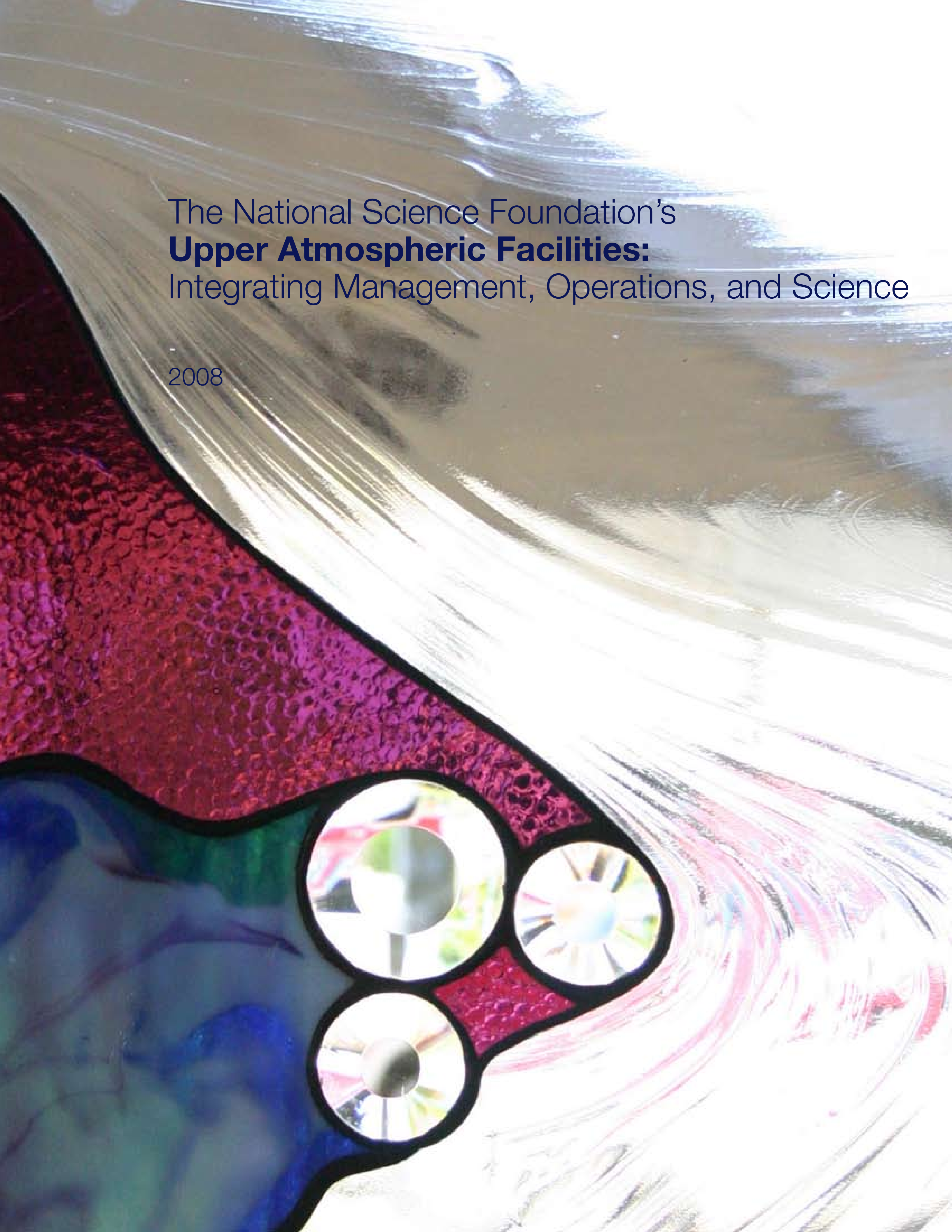
The National Science Foundation's
Upper Atmospheric Facilities:
Integrating Management, Operations, and Science

2008



Acknowledgements

The construction and operation of the upper atmospheric facilities have been tremendous engineering achievements, but the many contributions these facilities have made to the progress of science and technology could not have been realized without the dedicated and talented staff of the institutions charged with managing and operating them through the past five decades. In addition, the facilities have benefited enormously from the creativity and skill of facility users in the larger scientific community. The success of the facilities is in large part attributable to excellent working relationships established over many years between facility staff and experienced scientific users.

The institutions involved with managing and operating the facilities include Cornell University, Johns Hopkins University, the Massachusetts Institute of Technology, SRI International, and, more recently, Virginia Polytechnic Institute and State University. This document was produced by a subcommittee of staff members from these institutions whose names are listed below. Non-subcommittee contributors to the report include Nestor Aponte (Arecibo), Jorge Chau (Jicamarca/Cornell), Donald Farley (Cornell), Larisa Goncharenko (MIT/Haystack), Frank Lind (MIT/Haystack), Larry Lyons (UCLA), Mike Nicolls (SRI), Ennio Sanchez (SRI), Joshua Semeter (Boston University), Anja Stromme (SRI), Michael Sulzer (Arecibo/Cornell), Wesley Swartz (Cornell), Jeff Thayer (University of Colorado), and Hien Vo (Arecibo/Inter American University).

This report was motivated by recommendations from two facility site review panels that produced reports in 1997 and 2004. The 1997 review panel included Bela Fejer, Rod Heelis, Michael Mendillo, John Meriwether (chair), and Richard Vondrak. The 2004 site visit panel included Susan Avery (chair), C. Robert Clauer, Maura Hagen, John Mathews, John Sahr, and Michael Taylor. The 2004 panel specifically recommended the facilities develop an integrated science plan, for which this document lays the groundwork.

We also thank Chris Philipp and Laurie Ray from the Office of Publications and Marketing at Cornell University for their editing and graphic design services.

This report is gratefully dedicated to Dr. William E. Gordon, whose brilliant vision 50 years ago opened the door to a new era of ionospheric and upper atmospheric research. Perhaps equally important has been Dr. Gordon's continued leadership, inspiration, and mentoring from which we all have directly or indirectly benefited.

UAF Report Subcommittee

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Executive Summary

The Upper Atmospheric Facilities (UAF) Program in the Division of Atmospheric Sciences at the National Science Foundation (NSF) was created in 1983 to oversee the scientific operation of a network of radars used to probe the upper atmosphere and ionosphere. The program originally supported radars with technology based on the incoherent scatter mechanism for generating radar echoes. Incoherent scattering of radio signals from the ionosphere was predicted by William Gordon in 1958. After experimental confirmation of the theory, incoherent scatter radars were constructed at various locations around the globe. In the 1970s, NSF took over operation of four of these: the Jicamarca Radar in Peru, the Arecibo Radar in Puerto Rico, the Millstone Hill Radar in Massachusetts, and the Chatanika radar in Alaska (relocated to Greenland in 1983). Because the incoherent scatter radars are able to measure height profiles of the most fundamental ionospheric properties, data from these instruments are used for a broad range of research studies pertaining to the upper atmosphere, ionosphere, and magnetosphere.

The UAF program, initially established to support the original four incoherent scatter radars, has evolved over the last 25 years. In the 1990s, the UAF program began support for the U.S. contribution to an international network of coherent scatter radars called SuperDARN. These coherent scatter radars provide nearly continuous measurements of the drift of ionospheric plasma on a global basis. In January 2007, the NSF-funded solid-state, phased-array incoherent scatter radar at Poker Flat, Alaska, began routine operations. A similar radar is under construction at Resolute Bay in the Canadian Arctic and will begin operations by the end of 2008.

Over the last three decades, the upper atmospheric facilities have proven to be invaluable tools for atmospheric and space scientists. Each of the radars is unique, and each builds on its specific strengths and observational capabilities.

- At the equator, the Jicamarca Radio Observatory measures properties of the equatorial ionosphere, the site of small-scale irregularities that can disrupt navigation and communication signals.
- The Arecibo Observatory is the most sensitive incoherent scatter radar in the world. It observes the mid-latitude ionosphere from the D-region into the topside ionosphere. A new ionospheric heating facility being constructed at Arecibo will provide opportunities to study ionospheric instabilities associated with energy input.
- The Millstone Hill Observatory includes a steerable dish antenna allowing measurements over a broad horizontal extent. Millstone has conducted landmark studies of dramatic ionospheric features at mid-latitudes originating from large geomagnetic storms.
- The Poker Flat Incoherent Scatter Radar (PFISR) is the first system using the Advanced Modular Incoherent Scatter Radar design. This solid-state, phased-array radar is capable of pulse-to-pulse beam steering to allow probing of plasma parameters in the dynamic auroral ionosphere.
- The Sondrestrom Radar in Greenland measures properties of the boundary region of the auroral zone and the polar cap. Sondrestrom data are used to determine electrodynamic parameters such as conductances and currents, essential for studying the coupling of the ionosphere along magnetic field lines to the magnetosphere and solar wind.
- Finally, the SuperDARN radars measure ionospheric drift velocities on a global basis in near real time. The convection patterns derived from these measurements, as well as other derived parameters, are used extensively by space scientists in studying the response of the ionosphere to forcing from above and below.

Taken together, the radars supported by the UAF program provide critical measurements of ionospheric properties from the magnetic equator to the northern Polar Regions.

In addition to the radars operating at these locations, many of the facilities also support complementary instruments, resulting in a more complete understanding of the near-Earth space environment.

The record of scientific contributions from these facilities has been tremendous, and continued improvement in the techniques and data analysis algorithms will ensure that this record of achievement endures. Many of these improvements have been enabled by advancements in radar transmitter and computing technology, but others stem from the ingenuity and creativity of facility staff and users of the radars. Thus, the success of the facilities is equally attributable to the knowledge and skill of the people who operate and use them.

Each of the facilities is typically funded by NSF for five years based on reviews of unsolicited proposals. The management and outcomes of the UAF program investments are reviewed every two to three years as part of the NSF-mandated Committee of Visitors process. Oversight and planning of facility activities are also conducted on an informal basis during all-facility workshops held approximately every two to three years. In addition, the facilities underwent comprehensive reviews by external panels in 1996 and 2003. These reviews involved site visits to each of the facilities and resulted in reports with important recommendations that were used in the evaluation of subsequent proposals. The 2003 panel recommended that the facilities work together to produce an integrated science plan. This document is the result of many months of cross-facility discussions on common issues related to the management, operations, and science associated with the upper atmosphere radars.

It is difficult to imagine an area of space science research that does not benefit from the data provided by the upper atmospheric facilities. The facilities actively participate in major research initiatives with excellent scientific merit and important societal consequences.

- In the area of space weather, the knowledge gained from facility observations has helped make predictive models more accurate and robust. Facility data are often used to test and validate new space weather models. The future will see more facility data available in real time for use in operational forecasts and models.
- Facility data are used for studying climate change. The decades of observations comprise a valuable database for studying long-term trends in ionospheric and thermospheric properties. Facility data are also used in studying the fundamental mechanisms by which the atmosphere changes in response to natural and anthropogenic effects.
- The upper atmospheric radars contribute to the planning and execution of space missions and rocket campaigns. Ground-based measurements are used to validate and calibrate data from satellites on orbit. Radar measurements coordinated with satellite overpasses allow for more accurate interpretation of data by providing a context for the observations and a time record both before and after the spacecraft sampling. For rocket campaigns, radars monitor and help identify the proper launch conditions even in the presence of cloud cover.
- Radar experiments are the primary means for research in radio science, which has important applications to communication, navigation, and surveillance. This discipline is critical to ensuring the operation of systems that are vital to national health, security, and economy.

Continued usefulness to the space science community requires facility staff to carefully consider experimental requirements in planning upgrades, developing software, improving operational modes, and exploiting new technology. Some of the important experimental drivers for radar technology include:

- High effective radiated power
- Conversion and storage of digital voltages
- Reliable knowledge of the experiment process
- Processing of voltages for plasma parameter extraction
- Reliable setup, control, and monitoring of experiments
- Knowledge of the geophysical context of an experiment
- Timely delivery of data to multiple end users
- Quick response capability
- Maintenance of capability infrastructure
- International coordination

Education and outreach remain a high priority among the upper atmospheric facilities as a new generation of radar experts is essential to ensure continued scientific output. The facilities support educational activities beginning with programs for K–12 students and teachers and extending to research opportunities for both undergraduate and graduate students. These efforts will be expanded and strengthened through focused workshops and radar schools aimed at establishing a well-educated and experienced user community, as well as experts in radar technology who will develop the next generation of radars.

As new radars come on line and budget stresses constrain the level of effort that can be applied to radar operations and the research enabled by the radars, more careful planning and coordination among the facilities is essential. History has shown that it is often not enough to coordinate observations among different instruments. It is important to coordinate the research activities that accompany these observations. Furthermore, there is much to be gained through exchanging information and knowledge among the facilities to reduce redundancy and stimulate creativity. A cross-facility scientific steering group is needed to implement strategies that will promote coordination among the facilities, ensure effective communication, and monitor facility responsiveness to new requirements by the user community. The steering group would also be responsible for scheduling meetings and workshops as appropriate to address specific research needs and common facility challenges.

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BACKGROUND

Introduction

The Upper Atmospheric Facilities (UAF.) Program in the Division of Atmospheric Sciences at the National Science Foundation (NSF) was created in 1983 to oversee the scientific operation of a network of radars used to probe the upper atmosphere and ionosphere. The scope of the program has grown through the years to include five incoherent scatter radars (ISRs) and the U.S. portion of the international SuperDARN network. The ISR sites include the Sondrestrom Facility, the Millstone Hill Observatory, the Arecibo Observatory, the Jicamarca Radio Observatory (part of the Geophysical Institute of Peru), and the Advanced Modular Incoherent Scatter Radar (AMISR) at Poker Flat, Alaska (Figure 1). When another AMISR is constructed at Resolute Bay, Nunavut, Canada, in 2008, the U.S. ISR chain will comprise six facilities.

The mission of the UAF Program is to enable basic research on the structure and dynamics of the Earth's upper atmosphere, ionosphere, and magnetosphere by supporting the development, operation, and maintenance of large ground-based observatories.

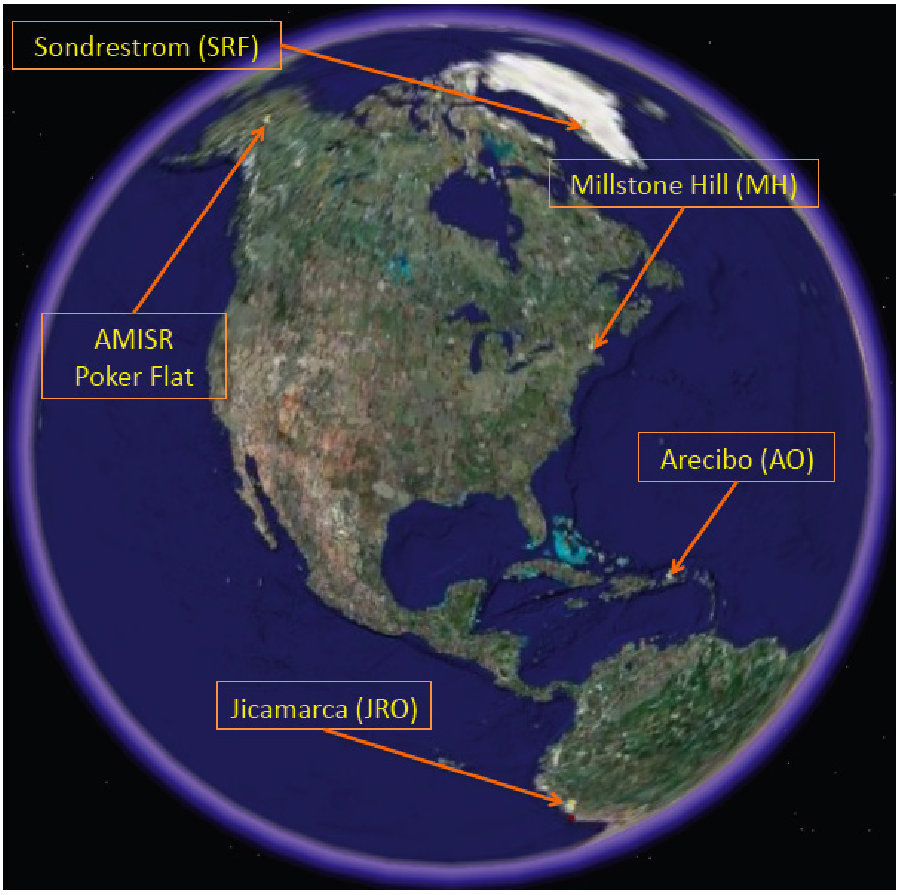
Within this mission, the program has three specific objectives:

1. to ensure that the science undertaken at the UAFs is of the highest quality and is coordinated with the university community to produce a synergistic effect in the advancement of upper atmospheric science;

2. to ensure that the facilities are maintained as state-of-the-art, cost-effective research tools available to all qualified scientists, and that the data and services provided by the facilities are adequate to meet the community's short- and long-range scientific objectives;

3. to educate the next generation of space scientists in the development, operation, and use of multiuser facilities, leading to the maintenance of a diverse, highly qualified user base for upper-atmospheric-research data.

Figure 1



UAF facilities superimposed on a world map.

The community of scientists using the facilities consists of a broad network of research groups based at universities, research centers, and other institutions throughout the world. The UAF Program is responsible for managing, maintaining, and upgrading the radar facilities, and organizing their operations in support of national, international, and individual research efforts. The program also develops the techniques and modes that optimize radar performance according to the individual needs of the scientific user community. Facility staff members are charged with developing, implementing, and promoting new means of using radar remote sensing in pursuit of the objectives of the broader aeronomy and space physics community.

Because of the importance of the upper atmospheric facilities in supporting space science research, it is important to ensure their operation and use are carefully coordinated and managed. An essential element in this oversight is the development of this document that defines the role of the facilities in conducting space science research and establishes a strategic framework to ensure they are meeting the needs of the user community.

This document represents a first step toward integrating the management, operations, and science activities among the upper atmospheric facilities. It begins with a brief explanation of radar techniques, followed by descriptions of the facilities. It then presents highlights of the scientific contributions the facilities have made and the role the radars have played in major scientific initiatives. The concluding sections describe specific strategies to be used in meeting experimental requirements and responding to scientific priorities. This document is meant to guide the management and operation of the upper atmospheric facilities over the next five to ten years.

Radar Techniques for Upper Atmospheric Research

The UAF Program supports two distinct types of radars. The ISRs depend on high-power transmitters and large antennas to detect the weak backscatter from the ionosphere. Coherent radars, such as the SuperDARN high-frequency (HF) radars, are lower-power radars that operate continuously to measure echoes from naturally occurring irregularities in the ionosphere.

Incoherent Scatter

The term *incoherent scatter* of an electromagnetic wave from an ionized gas, as used here, means the extremely weak scatter resulting from minute fluctuations in plasma density caused by the purely random thermal motions of the ions and electrons. The idea that the scatter from individual electrons with uncorrelated (hence the term "incoherent") motions might provide a powerful diagnostic tool for studying the Earth's ionosphere was first proposed by W. E. Gordon in 1958 (Gordon 1958) and was verified by K. L. Bowles (Bowles 1958) just a few months later. The electron motions are not, in fact, completely uncorrelated, but the name incoherent scatter is now firmly established anyway. At Arecibo, the electron component of the ISR spectrum (i.e., the component that is most closely related to the original concept of 'true' incoherent scatter) was first detected in 1976 (Hagen and Behnke 1976).

The strength of the scatter is roughly what one would expect from truly incoherent electron motion, with each electron having a radar cross section of $1x10^{-28}$ m^2 and the individual powers adding (because of the random phases associated with the random positions) to produce the total scattered signal. The total cross section of, say, 10-cubic kilometers (km) of the ionosphere with a density of a typical ionospheric maximum value of 10^{12} m^{-3} is only about 10^{-6} m^2. So a radar designed to probe the ionosphere with a spatial resolution of a few kilometers is faced with the problem of detecting a target the size of this dot (·) or smaller at a range of 300 km or more. Although the cross sections are very small, and the scattered signals very weak, they can be detected by sufficiently powerful radars. The scattering is not truly incoherent because in most cases the electron density is high enough that correlations in the electron motions associated with collective plasma interactions (the Debye shielding "clouds" surrounding individual ions and electrons) alter the shape of the backscattered spectrum. These correlations change the total scattering cross section only moderately (typically reducing it by a factor of roughly two), but have a profound effect on the Doppler spectrum of the scattered signal and result in different components which are named according to the physical process they are most closely related to. Some examples include the ion line, electron line, the electron gyroline, ion gyrolines, and the plasma line. As a result, the signal is far more difficult to interpret than was originally envisioned by Gordon, but the effects that add complexity greatly increase the information contained in the returned signal and allow for the determination of the values of many more geophysical parameters than Gordon initially suspected.

To varying degrees, the electron and ion temperatures, ion composition, ion and electron collision frequencies, plasma drifts and currents, magnetic field, and electron density all affect the shape of the power spectrum of the scattered signal. Most of the important plasma parameters in the ionosphere can be determined over an altitude range that (depending upon the radar parameters) may extend from 60–70 km (the D region) to altitudes of several thousand kilometers (the so called topside region or lower plasmasphere). Incoherent scatter is by far the most powerful remote probing tool for the study of ionospheric photochemistry and dynamics. Furthermore, the direct measurements of the plasma parameters can provide good indirect data on some parameters of the neutral atmosphere, such as temperature and wind velocity.

In the late 1950s and early 1960s, three large radar facilities were constructed and used for incoherent scatter observations of the ionosphere. The Jicamarca Radio Observatory in Peru was built by the National Bureau of Standards, the Millstone Hill Observatory was built by the Massachusetts Institute of Technology's (MIT's) Lincoln Laboratory, and the Arecibo Observatory was built by Cornell University and originally funded by the Advanced Research Project Agency (ARPA). In 1965, with funding from the Defense Nuclear Agency SRI constructed a large coherent L-band radar for high-altitude nuclear diagnostics. This radar was moved to Chatanika, Alaska, in 1971 and operated as an ISR, and in 1982 it was moved once again, this time to Sondrestrom, Greenland. In the 1970s, the NSF took over the operation of three of these radars and provided most of the operational support for the fourth (Jicamarca). The concept was to operate a longitudinal chain of upper atmospheric observatories and thus obtain data that could help in studying the ionosphere and upper atmosphere as a global system.

At the same time as U.S. efforts to build ISRs were underway, parallel development of incoherent scatter radar was being carried out in other parts of the world. Observations were made in Nancay, France, and Malvern, England, in the 1960s and 1970s, but both of these observatories were closed before 1980. Observations have been, and still are, being made in the former Soviet Union, but little of that data has been published until recently. The 50 MHz MU radar in Japan, with its electronically steered beam, can be, and has been, operated as an ISR. One of the most sophisticated of all the current ISR facilities is the "next generation" EISCAT (European Incoherent SCATter) radar in northern Scandinavia (Baron 1984; Rishbeth and Williams 1985). It has both a VHF (224 MHz) and a UHF (930 MHz) radar and an associated HF transmitter system for ionospheric interactions experiments. The transmitters are both in Tromsø, Norway. The UHF system is tristatic (receivers in Norway, Sweden, and Finland), permitting the unambiguous measurement of vector plasma drift velocities. Recently, an additional EISCAT radar has been added to the island of Svalbard, off the northern coast of Norway. The AMISR, a modern, modular, UHF phased array radar system, is being constructed with support from NSF. The first AMISR system has been operating at Poker Flat, Alaska, since January 2007. Two more AMISR antenna faces are under construction at Resolute Bay, Canada, with estimated completion in Fall 2008. Table 1 lists the properties of incoherent scatter radars currently operating around the world.

Coherent Scatter

Coherent scattering from the ionosphere can be detected at much lower power levels than those associated with ISR. Coherent scatter is due to fluctuations in plasma density that have been amplified far above thermal levels by processes of plasma instability. Ionospheric plasma becomes unstable to the growth of irregularities because of the presence of electric fields and gradients in density and temperature. Unlike the ionosphere itself, the irregularities are not always present, but they occur frequently enough to provide targets for routine radar monitoring of ionospheric conditions. The irregularities are aligned with the geomagnetic field lines such that significant backscatter is generated only when the sampling radar wave vector propagates nearly in the plane orthogonal to B. The restriction to small magnetic aspect angles limits the coherent scatter technique to certain locations and viewing geometries. The first observations of coherent scatter at the magnetic equator were made by Bowles et al. (1960) who reported a resemblance to coherent scatter observed at auroral latitudes. Because the costs associated with coherent scatter radars are relatively modest, they can operate continuously and be assembled into global networks.

The most important parameter derived from coherent scatter observations is the Doppler shift imparted to the transmitted signal by the motion of the irregularities. At F region altitudes this motion is dominated by the drift of the ambient plasma in the plane orthogonal to the magnetic field **B**, which is controlled by the electric field **E**, according to **ExB** drift of the ambient plasma. At E region altitudes the situation is more complicated and the irregularity motion does not track the **ExB** drift over its entire range. A coherent scatter signal at any altitude contains information on irregularity amplitude and the conditions of plasma instability in the ionospheric medium. At high latitudes, aspects of coherent scatter spectra have been shown to relate to such geophysically significant features as the cusp/cleft region and the open/closed field line boundary. At mid latitudes, coherent scatter serves as a tracer for traveling ionospheric disturbances, irregular sporadic E layers, and storm-time electric field dynamics. At low latitudes, plasma density profiles can be inferred from coherent scatter by means of Faraday rotation, and transverse drifts can be measured using interferometry. The decay rate of coherent scatter from naturally and artificially generated plasma irregularities is indicative of the temperature, and neutral winds can sometimes be inferred from coherent echoes from the E region.

SuperDARN is a global network of coherent scatter radars that grew out of an earlier collection of radars called DARN (Dual Auroral Radar Network). The basic instrument is a phased-array radar that operates at frequencies in the high frequency (HF) band between 8 and 20 MHz and utilizes multipulse sounding techniques. The dual aspect of the experiment derives from the interest in arranging radars in pairs so as to observe common volumes. At high latitudes, the geomagnetic field lines are almost vertical and the **ExB** drift lies nearly in the horizontal plane. By combining stereoscopically the line-of-sight velocity measurements from crossed radar beams, the two-dimensional convection electric field vector can be resolved unambiguously. The radars operate continuously using standardized operating software and generate common data products.

The first HF radar of the SuperDARN type was built in Goose Bay, Labrador, in 1983 by Johns Hopkins University's Applied Physics Laboratory (JHU/APL). This was followed by a collaboration with the British Antarctic Survey to build a radar at Halley Station, Antarctica, with a field of view that is geomagnetically conjugate to that of Goose Bay.

In the 1990s, the international SuperDARN collaboration was formed to pursue the deployment and scientific use of longitudinal chains of HF radars at high latitudes in both the northern and southern hemispheres. These chains now consist of nine radars in the north and six in the south. Within the last few years, the scope of the SuperDARN observations has been increased with the deployment of two new radars at polar latitudes and three at mid-latitudes.

Table 1. Radars used for upper atmospheric research and their characteristics.

