendees of the Antarctic ISR Workshop held in August 2008 during the XXIX general assembly of URSI.

Workshop Attendees/Affiliation

Alan Rodger	British Antarctic Survey, UK
Ian McCrea	Rutherford Appleton Laboratory, UK
Jian Wu	National Key Laboratory of Electromagnetic Environment (LEME), China
Ryoichi Fujii	STELAB, Nagoya University, Japan
Toru Sato	Kyoto University, Japan
Robert A. Vincent	University of Adelaide, Australia
David Walker	University of KwaZulu-Natal, South Africa
Ron Woodman	Geophysical Institute of Peru
Joshua Semeter	Boston University, USA
Allan Weatherwax	Siena College USA
Ray Greenwald	Virginia Polytechnic Institute and State University, USA
Bill Bristow	University of Alaska, Fairbanks, USA
Mike Kelley	Cornell University, USA
John Foster	Haystack Observatory, USA
Ramon Lopez	University of Texas, Arlington, USA
Umran Inan	Stanford University, USA
Alex Glocer	University of Michigan, USA
Craig Heinselman	SRI International, USA

NSF

Vladimir Papitashvili	National Science Foundation, USA
Bob Robinson	National Science Foundation, USA
Rich Behnke	National Science Foundation, USA

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John Kelly	SRI International, USA
Robert Clauer	Virginia Polytechnic Institute and State University, USA
Ennio Sanchez	SRI International, USA
Anja Strømme	SRI International, USA
Tony van Eyken	EISCAT Scientific Association

Workshop Agenda

The Workshop was held in the Acapulco room on the gold level in the West Tower at the Hyatt Regency Hotel in Chicago, 8 – 9 August 2008.

FRIDAY 8. AUGUST

09:00 - 09:15	Welcome and opening words from the organizers.
09:15 - 09:30	Opening comments from NSF
09:30 - 10:15	Introductory presentation about the capabilities of current Incoherent Scatter Radars and a description of AMISR.
10:15 - 10:45	Coffee break

Session on Interhemispheric Studies

10:45 - 11:00	Introduction by Bob Clauer
11:00 - 11:10	Ian McCrea and Mike Lockwood "Inter-hemispheric comparisons of reconnection signatures as a means of understanding IMF Bx control and magnetospheric asymmetry"
11:15 - 11:25	Alex Glocer "Magnetosphere Ionosphere Coupling - Physical Processes and Modeling"
11:30 - 11:40	Joshua Semeter "Conjugacy of Auroral M-I coupling"
11:45 - 11:55	Nikolay Østgaard "Auroral Conjugacy Studies" presented by Tony van Eyken
12:00 - 12:10	Kirsti Kauristie "Some thoughts about Antarctic ISR as a scientific instrument, technological challenges and international collaboration project" presented by Tony van Eyken
12:10 - 13:45	Lunch

Session on Interhemispheric Studies continues

13:45 - 13:55	John Foster "Conjugacy Characteristics of Polar Tongue of Ionization"
14:00 - 14:10	Ramon Lopez "Interhemispheric Ionospheric Potential Differences"
14:15 - 14:25	R. A. Vincent "Interhemispheric differences in wave dynamics and coupling into the SH MLT and above"
14:30 - 14:40	Ian McCrea et al. "Comparative observations of mesospheric echoes, winds, tides and layer height trends in the Arctic and Antarctic"
14:45 - 14:55	Ron Woodman "AMISR in Antarctica: PMSE Related Questions"
15:00 - 15:30	Coffee break
15:30 - 16:30	General discussions about the Interhemispheric Session
16:30 - 16:45	Short break
16:45 - 17:45	General discussions
19:00	Dinner at Bistro 110

SATURDAY 9. AUGUST

09:00 - 09:15	Opening comments from the organizers

Session on Uniqueness of the Southern Hemisphere

09:15 - 09:30	Introduction by Alan Rodger
09:30 - 09:40	Ryoichi Fujii "On the performance and location of a new IS radar from the view-point of scientific purposes and compre-hensive observations"
09:45 - 09:55	Bill Bristow "Antarctic SuperDARN and AMISR"
10:00 - - 10:10	A. D. M. Walker "Can AMISR Techniques Contribute to the Understanding of Short Period Ionospheric and Magnetospheric Fluctuations?"
10:15 - 10:45	Coffee break
10:45 - 10:55	Allan Weatherwax "An Overview of Existing and Planned Space Physics and Aeronomy Projects in Antarctica: Understanding the Sun's influence on Earth's Global Space Environment"
11:00 - 11:10	M.C. Kelley et al. "Detection of iron layers, PMSE and noctilucent clouds in conjunction with a Space Shuttle launch"
11:15 - 11:25	K. Sato et al. "Coordinated observation of PANSY and AMISR in the Antarctic"
11:30 - 11:40	Francois Forme "Small-Scale Plasma Physics using IS radars" presented by Anja Strømme
11:45 - 12:15	General Discussions about the Southern Hemisphere Session
12:15 - 13:45	Lunch
13:45 - 14:15	Summary with a list of "Outstanding Questions" - both scientific and strategic - compiled from the presentations and discussions.
14:15 - 15:00	Round table discussions on selected "Outstanding Questions"
15:00 - 15:30	Coffee break
15:30 - 16:00	Round table discussions continues
16:00 - 16:30	Form a committee to proceed with the work
16:30 - 17:00	Concluding Remarks