Observatory	Initial Year of Operation	Location	Latitude	Longitude	Corrected Geomagnetic Latitude	Frequency (MHz)	Antenna Type	Antenna Size	Peak Power (MW)	Maximum Duty Cycle %
Poker Flat Incoherent Scatter Radar	2007	Poker Flat, Alaska	65.10	212.55	65.4	449	Phased Array	32m X 28m	2	10
Sondrestrom Radar Facility	1983	Kangerlussuaq, Greenland	66.99	309.05	72.6	1290	Steerable parabolic dish	32 m	3.5	3
Millstone Hill Observatory	1960	Westford, Massachusetts	42.62	288.51	52.1	440	One fixed and one steerable parabolic dish	46 m steerable; 68 m fixed	2.5	6
Arecibo Observatory	1962	Arecibo, Puerto Rico	18.35	293.24	27.6	440	Spherical dish	305 m	2.5	6
Jicamarca Radio Observatory	1961	Jicamarca, Peru	-11.95	283.13	0.3	50	Square phased array	290 m X 290 m	3	6
EISCAT UHF	1981	Tromsø, Norway	69.58	19.22	66.7	928	Steerable parabolic dish	32 m diameter	2	12.5
EISCAT VHF	1985	Tromsø, Norway	69.58	19.22	66.7	224	Offset parabolic cylinder	120 m X 40 m	3	12.5
EISCAT Svalbard Radar	1996	Longyearbyen, Norway	78.15	16.03	75.4	500	One fixed and one steerable parabolic dish	32 m steerable; 42 m fixed	1	25
Middle and Upper Atmosphere (MU) Radar	1985	Shigaraki, Japan	34.85	136.1	280.4	46.5	Circular phased array	103 m diameter	1	4
Kharkov Radar	Not available	Kharkov, Ukraine	50.00	36.23	45.8	150	Fixed and steerable dishes	100 m and 25 m	2.5	6
Irkutsk Radar	Not available	Irkutsk, Siberia	52.87	103.28	48.2	154-162	Sector horn	250 X 12 m aperture	3.2	Not available
ALTAIR	Not available	Kwajalein Marshall Islands	9.40	167.48	4.2	VHF/UHF	Steerable parabolic dish	46 m	6 MW	1.5/5%

The Jicamarca Radio Observatory

The radar at Jicamarca, Peru, (Figure 2) was built by the National Bureau of Standards in 1961. Located about 30 km east of Lima, Peru, the Jicamarca Radio Observatory (JRO) is at the equatorial end of the UAF chain. The observatory is owned by the Peruvian Geophysical Institute (Instituto Geofísico del Perú, or IGP), but Cornell University has operated the site for NSF since 1981.

The primary mission of the Jicamarca Radio Observatory is to deepen our understanding of the equatorial and low-latitude atmosphere and ionosphere and the systems to which they are coupled. In addition, the Jicamarca Observatory fosters the creation of avant-garde radar and radio remote sensing techniques, trains and educates new generations of space physicists and radio scientists and technicians, and expands its own capabilities through upgrade and invention. Like the other ISR facilities, Jicamarca is used to measure plasma number density, temperature, composition, and drifts in the ionosphere, along with fluctuations and waves in the ionosphere and neutral atmosphere.

Jicamarca contributes to aeronomy research by participating in global and regional campaign studies, by supporting visitors and remote users along with its own specialized community of investigators, and by supplying real-time data to relational databases. It is also used for satellite calibration and validation.

Jicamarca possesses unique attributes that set it apart from the other radars in the chain. Operating at a relatively low frequency (50 MHz), Jicamarca is particularly sensitive to fluctuations caused by neutral turbulence. It is the only radar in the world capable of detecting echoes continuously from tropospheric to thermospheric altitudes. Likewise, Jicamarca does not suffer from Debye length effects at high altitudes and has been used to measure ionospheric parameters up to 6000 km.

Operating near the dip equator, the Jicamarca radar can measure incoherent scatter at zero magnetic aspect angle. The incoherent scatter spectrum narrows drastically under this condition, making it possible to measure plasma drift velocity profiles in the plane perpendicular to the geomagnetic field with extraordinary accuracies of about 1 m/s.

Figure 2

The Jicamarca Radio Observatory.

Furthermore, Jicamarca can observe along multiple, closely spaced antenna beams simultaneously, affording it the ability to measure vector drift velocities rather than just radial drift speeds. By operating in a dual-polarization mode, the radar can measure absolute electron densities from Faraday rotation without requiring ionospheric soundings for calibration.

Advances in both incoherent scatter theory and magnetoionic theory continue to be driven by experiments at small magnetic zenith angles at Jicamarca including for example the detection of the ion gyrolines which is not practical at any other facility. Looking perpendicular to the geomagnetic field, Jicamarca also observes intense coherent backscatter from field aligned irregularities generated by plasma instabilities and turbulence in the E, valley, and F regions. Groundbreaking research into the equatorial electrojet and equatorial spread F (ESF) continues to be performed at Jicamarca. ESF research in particular is an important component of the National Space Weather Program and NASA's Living With a Star program. Various anomalous phenomena, including the so-called 150 km echoes, long-lived meteor trail echoes, and daytime spread F, were discovered at Jicamarca and have become sources of vigorous debate and study in the community.

Jicamarca responded to a demand for more observations of plasma irregularities associated with ESF about a decade ago with the development of the JULIA system (Jicamarca Unattended Long-term Investigations of the Atmosphere), which excites the main antenna at low power levels and can run almost continuously at low cost and with little oversight and maintenance. Several thousand hours of JULIA mode operations are conducted each year, yielding almost continuous, real-time diagnostics of irregularities in the equatorial ionosphere as well as a comprehensive database spanning all seasons, solar flux levels, and geomagnetic conditions against which models of irregularity generation can be tested.

Jicamarca owes its prowess as a coherent scatter radar to the flexibility of its large (300 m^2) modular, phased-array antenna, which can be subdivided for transmission and reception into numerous configurations. Radar interferometry using two spaced receiving antennas forming a single baseline was introduced to the world at the observatory about two decades ago. Jicamarca currently supports up to eight distinct receivers that permit interferometry experiments with up to 28 nonredundant baselines. Using aperture synthesis imaging techniques pioneered at Jicamarca, the interferometry data can yield detailed images of the scattering structures within the volume illuminated by the radar beam. Jicamarca is promoting aperture synthesis imaging around the world. Jicamarca has proven itself to be uniquely well suited for the rapid development and deployment of radar systems for testing and validation. As a result, a steady stream of new experiment modes and techniques emerge from the observatory each year.

Jicamarca is the only facility among the UAF that is owned and operated by a foreign governmental authority, the IGP, with its funding supplied mostly from the NSF through a Cooperative Agreement. This arrangement necessitates a strong partnership involving the IGP, the nonprofit organization Ciencia Internacional, and Cornell University. The structure works to expand Jicamarca's role in the areas of education, professional development, and service to both Peru and the United States. Jicamarca has become a major trainer and employer of Peruvian scientists and engineers, young professionals who advance through the ranks at Jicamarca and who often seek advanced degrees in aeronomy-related fields in the United States. In return, JRO provides data products and technological innovations of practical value to the government and people of Peru. At Cornell, students from two departments straddling three colleges are recruited into the aeronomy and space physics fields, and material arising from Jicamarca research is integrated into a series of undergraduate and graduate courses and research projects.

The Arecibo Observatory, National Astronomy and Ionosphere Center

The Arecibo Observatory (Figure 3) was built in the early 1960s by Cornell University with funding from the Defense Advanced Research Project Agency (ARPA). The observatory is located in the north central part of Puerto Rico and provides a "middle" point along the UAF chain, between Millstone and Jicamarca. The Arecibo incoherent scatter radar was conceived by William Gordon (Appendix A), who oversaw its construction and directed the early years of operation. NSF took over the funding of operations in 1970 with supplementary support from NASA. At that time, several upgrades were made to the observatory. The original mesh surface of the antenna was replaced with perforated aluminum panels in order to increase the highest usable frequency to include L and S bands, and a high power CW S-band transmitter was added to perform planetary radar studies with a higher signal to noise ratio than was possible with the 430 MHz system.

The Arecibo Observatory is quite unique among the NSF funded incoherent scatter radars in that it is also an NSF funded radio astronomy telescope and planetary radar. Cornell University manages the facility for NSF in both disciplines. As an incoherent scatter radar, the primary mission of Arecibo is to further our understanding of the relatively "quiet" tropical (18 deg. N geographical, 30 deg. N geomagnetic) ionosphere, which is not regularly influenced by the electrodynamics of the equatorial or auroral regions. Nevertheless, the ionosphere over Arecibo can be quite dynamic, and more studies are pointing to the dramatic effects of the neutral atmosphere, as well as the signatures of the equatorial anomaly surging up to these latitudes.

This relatively quiet environment provides excellent conditions for studying the ionosphere as an unbounded plasma physics laboratory where ionospheric heating experiments can be conducted using the ISR as a powerful diagnostic tool. The first HF heating facility at Arecibo was constructed at the site of the main antenna, but was later moved to a nearby location. This heating facility was dismantled in 1998 after Hurricane Georges did extensive damage to the antenna field. A new facility is currently under construction at the Arecibo site and is projected to be completed by the fall of 2009.

The original ISR calculations by Bill Gordon called for a very large antenna (of the order of 1000 feet) and very powerful transmitters (at the megawatt level), in order to make up for the small scattering cross section of individual electrons, and thus be able to observe the wideband (megahertz) spectrum of true incoherent scattering from the earth's ionosphere. Even though it became known before construction that the observed spectrum was narrower than expected for true incoherent scattering (on the order of kilohertz), the plans went ahead to build what is still today (45 years after construction), the largest primary reflector in the world (305 m in diameter), and the most sensitive single dish radio astronomy telescope and incoherent scattering radar.

The sensitivity of the Arecibo instrument is what sets it apart from all other incoherent scatter radars and makes it the premier instrument for studying regions of the ionosphere from which the backscattered power is very low, like the D-region and the topside ionosphere. Arecibo is the only ISR that can routinely measure the incoherent scatter spectrum in the D-region to determine velocities, which in that region are closely coupled to the neutrals. Studies of the topside ionosphere above Arecibo in the 1990s led to the discovery of a nighttime helium ion layer, which occurs near the transition altitude between oxygen and hydrogen ions. The high sensitivity of the Arecibo radar has also made it possible to develop pulse-coding schemes that split the transmitted power into several frequency bands, equivalent to sampling the ionosphere with multiple radars. This technique has improved the accuracy of measurements in the F-region, which was especially needed for velocity measurements.

A second major upgrade of Arecibo took place in the 1990s. This upgrade involved the addition of a Gregorian feed system with secondary and tertiary reflectors to correct for the spherical aberration from the primary reflector. This allows for the use of wideband horn feeds instead of the narrow band linefeeds, thus extending the frequency range over which the telescope could operate. The Gregorian system contains several antennas, including a 430 MHz horn feed, which is used for both astronomy and aeronomy experiments. For aeronomy experiments, this antenna is connected to the 430 MHz transmitter, thus allowing for a second 430 MHz radar. This second radar is used quite extensively in a dual-beam configuration with the original linefeed antenna. The two feed systems move along opposite sides of the track located on the azimuth arm. Thus they

Figure 3

The Arecibo Observatory, National Astronomy and Ionosphere Center.

have oppositely directed horizontal components of their directional pointing vectors, but the angles from zenith are independently adjustable.

The dual-beam configuration is requested for most experiments, and it has turned the Arecibo ISR into a new instrument, which now can measure instantaneous 2-D velocities (at least one component of the electric field with high time resolution), horizontal fluxes and horizontal gradients of scalar ionospheric parameters like electron density and electron and ion temperatures. By keeping one beam vertical and the other rotating continuously in azimuth, it is possible to measure vertical electron densities (suitable for studies of layers and gravity wave effects), while the rotating beam provides 3-D ion velocities (and associated electric fields), and all other ionospheric parameters along the rotating line of sight direction.

Recent studies that exploit the large sensitivity of Arecibo are driving progress in the incoherent scatter theory in very specialized problems. For example, a theory including kinetic effects and the magnetic field is being developed to explain the asymmetry between the upshifted and downshifted components of the plasma line. The information from this asymmetry is very valuable as it can yield electron temperature, independent from the ion line, and even information about currents. Arecibo is the only ISR that can measure this asymmetry accurately enough as a function of altitude. Under very special conditions (very low electron densities and high temperatures), Arecibo can observe the true incoherent scattering spectrum at very high altitudes. A very interesting data set of this electron line from Arecibo shows that the present IS theory cannot explain those measurements. Research is also taking place to understand yet another portion of the incoherent spectrum, the electron gyroline.

The Arecibo Observatory also includes both passive and active optical instruments for studying upper atmospheric phenomenon. An optical building contains two tilting-filter photometers, an Ebert-Fastie Spectrometer, and two pressure-scanned Fabry-Perot Interferometers. Two all-sky imagers are also operated at the site. A separate lidar building houses a Potassium Doppler resonance lidars, a sodium/calcium resonance lidar, and a Doppler Rayleigh-Mie lidar. The lidar building has four fully steerable, 80 cm diameter telescopes used as part of the lidar receiving system.

Taken together, the instruments at Arecibo provide information about the tropical atmosphere and ionosphere over an extended height range. The S-band transmitter has been used to observe turbulence in the stratosphere with a height resolution of 15 m. Lower atmospheric winds and turbulence have been studied using 46.8 and 430 MHz radio transmissions, revealing the spectral properties of the turbulence. Improved coding techniques have led to enhanced capabilities in E and F region backscatter observations. F-region drift measurements have been compared with Fabry-Perot Interferometer observations to study coupling between the ions and neutrals. Drift measurements have been extended to altitudes up to 2500 km where escaping hydrogen can be observed. The association between the sudden appearance of sporadic-E layers and intense sodium layers, detected with lidar, offers a key to solving problems related to middle atmosphere chemistry. The coded long-pulse technique for plasma line detection implemented at Arecibo yields highly accurate electron density measurements with 150 m range resolution in times as short as 12.5 sec. The coded long-pulse technique was especially useful for radar operations in conjunction with the HF heating facility. These experiments show the development of small-scale irregularities resulting from HF heating and exemplify the fundamental plasma physics studies that can be conducted using the combined facilities.

The Millstone Hill Observatory

The Millstone Hill Radar was built by MIT's Lincoln Laboratory in 1957 to 1958. Over the last five decades, Millstone Hill has evolved into a broad-based observatory capable of addressing a wide range of atmospheric science investigations in keeping with recommendations and support from the space science community. Millstone Hill's ISR facility has been supported by NSF since 1974 for studies of the earth's upper atmosphere and ionosphere. During that time, the facility has changed from a part-time research operation sharing radar cooling and power supply elements with the MIT Lincoln Laboratory Millstone satellite tracking radar to a separately funded, operationally independent system dedicated to upper atmospheric research.

The research facilities of the Millstone Hill Observatory, including the UHF radars, atmospheric optical equipment, and the Atmospheric Sciences buildings, are located in Westford, Massachusetts, and are owned and operated by MIT. The Atmospheric Sciences Group, which staffs and manages these facilities, is a part of MIT's Haystack Observatory, a basic research organization whose focus is radio wave and radar science, instrumentation, and techniques. The Haystack Observatory maintains a research and support staff of over 100 in several research groups. Major research areas are radio astronomy, very long baseline interferometry, and atmospheric science. The principal Haystack research instrumentation includes the Haystack and Westford radio telescopes and the Millstone Hill UHF radars (Figure 4). The Haystack Observatory facilities in Westford are co-located with those of several MIT Lincoln Laboratory field station programs but are administratively separate from them, although a mutually beneficial level of cooperation exists.

For atmospheric science, the Millstone Hill facility consists of a high powered UHF (440 MHz) radar system and associated computer, engineering, and analysis functions. The main components of the current UHF radar instrumentation are two 2.5 MW UHF transmitters, a zenith-directed 68 m fixed antenna constructed in 1962, a fully steerable 46 m antenna installed in 1978, and dedicated receiver and computer facilities. An advanced analysis capability has evolved among the facility staff in parallel with the radar hardware so that the data acquired can be quickly and efficiently processed, distributed, and analyzed.

The Millstone Hill Radar measures plasma drift velocities, electron and ion temperatures, electron densities, ion composition, and ion-neutral collision frequencies over an altitude range extending from less than 100 km to a thousand kilometers or more. Advanced waveform and analysis techniques have been developed that allow these measurements to be made with an altitude resolution of hundreds of meters. The facility is situated on a hilltop at 55º magnetic invariant latitude, such that its extensive field of view for ionospheric observations encompasses the full extent of mid-latitude, sub-auroral, and auroral features and processes. The location of Millstone Hill at the nominal latitude of the plasmapause and inner magnetosphere/plasmasphere boundary, combined with the wide reach of its steerable antenna (called MISA, for Millstone Hill Steerable Antenna) that covers a radius of more than 1500 km, have made it a premier facility for midlatitude ionosphere, magnetosphere, thermosphere, and space weather research. The complete radar steerability, combined with the wide visibility afforded by hilltop antenna locations, allows horizontal ionospheric gradients, structure, and vertical variations to be examined over much of eastern North America.

Scientific studies using the Millstone Hill radar have focused on the large- and small-scale structure of ionospheric plasma density, temperature, and velocity. Quiet time observations have been used for climatologies and long-term/short-term variability determinations. Measurements in periods of magnetic storms and substorms have yielded important information on microscale to mesoscale plasma irregularities and energy cascades, global and local electric field signatures, neutral wind storm surge and compositional differences, and magnetosphere-ionosphere coupling processes. Coordinated optical/radar measurements made with a Fabry-Perot interferometer at Millstone have been used for studies of vertical winds and neutral oxygen densities.

Recent work has significantly advanced our understanding of magnetosphere-ionosphere coupling and global plasma disturbance processes. These findings were made through examination of dusk-sector plasmasphere boundary-layer perturbations, storm-enhanced density plumes, electric fields driving the sub-auroral polarization stream, and severe total electron content gradients. Millstone Hill's observations and studies of these phenomena have had a large influence on the national space weather effort to better characterize and forecast ionospheric changes and their effects on human activities.

The Millstone Hill system is composed of a number of hardware and software elements that work in synergy to form a complete ISR. Hardware elements include antennas,

Figure 4

The Millstone Hill Observatory.

transmitters, control systems, receivers, and data processing computers. Software elements include control, signal processing, analysis, and engineering level debugging complements to hardware systems. Several generations of hardware are present in the system, from 1950s-era transmitters to modern radar control and analysis devices. Recent efforts have focused on a comprehensive fiber-optic-based modernization of the control systems, which will upgrade important communication paths driving the transmit/receive switch, antenna controller, and noise-injection subsystems. Following this effort, staged upgrades of the timing system, control elements, antenna controller, and control software will occur that take direct advantage of fiber-optic links.

Millstone Hill's transmitter systems are stable following the successful salvage of Litton 5773 klystrons from Clear Air Force Base, Alaska, the return of transmitter U1 to regular operations, and the implementation of new, remotely monitored peak-power measurement systems. Improvements to the physical infrastructure and control systems of the 46 m MISA antenna are also underway.

Recent work on receiver systems has focused on a software radar architecture, in which digital receivers perform down-conversion, detection, and signal processing operations in software on general-purpose computers. The flexibility of the software radar paradigm has yielded significant advantages in accomplishing the core goal of long-term, production-quality processing of ISR signals, from RF down-conversion through a signal chain, yielding final fitted physical ionospheric parameters. Tool sets for capturing, manipulating, and processing voltage-level radar data have been created, including software-based correlation, waveform decoding, and lag profile matrix generation. Significant calibration, monitoring, and debugging programs have also been developed. The INSCAL analysis program, which has a more than 25 year history at Millstone, is used to analyze lag-profile matrix products in command/status format in order to produce fitted results.

Computing resources include a gigabit-networked cluster computer shared with the Air Force Office of Scientific Research–sponsored Intercepted Signals for Ionospheric Science project. The computer has an aggregate sustained 30-giga-complex floating-point operation rate and 30-terabyte storage capability. These resources allow Millstone Hill to retain voltage-level data for all experiments since the software radar first came online in late 2001. Considerable flexibility is maintained since the received voltages encapsulate all information about the returned scattering process, allowing future reanalysis of experiments with different resolution and statistical variance tradeoffs (e.g., for short-duration event studies). The creation, debugging, and execution of the MIDAS-W Software Radar production-level software occurs in an open-source framework through the Open Radar Initiative.

A key infrastructure component to the Millstone Hill radar is the Madrigal database system, first developed at MIT Haystack in 1980. Madrigal encompasses ground-based measurements and models of the upper atmosphere and ionosphere, and has close ties to the Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) database at the National Center for Atmospheric Research. It has evolved into a robust, web-based distributed system capable of managing and serving archival and real-time data from a wide variety of CEDAR instruments, including the Millstone Hill ISR. Since the web interface became operational in 1994, Madrigal data have been downloaded to several hundred external computers. A key feature is the seamless integration of real-time and archival data, with the same user interface for either type. Data are arranged into "experiments," which may contain data files, images, documentation, links, and other items. In particular, almost all Millstone Hill radar experiments since 1976 are available online (over 1000 experiments), along with many measurements by other instruments.

Results from the Millstone Hill INSCAL fitting program, the final step in the ISR signal chain, are placed directly into the Madrigal system, whether in real-time or in retrospective analysis mode, and are immediately available to users. User interfaces available include a standard table-based text output ("isprint") and a new interactive plotting capability. Application programming interfaces are also available in the MATLAB and Python languages, which allow direct access to Madrigal data files from any computer on the internet through any Madrigal database website. Madrigal database sites are now hosted by each of the UAF radar facilities and internationally by many U.S., European, and Asian groups. Another recent development employing the Madrigal interfaces is the production of empirical radar models of several ISR systems using archived data, yielding virtual radars that can be queried to predict conditions for a given set of geophysical and geomagnetic parameters. Madrigal development is conducted in an open-source manner. It is freely accessible to community participation, with a central website, a complete archive of all Madrigal software, mailing lists, and user forums.

The Sondrestrom Radar Facility

The Sondrestrom Radar was built by SRI International in the late 1960s with funding from the Defense Nuclear Agency. Designed to be portable, the radar was moved in 1971 from its site on the Stanford University campus in California to Chatanika, Alaska. After more than ten years of operation in Alaska, the radar was moved to Greenland to perform observations at even higher magnetic latitudes where comprehensive measurements were almost nonexistent. Many of the scientific studies conducted at Sondrestrom are concerned with electrodynamic coupling between the magnetosphere and ionosphere. The site is host to an extensive array of atmospheric remote sensing instruments and many other instruments have been deployed there on a temporary basis in connection with various campaigns.

The Sondrestrom Radar Facility, shown in Figure 5, is located just north of the Arctic Circle on the west coast of Greenland near the town of Kangerlussuaq. Its geomagnetic location of 72.6° puts it near the poleward boundary of the nighttime auroral oval and under the noontime cusp/cleft region for what is considered average magnetic activity. The facility currently hosts and supports 27 instruments from 19 institutions. These instruments contribute to many disciplines besides aeronomy—from cryospheric research of the ice mass balance and crust deformation (using the absolute gravimeter and solid-earth GPS instruments) to the deterrence of nuclear proliferation (using the seismograph, which is part of a UN-based global network). The many instruments that are complementary to the ISR measurements have contributed greatly to studies of ionosphere-magnetosphere coupling, aeronomy, E-region electrodynamics and neutral dynamics, ion upflow, and to identifying ionospheric signatures of magnetospheric boundaries.

The facility's ISR consists of an L-band transmitter, normally operated at 3 MW peak power, a 32 m parabolic fully steerable dish antenna, and three receiver channels (currently being expanded to six). The transmit frequencies are 1290.0 and 1290.6 MHz (wavelength=0.2323m). The pulse length can be from 2 to 500 μs, and the klystron duty cycle is 3 percent. The full-width half-power antenna beamwidth is 0.5°, which is roughly 1 km in the E region and 3.5 km at the average peak of the F region. The receiver has a system temperature of ~80K. Bi-phase coding of the transmitted waveforms and associated signal processing allow for range resolutions down to 150 m. Typical E-region measurements provide full plasma-parameter profiles with 3 km range resolution. F-region measurements are typically made with 48 km range resolution and can provide coverage from 69–80° invariant latitude. The elevation limit of the fully steerable antenna is 25–30°, depending on the azimuth. The look angle anti-parallel to the magnetic field in the F region is 80.4° elevation and 141° azimuth, making measurements along the field line routine. Table 2 shows the parameters that can be directly or indirectly measured with the Sondrestrom Radar.

In recent years, the Sondrestrom ISR has averaged over 160 hours of data per month. Of these 2000 hours/year, 37 percent of the operations have been in support of the Incoherent Scatter Coordinated Observation Day (or World Days) and the vast bulk of the remainder has been at the request of the user community. Each winter season, the facility crew hosts optical campaigns, which it provides with logistical and engineering support as well as ISR operations. These ISR runs are tailored to meet the needs of the user.

Because of Sondrestrom's location under the boundary between the nighttime auroral oval and polar cap, the ISR data, alone and coupled with optical measurements, have been instrumental in studies of magnetosphere-ionosphere coupling. Examples include studies of E-region electrodynamics, auroral precipitation, and Joule heating.

Many of the solar-wind effects that are global begin in the

Figure 5

The Sondrestrom Radar Facility.

Polar Regions. As the northernmost link in the UAF chain, Sondrestrom's measurements of the F-region convection over ~12° of latitude have been a valuable contribution to many studies involving the global response to changes in the solar-wind parameters. Increases in convection strength quickly penetrate equatorward of the equatorial boundary of the plasma sheet (prompt penetration electric fields) causing low-latitude plasma drifts as measured by other ISRs. Studies of magnetospheric boundaries and their manifestation in the ionosphere have been conducted with the ISR during spacecraft conjunctions (e.g., ISTP, TIMED, DMSP, Cluster). Many of these operations have been coordinated with the EISCAT radars and the Millstone Hill ISR.

The inclusion of other CEDAR-funded instruments at Sondrestrom showed the importance of clustering complementary instrumentation at a facility. This has allowed for high-time resolution studies of auroral arcs with hyper-spectral imaging of small-scale structures, as well as simultaneous lidar and radar measurements of the formation of high-latitude metallic, sporadic E and sodium layers.

Table 2. List of ISR observables and derived quantities.

Parameter
E & F Regions (90 to 800 km)
Electron density
Ion temperature
Electron temperature
Ion line-of-sight velocity
Ion velocity vector
Hall conductivity
Pedersen conductivity
Passive energy deposition rate
F Region (> 200 km)
Plasma drift velocity
Electric field
Meridional neutral wind
Ion composition
E Region (90 to 150 km)
Current density
Electromagnetic energy transfer rate
Joule heating rate
Mechanical energy transfer rate
Neutral winds (90–120 km)
Ion Neutral collision frequency
Differential number flux spectra
Total energy flux
Characteristic energy
Photoelectron flux

SuperDARN

SuperDARN is a network of HF Doppler radars located in the high-latitude regions of the northern and southern hemispheres, developed in collaboration with scientists from ten countries. The radars are sensitive to backscatter from ionospheric electron density irregularities. Their primary data products are the drift velocity of the irregularities and the magnitude and direction of the ionospheric electric field that produces this drift. SuperDARN is the only experiment technique currently available that can provide continuous observations of the high-latitude electric field. SuperDARN data are used routinely to produce maps of the high-latitude convection pattern driven by magnetospheric forcing. These maps are an essential tool in modeling the electrodynamics of the ionosphere and estimating electrojet currents and Joule heating.

The origin of SuperDARN can be traced to the construction of the first HF radar in Goose Bay, Labrador, Canada, by JHU/APL in 1983. Financial support was provided by NSF and the Air Force Office of Scientific Research, while building assistance was provided by the Air Force Geophysics Laboratory. This instrument employed phased-array technology and sophisticated multipulse sounding techniques and became the model for subsequent HF radar development; it remains in operation as an important element in SuperDARN. The system has relatively low power requirements and is inexpensive to build and operate. It utilizes refraction in the ionosphere at frequencies between 8 and 20 MHz to generate backscatter from long ranges and runs automatically and continuously according to a pre-set schedule.

The second HF radar was constructed at Halley Station, Antarctica, by the British Antarctic Survey (with assistance from JHU/APL and NSF) in 1987 with a field of view magnetically conjugate to that of the Goose Bay radar. Together, these instruments produced the first simultaneous, conjugate images of the reconfiguration of ionospheric plasma convection following a change in the orientation of the interplanetary magnetic field (IMF) (Greenwald et al. 1990). At a meeting of international scientists in 1991 at JHU/APL it was agreed to form the SuperDARN consortium to pursue the development of additional HF radars in both hemispheres. Within two years research initiatives had been funded in Canada, France, Japan, the United Kingdom, and the United States. The first new radars of the SuperDARN era came online in 1993. More countries have since joined the effort and new radars continue to be built. The concept of the SuperDARN collaboration was described by Greenwald et al. (1995). A comprehensive review of the scientific accomplishments of

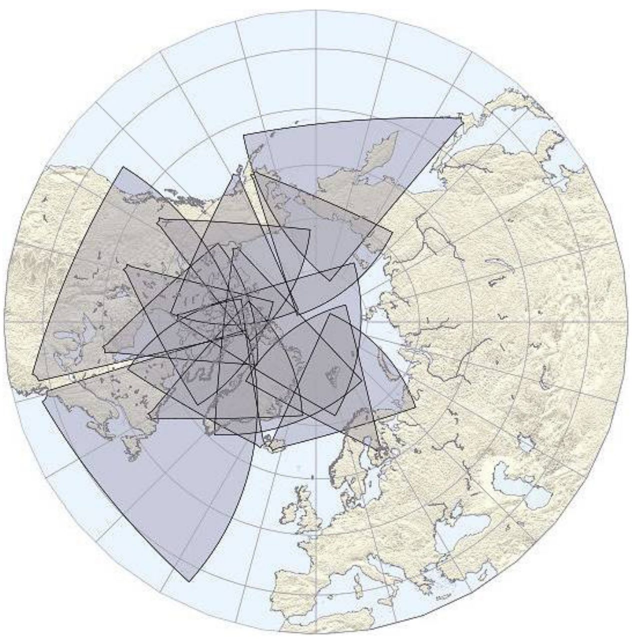
SuperDARN has recently been published by Chisham et al. (2007).

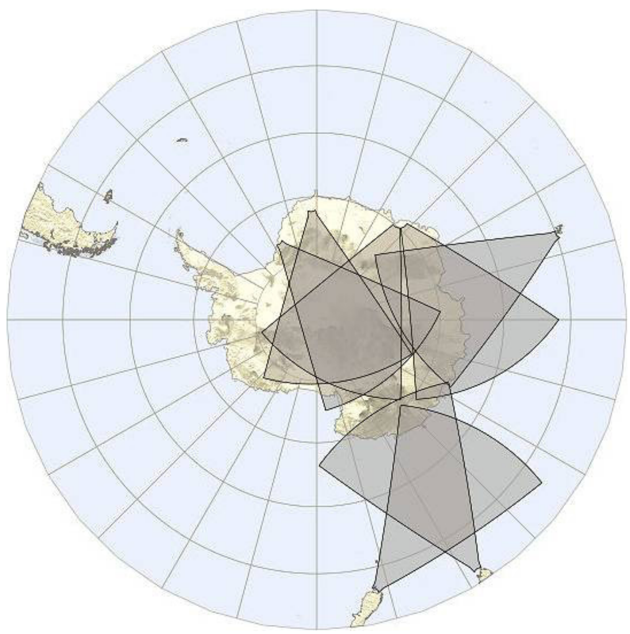
The original concept of SuperDARN was for chains of radars at high latitudes with fields of view that overlapped in the auroral zone. Within the past few years this has expanded to include a common-volume pair of radars at polar latitudes and three thus far unpaired radars at mid-latitudes (two in the state of Virginia and one on the Japanese island of Hokkaido). The current distribution of radars is shown in Figure 6. There are a total of fourteen SuperDARN radars operating in the northern hemisphere and seven in the southern hemisphere. Within the UAF program, NSF has traditionally supported the operation of the radar at Goose Bay and another at Kapuskasing, Ontario, Canada, and related scientific activities centered at JHU/APL. Data from all the radars are distributed to the entire SuperDARN community so that U.S. scientists have access to the full set of data products through liaison with the UAF-supported SuperDARN facility. Radar operation and data formats are standardized across SuperDARN to ensure compatibility and key software is maintained at JHU/APL. Once a year, the SuperDARN groups gather for a one-week meeting to discuss science topics, radar techniques, and future operations. Improvements developed by the individual groups are often introduced and disseminated to the wider SuperDARN community.

In 2005 the JHU/APL group built a new radar at Wallops Island in cooperation with NASA/Goddard Space Flight Center. This was the first SuperDARN radar constructed at mid-latitudes and it features several significant modifications to the antenna design and control electronics. Japanese colleagues followed by building the Hokkaido radar in 2006. The success of these instruments spurred discussion of the value of a second radar in Virginia and a collaboration was formed between JHU/APL, Virginia Tech, and the University of Leicester to build a radar at Blackstone. This radar, which became operational in February 2008, complements Wallops by providing coverage over central North America. The management of the Wallops and Blackstone radars has been added to the program of the UAF SuperDARN facility.

It should be noted that the UAF SuperDARN group is undergoing an important transition. Upon the retirement of the SuperDARN principal investigator (PI) from JHU/APL in February, 2008, a new PI was appointed and it was agreed by JHU/APL and Virginia Tech that the main part of the scientific SuperDARN staff will move to Virginia Tech and that the cooperative agreement that funds the UAF SuperDARN facility will transfer with it. Activities in support of SuperDARN at JHU/APL will continue to be funded under a subcontract from Virginia Tech. Thus, in the future, the UAF SuperDARN facility will consist of two groups, one sited at Virginia Tech and the other at JHU/APL. The activities of the UAF SuperDARN facility will expand greatly in the areas of education and training while the vital centralizing role traditionally played by the UAF

Figure 6





SuperDARN Network.

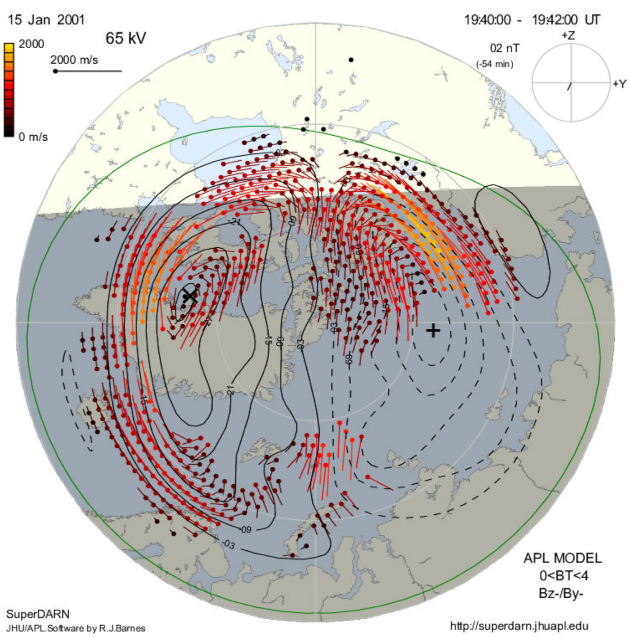
facility in SuperDARN will be preserved between the two institutions.

The primary goal of the SuperDARN radars is to obtain line-of-sight Doppler information from at least two viewing directions in order to make accurate determinations of the convection velocity of the ionospheric plasma within the common volume. Another goal is to cover as much of the high-latitude zone as possible so as to capture the larger picture of plasma convection. Analytic procedures have been developed at JHU/APL to incorporate the SuperDARN data into hemispheric maps of the ionospheric convection (Ruohoniemi and Baker 1998; Shepherd and Ruohomiemi 2000). The SuperDARN convection maps are generated routinely and posted to the JHU/APL website, both for analysis at JHU/APL and as a service to the community. Figure 7 shows an example. The line-of-sight velocities from the radars have been fitted to an expansion of the electrostatic potential function in terms of spherical harmonic functions. The contours show the "best-fit" for the distribution of electrostatic potential, with the velocity vectors indicating the locations of supporting velocity measurements. The convection conforms to a two-cell pattern that is characteristic of southward IMF. The total cross-polar-cap potential variation is 65 kV. SuperDARN is the only technique for imaging the instantaneous pattern of convection on global scales using direct measurements of the plasma drift. A space weather "nowcast" of the current convection pattern is posted at the JHU/APL SuperDARN website, which also includes links to the individual radars and to SuperDARN data products of interest to the wider research community.

In addition to their use in studying ionospheric convection, the SuperDARN data are being used to better understand Joule heating, magnetic conjugacy, ULF pulsations, M-I coupling, and auroral substorms, and to develop comprehensive models of ionospheric and magnetospheric processes. Unexpectedly, it has turned out that important topics in atmospheric research can be addressed with secondary HF data products. These include the propagation of atmospheric gravity waves that produce detectable perturbations to the ionospheric layers and neutral winds at mesospheric heights, which are measured by their effect on backscatter from meteor trails.

SuperDARN is expected to continue to grow with the addition of new radars. There are plans to extend the high latitude chains in both hemispheres. The heightened interest in polar cap processes that will accompany the relocation of AMISR to Resolute Bay has spurred consideration of a third polar SuperDARN radar. At mid-latitudes there are efforts to assemble a longitudinal chain of common volume radar pairs that will extend global-scale SuperDARN coverage from the pole to the inner magnetosphere.

Figure 7



Convection map derived from SuperDARN.

The Advanced Modular Incoherent Scatter Radar (AMISR)

AMISR is the first incoherent scatter radar built with NSF funding. Based on solid-state transmitter technology and modular, phased-array antennas, the design allows for easy and cost-effective relocation of the radar. Ideally, a global array of ISRs is needed to provide the comprehensive measurements necessary to study the wide range of temporally and spatially varying ionospheric phenomena. Because such an array is not practical, a modular system allows the radar to be dismantled and moved to locations selected on the basis of current scientific priorities.

AMISR uses a phased array of dipole antennas, each driven by a 500 watt, solid-state transmitter that can operate between 430 and 450 MHz. The phased-array design and solid-state circuitry allow instantaneous beam swinging on a pulse-to-pulse basis. The fundamental building block of AMISR is a panel measuring approximately 2 m by 4 m in size and containing 32 solid-state, transmit/receive units. Panels can be assembled in many different configurations, with a minimum of 16 necessary for incoherent scatter observations.

AMISR will initially consist of three independent antenna faces deployed in two locations: Poker Flat, Alaska, and Resolute Bay, Nunavut, in northern Canada. Each of these antenna faces will have a sensitivity roughly twice that of the Sondrestrom Radar. The field of view of a single face is approximately a cone with a radius of about 25°. In Alaska, the face is canted toward the north to better cover the portion of the ionosphere beneath the trajectories of sounding rockets launched from Poker Flat. At Resolute Bay, the two faces will be canted in the north and south directions for extended coverage of the polar cap. The radar at Poker Flat, Alaska, began scientific operations in January 2007 (Figure 8). The first face at Resolute Bay is currently under construction and will be operational by the end of 2008.

Generally, the AMISR system at Poker Flat (the Poker Flat Incoherent Scatter Radar, or PFISR) will be used to investigate auroral processes, such as the origin and nature of auroral arcs, diffuse aurora, pulsating aurora, and westward traveling surges. The radar measures the height profile of ionospheric properties, which can be used to study energy balance in the upper atmosphere and the exchange of mass and energy between the thermosphere and magnetosphere. The location at Poker Flat is also ideal for studying the auroral electrojet and how the high latitude ionosphere is electrodynamically coupled to the solar wind and magnetosphere. Whenever possible, PFISR observations are coordinated with launches of sounding rockets from the rocket range. In addition to the existing optical equipment at Poker Flat, a suite of new instruments has been deployed to operate in conjunction with PFISR. These include, Fabry-Perot Interferometers, all-sky cameras, and spectrometers. These facility-class instruments will provide radar users with an extensive array of diagnostic measurements in addition to the AMISR observations.

At Resolute Bay, the AMISR system (the Resolute Incoherent Scatter Radar or RISR) will observe polar cap arcs and how they relate to and reflect the magnetic structure of the magnetosphere. The development and motion of polar auroral forms are intricately tied to variations in the solar wind. The electric fields in the polar cap are also a direct consequence of magnetic coupling to the solar wind. RISR will observe the polar wind, which is an important source of ionospheric ions in the magnetosphere. Ionospheric structures observed by RISR will be used to study the origin and evolution of large-scale plasma clouds that originate in the dayside and are convected anti-sunward across the poles. This large-scale plasma structure is related to small-scale structure that produces scintillation of radio signals.

AMISR represents a huge leap forward in ISR design. It not only features instantaneous beam steering and modularity. Its solid-state design also enables remote operation using a laptop computer. This makes AMISR not only convenient for radar experimenters, but also an excellent resource for teaching and demonstrating incoherent scatter techniques to students.

Facility Management and Review

The operation of the upper atmospheric facilities is supported by NSF through cooperative agreements with institutions awarded five years of support on the basis of successful peer review of unsolicited proposals. In addition to the standard NSF review criteria, reviewers are asked to address the following issues related to how the scientific community uses the facility.

1) Quality of science enabled by the facility and quality of science conducted by facility staff.

2) Ability to maintain and operate instrumentation as a national facility

3) Quality of the data provided by the facility

4) Effectiveness of procedures to disseminate the data to scientific users

5) Extent to which the data are being used for research

Figure 8

AMISR at Poker Flat.

6) Effectiveness of programs to educate prospective users of facility data, students, and the general public

7) Scientific leadership demonstrated by the facility staff

Cooperative agreements for the operation of facilities contain special requirements to ensure the institutions operating facilities are aware of the responsibilities they have in meeting community expectations. All of the facility cooperative agreements have five-year durations. Institutions submit annual reports to NSF for approval prior to receiving fiscal-year funding increments. The annual reports contain descriptions of scientific and technical accomplishments during the previous year and a plan for operations and science during the next year.

In addition to being reviewed upon submission of proposals, the facilities have undergone two comprehensive reviews, the first in 1996 and the second in 2003. In each of these reviews, NSF selected a panel of five or six external reviewers that traveled to each of the facilities. During the two-day site visits, the panel toured the facilities and heard a series of presentations on facility accomplishments, status, and plans. After all the site visits were complete, the panels submitted reports of their findings to NSF. The results of the review were used by NSF in subsequent discussions with the operating institutions to ensure that issues raised were promptly and effectively addressed. In some cases, a facility's response to the panel findings was used in the evaluation of its proposal for continued funding. The most recent site visit panel recommended the development of an integrated science plan for the facilities. Keeping to an approximate seven-year interval between site visit reviews, the next all-facility-site-visit panel review will begin in 2010.

An important aspect of facility management is coordinating scientific and technical activities among the institutions and personnel involved in operating the sites. This is primarily accomplished through three- or four-day workshops wherein facility staff members meet and exchange information. Three such workshops have been held in the last 12 years. The last workshop was in September, 2008 and the next is planned for 2010.

Table 3 shows a timetable for facility review activity over the next nine years.

Table 3: Timetable for facility review activities.

Event	2008	2009	2010	2011	2012	2013	2014	2015	2016
All-Hands Facility Meeting									
All-Facility Site Visit Review									
Millstone Hill Renewal									
Sondestrom Renewal									
SuperDARN Renewal									
Jicamarca Renewal									
Arecibo Renewal									
AMISR Renewal									

The mission of the UAF Program is to enable basic research into the structure and dynamics of the Earth's upper atmosphere, ionosphere, and magnetosphere by supporting the development, operation, and maintenance of large ground-based observatories. The program began with a core group of ISRs but has grown to include the U.S. contribution to the SuperDARN radars and the AMISR.

Throughout the years, the upper atmospheric facilities have participated in numerous scientific campaigns and research activities. Not only are the data from facilities critical to addressing science problems, but facility scientists are important as well for leading these efforts and demonstrating the use of facility data. As a consequence, facilities have built up a staff of outstanding scientists with extensive experience in many areas of research.

Rather than attempting to review all the contributions the facilities have made in the past three decades, the following sections include examples of ways in which the facilities have demonstrated scientific leadership in high-priority research areas and set the stage for future advancements in knowledge and understanding.

Ionospheric Irregularities

When sufficient free energy builds in the ionosphere, the spontaneous generation of plasma waves and irregularities can occur through the formation of plasma instabilities. Plasma irregularities are observed at all latitudes and altitude regimes in the ionosphere (including the D region, where they occur as byproducts of neutral atmospheric instabilities and turbulence) and exhibit a range of scale sizes, from centimeters to hundreds of kilometers. In and above the E region, irregularities are highly elongated along the Earth's magnetic field lines and can give rise to intense radar backscatter when the Bragg scattering condition is satisfied. Such backscatter is termed "coherent' to differentiate it from the generally much weaker incoherent scatter that the original upper atmospheric facilities were designed to detect.

Ionospheric plasma instabilities are driven mainly by inhomogeneity in configuration space (conductivity gradients) or in phase space (currents). Examples of each, respectively, are the gradient drift and Farley Buneman instabilities known to operate in the equatorial electrojet, midlatitude sporadic E layers, and the auroral electrojet. In the equatorial and auroral F regions, closely related Rayleigh Taylor and **ExB**/current convective instabilities are responsible for irregularity production. Several other instability processes are also at work. The instability mechanism responsible for midlatitude spread F, so-called "150 km" echoes seen in the equatorial valley region, and "quasiperiodic" echoes from the midlatitude E region, remain subjects of debate. While some instabilities produce plasma waves directly at the scale required for coherent scatter, others preferentially excite large-scale waves, which then transfer energy to smaller scales via nonlinear mode coupling and/or turbulent cascades.

Plasma irregularities are of interest for three main reasons. First, they provide radar targets of opportunity, making it possible to remotely sense extensive regions of the ionosphere using relatively low-power radar systems. Using different techniques, plasma drifts, number densities, electron temperatures, neutral winds, and gravity wave parameters can be estimated from characteristics of the backscatter. Second, the irregularities provide a window into microphysical processes in the ionosphere, since the properties of the radar backscatter are, in some circumstances, indicative of processes occurring at the scale of the radar scattering wavelength. Third, plasma irregularities act like a diffraction screen for communication and navigation signals passing through the ionosphere, and the associated radio scintillations constitute hazards for critical human activity. They are a major component of ionospheric space weather and must be understood if they are to be anticipated and mitigated.

Ionospheric irregularities that can be utilized by radio scientists for ionospheric diagnostics include specular meteor trails, equatorial 150 km echoes, and irregularities in the equatorial and auroral electrojet, among others. The most important targets of opportunity for the aeronomy community, however, are the F region auroral zone irregularities from which the SuperDARN radars receive backscatter. These irregularities are generated by **ExB** and current convective instabilities and give rise to strong radar backscatter at high frequencies. Their Doppler shift is taken to be a good approximation of the line-of-sight **ExB** drift speed and, consequently, a good indication of one component of the electric field. High frequencies are used because the condition for field-aligned backscatter from the F region can generally be satisfied only with the aid of significant refraction.

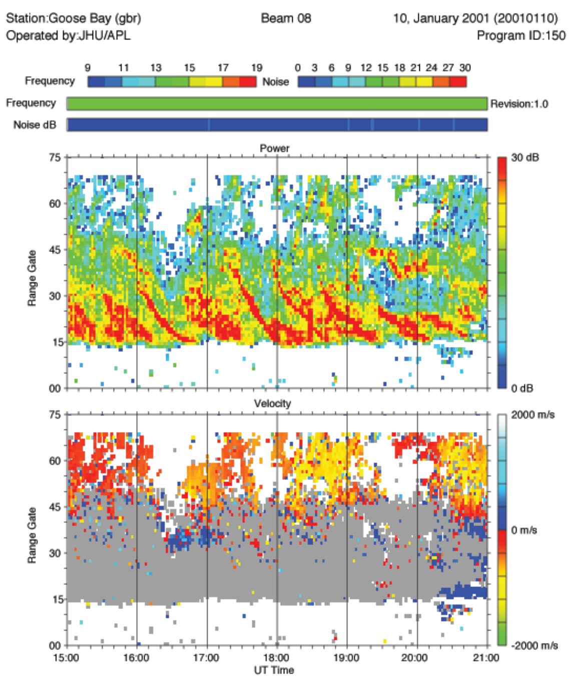
Figure 9 shows sample backscatter data collected with the SuperDARN HF radar located at Goose Bay, Labrador. The observations were made on January 10, 2001, during the 15–21 Universal Time (UT) interval. The radar scans in azimuth through 16 distinct beam directions; for a central beam that was directed somewhat east of magnetic north the figure shows range-time-parameter plots of the backscattered power in dB (upper panel) and Doppler velocity in meters/second (lower panel). The velocity data are color coded with red and yellow indicating motion away from the radar. The gray-colored velocity data represent backscatter from the terrestrial surface (“ground scatter”) that is generated after an HF signal is refracted downward by the ionosphere.

A comparison of the power and velocity maps in this example indicates that the ground scatter is dominated by trains of backscattered power enhancements that move closer to the radar with time. These are due to atmospheric gravity waves that propagate away from the auroral zone and perturb the layers of the ionosphere in a manner that alternately focuses and defocuses the backscattered signal with range. At greater ranges, the backscatter is dominated by returns from decameter-scale irregularities in the F region ionosphere. Processes of plasma instability have amplified the irregularities to amplitudes far above those of the thermal fluctuations in the ambient plasma, which made them visible to the relatively low-power HF radar as targets for coherent backscattering. The irregularities are carried along by the **ExB** drift of the plasma. The Doppler velocity measurements characterize the plasma convection. The gravity wave activity viewed in the ground scatter can often be traced back to activations of the high-latitude convection seen in the irregularity backscatter data.

Unlike the echoes detected by SuperDARN, coherent echoes from directly driven Farley-Buneman waves (so-called type I echoes) do not have Doppler shifts equal to the line-of-sight electron drift speed. Instead, the Doppler shifts are related to the ion acoustic speed, which can therefore be estimated via remote sensing. In addition to serving as diagnostics of the ionospheric plasma, however, Farley-Buneman waves also modify the ionosphere through wave heating. An empirical relationship between the driving-convection electric field and the elevated ion-acoustic speed in the auroral E region has been established by experiments at EISCAT and at Millstone Hill. At Millstone, F region drifts are measured using incoherent scatter, and E region coherent echo Doppler shifts are measured on the same magnetic flux tube simultaneously through a sidelobe in the radiation pattern. Example data are reproduced in Figure 10, which shows how both the intensity and the Doppler shifts of the coherent scatter vary with convection strength (Foster and Erickson 2000). Numerical simulations by a number of research groups are helping to place these empirical laws on firm theoretical ground.

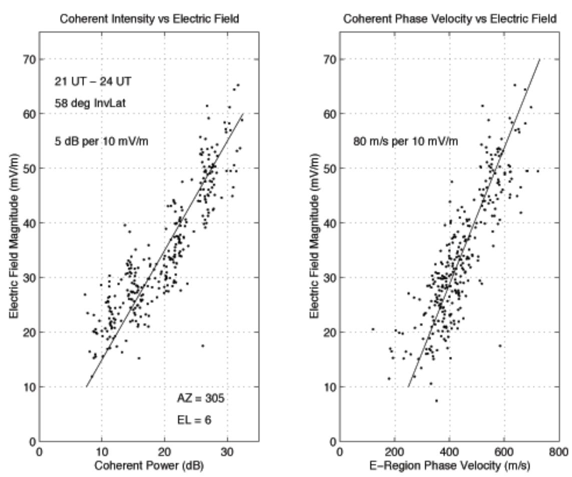
Wave heating is thought to be mainly due to the small-scale, parallel electric fields produced by Farley-Buneman waves. Together with Joule heating, wave heating represents an important mechanism for dissipating energy of magnetospheric origin in the ionosphere. Farley Buneman waves concentrate at the edges of auroral arcs and are highly variable in space and time. Also, under conditions of strong-convection electric fields, electron temperature in the ionospheric E-region (100–130 km altitude range) can be significantly increased due to Farley-Buneman two-stream plasma instabilities. This effect, which is often called anomalous electron heating, correlates with the magnitude of the electric field and has been previously demonstrated in numerous radar observations. Milikh et al. (2005) found that anomalous electron heating also leads to an increase in electron densities at altitudes of ~110 km due to suppression of recombination rates. Comparison of theoretical models of anomalous electron heating with experiment data obtained by the Sondrestrom ISR showed good agreement. This is the first reported case of an increase in electron density during a naturally

Figure 9



Time series of data from 15–21 UT collected on a central beam of the Goose Bay radar. The upper plot shows backscattered power, the lower plot velocity. The ground scatter contains trains of power enhancements that are due to equatorward propagating gravity waves in the neutral atmosphere. These are launched by surges in the high-latitude convection, which the radar monitors by virtue of the irregularity backscatter (color-coded in the velocity plot).

Figure 10



Scatter plot of logarithmic coherent power in dB and two-stream irregularity-phase velocity versus electric-field magnitude, derived from simultaneous E-region irregularity and F-region plasma-parameter observations at UHF using Millstone Hill on August 27, 1998.

occurring event, although the effects of electron heating on ionization/recombination balance were established in several active ionospheric modification experiments during the 1980s. Such increases in the ionospheric electron density and ionospheric conductance due to anomalous electron heating can have significant effects on the whole ionosphere-magnetosphere system.

Another example of ionospheric irregularities studied with ISRs is spread F. Spread F involves a drastic reconfiguration of the post-sunset F layer accompanied by the production of an intense, broadband spectrum of ionospheric irregularities. The irregularities act like a diffraction screen and are known to disrupt satellite communications and navigation systems, terrestrial communication links, ionospheric sounders (from which the “spread” terminology is derived), and space-based remote sensing systems such as synthetic aperture radar (SAR). While spread F is affected by geomagnetic activity, it can occur during geophysically quiet periods and exhibits considerable, unexplained variability. Mitigating and eventually anticipating the effects of spread F are key objectives of the National Space Weather Program.

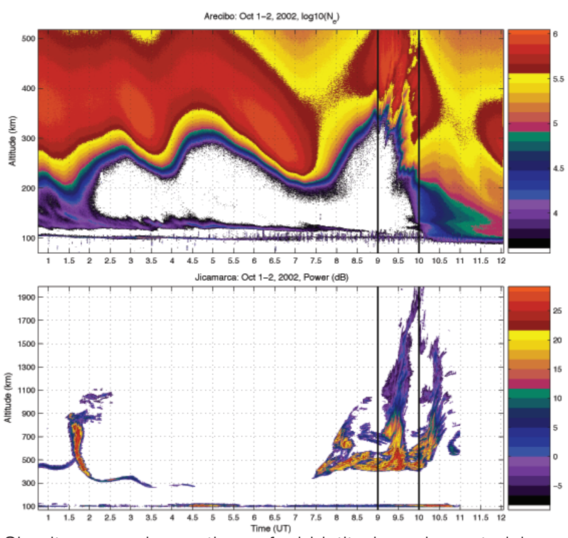
Equatorial spread F is known to be caused by Rayleigh-Taylor-type plasma instabilities acting on the steep bottomside F region-density gradient that forms after sunset. Large-scale waves with wavelengths of tens to hundreds of km are generated directly. A spectrum of irregularities is then produced through nonlinear mode coupling that extends to cm wavelengths. The irregularities are highly field aligned and are known to rise, sometimes at supersonic speeds, to magnetic apex altitudes of 2000 km. While spread F onset occurs immediately after sunset, a special class of irregularities is observed prior to sunrise on magnetically disturbed days. The longitudinal, seasonal, solar-flux, and storm-time climatology of equatorial spread F is well established. Considerably less is known about midlatitude spread F since there is no consensus regarding even the main plasma instability at work. Radar observations of the phenomena have been made mainly at Arecibo and with the middle and upper atmosphere (MU) radar in Kyoto, Japan. Spread F occurs mainly on summer nights during low solar-flux periods and is phenomenologically related to the occurrence of strong traveling ionospheric disturbances.

A revealing example of simultaneous equatorial and midlatitude spread F events recorded at Jicamarca and Arecibo is shown in Figure 11. This figure depicts a disturbed day when Kp was as high as 7+. Incorporating GPS data into their analysis, Nicolls et al. (2004b) showed that the midlatitude event was associated with the passage of multiple traveling ionospheric disturbances (TIDs) propagating equatorward from the auroral zone. It is likely that the presunrise equatorial event was triggered by disturbance dynamo-enhanced electric fields. The equatorial plasma irregularities reached altitudes within a few hundred km of the flux tubes intercepted by the irregularities at midlatitudes. The relationship, if any, between midlatitude and equatorial spread F remains a topic of investigation and debate.

Another type of ionospheric irregularity is associated with medium-scale (50–1000 km horizontal wavelengths) traveling ionospheric disturbances (MSTIDs), which have been studied for decades using ionosondes. These are to be distinguished from large-scale TIDs, which are thought to be generated in the auroral oval and to propagate equatorward at high velocity. The main effect of the latter is to push plasma up and down magnetic field lines. A recent spectacular example of this, using Arecibo data, has been published by Nicolls et al. (2004b). MSTIDs propagate to the southwest in the northern hemisphere at relatively slow velocities in the range of 50–100 m/s, and they are usually highly electrified. The first dynamical study of this phenomenon was done at Arecibo by Behnke (1979) who reported an electric field of 17 mV/m internal to the structure. This field corresponds to a plasma velocity perpendicular to the magnetic field of over 400 m/s. Little subsequent progress was made until imagers were fielded at Arecibo and later in Japan to provide a two-dimensional context within which to interpret radar and satellite data. It was verified that plasma uplifts accompanied the internal electric field structure and that the field was often many times the background electric field (Kelley et al. 2000).

Many mysteries remain, including a complete theory for the process. The only theoretical framework that exists is the linear theory of Perkins (1973) which has many flawed predictions. The one surviving prediction, though, is the preferred propagation direction. This is such a powerful result that the theory remains in favor. A key to the solution of this problem may lie in its inherent three-dimensionality. As plasma is pushed up perpendicular to the magnetic field

Figure 11



Simultaneous observations of mid-latitude and equatorial spread F events observed, respectively, at the Arecibo and Jicamarca Radio Observatories. Arecibo was used to observe incoherent scatter, which conveyed information about large-scale wave activity, whereas Jicamarca observed coherent scatter from small-scale (3 m) irregularities serving as tracers of the flow.

it must begin to fall down the field to the north. Meanwhile, the structure is propagating toward the west. Unfortunately, no one has yet attempted a three-dimensional version of Perkin's calculation, although computer power is probably close to being adequate. Likewise, the sources of these structures are not understood.

Despite many years of investigation, fundamental problems regarding the interpretation of coherent scatter persist. Coherent scatter spectra are not rigorously related to state variables in the plasma, and the relationships between the spectral moments and background ionospheric parameters are tentative. First-principles theories for interpreting the spectra are undeveloped. It is unknown precisely how or why echoes from Farley Buneman waves are indicative of the ion-acoustic speed, for example. Nor is it clear what backscatter spectra from spread F irregularities signify about the dynamics. The mechanisms responsible for midlatitude irregularities and 150 km echoes themselves remain unidentified. Future collocation of coherent and incoherent scatter radars and other instruments is the most promising avenue toward progress in these areas. The relocatable AMISR systems will therefore play a significant role. Other actively researched sources of enhanced backscatter include naturally enhanced ion-acoustic lines, first captured at Millstone Hill (Foster et al. 1988) and seen more recently with the EISCAT and PFISR radars. They are thought to be driven by some form of current instability but require more observation and analysis.

Lower Thermosphere–Ionosphere Coupling Studies

The long-running Lower Thermosphere–Ionosphere Coupling Study (LTCS) within the CEDAR program has focused on the very dynamic interface layer between the neutral and ionized atmosphere near 100 km altitude. In this region, electrons remain strongly attached to the background magnetic field, while ion-neutral collisions are sufficient to partially demagnetize ions. This results in charge separations leading to significant ambipolar electric fields that initiate powerful and complex feedback mechanisms between neutral winds and ion velocities, densities, and temperatures. ISR data, together with first-principles physical knowledge about the nature of ion-neutral coupling, have been instrumental in exploring the details of these mutually dependent influences. This is true in particular because ISRs can derive both zonal and meridional components of thermospheric winds at altitudes ~100–130 km, levels inaccessible in large extent to other ground-based (i.e., medium-frequency and meteor radars) and space-based observational techniques. Following are examples of contributions LTCS has made to understanding the coupling between ions and neutrals in the lower thermosphere.

Seasonally averaged neutral-wind data at altitudes of 94–130 km—from the Millstone Hill ISR and the WINDII instrument on the Upper Atmosphere Research Satellite (UARS)—were found to be in good agreement, with similar structures and similar magnitudes (Zhang et al. 2003). Winds from both instruments show an annual variation with a winter minimum. Climatology results reveal that winds in spring and summer are generally about a factor of two larger than those in fall and winter. Intriguingly, the good agreement between Millstone Hill ISR results and WINDII contrasts with differences found in other studies comparing winds measured by medium-frequency (MF) radars and HRDI and WINDII instruments at 75–95 km. Future studies will attempt to resolve these discrepancies.

ISR studies of variations in the lower thermosphere (Goncharenko et al. 2004) at subauroral latitudes during intense geomagnetic storms have revealed strong E-region plasma drifts, primarily in the two-cell-convection-pattern direction, with magnitudes 300–1000 m/s. The disturbed neutral-wind magnitude during such events, typically ~100 m/s during quiet conditions, can reach in excess of 700–800 m/s at 120–130 km altitude, with the zonal-wind component driven primarily by enhanced ion drifts through the ion drag mechanism and a complex response to geomagnetic forcing in the meridional component. The semidiurnal pattern of the wind flow is severely disrupted, and the influence of storm effects can be seen at altitudes as low as 100 km. Increased ion convection, a necessary condition for effects on lower thermospheric dynamics, is a possible result of equatorward expansion of the auroral convection pattern or (more likely) the consequence of magnetosphere-ionosphere coupling in the dusk sector subauroral ionosphere. Ongoing studies of this connection suggest direct links between variations in the plasmasphere boundary layer (Carpenter and Lemaire 2002) and other signatures of outer plasmasphere erosion, and dynamics in the lower thermosphere.

Goncharenko et al. (2004) found a large increase in ISR-measured ion temperatures at subauroral latitudes during intense geomagnetic storms. This increase was observed during periods of large electric fields due to subauroral polarization stream (SAPS) events and could be produced by frictional heating. The initial results of a statistical study of Millstone Hill-produced ion-temperature data in the E-region show that during geomagnetically active periods, ion temperatures increase with increasing Kp. This is a work in progress, but initial results suggest that this increase is a persistent feature that could also result from the effects of SAPs on the lower thermosphere.

ISR observations can make a significant contribution to our understanding of variations in the wind flow. Particularly strong winds are often seen in ISR data at the altitude of water vapor deposit (i.e., ~110 km altitude). Accordingly, the focus of recent activities in LTCS campaigns has been the quantification of variability in the wind flow. Although the wind flow in the lower thermosphere is dominated by tides, large variability in tidal amplitudes is not yet well understood. Possible sources of such variability include nonmigrating tides, planetary waves, and geomagnetic effects. Recent 30-day ISR World Month campaigns, conducted in September 2005 and March 2006, provide large datasets which will be used in upcoming studies to quantitatively characterize variability in the wind flow and to compare variability for different equinoxes. The unique scope of the ISR measurement technique will allow researchers to characterize and compare variations in wind flow at different latitudes using ISR data in aggregate from all available sites: Arecibo, Millstone Hill, Sondrestrom, Poker Flat, EISCAT, and Svalbard. Such studies are very difficult to accomplish using any other observational technique.

Topside Ionosphere

The ability to probe the topside ionosphere was one of the early drivers for building ISRs, and still remains a high-priority area of research. Topside observations were first made at Jicamarca, which measured electron-density profiles up to 4000 km altitude in 1965. Arecibo began making topside measurements in 1966 (Carlson and Gordon 1966a, b) and has continued to make such measurements with dramatic improvements in analysis techniques and system performance in the last decade (González et al. 2004). Major objectives of topside observations include:

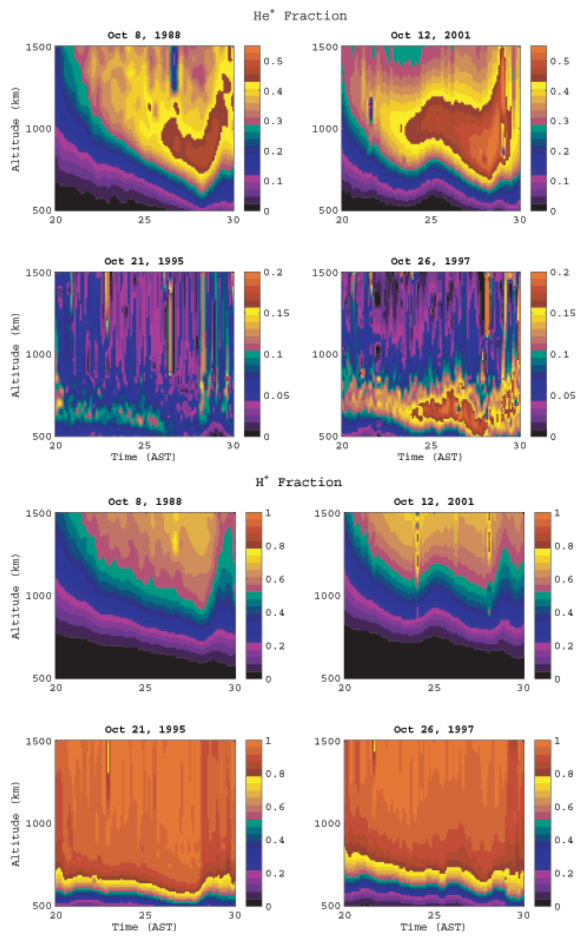
- high-altitude ISR measurements of composition distributions, and densities, temperatures, and plasma velocity variations under varying solar cycle, seasonal, and magnetic conditions;
- studies of the role of plasmaspheric flux on the maintenance of the nighttime F;
- optical studies of metastable He in the upper thermosphere and lower exosphere, typically during twilight conditions;
- and derivations of neutral oxygen and hydrogen density by combining ISR and/or optical observations with the relevant theoretical calculations.

The Arecibo Observatory, because of its great sensitivity, has been particularly effective in studying the topside ionosphere. At Arecibo's latitude, there is efficient transfer of light ions from the equatorial region via the fountain effect during the daytime. These light ions persist for long periods because of negligible recombination at the high altitudes where the light ions exist. Nevertheless, the light ion fractions are highly dependent on solar cycle, season, and magnetic activity. These dependencies result from variations in production, neutral He, and low-latitude vertical plasma drifts. Representative layers are shown in Figure 12, where the He^+ and H^+ fractions are plotted for four different nighttime experiments. The four dates correspond to quiet conditions in equinox for varying solar-flux conditions. The low-solar-flux nights (the 1995 and 1997 nights) have significantly lower He^+ concentrations than the high-solar-flux nights (1988 and 2001). The peak He^+ fraction in the low-solar-flux data is 10–12 percent for the 1995 night and about 20 percent for the 1997 night, and occurs at altitudes between 600 and 700 km. On the high-solar-flux night, the peak fraction is over 50 percent at a much higher altitude, near 1000 km. The He^+ layers are also much thicker during the high-solar-flux equinox conditions. The interaction of He^+ with other ions causes the height of the layer to be correlated with the O^+ to H^+ transition height, which depends on solar cycle. Notice the near absence of a protonosphere during high-solar-flux conditions. Furthermore, a lower layer at low solar flux leads to higher recombination, reducing the He^+ density.

In addition to studies of He^+ climatology, advances in the measurement techniques and processing have been used for new kinds of studies. These include the simultaneous measurements of O^+ and H^+ temperatures in the topside ionosphere over Arecibo (Sulzer and González 1996) and the measurement of separate O^+ and H^+ line-of-sight (typically vertical) velocities. With the dual-beam system, it may be possible to measure vector velocities in the topside mode in addition to horizontal gradients, although this ability is limited by transmitter power.

Other topside work at Arecibo has focused on

Figure 12



Comparison of He+ (top two rows) and H+ (bottom two rows) fractions for four data sets. (AST=UT-4) complementing the ISR measurements with optical instrumentation. Some studies have indicated that plasmaspheric flux is very important for understanding the electron density characteristics of the nighttime F region (Vlasov et al. 2003, 2005). However, interpretations of plasma flux are often unintuitive. For example, it is often assumed that when winds turn northward near midnight at Arecibo and the layer begins to fall (the so-called midnight collapse), that the density decreases regularly due to recombination. However, it is often observed that the density increases. This is due to downward plasma flux from the plasmasphere, which can be as large as 10^9 $cm^{-2}s^{-1}$.

The source of this plasmaspheric plasma is often strong southward winds. Vlasov et al. (2005) showed how the flux is important for both the peak electron density of the F layer and the profile shape, and how the flux can be estimated from optical airglow measurements at 630.0-nm. The logic behind this determination is that a density increase due to plasma flux is often required to explain the observed zenith airglow intensities, which often increase near midnight due to the midnight collapse. The plasma flux can be estimated from this intensity. With the recent installation of a local dual-frequency GPS receiver at Arecibo, further studies of plasma flux may be possible in combination with topside experiments. Preliminary data show very high values of total electron content, which can be used to determine the plasmaspheric content. Perturbations in the total electron content (TEC) may be a tracer for plasma flux (Nicolls et al. 2004a) as are fluctuations in H^+ density.

The first optical measurements of neutral metastable He at Arecibo were reported by Noto et al. (1998). The emission signature of the metastable He at 1083 nm, generated by photoelectron impact on ground-state He, is bright (~1 kR) and is thus useful for sensing the neutral temperature and dynamics (Waldrop et al. 2005). The conditions for observing the 1083-nm emission are limited by the brightness ratio of the signal to the solar continuum noise and are most favorable during morning and evening twilight. It was suggested by Noto et al. (1998) that He^+ recombination might be important compared to photoelectron impact. One signature of this effect would be that the temperature determined from the metastable He might be closer to the ion temperature than the neutral temperature. Using the Arecibo ISR observations, Waldrop et al. (2005) concluded that indeed the He^+ recombination is a significant source of metastable He, especially at high zenith angles during equinox conditions. This leads to ambiguity in the determination of the exospheric temperature using this technique. The brightest 1083-nm emission for large solar-zenith angles is in the winter, due primarily to larger ground-state He densities and to illumination of the conjugate thermosphere (Waldrop et al. 2005). In addition, increased solar activity results in enhanced photoelectron flux. At large solar zenith angles, He^+ can contribute more that 50 percent of the 1083-nm emission during equinox at high solar flux. But the largest contribution from recombination is actually during the summer. This is the case because there is no impact from conjugate photoelectrons and because ground-state He densities are low during the summer (Waldrop et al. 2005).

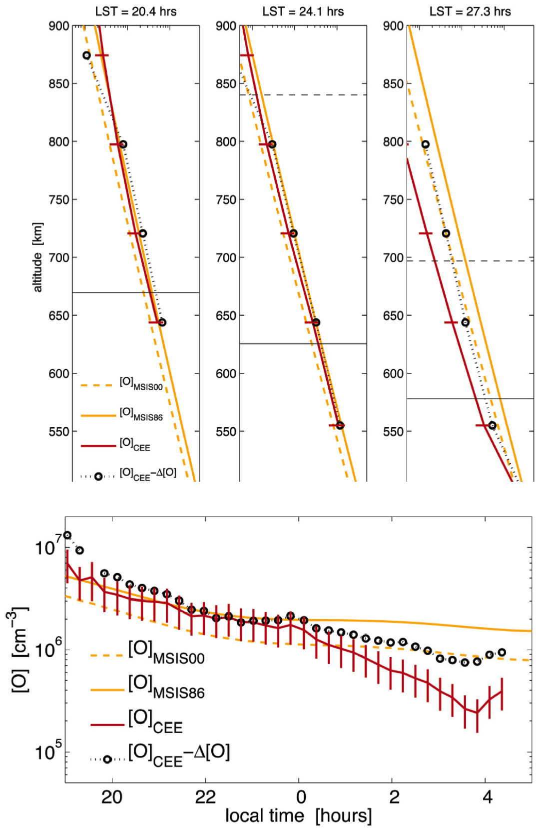
Another emerging line of investigation involves the derivation of neutral oxygen density using resonant charge-exchange assumptions. The new technique exploits the nearly resonant charge-exchange coupling between neutral and ionized hydrogen and oxygen above the F-region peak (Waldrop et al. 2005). Under these charge-exchange assumptions, the neutral-density ratio [H]/[O] is proportional to the ion-density ratio $[H^+]/[O^+]$, with the proportionality constants corresponding to rate constants of the charge-exchange reactions, which depend on the ion and neutral temperatures (Waldrop et al. 2005). Using measurements of the neutral atomic-hydrogen-density profile from the 656.3-nm twilight-geocoronal-Balmer emission, the neutral atomic-oxygen density can then be derived.

An example of the technique for deriving neutral atomic-oxygen density is shown in Figure 13 (next page). The top panel shows altitude profiles of [O] compared to MSIS. The red curve is that derived using the charge exchange equation. It can be seen that the charge exchange [O] is much lower than the MSIS [O] at some local times (such as 27.3 LT). However, the charge exchange equations neglect proton flux and variations of H^+ in time. These terms can be estimated from ISR measurements, and those adjustments are depicted as the black circles. These corrections bring the results into good agreement with MSIS densities. The bottom panel shows [O] as a function of local time for one night. The red curve, the [O] from charge exchange, agrees well with MSIS early in the night, but begins to diverge significantly after midnight. Using the corrections for plasma flux, however, we see that the estimates are brought into good agreement with the MSIS predictions. Note that the flux becomes important after the midnight collapse, as previously discussed.

Topside measurements can be made at the other ISR facilities, most notably at the Jicamarca Radio Observatory. Figure 14 (page 29) shows the light ion composition over Jicamarca for a few consecutive days in September 2004. The boundary of the protonosphere has a regular diurnal pattern, and trace amounts of He^+ can be found concentrated along the O^+ to H^+ transition height. The tendency for He^+ layers to accumulate in layers in postmidnight hours is much less pronounced than at Arecibo. However, these data raise the possibility of using Jicamarca and Arecibo to study plasma composition and particle fluxes on something like a common flux tube. Both facilities are working toward that goal.

Topside data are recorded at Jicamarca using a conventional long-pulse experiment that has the sensitivity necessary to reach H^+ dominated regions of the ionosphere, but that introduces artifacts associated with the ambiguity function of the pulses. In order to overcome the problem, so-called full-profile analysis techniques introduced at Millstone Hill (Holt et al. 1992) and EISCAT (Lehtinen et al. 1996) are being adapted to afford simultaneous density, temperature, and composition profile measurements. Unlike a conventional gated analysis, full-profile analysis yields results for all the profiles simultaneously, which are consistent with the measured data and their theoretical confidence limits, the radar ambiguity function, and with other prior information. This is a challenging and computationally intensive problem being addressed through collaborations within the UAF community.

Figure 13



Atomic oxygen profiles deduced from charge exchange calculations. Top panel shows [O] altitude profiles at three different times (see legend for details). Bottom panel shows [O] as a function of time at 650 km.

The characterization of the topside ionosphere presents a unique set of experiment challenges for ISR observations. Special pulse patterns have been developed to achieve adequate lag (or frequency) resolution to resolve mixtures of light ions with atomic oxygen at modest and low signal-to-noise levels. At Jicamarca, conventional topside data acquisition schemes can produce reasonable profiles of ion composition and temperature from about 200 km to 1200 km, depending on the time of day, season, or solar cycle, except where He ion layers might be present. The analysis-confidence levels for He densities are rather poor, even where the fitting appears reasonable. Therefore, it is necessary to begin coupling photochemical and dynamical modeling directly in the data analysis to help constrain and interpret the results.

In addition, echoes from satellites and space debris are particularly troublesome in this region because the long radar pulses involved scatter the clutter into a wide range of altitudes and because these echoes can be much stronger than the incoherent scatter signal. These echoes often contaminate the data to the extent that the plasma parameters are lost for tens of seconds or minutes at a time. Even relatively weak clutter, invisible in power profiles, can contaminate lag-profile measurements past the point of reasonable parameter estimation. Developing more sophisticated algorithms for clutter removal remains a high priority.

Magnetosphere-Ionosphere Coupling at High Latitudes

The UAF chain has played a key role in shaping our understanding of the processes involved in magnetosphere-ionosphere coupling. Below, selected aspects of the MI coupling problem being addressed by the ISRs and HF radars are highlighted.

Electromagnetic energy flux or Poynting flux is a fundamental physical quantity involved in high-latitude magnetosphere-ionosphere-thermosphere coupling. The net electromagnetic energy transfer between the high-latitude magnetosphere and ionosphere-thermosphere system is contained within the resulting currents and electric fields that are established between the two systems. A measure of the current and electric field can determine how much electrical energy is necessary to power the magnetospheric field lines through the collision-dominated ionosphere. Where currents flow in the plane of an electric field, energy is exchanged between the plasma and the electromagnetic fields, as described by Poynting's theorem. This exchange leads to significant heat and momentum transfer to the thermospheric gas.

High-latitude electric fields are routinely measured by the Sondrestrom ISR and are used in many different studies of magnetosphere-ionosphere coupling. The challenging measurement is the horizontal ionospheric current, as most of the electrical energy generated or converted in the ionosphere comes from the current and electric field perpendicular to the magnetic field. It is more difficult to measure because it relies on many height-dependent factors throughout the conducting ionosphere-thermosphere system (e.g., neutral winds, electron density, and ion-neutral collision frequency). However, it should be noted that a direct measurement of current does not rely on measuring each of these parameters independently but inherently contains their effects. Unlike the electric field, which remains basically uniform with height through the ionosphere for scale sizes in excess of 10 km (Heelis and

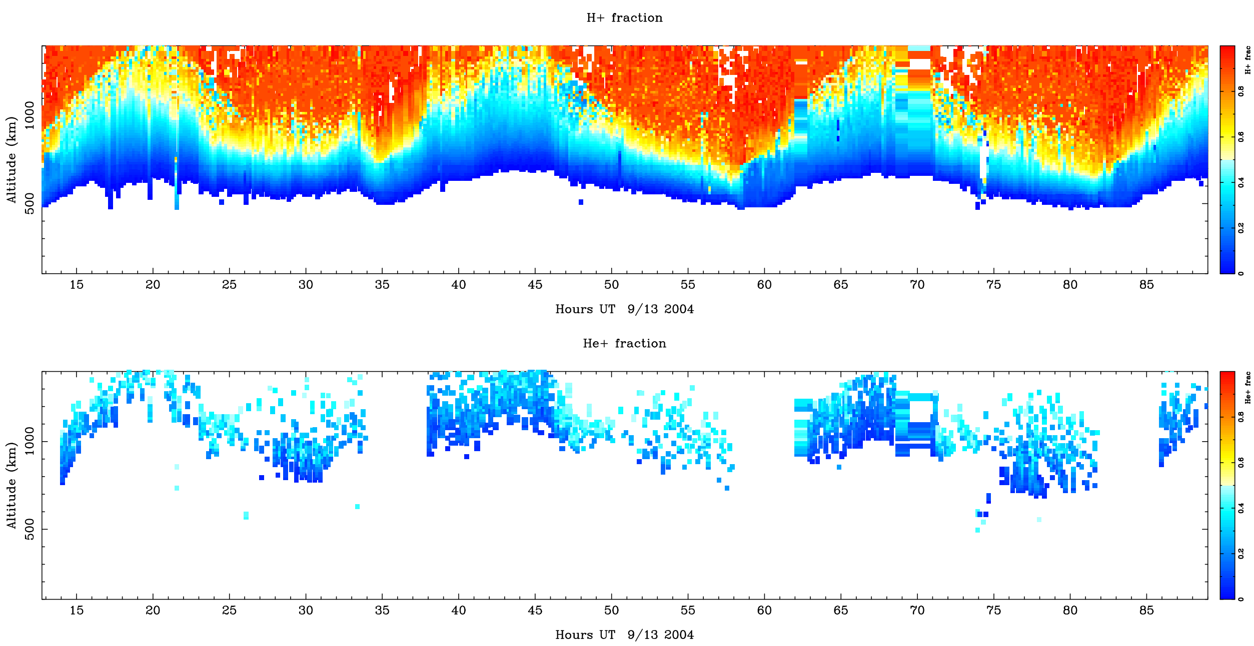
Vickrey 1991), the current density can be rather structured because of these height-dependent parameters.

The ISR technique offers the most comprehensive ground-based measurement of E-region properties for electrodynamic studies (e.g., Thayer 1998a). The improvements made over the past years in the measurement capability and spatial resolution of the Sondrestrom radar has enabled unique E-region research. Empirical studies to characterize detailed electrodynamic behavior and electrical energy transfer at high latitudes have relied on the unique measurements afforded by the ISR technique (e.g., Brekke and Rino 1978; Thayer 1998 a,b; Sanchez et al. 1998; Fujii et al. 1998, 1999; Richmond and Thayer 2000; Thayer and Semeter 2004). These radar measurements have led to estimates of the height-resolved Joule heating rate in the E-region. This capability, which is critical to understanding energy transfer and magnetosphere-ionosphere coupling, has become a routine measurement of the Sondrestrom radar.

The aurora is a visible manifestation of the conversion of electromagnetic-energy flux to particle kinetic-energy flux in the near Earth magnetosphere. As previously discussed, electromagnetic flux can be evaluated from ISR measurements of conductance and cross-field ion motion. Kinetic-energy flux can also be quantitatively determined using ISR. A precipitating particle flux will create field-aligned perturbations to plasma-state parameters (i.e., density, ion temperature, electron temperature, and bulk velocity), which can be inverted through a suitable model of electron penetration in the atmosphere to obtain an estimate of the incident electron spectrum. For primary electron beams with characteristic energy >1 keV, the principal ionospheric response is an enhancement in E-region plasma density, which presents a straightforward 1-dimensional inverse problem (e.g., Semeter and Kamalabadi 2004, and references therein). For lower energy beams, the complete response of the ionosphere, including transport effects and temperature response, must be considered (e.g., Otto et al. 2003).

The ability to evaluate the partitioning between electromagnetic flux and kinetic-energy flux is a powerful, enabling ISR application. Magnetosphere-ionosphere coupling in the vicinity of dynamic auroral forms remains poorly understood, however. Early rocket overflights suggested that the conversion between electromagnetic and kinetic-energy flux across an arc boundary may be smooth (Evans et al. 1977). This would imply that auroral arcs result from an adiabatic conversion of electromagnetic to kinetic-energy flux in the auroral acceleration region. However, ground-based measurements of fields and precipitation patterns in the vicinity of auroral arcs have been inconsistent (de la Beaujardiere et al. 1977; Marklund 1984; Robinson and Vondrak 1990). The discrepancy between these findings is probably due to spatial-temporal ambiguity: Satellites and rockets provide a "snapshot" of

Figure 14



Topside light ion composition data from Jicamarca on September 2004. Top panel: H+ fraction. Bottom panel: He+ fraction. Note that UT=LT+5hr.

a time-dependent process (e.g., McFadden et al. 1999), while ground-based sensors provide contiguous samples of the same time-dependent process but through a spatio-temporal averaging window. Neither perspective is optimal. A complete model of auroral magnetosphere-ionosphere coupling will likely require a coordinated analysis of space-borne particle and field measurements and ground-based radio and optical measurements (e.g., Robinson et al. 1989; Semeter et al. 2005).

Ion drifts are one of the routine measurements of the HF and incoherent-scatter radars. Depending on the operation mode designed for a specific observational period, the incoherent-scatter radars observe either line-of-sight or vector-ion drifts over the radar field of view. With the expansion of HF radars, particularly the SuperDARN, global-scale ionospheric-plasma convection can now be monitored continuously in both northern and southern hemispheres.

The boundary between the open and closed magnetic-field lines reveals important information about solar-wind magnetosphere-ionosphere coupling. The plasma flow across this boundary is a direct measurement of the reconnection rate at which the IMF interacts with the magnetosphere through the process of magnetic reconnection. De la Beaujardiere et al. (1991) first reported a technique of using the Sondrestrom incoherent-scatter radar to identify the open-closed boundary. By examining the precipitating particle measurements from satellites in the dayside sector, they found that a cutoff electron density of $3x10^4$ cm^{-3} in the E region appears to be closely related to the open-closed boundary. The same technique was later applied by Blanchard et al. (1996) to determine the nightside auroral boundary, and they found the open-closed boundary from the radar coincides very well with the poleward boundary of the red-line (630 nm) emissions from the all-sky camera.

Several studies have shown that the broad spectral width regions observed by HF radars are a good proxy of various magnetospheric boundaries. Milan et al. (1999) showed good agreement between the equatorward edge of the 630 nm emission and the enhanced spectral-width band seen in the HF-radar data. Lester et al. (2001) reached the same conclusion about the relationship between the open-closed field line boundary and the Doppler-radar spectral width. Baker et al. (1995) were the first to show that the equatorward edge of the region of large spectral widths is highly correlated with the equatorward edge of the particle precipitation region associated with the cusp. Similar findings are also reported in several more recent studies (e.g., Pinnock et al. 1999; Andre et al. 2002; Villain et al. 2002; Woodfield et al. 2002). A sharp latitudinal gradient in the HF-Doppler-spectral width is also observed in the evening and nightside sectors. This gradient has been shown to be coincident with the boundary between the central plasma sheet and the boundary plasma sheet (Dudeney et al. 1998; Lewis et al. 1999).

A prominent feature of magnetosphere-ionosphere coupling is the outflow of ionospheric plasma along open- and closed-field lines at high latitudes. The ionosphere is the dominant source of heavy ions in Earth's magnetosphere. The transport of ions from the polar ionosphere to the plasma sheet requires a coupling between two processes—the upflow of the bulk ionospheric plasma at thermal velocities (<1500 m/s) at ionospheric altitudes, and the outflow of ions having reached escape velocity (~10 km/s) from Earth's ionosphere above the auroral acceleration region (~2000 km). High-latitude ISRs often observe a clear correlation between auroral precipitation and ion upflows (e.g., Jones et al. 1988; Wahlund et al. 1992), where thermal expansion caused by enhanced electron and/or ion temperatures acts as the primary driver. Sondrestrom ISR observations of polar-cap-boundary ion upflows during the passage of F-region polar patches suggest a connection between horizontal plasma transport on the dayside and vertical plasma transport along the nightside (Semeter et al. 2003).

Substorms and Related Disturbances

Transient enhancements of auroral emissions and ionospheric currents often occur within the Earth's auroral zones, which typically lie at geomagnetic latitudes between ~ 65° and ~75°. Substorms are the most actively studied of these disturbances, and substorm physics is currently a subject of much controversy and many conflicting theories, none of which has attained wide acceptance. In addition to substorms, there are also several other types of significant transient disturbances, including poleward boundary intensifications that can extend through the auroral zone as north-south structures, and enhancements in solar-wind dynamic pressure. All these auroral-zone disturbances occur within the ionospheric extension of the plasma sheet, and all are a result of the electrodynamic coupling between the plasma sheet and the ionosphere. Plasma-sheet dynamics drive these disturbances via current divergences associated with time-dependent spatial gradients in plasma pressure. The ionosphere responds by forming electric fields with a two-dimensional horizontal structure that maintains current continuity in the magnetosphere and ionosphere.

While spacecraft observations are critical to the full understanding of auroral disturbances, they cannot provide the crucial two-dimensional structure of plasma-sheet dynamics. Electric fields, however, are a fundamental aspect of these dynamics and can be evaluated in two dimensions from ground-based radar observations of ionospheric flows. An example is the study of de la Beaujardiere et al. (1994), which used the Sondrestrom ISR to resolve localized enhancements in nightside convection associated with auroral intensifications along the poleward auroral boundary.

The ability to measure the flows related to disturbances is now being expanded with the construction of SuperDARN HF radars at midlatitudes. These instruments are being positioned to observe the onset of auroral disturbance within the equatorward portion of the auroral oval, which is the location where the substorm auroral disturbance initiates. The initial location of the new AMISR in Poker Flat, Alaska, is also favorable for substorm studies. The application of phased-array technology to incoherent scatter offers unprecedented opportunities for measuring simultaneously the two-dimensional ionospheric electric fields and conductivities with good time resolution. Furthermore, this radar should make it possible to distinguish between aurora resulting from highly time dependent Alfvénic-wave electron acceleration and those resulting from static field-aligned potential drops (inverted-V aurora). The aurora would be differentiated by their ion density versus height profiles. It is expected that the new radars will reveal important differences in the electrodynamics of the two types of aurora.

Another feature of the current array of coherent and incoherent scatter radars is their wide distribution with longitude. This is significant because auroral-zone disturbances, including substorms, are connected to the coupling of solar-wind energy to the magnetosphere-ionosphere system, and a manifestation of this coupling is the strength of convection within the polar-cap ionosphere. The strength and evolution of this convection can be estimated by measuring ionospheric convection on the dayside near the open-closed field line boundary. Using radars on the dayside and nightside, dayside convection measurements can now be made simultaneously with the evolution of nightside electric fields. This can be accomplished with just the coherent scatter radars, with just the ISRs, and by using both. Thus, many periods of simultaneous data can be made available. Furthermore, starting in late 2008, coordination will also be possible with the Resolute Bay AMISR measurements of convection deep within the polar cap.

Finally, it is important to note that NASA has just successfully launched the THEMIS spacecraft, which have as their primary goal the study of the auroral zone disturbances discussed here. Several times per month during the next two to three winter seasons, there will be conjunctions with four to five spacecraft that are in the equatorial nightside plasma sheet region while ground radars are observing the two-dimensional evolution of the nightside electrodynamics from the ground. These conjunctions provide a unique opportunity for coordinated studies using the radars and the multiple THEMIS spacecraft.

Magnetosphere-Ionosphere Coupling at Mid- and Low Latitudes

The Earth's magnetosphere is intimately coupled to the underlying ionosphere, in large part through the forcing influences of field-aligned currents and perpendicular electric fields. Once thought to be a passive load, it has been discovered recently that the ionosphere exerts considerable electromagnetic and particle influence on magnetospheric regions, supplying heavy cold ions and modulating current interchange in positive feedback mechanisms. The topic of magnetosphere-ionosphere coupling is especially important at mid- and low latitudes, as the relatively cold, co-rotating plasmasphere transitions to the dynamic, open field line convection patterns characteristic of the polar cap. Understanding the coupling physics in this region during disturbed conditions is a high priority from a space-weather-applications standpoint as well, since many of the consequential effects on terrestrial radio propagation and navigation systems take place over the heavily populated North American continent.

The prompt penetrating electric fields are a lower-latitude phenomenon discovered using the chain of upper atmospheric radars (Fejer and Scherliess 1995; Fejer and Scherliess 1997). These fields are remarkably similar to the interplanetary electric field, with correlation coefficients over 80 percent at times. They are detected throughout the magnetosphere and plasmasphere with very clear signatures at the magnetic equator and in plasma drift effects at midlatitudes (Scherliess et al. 2001; Huang et al. 2002). To first order, the daytime and nighttime perturbations are of opposite sign, but our knowledge of the longitudinal dependence is poor. In addition to these prompt effects, a disturbance dynamo can create electric fields deep in the magnetosphere. These electric fields are delayed by propagation effects since the velocity of the disturbance must be less than the speed of sound. Our knowledge of the longitudinal dependence of the disturbance dynamo is more limited than that of prompt fields, and ongoing research is exploring the penetration efficiency and characteristic time scale of these mechanisms (Huang et al. 2005; Huang et al. 2007) A great opportunity is possible now with the launch of the C/NOFS satellite, which measures the global equatorial electric field every 90 minutes. Efforts are being made by UAF staff to operate the chain of radars in conjunction with the satellite during disturbed times. This allows both latitudinal and longitudinal measurements to be made. In addition, it will be possible to determine the role these winds and electric fields play in creating or suppressing plasma instabilities.

At midlatitudes, radar measurements can be used to identify an important boundary region where the cool, dense plasmasphere interacts with hot, energetic plasmas generated by plasma sheet and ring current processes in the magnetosphere. Carpenter and Lemaire (2004) call this the plasmasphere boundary layer, and point out that classic textbook descriptions of this region are often limited in scope and out of data, leading to the view that the formation of the plasmasphere (and its boundary, the plasmapause) is a static, well-understood phenomenon entirely determined by the stagnation point existing between closed co-rotational plasmas and open-field-line solar wind-determined electric fields. However, the space physics community has been recently engaged in an intense reexamination of the very dynamic plasmapause region, and has uncovered a wealth of magnetosphere/ionosphere coupling phenomena that are scientifically challenging. Probing of the complex ionospheric response and its overall role in dynamic reconfigurations of the near space environment during geomagnetic disturbances clearly requires a large, diverse body of observational evidence to test theories and discover new features.

UAF data and studies are providing this kind of evidence. In the 1980s and 1990s, Millstone Hill scientists, using the facility's 55º magnetic-invariant-latitude location that affords excellent visibility of the ionospheric projection of the plasmapause and the accompanying plasmasphere-boundary layer, identified storm-enhanced density (SED) as a regular feature of the dusk sector midlatitude ionosphere (Foster 1993). Large plumes of enhanced electron density, with magnitudes up to ten times background levels, were repeatedly observed during moderate to large disturbance levels (Kp=3+) streaming from the premidnight subauroral ionosphere across North America towards the noontime cusp.

The unique measurement capabilities of the ISR have shown that the drivers of these density structures are long-duration, large-latitudinal-extent, poleward-directed electric fields causing sunward plasma drift, equatorward of (and separated from) the evening auroral convection cells (Yeh et al. 1991). Spurred by these results, other studies have mined the ISR data to reveal the statistical persistence of SED features in the dusk sector ionosphere (Foster and Vo 2002; Vo and Foster 2002) and have found similar cross-field drifts in Defense Meteorological Satellite Program (DMSP) satellite data (e.g., Figure 5 of Foster et al. 2004). These efforts have helped define the organizing physical process as a fast-moving convection channel, dubbed the sub-auroral polarization stream SAPS (Foster and Burke 2002). Subsequent research is exploring the complex relationship between the broad SAPS channel and the highly variable, localized drift-velocity features seen for many years with satellite ion drift and electric field meters, which are known as subauroral ion drifts or SAIDs (Anderson et al. 1991). Millstone Hill simultaneous incoherent scatter and UHF coherent scatter observations (Foster and Erickson 2000) have been used by researchers to make very high-resolution measurements of electric fields in the SAPS region. The data have also shown evidence of significant structuring on time scales of one to two minutes and on kilometer spatial scales (Erickson et al. 2002). The severe variable-density gradients generated in this region serve as prime energy sources for instabilities leading to scintillation on transionospheric propagation paths, a concern of many operational users affected in the North American sector by space weather events.

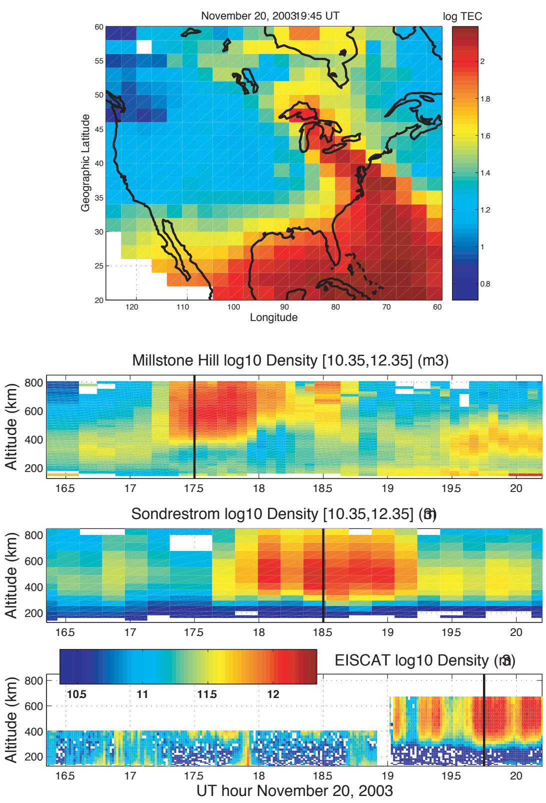
Follow-on studies combining ISR density and velocity measurements with GPS total-electron-content ionospheric mapping (Foster et al. 2002) provided the key observations, showing that SED plumes identified at low altitude map directly to magnetospheric boundaries of both the plasmapause and plasmaspheric sunward erosion plumes seen in extreme ultraviolet-helium-ion emissions captured by the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) satellite (Sandel et al. 2001; Foster et al. 2005). ISR-based direct flux measurements have quantified the ionospheric source of material feeding these large-scale sunward plasmaspheric plumes, showing a flow sufficient to deplete a 1-Re shell of the outer plasmasphere in one hour (Foster et al. 2004). Large tropical electron density enhancements in the Appleton anomalies, observed using combined Arecibo density and Jicamarca equatorial-electric-field measurements (e.g., Aponte et al. 2000; Makela et al. 2001; Vlasov et al. 2003), are a prime candidate for the source of SED material.

Chain studies employing Millstone Hill and Sondrestrom radar vertical velocity and density measurements in conjunction with the EISCAT mainland Tromsø radar and the SuperDARN HF convection network have led for the first time to complete simultaneous disturbance time mapping of plasma density and convection patterns from dayside midlatitude source regions to the nightside auroral F-region ionosphere (Foster et al. 2005). Figure 15 depicts ISR measurements of vertical F-region plasma density above the three mid- and high-latitude ISR facilities in the SED plume, along with GPS vertical TEC data over North America, which together place the radar data in a larger context. These studies reach the significant conclusion that the entire low-latitude, auroral, and polar-latitude regions are fundamentally coupled during the main phase of geomagnetic storms, creating a polar tongue of continuously streaming cold, dense plasma, along with oxygen ion outflows through the global convection pattern. These multiple views of disturbance time midlatitude coupling processes and the Earth-space system-level picture that is beginning to emerge have excited considerable interest and have had a deep and lasting influence on future science directions.

Despite this considerable progress, many questions remain about subauroral ionospheric behavior, and here again UAF radars are poised to make crucial contributions. For example, initial phases of a storm are known to create electric fields that penetrate eastward at the equator, uplifting plasma and leading to enhanced equatorial anomalies (Kelley et al. 2004). As mentioned previously, these enhanced densities may be a source for SED plume material (Foster et al. 2005), but much more information is needed on the exact sequence of events resulting in the eventual entrainment of tropical plasma in the SAPS stream and the subsequent development of the dusk sectormid-latitude trough. Simultaneous detailed disturbance time density and velocity (i.e., electric field) measurements in a UAF-radar-chain mode using Jicamarca, Arecibo, Millstone Hill, and Sondrestrom will provide the needed information in conjunction with contextual data from satellite topside drifts, SuperDARN convection patterns, and GPS TEC observations. Future work can also couple this information with observed and modeled characteristics of penetration electric-field progressions from pole to equator and the dynamics of under-shielding events near the footprints of ring current and plasma sheet field aligned currents.

Another topic to be explored concerns changes in the altitude distribution, temperature, and ion composition of the cold, dense plasmaspheric material swept up by SAPS electric fields as it passes through the cusp and into the nighttime sector. Multievent studies using Arecibo topside plasmaspheric composition observations, combined with Millstone Hill, Sondrestrom, and AMISR radar sector scans (e.g., Foster et al. 2005), will be crucial in elucidating the various flux contributions to inner-magnetospheric ion populations and contributing evidence of their ionospheric origins. Mid- to high-latitude UAF-radar data in aggregate from Millstone Hill, Sondrestrom, and the forthcoming Resolute Bay AMISR deployment will address the universal and local time dependence of SED magnitude. This aggregate data will also quantify variability in the plasmasphere boundary layer, in particular expanding on the statistical distribution of plasma density and temperature gradients, their time history near SAPS channels and SED structures, and comparisons with overall plasmasphere structuring seen in EUV and FUV instruments such as IMAGE. Such climatological information will be especially important for understanding the spatial gradient spectrum and energy cascade, which will in turn expand understanding of the important relationships among density gradient magnitudes, electric fields, irregularity distributions, and observed radio scintillations and their effect on space weather and on GPS and beacon satellite paths.

Figure 15



GPS vertical TEC measurements over North America (top) and vertical profiles of F-region plasma density (bottom) above Millstone Hill, Sondrestrom, and EISCAT during the height of the November 20, 2003 storm event. An intense plume of storm-enhanced density with TEC > 100 TECu extends from Florida to the polar cap, and is sampled by each radar for approximately one hour as the SED plasma passes overhead. From Figures 2 and 7 of Foster et al. (2005).

D-Region, Mesosphere, and Meteors

Low levels of ionization ($5x10^4$ electrons/cm^3) in the 60–100 km atmospheric region, called the mesosphere and ionospheric D region, make it accessible by all the ISRs of the UAF chain under at least some conditions. The higher latitude radars (Arecibo, Millstone Hill, Sondrestrom, and AMISR) can observe thermal fluctuations in the index of refraction. The low-latitude radars (Jicamarca and Arecibo), meanwhile, can also observe daytime coherent scatter echoes caused by atmospheric turbulence (e.g., Woodman and Guillen 1974) in the so-called mesosphere-stratosphere-troposphere (MST) mode.

Although the D region/mesosphere is at close range, it is one of the hardest regions to observe using ISR techniques. Currently, Arecibo and PFISR are the only radars that can routinely observe the D region in ISR mode. Millstone Hill and Sondrestrom are mainly limited to observing it under special events (e.g., strong solar flares). PFISR is capable of improved D-region ISR observations with its rapid beam steering capabilities, decreasing the F-region clutter. In the case of Jicamarca, D-region ISR observations have not been possible in the past due to the existence of thin mesospheric turbulence layers. Thanks to recent system upgrades (digital receivers, faster acquisition systems), Chau and Woodman (2005) and Chau and Kudeki (2006) have been able to measure the first D-region ISR densities and spectra, respectively, at Jicamarca. These measurements have been made with very high altitude resolution (150 m), allowing measurements between the thin mesospheric layers.

The D region and mesosphere (sometimes called the "ignorosphere") are poorly characterized (e.g., Friedrich 2004), but the ISRs are contributing to their understanding by providing measurements of electron densities (from total power) and 3-D winds (from mean Doppler shifts). The spectral shape of the ISR signal is a function of electron/ion temperatures, ion concentrations, and ion mean masses (e.g., Mathews 1986). Unlike the E and F regions, these parameters are difficult to separate in the D region with single ISR observations, but they can set constraints for models or other instrument measurements.

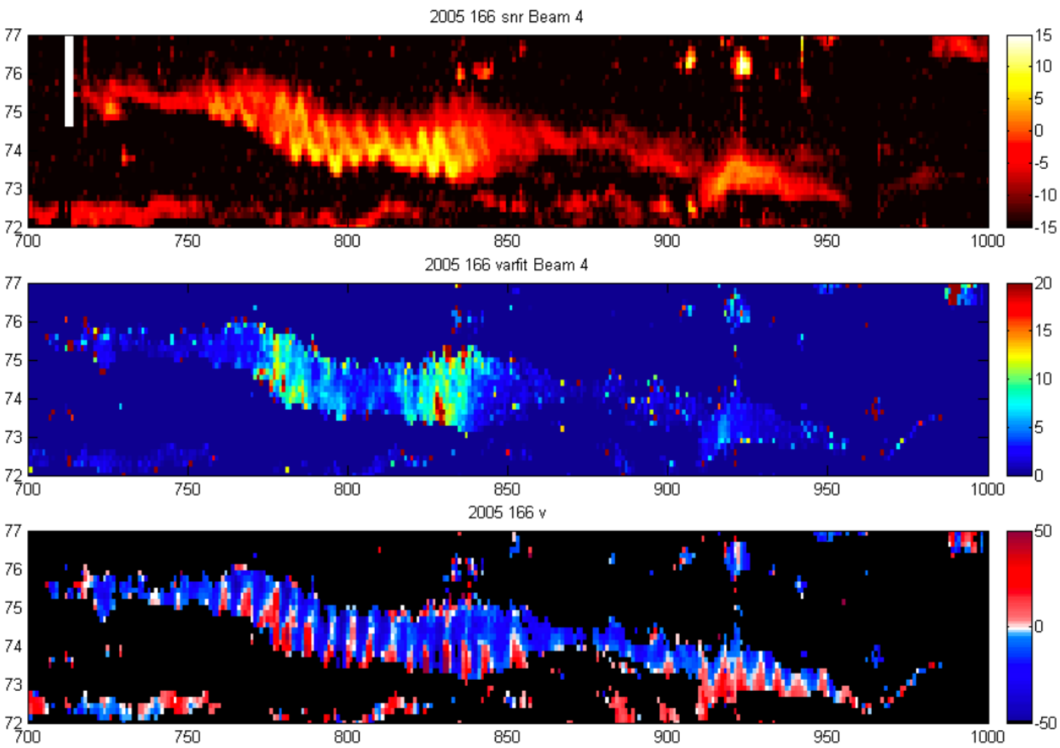
In the case of Arecibo and Sondrestrom, the mesospheric measurements are being complemented with optical instruments, in particular with lidars. Rayleigh Lidars measure the neutral density and temperature profiles, while Resonance lidars measure gravity wave energy and metallic density in this altitude region. Lidar measurements at Sondrestrom are allowing studies of noctilucent clouds (e.g., Thayer and Pan 2006), which are related to Polar Mesospheric Summer Echoes. At Arecibo, lidars are being used to study the dynamics and chemistry of atomic layer enhancements (Tepley et al. 2003), tides, and gravity waves, in conjunction with the ISR system (Zhou et al. 2005).

At Jicamarca, the mesospheric region is mainly studied by measuring the echoes due to irregularities. Since 1974, mesospheric winds (including the vertical component) have been obtained on a campaign basis (e.g., Hitchman et al. 1997). Again, thanks to recent advances in the receiving and acquisition systems, these observations are now possible with much better time (1 min) and altitude (150 m) resolution (e.g., Sheth et al. 2006). Using four simultaneous beams pointing 2.5° off-vertical in the four cardinal directions, very accurate daytime horizontal and vertical winds are possible. Moreover, the morphology of the turbulent layers can be readily identified and studied. Figure 16 shows a typical example of the type of mesospheric structures detectable at Jicamarca. Currently, these observations are being complemented with concurrent F-region ISR measurements by Dr. E. Kudeki et al. (MST-ISR mode) in order to get absolute cross-sections of the mesospheric turbulent layers. Understanding the generation and characteristics of these perennial equatorial mesospheric echoes (PEME) might provide clues to understanding the polar mesospheric summer echoes (PMSE) related to the polar mesospheric clouds (R. Woodman, personal communication).

Gravity-wave momentum fluxes in the mesosphere are poorly characterized by current atmospheric models (D. Fritts, personal communication). ISRs, in particular Jicamarca and Arecibo, can provide horizontal and vertical winds with enough precision to measure the "instantaneous" momentum fluxes. In the case of Jicamarca, those measurements are obtained from the coherent echoes mentioned above. Moreover, these measurements are usually extended down to the stratosphere and lower troposphere (e.g., Riggin et al. 2004). At Arecibo, momentum flux measurements are now possible with the recent dual-beam capability, allowing simultaneous observations of ISR winds at two symmetrical beam positions with respect to vertical (Zhou and Morton 2006).

Another active research area in this altitude region (and a few kilometers higher into the E region) is the study of meteors with ISRs. All the ISRs are considered high-power, large-aperture radars and are able to detect, with different degrees of sensitivity, meteor-head echoes. In addition, the Jicamarca VHF radar is also sensitive to so-called nonspecular meteor echoes observed at angles close to perpendicular to the magnetic field (Chapin and Kudeki 1994). Meteors have been studied routinely with very small systems that detect the specular meteor echoes. From them, one can determine mesospheric neutral winds,

Figure 16



Mesospheric turbulent layers over Jicamarca.

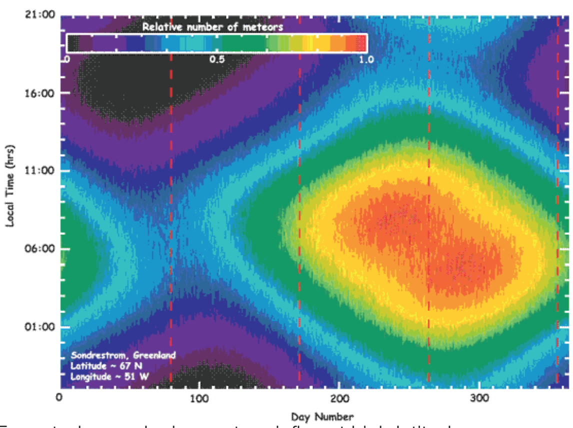
temperatures, and some astronomical parameters. By observing the meteor-head echoes, ISRs are contributing significantly to the understanding of the meteoroids that are responsible for most of the metallic-ion deposition in the upper atmosphere. For example, Janches et al. (2006), using Jicamarca and Arecibo meteor observations, recently developed an empirical global micrometeor model. The model has been tested against Sondrestrom and Jicamarca meteor-head observations. Figure 17 shows the expected micrometeor influx over the whole year at Sondrestrom-like latitudes. Similar diurnal and seasonal curves can be generated for any site.

Recently, Chau et al. (2006) have calculated the sporadic meteor population by using the Jicamarca radar in interferometer mode to detect close to 200,000 meteor-heads in less than 90 hours of observations. In general, these populations are in good agreement with previously reported populations based on many years of specular meteor observations, but differences need to be accounted for in any new model. In particular, high-power, large-aperture radars appear to observe a higher-altitude meteor population not well characterized in the past.

Lastly, echoes from nonspecular meteors are known to come from field-aligned irregularities. As in the case of other ionospheric irregularities, these nonspecular meteor echoes are also good tools for aeronomy and plasma physics studies. Many research groups are currently studying them with improved radar capabilities at Jicamarca (high-altitude resolution, imaging, and interferometric techniques, multifrequency experiments), very intensive numerical simulations, and theory, in an effort to not only understand them, but also to use them for diagnostics (e.g., Dyrud et al. 2004).

Recent hardware upgrades at several ISR facilities should permit improved measurements and new discoveries in the mesosphere/D region. For example, with its dual-beam capabilities, Arecibo will be able to obtain instantaneous momentum flux measurements in the mesosphere with unprecedented accuracy. At Jicamarca, the use of interferometry, digital receiver technology, and wider bandwidth transmitters will allow measurements with very high-temporal and-range (150 m) resolution of a variety of coherent scatter echoes, including the different echoes from meteors. Two hotly anticipated developments that should be possible with the new hardware are (1) routine measurements of the still-to-be understood time gap between the meteor-head and the nonspecular meteor trail, and the (2) first incoherent scatter measurements in the D region between the coherent echoes from very thin mesospheric layers.

Figure 17



Expected annual micrometeor influx at high latitudes.

FACILITY CONTRIBUTIONS TO MAJOR SCIENCE PROGRAMS

The upper-atmospheric facilities represent a valuable resource for researchers studying high-priority science topics with important societal relevance. Almost every research project dealing with the upper atmosphere and the near-Earth space environment can benefit from data provided by the facilities. The facilities have responded to community-driven research by developing new experiment techniques, observing modes, coordination protocols, and data acquisition and processing strategies. The upper-atmospheric facilities function as a distributed, virtual center, maintaining and expanding expertise in a number of critical scientific and engineering disciplines. Among these are high-power and large-scale radio-frequency engineering, radio-wave propagation, communications, magnetoionic theory, space plasma physics, atmospheric scattering, data acquisition, data transport, advanced signal processing, and remote sensing. These disciplines have applications in space exploration, security and defense, environmental monitoring and resource management, commerce, and other areas of national interest. Progress in these areas is a byproduct of research advancements in space physics and aeronomy.

Following are examples of ways in which the facilities have contributed to high-priority scientific research that is driven by societal needs and the quest for fundamental understanding of physical processes.

Space Weather

Space weather refers to conditions on the sun and in the space environment that can influence the performance and reliability of space-borne and ground-based technological systems, endangering human life or health. The National Space Weather Program is a multiagency program whose goal is to achieve an active, synergistic, interagency system to provide timely, accurate, and reliable space weather warnings, observations, specifications, and forecasts. The program is built on four strategic pillars: research, observations, modeling, and education. Two types of observations are called for. Those that provide the real-time information needed for space weather alerts and forecasts, and those that provide the data used by researchers and model developers to improve understanding of space weather and validate the models. To date, the upper atmospheric facilities have contributed primarily to the second type of observations, although the extent to which they contribute to space weather monitoring continues to grow.

Because of the limited time during which ISRs can operate, it is imperative that operating intervals be carefully considered in order to optimize observations for space weather objectives. In particular, there has been a tremendous demand among researchers for radar observations during large geomagnetic storms. This has driven the development of a facility-wide protocol to optimize radar observations during high geomagnetic activity, as shown in Figure 18. The protocol is based on attempts to predict magnetic storms with sufficient lead-time to initiate radar observations at as many facilities as possible. Occasionally, the 27-day rotation period of the sun can be used to estimate the time of occurrence of solar disturbances that might produce geomagnetic storms. Alternatively, space-based observations of coronal mass ejections are used to give the facilities a day or two to adjust schedules and initiate radar operations before the solar-wind disturbance reaches Earth. The use of these methods to optimize radar experiments will become more common as facilities develop more efficient procedures for receiving space weather information and coordinating observations.

The data obtained by the radars provide the fundamental properties of the upper atmosphere and ionosphere that are essential for input to, and testing of, space weather models. Particularly important is the high-latitude convection pattern, which is now specified in real time using data from the SuperDARN network. Although SuperDARN coverage is not complete over the high-latitude regions, sophisticated algorithms have been developed to combine the observations with physical constraints and empirical models to produce a complete map of the polar plasma velocities. When any of the ISRs are operating, the convection velocities measured by those facilities can provide additional data to improve and extend the coverage obtained from SuperDARN.

Another important parameter in space weather modeling is the ionospheric electrical conductivity. The most accurate way to determine the conductivity is to measure the height profile of electron density, which only ISRs are capable of doing unambiguously. Radar measurements of conductance are often used with empirical models to produce a global conductance specification that is critical to modeling ionospheric electrodynamics and magnetosphere-ionosphere coupling. Radar measurements of conductance are also used to validate other techniques for calculating conductance, such as those that rely on space-based measurements of optical emissions or in situ particle precipitation. By measuring both conductance and plasma velocities (electric fields), the radars provide the two measurements needed to calculate ionospheric horizontal currents and Joule heating. The Joule heating can be combined with particle-energy input to determine the total energy input from the magnetosphere into the ionosphere. The divergence of the horizontal current yields the field-aligned currents at high latitudes, which are critical to understanding magnetosphere-ionosphere coupling. All of these parameters are essential elements in the chain of space weather models that link the sun to Earth's ionosphere and upper atmosphere. The role that the upper atmospheric facilities play in developing and validating these models will continue to grow.

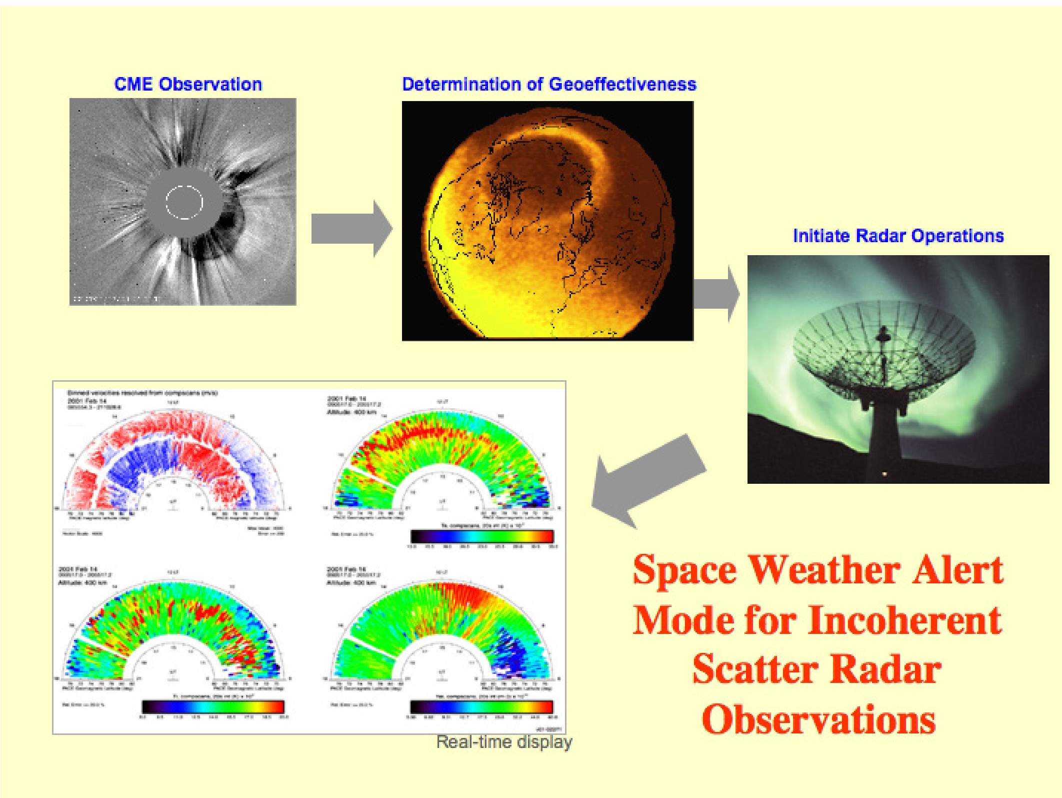
The upper atmospheric facilities also contribute to the GEM (Geospace Environment Modeling) Program by providing important data for studying magnetosphere-ionosphere coupling. The purpose of the GEM program is to study the dynamical and structural properties of geospace in order to construct a global Geospace General Circulation Model (GGCM) with predictive capability. The model is critical to our understanding of the effects of solar-energy and solar-wind-energy inputs on space weather and their associated impact on technical systems.

Global Change

Like space weather, understanding global climate change depends on two important activities: making routine measurements of atmospheric properties on a regular basis over a long period of time, and studying the fundamental physical processes that modify the state parameters of earth's atmosphere. The upper atmospheric facilities contribute to both of these activities. Routine measurements of ionospheric electron density, ion and electron temperatures, and plasma drift velocities have been made for more than four decades using the ISRs. The regularity and consistency of the observations have been formalized by the Incoherent Scatter Working Group (ISWG) of the International Union of Radio Science (URSI), which coordinates periods of global ISR measurements scattered throughout each year. Data from these World Day experiments have been carefully calibrated, checked for accuracy and validity, and archived on an easily accessible database. The analysis of these data to identify long-term trends is just beginning, but researchers are already seeing systematic variations in ionospheric parameters that may be linked to global climate change. Of course, the significance of any variations gleaned from the long-term databases cannot be established without concurrent improvement in understanding of the fundamental processes. For this, it is helpful to conduct case studies of specific events for which comprehensive observations have been made, both locally and globally.

The chain of ISRs, along with the SuperDARN radars, helps provide the data necessary to study how the upper atmosphere responds to energy input from above and below, and at short and long time scales. These data

Figure 18



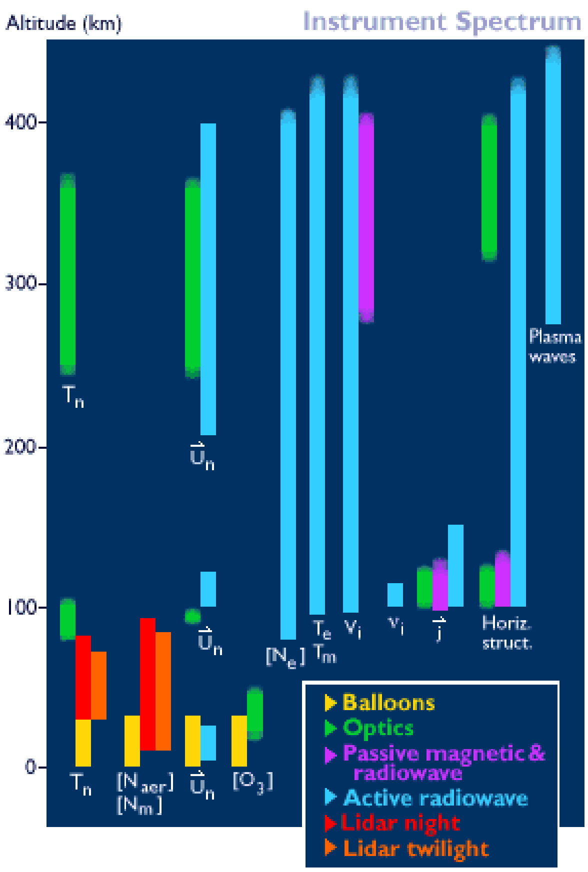
Space weather operations protocol for ISRs.

also aid studies of how the various atmospheric layers are linked, chemically, dynamically, and electrically. The Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) Program began as an element of the U.S. Global Change Program. Through CEDAR funding, each of the upper atmospheric facilities has been enhanced over the past 20 years to include *collocated* ancillary radiowave and optical instruments. These instruments have helped extend the range of altitudes observable by the radars so that researchers can better study the linkages between atmospheric layers. As an example, Figure 19 shows the altitude range and measurement capabilities of the instruments located at the Sondrestrom Facility in Greenland. Understanding the linkages between atmospheric layers is key to identifying the processes that are important to long-term climate change.

Space Missions

The UAF have been involved in the planning and execution of many research and operational satellite missions. In planning for space missions, it is critical to know the range of atmospheric conditions the spacecraft will experience so that payload instruments can be properly designed. The spatial and temporal variations of the upper atmosphere, as determined from many years of ground-based observations, enter into considerations of orbital configuration and measurement cadence. In some situations, entire missions have been developed based on observations of phenomena first made using the ground-based facilities. In the execution of space missions, the measurements of atmospheric properties provided by the UAF are used to validate and calibrate the data from space-based instruments. Scientific research associated with many space missions is enhanced through coordinated observations and campaigns involving the UAF. Following is a brief description of some of the important space missions to which the facilities have made critical contributions.

Figure 19



Parameters measured at the Sondrestrom Facility important for global change studies.

Dynamics Explorer (NASA): The Dynamics Explorer (DE) mission's general objective was to investigate the strong interactive processes coupling the hot, tenuous, convecting plasmas of the magnetosphere and the cooler, denser plasmas and gases co-rotating in the earth's ionosphere, upper atmosphere, and plasmasphere. Throughout the mission, which lasted from 1981 to 1990, the UAF made coordinated measurements with both the high-altitude DE-1 satellite and low-altitude DE-2 satellites. In particular, the Chatanika Radar, Sondrestrom Radar, and SuperDARN made observations of high-latitude electrodynamic properties that helped research aimed at understanding magnetosphere-ionosphere-thermosphere coupling.

International Solar Terrestrial Physics Program (NASA, ESA, ISAS): The Sondrestrom Facility and the SuperDARN radars were both selected for funding as part of the ground-based segment of this mission, which included the Polar, Wind, and Geotail spacecraft. The goal of the International Solar Terrestrial Physics Program (ISTP) was to develop a comprehensive understanding of the generation and flow of energy from the sun through Earth's space environment, and to define the cause-and-effect relationships among the physical processes that link different regions of this environment. By integrating the ground-based observations into the planning and operational phases of this mission, coordinated ground- and space-based studies were optimized and the resulting scientific research results tremendously enhanced.

Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) satellite (NASA): The TIMED satellite was launched in 2001 and is still operating in an extended mission phase. The goal of TIMED is to study the chemistry and flow of energy to and from the mesosphere, lower thermosphere, and, ionosphere. A joint research opportunity funded by NASA and NSF supported observations and scientific studies from an extensive array of ground-based instruments. All of the UAF provided data in support of TIMED observations (e.g., Zhang et al. 2003, Zhang et al. 2005). The data from these coordinated observations are still being examined to improve understanding of ionospheric irregularities, topside ionospheric properties, high-latitude electrodynamics, and neutral wind climatologies.

Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) (NASA): The IMAGE satellite's nearly 6-year mission, from launch in 2000 to failure in late 2005, had the general objective of using neutral atom, ultraviolet, and radio imaging techniques to study the inner magnetosphere. UAF data, particularly from Millstone Hill, has been used extensively in combination with IMAGE extreme-ultraviolet data and GPS total-electron-content mapping throughout the basic and extended mission. By providing ground-based contexts, the resulting investigations have greatly improved understanding of storm-time magnetosphere-ionosphere coupling mechanisms with significant space weather consequences near severe ionospheric density gradients. The results of this research are still ongoing, but they have already led to numerous presentations, publications, and American Geophysical Union (AGU) monographs describing the dynamics of the plasmasphere boundary layer and the dense ionization plumes known as plasmaspheric tails. UAF ionospheric data and associated system-level science understanding has also had considerable impact on future NASA mission planning in the critical magnetosphere-ionosphere interaction areas addressed by IMAGE. An example of this is shown in Figure 20, composited from Foster et al. (2002), which compares Millstone Hill radar scans and GPS TEC maps with IMAGE EUV plasmaspheric images to definitely associate storm-enhanced density plumes with erosion of the plasmasphere by strong subauroral polarization electric fields.

Defense Meteorological Satellite Program (DMSP): Coordinated measurements involving the DMSP satellites and the upper-atmospheric facilities have been made for more than two decades. Facility data are used for the calibration and validation of new DMSP instruments, as well as for scientific studies of ionospheric processes. The primary function of DMSP spacecraft is to provide operational support to the Department of Defense, but the use of DMSP data for research has been enabled and enhanced by ground-based observations. The combined data obtained in these experiments constitute an extremely valuable scientific resource that is being effectively exploited even after the operational usefulness of the data expires.

Global Positioning System (GPS): The phase delay of GPS transmissions measured by ground-based receivers can be used to measure the total electron content TEC through the ionosphere. This technique is being used to determine global maps of ionospheric electron density, which can be updated every few minutes to provide continuous information about the time variations of ionospheric structure. However, definitive validation of the technique for calculating TEC in the presence of spatial and temporal variations can only be accomplished using coordinated measurements by ISRs. This technique is being extended to space-based receivers, which use occultation of the signals from GPS satellites to get a better estimate of the height profile of ionization. This technique will also require validation by ISRs, as the radars are the most accurate means for measuring the altitude profile of electron density. The University of Texas, Austin, deployed a latitudinal chain of four receivers in Greenland and made coordinated measurements with the Sondrestrom ISR in an effort to validate this tomographic technique (Kersley et al. 2005).

COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate): COSMIC is a joint Taiwan-U.S. satellite mission that was launched on April 14, 2006. The six COSMIC satellites in low-Earth orbit contain GPS radio occultation receivers to make global measurements of lower atmospheric properties and ionospheric electron density. The comprehensive database of measurements will provide many opportunities for comparison with ISR observations of electron density profiles. The combined data sets also will be used to study fundamental processes in the ionosphere at all latitudes, including ionospheric irregularities, geomagnetic storm effects, and magnetosphere-ionosphere processing.

Time History of Events and Macroscale Interactions during Substorms (THEMIS): NASA's THEMIS mission focuses on the origin of magnetospheric substorms. THEMIS includes an extensive ground-based array of all-sky cameras to enable observations of the origin and evolution of auroral forms associated with substorms. Incoherent scatter radar and SuperDARN measurements are critical in providing measurements of ionospheric electrodynamic parameters. These observations are used to interpret the THEMIS observations and allow for a detailed analysis of ionospheric processes at a specific location.

The facilities are regularly included in the planning for space missions, as well as balloon and rocket campaigns supported via NASA's suborbital programs. Because of the growing recognition of the role played by the facilities in the planning and execution of space missions, coordination with the facilities is more often integrated into mission planning at the very start. In general, the more lead time there is in the planning of coordinated experiments with the UAF, the more the scientific research is enhanced through facility participation. Researchers are becoming increasingly aware of this, and the demand for facility coordination is increasing. Conversely, facility staff members are becoming more proactive in ensuring that potential facility contributions to space missions are recognized early in the planning stages.

Radio Science

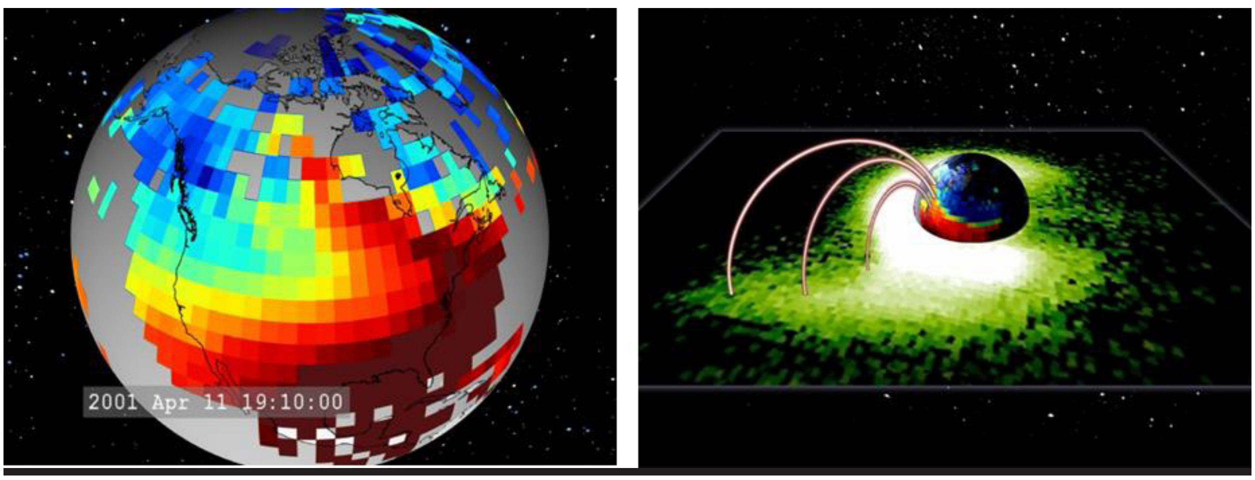
Ionospheric reflection and refraction, fading, multimode propagation, and birefringence were discovered in the early days of radio, and the field of radio science grew out of a desire to understand and predict such phenomena to exploit better the new medium. The spreading of ionosonde traces, coherent scatter, and incoherent scatter were discovered subsequently as systematic studies of the ionosphere were made with increasingly sophisticated instruments. From the advent of spacecraft, and continuing in the era of GPS, ionospheric group delays and radio scintillations became increasingly important to model and anticipate. Radio astronomers also contend with ionospheric effects on radio propagation, and utilize these effects to probe both near and deep space. In recent years, ionospheric modification using high-power radio waves has afforded investigators a rare view of complicated nonlinear plasma physics processes. Contemporary, assimilative space-weather forecast models depend on unambiguous real-time profile measurements from ISRs.

Radio science is a deep and compelling field with practical implications for communications and navigation, ionospheric specification, material science and plasma physics, and radio and radar astronomy and remote sensing. The UAF are laboratories as well as observatories that continue to make regular contributions to the field of radio science. One way they do this is by driving development of the theory of incoherent scatter. This theory predicts the characteristics of thermal fluctuations in a plasma and the corresponding spectrum of the scattered spectrum in terms of its state variables, including number density, temperature, composition, and drift velocity. Current theory is complicated enough to embody most phenomena of interest, but simple enough to be derived analytically. The formulation of this very successful and expansible theory represents a triumph of applied physics. Nevertheless, some domains of interest are not yet completely accounted for by the theory. Contemporary research focuses on including the effects of Coulomb collisions, which are important at small magnetic aspect angles, on gyroline resonances, which have been observed with the EISCAT mainland radar and Arecibo but are not well understood quantitatively, and on treating non-Maxwellian plasma populations, as are found at high latitudes. Additionally, whereas the forward incoherent scatter problem is well established, the inverse problem has not been formulated optimally, and a number of efforts are underway to incorporate statistical inverse theory in the state variable inference. Inverse theory cuts across the natural and life sciences as well as engineering. Progress with the incoherent scatter problem contributes to a wide range of disciplines.

Another contribution comes in the form of the continued testing and refinement of magneto-ionic theory. This theory describes the dispersion and propagation of radio signals in a plasma in a background magnetic field. The theory governs the refraction of radio waves in the ionosphere and underpins the interpretation of SuperDARN observations. It also predicts the Faraday rotation of radio signals, a phenomenon utilized at Jicamarca and elsewhere as an independent, deterministic means of measuring ionospheric electron-density profiles. Applying magneto-ionic theory at small aspect angles where wave propagation characteristics change rapidly with bearing is currently very challenging. It remains an area of active research in the UAF community with implications in laboratory plasmas and material science.

A third contribution to radio science is in the broader area of radio engineering. The UAF facilities are among the largest RF installations in the world and pose significant technical challenges to pulsed-power generation, structural engineering, remote access and data transport, and optimization and control. The new AMISR radars, especially, pose special technical challenges by virtue of their autonomous functionality, large size, and solid-state, modular design. The UAF program will contribute substantially to radio science by demonstrating how to design, build, maintain, diagnose, upgrade, and most effectively utilize such large phased-array radars in a manner that maximizes science value per unit cost.

Figure 20



Simultaneous GPS TEC measurements and plasmapause observations from the IMAGE satellite.

FACILITY STRATEGIES

The upper atmospheric facilities have been a catalyst for important and innovative research for more than four decades. This success is in large part due to effective use of technology and experimental methodology in the pursuit of high-priority scientific objectives. Other strategies have come into play as well, as illustrated by the examples described earlier in this report. The future of the facilities depends on the extent to which these strategies, along with improved technology, can be exploited as new scientific needs and priorities emerge.

This section discusses the experiment requirements that drive strategies and technology development. ISRs are complex machines, and the demanding requirements of the incoherent scatter technique are met in overall radar system design through an architecture of multiple subsystems, some with significant maintenance requirements and finite lifetimes. Each subsystem has its foundations in computing and radio frequency (RF) technology, which constantly shift according to the demands of the commercial marketplace and not the ISR community—a very small fraction of this customer base. Changes in underlying technology can have two contrasting impacts on UAF facility operations. On one hand, new capabilities can be realized for ionospheric radar measurements if technical shifts enhance performance, make maintenance easier, and/or prolong system lifetimes. On the other hand, significant challenges can arise if shifts occur that make core radar technology obsolete, or if market forces raise the cost of subsystem maintenance to prohibitive levels. This latter aspect is especially important when one considers that UAF science goals, especially in the area of long-term trend studies, can require continued stable operation over many decades, a time horizon much longer than typical product life cycles.

The opportunities and challenges raised by continually evolving technology have been successfully managed by the UAF chain to date. Facilities must continue to deal effectively with this issue in order to maintain their role in the aeronomy community as a dependable, high-quality observational source of key ionospheric parameters. In this section, we explore the ways facilities can meet this challenge in the future by organizing the present state of the art around ten key experiment requirements that a UAF facility must meet in order to deliver useful data to the space physics community. For each requirement, we survey the key features and discuss significant challenges and new opportunities presented by current engineering and computational technology.

Experiment Requirement #1: High Effective Radiated Power

A fundamental requirement for incoherent-scatter measurements is a radar system with sufficient power aperture to detect scatter from the ionospheric plasma. The low scattering cross-section of the electron and the need for a signal-to-noise ratio near or better than unity is a strong physical constraint. This drives the need for a large power aperture in order for measurements to be made with useful integration times. The size of the required aperture and the power levels required are set by plasma physics and are fundamentally independent of the technology used to obtain them. A certain class of techniques and parameters only become available to high signal-to-noise ratio radars such as Arecibo, but in general all UAF facilities have a need to maximize their effective radiated power aperture through high-power RF and antenna systems.

High-power RF technology is necessary for production of the probing radio wave. This can be divided into solid-state and tube-based categories, both of which are only developing slowly. Solid-state systems are most easily used in phased arrays, due to overall cost considerations and the losses present in the combining network necessary for use with a single feed dish. In array configurations, ISR solid-state systems such as the AMISR feature a rapid pulse-to-pulse electronic steering capability with considerable potential benefits to observers, as this can be very useful in untangling spatial and temporal ambiguities during changing ionospheric conditions (e.g., at high latitudes). However, several challenges exist which must be carefully managed. The long-term lifetime of solid-state transmit/receive modules is unknown. The required replacement rate will eventually be determined, but the engineering costs involved in each replacement cycle are unclear. Gradual shifts in the underlying technologies almost ensure that a given transmit/receive module design will have to be refreshed or redone periodically. The overall performance of solid-state devices is unlikely to change significantly due to the inherent limits of heat dissipation in the devices (perhaps by factors of two, but almost certainly not by factors of ten). Maintaining the ability to produce transmit/receive modules in quantity may require ongoing production activity commitments at some level.

Transmitting tubes for high-power RF-wave production are essentially custom designed for each application by a very limited number of companies and are therefore very expensive. However, they are a mature technology and have reached very high-power density and excellent efficiency. Solid-state modulation designs for high-voltage systems are also at a mature stage, making a tube-based design highly reliable and relatively easy to automate. These features are a significant enabling factor for maintaining and extending the life of existing klystron-based transmitters.

Market forces present the greatest challenge to obtaining and maintaining the transmitting tubes. UAF installations do not use a uniform tube type or operating frequency, which makes designing a tube suitable for all radar systems impossible. Even if a uniform type was used, the facilities are not large enough consumers to maintain a design in production. In practice, UAF facilities will need to continue their strategy of employing significant customization to adapt technology from products driven by other end users, provided a suitable tube continues to be available. Demand for new tubes currently comes mainly from commercial television applications and the particle accelerator community. In this regard, transmitter designs based on commercial broadcast tubes are likely to remain viable, but it is important to note that the broadcast community needs continuous-wave transmission at maximum efficiency, rather than peak power at relatively low duty cycles. This can necessitate a large number of tubes for pulsed operation, although some designs potentially could be scaled in operating power.

High-gain antennas constitute the other portion of the power-aperture equation. Phased-array systems synthesize their gain in free space as a straightforward function of the number of elements used. UAF facilities will likely maintain access to the required engineering and manufacturing expertise necessary for well-engineered and -constructed large-aperture antennas. However, such expert work is expensive. Cost-reducing advances have occurred at high frequencies, but far less so in a frequency range appropriate for ISR systems. This leads to a net cost increase proportionate to material and labor rates, which makes maintaining existing antenna systems significantly more expensive. Unfortunately, this situation is unlikely to improve substantially in the future.

The great success of the AMISR phased array system can be extended in the future with designs that utilize per-element, full digital control for both transmit and receive. Backed by supercomputing resources, this level of control allows a transformative measurement capability for atmospheric science, in which the instrument becomes a hybrid of both radar and synthesis radio-telescope approaches. In particular, such systems have the possibility of adaptive transmit beam generation, active suppression of radar sidelobes in unwanted directions, and multi-beam volumetric imaging for some classes of targets. Suppression of unwanted transmission sidelobes also has the benefit of enabling high power radar use in semi-urban populated environments with low elevation angle RF safety restrictions.

The optimum strategy for achieving high effective radiated power is to pursue both phased-array and high-power single-dish radar technology. Very often, scientific requirements and logistical considerations will dictate which technology is best for a given situation. By maintaining expertise in both types of radar systems, the facilities will be poised to take advantage of breakthroughs in either area as they occur and to apply the soundest and most cost-effective solution to scientific challenges.

Experiment Requirement #2: Reception of RF Signals and Conversion to Digital Voltages

Reception of radio-wave energy scattered by the ionosphere, and the conversion of this signal into an appropriate voltage representation, is a key aspect of making radio science measurements. The process incorporates a range of analog technologies that filter and convert the received energy while isolating sensitive components from the outgoing transmitter waveform. In modern systems, the conversion process ultimately terminates at an A/D converter followed by a digital down-conversion stage. This is often combined in one device referred to as a digital receiver, although the processing after the A/D converter can be implemented in programmable logic or general purpose software. Linearity, stability in time and frequency, and dynamic range are the primary characteristics required of this process. The analog and digital processing results in a complex amplitude response with the requirement of proper characterization for use in subsequent incoherent-scatter data analysis processing stages.

The transition to digital receivers for RF waveform capture has essentially happened, with all of the UAF employing this technology at some level. Digital receiver technology is continuing to develop at a rapid pace, and yet modern digital receivers are already difficult to fully exploit due to their large configuration space. The next generation of receivers will be even more complex and higher in performance. Progress in this area will be made primarily in the direct acquisition of larger bandwidths at higher frequencies and at increased dynamic range. Some very experimental systems are achieving extraordinary dynamic ranges and bandwidths, which would allow the full direct digitization of RF bandwidth for any radar used for incoherent-scatter applications.

It is important to note that a functioning digital receiver is by no means a complete radar processing solution. In general, the exact type of unit used is far less important than how it is applied and matched to the software capabilities of the signal processing chain whose final output is geophysical parameters as a function of space and time. Digital receivers produce a vast amount of data, and managing this information flow in anything other than a one-shot experiment is complex and difficult. Management of the data life cycle from its creation by the radar hardware to its end use by a scientist is very important to the overall utility of an ISR system. Long-term archival of this information must also be considered as part of the overall lifecycle. It would be advantageous to preserve the underlying samples from the digital receivers, but this is expensive for anything other than modest bandwidths.

The concept of "standardizing" digital receivers across facilities is problematic as it overlooks the very heterogeneous nature of the systems they must connect to. These systems are varied because of their unique histories, geophysical locations, and available hardware and software resources. Over time, each facility has implemented end-to-end systems appropriate to local capabilities in response to different user demands and as a result of different implementation schedules. Implementing a uniform solution would be complex to coordinate and require many more personnel resources (not less) than are currently required. Procuring the modern digital receivers necessary for a standardized system may be prohibitively expensive. Additionally, some degree of redundancy in the UAF community in the development of systems using such receivers is not always a liability. Maintaining the skill set necessary to implement such complex radar systems requires a high level of technical talent and staff diversity. Students also need the opportunity to work with this type of hardware if future experimentalists are to emerge and be available to the community.

However, some coordination of work is possible in subsets of the end-to-end processing task. The UAF have already started some coordination initiatives (e.g., the Open Radar initiative), especially in the area of software processing chains and standardized outputs. One particular area where collaboration would be useful is the development of a common format for the voltage level-data from such systems. RF voltage-level receiver data is rapidly becoming the natural choice for reanalysis and archival purposes, as it captures all possible information about the geophysical process under remote observation (with proper center frequency and bandwidth selection). A common format should be developed and maintained based on open standards and with the capabilities required for use in high-performance computing environments and networks. It should also be possible to produce common formats for lag-profile-matrix-based analysis systems, spectral analysis systems, and fitted ISR output products. Such efforts, which have been made before (e.g., Millstone Hill, EISCAT), can allow a greater degree of interoperability among facility software. However, the effort involved in such a large-scale standardization is considerable.

Finally, we mention that effective reception of RF signals also implies a robust method of rejecting radio frequency interference and other undesired environmental signals that appear in-band with the desired ionospheric radar return. This characteristic is especially important for siting of ISR systems near populated areas that are large sources of these signals. One approach involves signal processing algorithms in the general class of clutter subtraction and adaptive filtering. These exploit characteristic differences in signal coherence between wanted and undesired signals, and are in production use today (e.g., Millstone Hill). In the future, use of phased array systems with fine scale, element level control of phase and amplitude on reception enables the application of space-time adaptive processing (STAP). STAP offers many advantages including the possibility of adaptively placing antenna pattern nulls for signal rejection in appropriate directions. However, this requires significant computing resources and a considerable development effort to enable production quality real time systems.

Experiment Requirement #3: Reliable Knowledge of the Experiment Process

Voltages by themselves are devoid of meaning without detailed knowledge of the instrument configuration and mode of operation. Tracking this information in sufficient detail and generality is a significant task. The nature of an instrument changes with time in both planned and unplanned ways, and these changes can have significant impact on the collected data. Tracking such information is necessary to allow analysis of an experiment in a manner consistent with, and not subject to, the introduction of unknown biases. When this control and tracking is done properly as part of the experiment process, the result is a production-level system that allows for a sufficient understanding of the instrument function at any point in time.

The existence of production-level ISR systems is an important emerging trend over the last few decades, as the incoherent-scatter technique has moved from its initial exploratory phase to one in which measurement techniques are both repeatable and refined. There is a fundamental difference between experimental and production-level systems. Many student projects fall into the experimental category when a particular system configuration or analysis tool is developed for one application within the student-project lifetime and then is not used again. By contrast, production-level systems require a higher level of engineering, calibration, validation, and documentation.

In general, user demand has shifted over the last several decades to the production model, and the UAF are expected to have the ability to generate a set of basic ISR measurements at a production level (e.g., electron density, electron temperature, ion temperature, line of sight velocity, vector electric fields, and neutral winds) with variances, good calibration, and a lack of systematic biases. The user community is often very interested in near-real-time results at this level of quality for support of experiment campaigns or flexible alteration of measurement strategies. Production-level processing of incoherent-scatter data is especially important when considering that data products are used in long-term trend studies, which may occur decades later, or in predictive assimilation models that critically depend on accurate parameter estimation variances.

Other facility capabilities will likely always be of a more experimental nature, but it is important for the UAF to continue emphasizing, and investing effort in, the development of production-level techniques. However, because this is an ongoing and resource-intensive process, there is a balance to be struck between the scope of such efforts and the resources required for developing new techniques and executing scientific experiments.

Experiment Requirement #4: Processing of Voltages for Plasma Parameter Extraction

It is necessary to process voltages collected by an ISR system with signal processing and analysis techniques in order to extract physical parameters that are meaningful representations of the state of the ionosphere. Software is increasingly important as an enabler of innovation, underpinned by computing systems that are applied in increasingly large numbers (i.e., clusters and grids).

Virtually all signal processing and analysis is performed with software today, in most cases on general-purpose computing systems. This has the considerable benefit that, once implemented properly, a software processing system is likely to remain viable for a long time since it does not suffer calibration drift as can occur with analogue methods. This remains the case as long as the tools used to create the software are well selected and remain readily available in the future. A very significant accompanying challenge (perhaps even a requirement) is the need for formal development methods and techniques.

Software of even moderate complexity is difficult and labor intensive to create, and robust formal development techniques are outside the experience of many scientists. An example of such a technique is revision control, an essential step to ensure that data taken and processed by signal processing/analysis software can be understood much later if needed (e.g., retrospective determination of whether data show an artifact of the processing software or a real feature). This type of approach is crucial considering that software generated artifacts could be (and have been) mistaken for geophysically meaningful information. Facilities should continue to invest significant resources in calibration and stabilization of data analysis methods in order to ensure the future viability of their scientific results.

The learning curve necessary to create and maintain experiment systems that are modern in design and performance is steep. In practice, relatively few researchers or students are trained professionally in the needed skills for generally applicable, viable, and robust production-quality software for incoherent-scatter signal processing and analysis. In general, personnel in the UAF community with sufficient analytical and software development skills to exploit the increasingly available computing power are in short supply. The development challenges afforded by increased computing capacity often reach far beyond the use of prepackaged analysis routines, particularly when developing new techniques. This topic is intimately coupled to education and public outreach goals as well, since faculty and students must have flexibility and support in order to readily iterate and mature new techniques given the complexity of the tools that are available for their use. UAF facilities should continue to work closely with colleagues at university departments to attract and train new generations of scientists with the analytical capabilities to fully exploit the rich incoherent-scatter technique.

Computing capacity is still increasing and is often the driver of new techniques and methods. The integration of computing power at all levels of instrumentation and systems will remain a strong trend well into the future. This occurs all the way down to the power-plug level today and makes possible a high level of remote control and operations. Such levels of automation lead to feasible modes of operation in which the instruments, and more generally entire instrument networks, adapt their configuration and operation to the observed conditions or the requirements of particular experiments. These new capabilities can be exploited providing the facilities continue to stay well informed and share information on the latest computing advances.

Experiment Requirement #5: Reliable Setup, Control, and Monitoring of Experiments

There is a growing desire on the part of the user community to have the facilities provide remote operations (sometimes called “telescience”). This goal is also tied closely with recent emphasis on virtual observatory technology and the larger field of cyberinfrastructure. The efforts of the Cyberinfrastructure for Research and Development Committee, U.S. National Virtual Observatory, and International Virtual Observatory Alliance will continue to focus community attention on the definition of standards for interoperability and data exchange to facilitate science at a mesoscale level and beyond. These efforts are already resulting in successful implementation of prototypes within the UAF community, such as virtual observatory services from the Madrigal distributed database system.

Whether remote or local, operations are built upon the reliable setup, control, and monitoring of experiments and are greatly enabled by the integration of computer control and networking into the physical infrastructure of the facility instruments. In particular, the ability to have truly remote operations is often greatly hampered by the nature of the legacy hardware used to construct any given facility. In many cases, there is a physical operator behind the scenes ensuring that the hardware continues to function properly.

Networking capacity is the key enabler for telescience in this area. Networking power is roughly the cube of computing power and high-speed networks are already pervasive in most urban areas. More remote areas, many of which are scientifically interesting or unexplored, are far more difficult to access, with greater latency, reduced bandwidth, and intermittent availability. Some emerging technologies are attempting to increase bandwidth from remote locations (e.g., mesh networks or satellites). However, these depend on commercial drivers and, almost by definition, remote areas have little commerce. The experience of operating a facility located in a connectivity-rich location is potentially very different from one located in a remote region, where it is likely that users will be limited by reduced interactivity.

Remote operation of a facility is possible with even very limited bandwidth (e.g., SRI's network-news-based data transport system or NASA's Mars rovers). However, the level of flexibility and the richness of the experience are ultimately determined by the network bandwidth, the software that provides the interface, and the resources dedicated to offsetting the limitations of the communication infrastructure. It is possible that a truly global communications infrastructure will be developed which removes this problem to a greater or lesser extent. Unfortunately, commercial activity in this regard has waned somewhat recently and significant improvement may take some decades to occur.

The AMISR system uses an array of solid-state transmitters that can be more practically configured and operated remotely. Virtually all ISR experiments at Poker Flat are conducted with no on-site support. The ease and flexibility of operating AMISR provide many options to experimenters in terms of times of operation and operating modes, all of which can be reconfigured remotely in real time. The challenge for remote operation then is to adequately train remote users to best take advantage of this capability. Some standardization of operating modes is desirable so that once trained at a given facility, they can easily perform observations at other sites as well. Thus, the real challenges to remote operation are not so much the technical issues of running the radars remotely, but the efforts needed to educate the radar users of the future.

Where possible and economically feasible, onsite visits are a viable substitute for fully developed remote experiment execution, especially for campaign-oriented science. Facilities should continue to provide hosting services for visiting scientists and students (with an associated increase in net experiment cost). There is significant historical evidence as well that important pedagogical and training value is derived from having users experience first-hand the complex nature of ISR experiment execution, under the guidance of experienced facility technical and science staff. Maintaining the high rate of success that UAF radars have achieved in this regard will continue to require investment in talented long-term staff, and this should be a carefully considered aspect of facility planning.

Finally, reliable, stable operation of a facility in an on-demand manner can prove incompatible with requirements to develop and implement novel experiment techniques. Such technique development can "break" the production processing capability of a facility temporarily through the need for significant hardware and software reconfiguration. This can prevent remote operation of the facility in many cases and such changes must be managed carefully to ensure the impact is not too large. Since the division of radar operations into routine and experimental operation modes is driven largely by the nature of user requests, facilities should continue to engage the larger community in focused scientific and technical workshops (e.g., CEDAR workshops and URSI radar techniques sessions) in order to strike the right balance between ease of use and radio science innovation.

Experiment Requirement #6: Knowledge of the Geophysical Context of an Experiment

The geophysical context of measurements from UAF radars is very important for understanding experiments and extracting meaningful knowledge from them. ISR sites are natural locations to deploy and operate other instruments for observing the upper atmosphere and ionosphere. Other instruments provide information about atmospheric properties the ISRs cannot measure. The collocation of instruments provides opportunities for common volume measurements to enhance scientific analysis and improve observational accuracy. The logistical support typically available at the facility sites makes the operation of ancillary instruments cost effective and reliable. Over the years, a wide array of instruments has been deployed at the radar sites, often supporting areas of research outside of upper atmospheric and space sciences. Appendix B provides a description of the types of collocated instruments that have been deployed at UAF sites. Database services such as the CEDAR and Madrigal systems have ensured that data from UAF instruments and ancillary instruments are easily accessible to space science researchers worldwide.

In addition to instrument clusters around UAF sites, distributed instrument networks are also extremely useful for providing the geophysical context for radar measurements. The National Research Council's 2002 decadal survey of solar and space physics specifically mentioned the importance of such distributed instrumentation to space science research. A recent DASI (Distributed Arrays of Small Instruments for Solar-Terrestrial Research) workshop that explored the scientific rationale for arrays of small instruments found many compelling reasons for their construction. The availability of powerful networks and ubiquitous, GPS-derived temporal coherence has enabled entirely new classes of distributed instruments that are of growing importance to facility operations. In particular, GPS-disciplined oscillators and time sources provide a means of maintaining global phase coherence and high stability for a receiver system, enabling coherent networks of instruments which were previously cost prohibitive. Such global coherency is important for comparing data between instruments and is valuable for creating "ad-hoc" meta-instrumentation. The GPS technique itself has provided the first example of such a "meta-instrument," with wide-area TEC measurements now available in near-real time. Such mesoscale views of the ionosphere are scientifically very useful and provide important context for incoherent-scatter measurements.

One potential future role of the UAF in such instrument networks is in technical development and operational support. Exploiting such networks will require end-to-end management of the data life cycle involved as well as significant computing power and software expertise. The facilities are well positioned to provide technical expertise and leadership in these areas, and should actively contribute to their genesis and development. Distributed instrument networks also need to take advantage of advanced manufacturing capabilities to provide high levels of integration, uniformity, and greatly increased reliability and quality. Industry can readily supply such manufacturing, but exploiting it is beyond the level of engineering funded for most scientific projects. (A notable exception is AMISR, which has been developed in close coordination with the production engineering firm Sanmina SCI.) Future UAF efforts in the distributed instrument arena should consider at a very early stage how to create opportunities for partnering with talented engineering companies to realize economies of scale and, ultimately, robust products.

Beyond distributed instruments, a number of digital beamforming radio telescope systems are being developed by the radio astronomy community (e.g., LOFAR, Murchison Widefield Array, etc.). These systems are precursors to the much larger, next-generation Square Kilometer Array. Such systems are also likely to be extraordinary space-environment monitors because of their fundamental need to correct for transionospheric and transheliospheric signal effects. The UAF community has a significant (and arguably historic) opportunity to work with these emerging observatories to synergistically harvest and provide upper-atmospheric-data products. Such efforts should be pursued and expanded, as the benefit-to-cost ratio is likely to be high.

Another strategy for meeting scientific demand for global observations is to conduct experiment campaigns using portable instruments temporarily deployed to locations of interest. The AMISR design allows for relatively quick and cost-effective relocation as scientific priorities change. AMISR will initially operate at Poker Flat, Alaska, and Resolute Bay, Canada. Possible options for future relocations of AMISR may entail deployment of the three faces at three different locations. The three faces could be deployed at the same latitude to study the longitudinal variation of ionospheric phenomena, or in a meridian chain to study latitudinal variations with finer spatial coverage than the existing chain. Another option, of course, is to put all three faces at the same location to maximize sky coverage. It should be noted that if the three faces are oriented so that their fields of view intersect in some region of the sky, then the sensitivity of the combined radars at that location will be better than any other ISR except Arecibo.

Another option for relocating AMISR is to divide the faces into smaller antennas. Each face consists of 128 panels, but tests have shown that even 32 panels are sufficient to make reasonable incoherent-scatter measurements. Thus, AMISR could be divided into as many as 12 smaller radars. Furthermore, the shape of the AMISR antennas does not necessarily have to be a square. Linear arrays can be constructed to create beam patterns optimized to the phenomenon being observed. For example, at the equator, the equatorial electrojet can be observed with a linear array that gives greater steerability along the electrojet. This configuration will broaden the beam transverse to the electrojet, but this may be acceptable as the return signal from those locations is likely to be weaker anyway.

As experience in relocating AMISR is acquired, moving the radars will become more routine and less costly. More frequent relocations or reconfigurations will be possible, greatly expanding the options for scientific studies. More scientific campaign planning will be necessary to best take advantage of this capability. Also, greater flexibility and versatility in radar data processing software will be required to facilitate the use of AMISR systems at different locations and different transmit/receive configurations. Thus, the expanding science opportunities resulting from AMISR will call for better coordination among radar users, and more strategic planning of observations.

Experiment Requirement #7: The Timely Delivery of Data to Multiple End Users with Different Needs and Levels of Sophistication

The detailed level of control made possible by advanced software and network technology allows for complex radar experiments. Such complexity can be further compounded in signal processing and analysis, because it is now possible to analyze a single experiment in multiple ways. These capabilities are very powerful and can be applied to optimize the science yield of an instrument or facility. However, a significant portion of the science user community often wants this complexity (and indeed the inherent complexity of the incoherent-scatter measurement technique) to be hidden and managed transparently to them. Doing this implies an additional layer of complex software, and the resulting simplification can often greatly limit the ways in which an instrument is operated or the level at which it is understood by the end users.

Clearly, there is no single uniform solution for targeted delivery of user information. UAF sites should continue their research into ways to provide multiple views of their output data, each of which can optimally serve different science and technical consumers. Such efforts require close coupling with advances in databases, virtual observatories, and other cyberinfrastructure concepts. Care should be taken to ensure that these higher-level data products can be clearly understood and applied. Efforts to more widely educate the potential user community on the incoherent-scatter technique also should be continued and expanded.

Experiment Requirement #8: Quick Response Capability

As discussed in section four, space weather is becoming more important as the nation strives to protect the increasing number of sophisticated technical systems susceptible to conditions in the space environment. One of the most challenging aspects of space weather is predicting transient events, many of which have their origin on the sun. The lead time between when an event occurs on the sun and when it manifests effects in the ionosphere and thermosphere can be minutes to days. In either case, a quick response capability is essential to make the desired observations in Earth's atmosphere. Aside from SuperDARN and PFISR, and to some extent Jicamarca, the UAF do not run continuously, and in fact are only operational for at most 25 percent of the time. With operating schedules planned well in advance, the radars typically do not have the flexibility to initiate operations in response to every space weather event. Furthermore, even if the flexibility exists and a reliable prediction of an event is available, often technical, logistical, and personnel constraints limit the ability to respond appropriately. Many of these difficulties will be alleviated for the AMISR systems, as the solid-state transmitters allow the radars to be operated remotely with minimal onsite support. However, most of the other radars have limitations that make observations in response to events difficult.

Nevertheless, every possible means should be employed to optimize radar measurements during important space weather events. The first requisite is for the radars to continuously monitor the most accurate and up-to-date space weather predictions. The National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center provides space weather forecasts routinely, but the UAF should also directly monitor other sources of space weather data. When suitable thresholds for events have been established, a process should be put in place for automated notification of key facility staff members. Once notice of an impending event has been received, each facility should have its own decision-making process by which to trigger, or not trigger, operations. This formal process should be put in place and, if necessary, rehearsed to evaluate its feasibility and effectiveness.

One possibility to improve a radar facility's ability to operate in response to an event is to implement a standby mode based on a long-range prediction, perhaps using the recurrence of solar disturbances tied to solar rotation. A standby mode lasting several days will greatly increase the likelihood that a given radar can operate during an event without placing an undue burden on staff.

Experiment Requirement #9: Maintenance of Capability and Infrastructure

In the future, UAF sites will likely be presented with opportunities to leverage unforeseen technological developments with the goal of streamlining operations. However, these efforts face a fundamental installed infrastructure problem common to all large technological systems. Aging in such systems causes progressively increasing difficulty in maintenance and modernization. This is even true for the newest facility, AMISR, which has already needed to adapt its designs to market-driven manufacturing changes in available power-amplifier transistors. Maintenance and modernization is a resource-intensive activity. Constant change is required in order for an ISR facility to achieve the designation of "modern," and the complexity of meeting these requirements increases with time. The technology available to implement modern capabilities is also constantly shifting, and adapting to this change is difficult.

The technology necessary to maintain and upgrade an ISR tends to be complex, and maintaining an appropriate skill set among facility staff is quite difficult in the face of competition from industry. One advantage of traditional radar systems with separate transmitters and antennas is the feasibility of repeated modernization of subsystems at a relatively low cost. Experience will determine whether this holds as well for phased-array systems such as AMISR, which in their transmit/receive module systems have embedded communications networks and other design features with associated significant modernization costs.

Even with the development of new systems, it is critically important that adequate support be available well into the future for ongoing repair and preventative maintenance of existing sites. This should be a key focus of UAF planning activities, as it applies both to the legacy facilities as well as to the new AMISR system. Historical experience from radio astronomy and other communities shows that UAF-class facilities require an annual ongoing expenditure of approximately 10 percent of their inflation-adjusted cost for operations, maintenance, and upgrades. This estimate is not likely to decrease in the future. Appendix C describes plans for facility upgrades in the next five to ten years.

Experiment Requirement #10: International Coordination

The upper atmospheric facilities benefit enormously from collaborations with international partners. International collaboration among the facilities is accomplished in various ways: shared operational planning through the URSI Incoherent Scatter Working Group, shared observational campaigns with agreed objectives, public and unrestricted data access through MADRIGAL, shared expertise, staff exchanges, and reciprocal external membership in science and technical planning committees. There are also important specific synergies between the operations of the three EISCAT radars and the UAF sites at Poker Flat, Sondrestrom, Millstone, and SuperDARN. These facilities also cooperate on new hardware development in areas including interferometry, databases, and common equipment. . There is also competition amongst the international incoherent scatter community, for example, over plasma line techniques and coding schemes. International coordination will become ever more important as both the science and the scale of the investigations undertaken become increasingly global in nature.

Global problems, such as long-term trends in the atmosphere or climate change, almost mandate global solutions and approaches to observations and data. The UAF sites have been exemplary in this area. International collaboration provides a longitudinal dimension, in the case of the ISRs, and supports nearly complete coverage in both hemispheres, in the case of the SuperDARN radars.

Synergy between the science strategies of the UAFs and the EISCAT facilities in particular should drive wide-coverage collaborations, especially with regard to societally relevant research and science education. Shared scientific strategies and goals, and shared approaches to addressing societally significant problems, such as forecasting the geoeffective-impact of solar events and global climate change, have yet to be created, but detailed plans in specific areas are rather better developed. The SuperDARN community has a very well-developed international collaboration in place whereby all radars participating in the SuperDARN project adhere to basic performance and interface requirements, share common operating and analysis software, jointly construct the operating schedules, and provide their data in a timely manner to a central data archiving and clearing center. This structure has allowed SuperDARN to reliably produce its most visible data product, namely real-time high-latitude convection maps, and has directly led to the widespread use of SuperDARN data for a myriad of both scientific and user goals.

The ISR community also has a well-founded international collaborative program in place. Because the historical development of the individual radars has been unique, there has been limited collaboration at the hardware or control software levels. However, as the low-power-signal generation, reception, and signal processing related to these systems moves increasingly into the purely digital domain, the potential for effective practical collaboration, both within the U.S. facilities and in the wider international community, will increase significantly, allowing all the radars to leverage developments at other facilities to their mutual benefit.

Although the hardware implementations differ radically across the world's ISRs, the drive for increasing pulse compression and coding efficiency has already benefited substantially from the international dimension of the work. Alternating codes were developed for use on the EISCAT radars, for example, but have now found widespread application on several U.S. ISRs. The complementary work on coded long pulses at Arecibo, for example, has also been applied at EISCAT. At the analyzed-data level, most facilities now share data through the distributed Madrigal database system initially developed at, and maintained by, Millstone Hill.

A significant proportion of the observing time at UAFs and other ISRs around the world is coordinated through the URSI's Incoherent Scatter Working Group, which utilizes a peer-review process to decide on the timing and goals of joint programs totalling approximately 500 hours a year. These programs are included in the published Geophysical Calendar each year and provide a framework for wider cooperation with other instruments and techniques throughout the world. The yearly schedule of World Days provide for coordinated operations of two or more of the ISRs for common scientific objectives. The World Day periods are scattered throughout each calendar year to provide seasonal coverage, while the different locations of the radars provide global samples. Many years of data are available in the CEDAR database and other online databases.

Another area of cooperation involves worldwide efforts to exploit the opportunities represented by the International Polar Year 2007–2009. During the first 12 months, the ISRs arranged a substantive international collaboration whereby the EISCAT Svalbard Radar runs almost continuously throughout the interval, PFISR ran continuously in a low-duty cycle mode (when not performing other experiments), and Millstone Hill, Sondrestrom, PFISR, and the EISCAT Mainland Radar ran complementary programs every two weeks. The Sondrestrom radar provided planned backup coverage during Svalbard Radar maintenance intervals. All instruments distribute their data through the Madrigal database and the framework established for this venture will provide a firm foundation for future close integration of effort across the whole international, high-latitude community. A reduced effort is currently underway for the second year of the IPY.

While individual facilities are effective scientific tools in their own right, it is clear that assimilation of data from multiple sources is even more effective for some studies and allows the cooperating facilities to achieve higher returns than are possible if they work alone. For the newer facilities, such as the EISCAT Svalbard Radar, the AMISR systems at Poker Flat and Resolute Bay, and the planned new EISCAT_3D radar, there are practical possibilities for cooperation in most aspects of signal generation, processing, and control. However, all facilities, existing and planned, could share analysis software, particularly software and expertise for deriving further ionospheric and neutral atmosphere products from the basic core parameters measured by the instruments.

The AMISR, which combines unique new capabilities and a unique location, will become a pivotal element in the international incoherent scatter community. Together with the planned new EISCAT_3D facility, these instruments are likely to form the backbone of high-power upper-atmosphere instrumentation far into the future.

At its initial Resolute Bay deployment location, the AMISR will primarily interact with the existing high-latitude radars at Sondrestrom, Greenland; Longyearbyen, Svalbard, and Tromsø (two), Norway; and Millstone Hill, Massachusetts, as well as with the single AMISR face at Poker Flat, Alaska, and the distributed radars of the SuperDARN collaboration. In addition, the AMISR will form a crucial component of the extensive ground-based instrumentation deployed in northern Canada.

In the longer term, the UAF strategy should also consider the likely or possible developments in the wider international community. These include the planned Japanese radar in Antarctica, which will have significant capabilities as an ISR in addition to its main MST role, the EISCAT_3D initiative in Europe, and the planned Chinese radar, as well as relocated AMISR components and next generation phased array radar technologies. The relocatable nature of AMISR is important for future coordinated study possibilities.

Coherent and incoherent, scatter radars can also act as a vehicle for technology transfer and capacity building in developing countries. Indeed, geophysics research in general provides excellent opportunities for extremely effective activities of that type. By providing leadership in the design and construction of hardware and software, the upper-atmospheric facilities provide educational opportunities for young scientists and foster appropriate knowledge transfer and economic benefit.

EDUCATION and OUTREACH

The UAF sites described in this report have a long and impressive history of innovative science results and technique development. Their capability to extend this performance into the future is dependent on the quality of their education and public outreach (E/PO) activities. E/PO is essential for informing the general public about the exciting science possible with UAF instrumentation and for maintaining the supply of high-quality young scientists and engineers from universities and industry, in part by providing direct hands-on training for faculty and students. The education component is especially important in today's higher education climate where myriad career paths exist for the new graduate, many of which are extremely attractive from both a technical and professional standpoint. To recruit new scientists into the field of space physics, strong E/PO investments by UAF staff must illuminate the exciting and important challenges still remaining in space weather and upper-atmospheric physics research.

Fortunately, the explosive growth and availability of the public Internet presents an unparalleled delivery medium for science information. Students and the general public at all levels now use the web as part of their everyday activities, and increasingly rely on it for their primary information source. Web-based educational material and resources for teachers have developed into an excellent way to motivate and encourage interest in science topics. In particular, the current worldwide focus on global climate change issues is a natural opportunity to influence the thinking of an entire generation through internet-based initiatives highlighting the science results and leadership provided by UAF-associated research. The new medium of Internet audio and video podcasting provides unique access and a new way of delivering the message that radio science and UAF-driven atmospheric science discoveries remain at the cutting edge of human knowledge about our environment. While it is unrealistic to expect UAF staff members to become experts in editing and delivery strategies to optimally convey science excitement in these areas, numerous trained science writers and media consultants are available, and should be exploited by UAF E/PO activities. Some activity in this area has already started to occur, through NASA- and NSF-associated informal science-education programs and new media initiatives (e.g., MIT Haystack's partnership with a local children's discovery museum, and the NSF Research Experiences for Undergraduates program). More such projects should be pursued and encouraged, as detailed further in this section, in conjunction with established NSF and NASA media facilitation offices.

UAF E/PO activities are described below according to the following general categories:

- General public
- K–12 students and teachers
- Undergraduates
- Graduate students and postdoctoral researchers

These groups are quite different, and so effective programs must be tailored to their specific needs. We explore below some of the challenges and possible ideas for addressing them.

General Public

For members of the general public, many of whom were last exposed to science in high school, a successful strategy will engage their curiosity and sense of wonder about the universe and their place in it. Both the astronomy community and the excellent, vast NASA public-outreach program use this avenue in particular to maintain interest and increase traffic to websites and public programs. Yet, this task is a challenging one since many UAF science results and techniques require considerable educational backgrounds to fully appreciate their many facets.

Bridging the public gap is already being accomplished by many UAF facilities as part of outreach to their immediate local communities. For example, Arecibo's Angel Ramos Foundation Visitor Center serves over 100,000 public visitors per year—of which more than 30 percent are school children—through multimedia interactive exhibits. Millstone Hill/MIT Haystack is currently working with a local children's science discovery museum to design focused, self-contained radio-wave demonstration exhibits that link not only to fundamental physical concepts, but also to space weather measurements and UAF research.

Facilities offer regular public tours and open-house lectures giving overviews of ongoing and new research, linked to larger contexts such as the coupled Earth-Sun system. Efforts in this area should be maintained and expanded, with a particular eye towards producing engaging and accessible programs highlighting focused concepts, such as the existence of the solar wind or the overall atmospheric response to geomagnetic storms. Potential new avenues for accomplishing this include greater involvement in exhibitions and planetarium shows at science centers and museums, which see an enormous number of public visitors (e.g., 1.6 million per year at the Museum of Science in Boston, many of whom viewed the SOLARMAX Imax film featuring the Sondrestrom ISR and lidar footage). This can be facilitated through direct contact with program planners at these institutions, many of who are eager to add new topics to their repertoire.

Good media exposure is another well-proven technique for sending out the UAF science message. This is most efficiently done through working with a talented science journalist, who can work with a particular scientist to refine and simplify a UAF science study. These professionals can provide excitement and public connection, along with judicious use of multimedia in order to deliver a product that is immediately appealing and accessible. Links between UAF scientists and science writers could perhaps be coordinated through the AGU space physics and aeronomy section's E/PO committee, and could tap the existing AGU infrastructure designed to assist scientists with creating summaries for public consumption. Finally, outreach to minority and other normally underserved groups can take place through collaborations with existing programs (e.g., the Women in Engineering Organization, which promotes interest in science and engineering among girls and young women). NASA Space Science E/PO programs can be a valuable resource here, and its program officers are often very willing to help and provide cross-links from their own efforts.

K–12 Students and Teachers

Another key E/PO goal is to reach K–12 students while at the same time providing useful UAF originating materials for their science and math teachers. This effort needs to be vigorous to successfully compete for attention with the many other information sources flooding young people through traditional as well as new media. Even more than adults, young students must be shown an exciting and dynamic presentation highlighting interesting aspects of UAF science. Just as important is support of their teachers, as U.S. public and private school teachers are often overworked and under intense demands to produce a curriculum that meets strict state-mandated guidelines aimed at regular standardized testing. This last point is especially important for a successful effort since teachers may immediately discard material that is not directly relevant.

Fortunately, there are existing frameworks that can be adopted and expanded. The cross-cutting NSF Research Experiences for Teachers (RET) program supports the active involvement of K–12 teachers and community college faculty in engineering research in order to bring knowledge of engineering and technological innovation into their classrooms. The program has two mechanisms for support of in-service and pre-service K–12 teachers and/or community college faculty research: RET Supplements and RET Sites (e.g., Millstone Hill/MIT Haystack).

Principal investigators who receive UAF-associated grants could be encouraged to apply for RET supplements wherever possible. UAF science involves many topics (e.g., GPS navigation, transionospheric communication, scintillation), which can be directly related to impacts on the everyday lives of increasingly technically savvy students. Other NSF education grants are often available as supplements to existing research awards, including the main cooperative agreements that fund the UAF sites. Staff at the various UAF sites could be made aware of these opportunities through a central coordination effort by the UAF office at NSF.

Undergraduates

If competition for attention is intense at the K–12 level, it is doubly so for undergraduate students. Technical and science majors at most colleges and universities currently have a large and often bewildering array of career choices, some of which are perceived as being very "hot" (e.g., nanotechnology) and which receive considerable departmental and faculty advisor attention. With little time to select a major, these students need to have a compelling case presented that involvement in upper atmospheric facilities and incoherent scatter radars is just as exciting and challenging as these newer areas. (In fact, a good case can be made that UAF results continue to represent the cutting edge in U.S. radio science.) Additionally, they need to realize that while the entire knowledge base required for such tasks as interpreting recorded incoherent-scatter data or placing measurements in proper physical context can be large, portions of such efforts are readily accessible to students in basic physics and chemistry, information technology, electrical engineering, RF/radio science, and instrument design.

The program with the longest pedigree in this area is the very successful NSF Research Experiences for Undergraduates (REU) program, which has been supported for many years to involve students in meaningful ways within active research. Currently, both Millstone Hill/MIT Haystack and Arecibo have established REU programs, and each year several students get valuable upper atmosphere research experience in a one-on-one manner with a UAF mentor. Graduates of these programs are tracked for several years and have a high probability of remaining in science fields. In some cases, these students have eventually become active researchers in the space science community. REU efforts could be expanded in innovative ways to other UAF facilities, perhaps through adjunct connections to these existing REU programs.

An equally important task in this area is the support of teaching faculty, in particular by encouraging them whenever possible to incorporate elements of UAF science and techniques into courses fulfilling basic requirements of the major. Whether this is through examples of interesting applications or even as direct course projects, this kind of exposure can attract a student to later graduate work in UAF-related fields. Interested UAF staff can help promote UAF research and provide guest lectures to the tenure-track young faculty who often are assigned these courses. This should be encouraged whenever possible.

Graduate Students and Postdoctoral Researchers

At the graduate student and postdoctoral level, E/PO efforts focus along two lines. Historically, UAF research has benefited enormously from the talent that emerged from several research-class university departments that focused considerable time and effort on UAF-specific avenues (e.g., equatorial irregularities, optical imaging of atmospheric emissions, suborbital and satellite programs, and first principles modeling). A key goal for the community must be to maintain and expand these institutional programs and promote faculty positions with considerable UAF involvement, both as an influencing effect on graduate students and also as a future career choice for talented Ph.D. awardees. Young tenure-track faculty must engage their graduate students in projects that involve data or measurement techniques at UAF sites. This is a critical task designed to encourage graduate students to choose UAF-related dissertation topics, which will ensure that a next generation of capable individuals is available both to assume roles on facility staff and also to serve as educated consumers of the data flowing out from the facilities.

Ultimately, university departments themselves must determine the nature and direction of their research. However, the community can influence these decisions through efforts such as the NSF announcement for AMISR graduate student support. Funding of such a program that would cover all UAF sites should be encouraged. Expansion of UAF postdoctoral support would also provide a means to train young scientists to think of facility data, and employ it, as an essential and unique tool for advancing understanding of the upper atmosphere. This is especially important in light of the 2002 National Research Council's decadal survey of solar and space physics, which spawned the DASI workshop that explored the scientific rationale for arrays of small instruments as a next-generation method for pursuing aspects of solar-terrestrial science at a global level. The forthcoming DASI initiatives will concentrate on the overall picture of physical coupling in the upper atmosphere, and UAF data can provide detailed temporal and spatial resolution in focused experiments on features uncovered in DASI network results. However, the community must have knowledgeable scientists available to realize these types of synergistic connections. Postdoctoral students with significant exposure to UAF capabilities and results would meet this need.

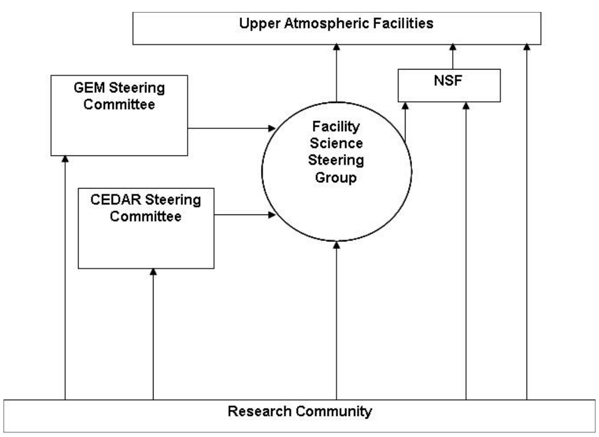
Graduate and postdoctoral experiences can also be enabled through extended visits to facility sites. A more coordinated approach to arranging such visits would help increase the number of visits and optimize their benefits. Given limited resources to support visiting scientists, it is important to take advantage of opportunities made available through other NSF and federally funded programs. In particular, support for visiting scientists could be funded through international programs at NSF and other agencies. Similarly, targeted programs aimed at students, particularly from under-represented groups, could help to increase the participation of students in upper-atmospheric research. A well-coordinated program to support visiting scientists to and from the facilities could be managed by a small group that includes representatives from the facilities and NSF.

IMPLEMENTATION

The previous sections have highlighted specific strategies through which the UAFs provide the best possible support to the scientific community. The broad range of contributions the facilities have made to scientific research is evidence for the effectiveness of these strategies over nearly four decades. Now, with an expanding portfolio of facilities and increasing scientific demand, a more formal approach to strategic planning is necessary. Fortunately, advances in technology, particularly related to web-based communication and interconnectivity, have made it easier for a coordinated approach to facility operations. Following are suggestions for ways to improve coordination among the facilities and more effectively plan experiments and provide data in support of scientific research.

The upper atmospheric facilities must remain in tune with the science priorities of the broader research community. A cross-facility science steering group should be implemented, consisting of one or two representatives from each facility. This group should take a proactive approach to obtaining community input. It should review facility usage and review plans for radar operations in the near future. The group must remain cognizant of opportunities for collaborative scientific research being conducted by NASA, NOAA, the Department of Defense, and other national and international agencies. If necessary, external advisors can be consulted as needed. This cross-facility working group should meet once per year, but be in continuous contact electronically throughout the year. Figure 21 illustrates the pathways through which the facilities would receive input from the science community. The Facility Science Steering Group (FSSG) would play a critical role in making sure that facility activities are optimally coordinated and responsive to the needs and priorities of the community.

Figure 21



Pathways for community input to the facilities.

In addition to the science steering group, focused working groups should be formed to address specific scientific and technical issues. For example, a group should be convened to continuously monitor progress in radar transmitter technology. Another group should be responsible for coordinating software development among the facilities. Another working group could be convened to establish a visiting scientist or personnel sharing program inclusive of all the facilities. In some sense, each of the facility strategies described above could be enforced via working groups consisting of members from the different facilities. However, many of these strategies have been satisfactorily implemented across the facilities, and dedicated working groups are not necessary at this time. Working groups could be formed to address specific scientific requirements, such as those driven by the launch of a satellite or a new experiment campaign. Working groups would be created by the science steering group as needed and would report back to that group so that appropriate changes in facility management and operations can be implemented.

The past three all-facility workshops have been a tremendous benefit in terms of sharing of information about best practices at the different facilities. The international partners involved in SuperDARN have met annually for many years. These meetings provide excellent opportunities for scientists to exchange information about past, present, and future radar observations. Because the range of topics that could be discussed at facility workshops is extensive, some amount of focusing is necessary to keep the depth of discussions meaningful. The FSSG should recommend the time and topic for each meeting. It should also invite attendees from outside the facilities as appropriate.

The suggestions for enhancing facility contributions to upper-atmospheric research all point to the need for improved communication and coordination among the institutions responsible for the sites. Even though the facilities have operated with relative independence for many years, rapidly changing scientific, technical, and programmatic demands are making this approach impractical. Recently, NSF funding for lidar projects at four institutions was consolidated under a consortium called the Consortium for Resonance and Rayleigh Lidars (CRRL). CRRL was funded by NSF as a four-institution collaborative effort, in which the participating institutions retain separate NSF awards, but one institution is designated as lead and carries the responsibility of managing the overall program. This approach is proving to be an effective vehicle for coordinating individual projects while retaining some degree of institutional autonomy necessary to motivate scientific productivity and expand the facility user base.

The international SuperDARN effort is another example of this type of loose confederation with many years of demonstrated success. The incoherent scatter radars may potentially benefit from this approach to coordination and integration.

The three objectives of NSF's Upper Atmospheric Facilities Program stated at the beginning of this report stress the importance of coordinated and synergistic activities that will enhance the facilities' role in upper-atmospheric research. While recognizing that each facility is unique in many ways, ultimately the scientific problems being addressed are common to all.

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APPENDIX A: A BRIEF HISTORY OF INCOHERENT SCATTER RADAR DEVELOPMENT

The early history of incoherent scatter reveals some interesting differences between the way science was done in the 1960s and the way it is done now. In 1958 William (Bill) E. Gordon was a professor of electrical engineering at Cornell University in Ithaca, New York. Gordon's background included training as a meteorologist for the Air Force during World War II, followed by work at the University of Texas at Austin studying propagation of microwaves through the atmosphere, including tropospheric ducting and scattering. In 1948, Gordon began working with Henry Booker. They both became interested in tropospheric scattering, stimulated by observations by the U.S. Navy of anomalously strong over-the-horizon propagation. This work led to the well-known Booker-Gordon scattering formula (Booker and Gordon 1950), which was part of Gordon's Ph.D. work. Because of their interest in using scattering for over-the-horizon communication, both Booker and Gordon tried to extend their ideas to first the stratosphere, then the lower ionosphere, and finally the upper ionosphere, since higher scattering altitudes mean longer links. But in the upper ionosphere, the neutral atmospheric turbulence responsible for the low-altitude scattering is not effective at the VHF and UHF frequencies of interest because of increasing mean free paths and viscosity. Nevertheless, Gordon kept musing about the problem.

One weekend evening in the spring of 1958, while at his home in the small village of Dryden, New York, Gordon had a breakthrough idea. The first step amounted to reinventing J. J. Thomson's 1906 calculation of the scattering from an individual electron. The cross section is very small, but there are a lot of electrons. But Gordon found that the scattering from even a great number of electrons is extremely weak, as already mentioned. He concluded that communications via scattering from individual electrons would be uneconomical because of the huge transmitters and antennas required. This was discouraging, but then Gordon wondered if you could use the scatter to study the scattering medium, the ionosphere. Indeed you could! Gordon did not abandon the calculation as hopeless when confronted with the idea of detecting a 1 mm diameter target at a range of 300 km or more. He showed that the radar technology of the late 1950s was up to the job, but you would need a *very* large antenna and powerful transmitter. With such a radar, using radar frequencies far above the maximum plasma frequency in the ionosphere, one could measure complete density profiles up to heights limited only by the radar sensitivity. This was in contrast to ionosondes, which work only up to the height of the electron density maximum. Gordon came up with a rough estimate of the type of system required: a 1000-foot diameter antenna and a transmitter of at least a megawatt or two at a frequency in the vicinity of 400 MHz. That system became the Arecibo Ionospheric Observatory (now the Arecibo Observatory) in Puerto Rico a few years later. The frequency choice was based on the fact that there is a broad minimum in the cosmic noise spectrum there. All of this happened in one evening, or at the most two. Gordon also proposed that one could measure the electron temperature by measuring the broad Doppler spectrum of the scattered signal resulting from the large electron thermal velocities. (We now know that the scattering process is more complicated than Gordon realized in 1958, however.)

Not long after the fateful evening, Gordon presented his ideas for the first time at a small electrical engineering colloquium (attended by the then-graduate student Donald Farley). Some weeks later Gordon talked to Kenneth Bowles, who had received his Ph.D. just three years earlier, about his idea. Bowles had access to a large 41 MHz transmitter (peak power output of about 1 megawatt) at a facility near Havana, Illinois. He needed a suitable large antenna, though. In just a few months he designed an array of 1024 half-wave dipoles, raised the money for it, and had it assembled by a tree surgeon he knew. Using this rather makeshift radar, Bowles made the first observations of incoherent scatter from the ionosphere during daylight on October 21 and 22, 1958 (Bowles 1958). Bowles' data processing procedure was a far cry from the sophisticated schemes in use today. He just displayed the amplitude of the echo on an oscilloscope, synchronized with the pulse repetition frequency, and then took a photograph of the scope face, using a time exposure of about 4 s. With a little tinkering, this simple averaging scheme can improve the effective signal-to-noise ratio by some 10–15 dB. Estimating the noise level by eye, subtracting it from a smoothed (by hand) profile of the signal plus noise (after squaring by hand the amplitudes), and then multiplying by range squared gave Bowles a result that did indeed look like an electron density profile.

Now it so happened that October 21st was also the day that Gordon was scheduled to give the first formal paper on incoherent scatter at an URSI Meeting at Pennsylvania State University. The paper was to be given in the afternoon, and Gordon had arranged to call Bowles at lunchtime, since he knew about the experimental effort underway. The result of the call was that Gordon began his talk more or less as follows (Gordon, private communication, 1995): "My purpose in speaking today is to tell you about incoherent back scatter from the ionosphere, and about the possibility of building a tool to make use of it in studying the ionosphere. And then I want to tell you about a telephone call that I just had."

After this dramatic introduction to the radiophysics community, incoherent scatter was rapidly developed into the exceedingly powerful probing tool that it is today. Gordon built his 1000-foot diameter reflector antenna, a spectacular engineering triumph, in a natural sinkhole in the mountains near Arecibo, Puerto Rico. The 430 MHz radar has expanded to become the National Astronomy and Ionosphere Center. Bowles expanded his horizontal dipole array into a much bigger array of 9216 crossed dipole pairs, operating at 50 MHz, at what is now the Jicamarca Radio Observatory located near Lima, Peru. This radar is now part of the Instituto Geofisico del Peru. Jicamarca began observations in late 1961 and Arecibo in 1963.

From a modern perspective, one amazing thing about this early development is that it all happened so fast. Gordon's original idea was probably in April 1958, give or take a month. Bowles heard about it some weeks later, designed, got the money for, and built the antenna in Havana, and then made the first observations, all in five months or less. Gordon's original paper was submitted to the *Proceedings of the IRE* on June 11, 1958, was reviewed and revised by August 25, and was published in the November 1958 issue—concept to publication in a non-letter journal in about seven months! Bowles got even quicker treatment: The paper on his first observations appeared in *Physical Review Letters* in December 1958. And the two major observatories, Arecibo and Jicamarca, went from rough concept to construction to operation at a similar amazing pace. Large sums of money (more than $10 million for Arecibo, more than $1 million for Jicamarca; and these were 1960 dollars) were raised quickly with comparatively short proposals and without long review processes. Major engineering (especially for Arecibo), diplomatic (for Jicamarca), and logistical (for both) hurdles were somehow overcome with a minimum of fuss and delay.

The history of the early days of construction of both observatories is full of fascinating episodes, most of which are still in the category of oral history. The news about Gordon's idea and the initial observations spread quickly. The early measurements by Bowles showed that the strength of the scattered signal was more or less as predicted by Gordon, but the spectrum was narrower by at least a factor of ten, perhaps more. In fact, if the spectrum had been as wide as originally predicted, Bowles' first experiments probably would not have succeeded. This discrepancy spurred several theoreticians to consider the problem of thermal density fluctuations in a plasma. This was in the early days of plasma physics theory, and so a number of people tackled the problem in very different ways, but arrived at what we now know is the correct result. The theoretical results predicting the shape of the Doppler broadened spectrum, and the precise quantitative agreement with observations, provide what may be the best confirmation of the validity of linear plasma theory. The early theory has withstood the test of time and has been extended to include the effects of collisions, unequal ion and electron temperatures, multiple ion species, relative motions of electrons and ions, and distortions due to non-Maxwellian velocity distributions. Thus, the ISR method of observing the ionosphere permits the study of a much richer variety of physical parameters than was initially envisaged by Gordon.

APPENDIX B: OTHER INSTRUMENTATION AT UAF SITES

ISR sites are natural locations to deploy and operate other instruments for observing the upper atmosphere and ionosphere. Other instruments provide information about atmospheric properties the ISRs cannot measure. The collocation of instruments provides opportunities for common volume measurements to enhance scientific analysis and improve observation accuracy. Following is a brief description of some of the other types of instruments typically operated in conjunction with ISRs.

High-Frequency and Coherent Scatter Radars

Incoherent scatter radar sites often host a variety of smaller radiowave instruments including medium frequency and meteor radars, ionosondes and HF radars, MST radars, and coherent scatter radars. While functioning according to the same basic principles, these devices detect different kinds of atmospheric and ionospheric inhomogeneities and irregularities, providing measurements of different neutral and plasma parameters and processes.

Specialized operating modes and signal processing algorithms are necessary for these radars, which often require expertise and support from outside the immediate UAF community. Individual investigators with their own low-power radars can meanwhile expand their research by deploying at a UAF site and exploiting the instrumentation, infrastructure, science, and technical staffs available there. Ionosondes can be used to help calibrate ISRs. They also expand the temporal coverage of the facilities by operating almost continuously, whereas ISRs typically operate for only about 1000–2000 hours each year. Long, unbroken databases with fast turnaround are thus established. Expanding the local time coverage of a facility is also a role for coherent scatter radars.

By making baseline measurements routinely, ionosondes and coherent scatter radars also free up the ISRs for specialized modes as needed, for example during storms, or for satellite support, or for more esoteric experiments. Peripheral radars also extend the spatial coverage of the facilities. For example, meteor and MF radars measure wind profiles at altitudes well below the nominal cutoff for incoherent scatter in the upper atmosphere, and MST radars extend those profiles through the lower atmosphere.

For many years, small ancillary radar systems have played an important role in enhancing observations at Jicamarca. For example, the JULIA radar is activated whenever the main radar is not operating. This low-power system is relatively sensitive because it uses the main antenna array and performs, at low cost, many of the experiments formerly carried out only with the main system. The main radar at Jicamarca has also been supplemented with the addition of a number of small radar antennas and systems tasked with carrying out specialized measurements independently of, or in conjunction with, the ISR. These include measurements of plasma number densities, electric fields, and neutral winds made using various innovative strategies. The Max Planck Institute for Aeronomy in Germany donated its VHF SOUSY radar to Jicamarca, where it has been upgraded and adapted to serve as both an ISR and an MST radar. It is able to probe a greater range of zenith angles than the main radar. Likewise, seven panels of the AMISR were deployed at Jicamarca in 2004. Its electronic steering capabilities can be used to study the zenith-angle dependence of 35 cm field aligned irregularities for comparison to results obtained at longer wavelengths.

Coherent scatter is generally the only means of remote sensing in the equatorial electrojet and valley regions, and new analysis methods have made it possible to infer plasma density and zonal wind profiles from coherent scatter in the former and electric fields in the latter. By utilizing refraction, HF radars and radio beacons can have much broader horizontal spatial coverage than even fully steerable ISRs and can help place local ISR measurements in context. Coherent scatter radars deployed with scattering volumes in common with the ISRs also provide crucial information about the stability of the volume. This kind of overlap is especially important for ISRs that cannot themselves observe perpendicular to **B**. Coherent scatter radars have been deployed close to Arecibo, Millstone Hill, Sondrestrom, AMISR, EISCAT, and the Altair radar on Kwajalein in order to investigate E- and F-region field-aligned plasma irregularities against the backdrop of ISR measurements. Geophysical phenomena of interest include sporadic E-layer instabilities, midlatitude spread F, and the radio aurora.

Whereas much of the common-volume radar work has been performed historically in campaign mode, permanent coherent scatter radars are beginning to appear in support of the facilities. Telescience must come into play, as the coherent scatter radars must be deployed at a distance from the facilities.

Finally, the various radars discussed above are only as useful as the signal acquisition and processing methods they utilize, and significant advances in radio science accompany their continuing development. Post-statistics and adaptive beam-forming, spaced antenna methods, spatial and frequency domain interferometry, pulse compression, antenna beam-forming, and radar imaging are some of the techniques to emerge from low- and medium-power atmospheric radar research. These techniques diffuse into the facility programs where appropriate, resulting in intellectual cross-fertilization. This component of the cluster is therefore an important catalyst for improvement.

The facilities program will move forward by completely exploiting the capabilities of low-power radars, supplementing those of the ISRs. Doing so will expand the temporal and spatial coverage of the facilities while increasing community participation in radio science there. In particular, coherent scatter radars permanently deployed with scattering volumes in common with the ISRs will permit more insightful investigations of ionospheric plasma physics and plasma instabilities than has been possible in the past. Cooperation with members of the MST, medium-frequency, and meteor-radar communities will promote innovation in techniques and instrumentation as in the past.

Lidars

Lidars provide high-resolution measurements throughout the middle atmosphere (~30–80 km for Rayleigh lidars, ~80–110 km for resonance lidars). Depending on the type of lidar, measurements of temperatures, winds, and atmospheric constituent densities can be made with range resolutions on subkilometer scales. Most lidars are limited to nighttime observations, but recent technical advances are making daytime observations possible. When combined with data from both coherent and ISRs, lidars offer a means to study the way in which atmospheric layers are coupled chemically, dynamically, and electrically. These middle-atmosphere lidar systems also provide important information concerning energy propagation from lower altitudes into the upper atmosphere.

At present, lidars are operating at the Arecibo Observatory, the Sondrestrom Facility, and the AMISR site at Poker Flat, Alaska. At Arecibo, calcium and potassium ion densities measured with resonance lidars were compared with electron densities measured by the ISR. These observations are important for studying the relationship between sporadic E and neutral layers. The abundance of various ions in the metallic layer is important for estimating total mass density of ions, which is required for determining the ion-neutral collision frequency. Similarly, simultaneous lidar and radar measurements at Arecibo were used to study the effects of tidal motion on sodium distribution. Strong enhancements in sodium concentration are found to be coincident with increases in ion-layer densities, suggesting that tidal motion in the ion layers creates sporadic E at lower altitudes.

At Sondrestrom, simultaneous measurements of electron densities and sodium layers during an auroral event were used to show that auroral precipitation can decrease the sodium column content by 50 percent over tens of minutes (Heinselman et al. 1998). The sodium response to auroral precipitation is believed to be a result of production of molecular ions by incoming electrons. The presence of molecular ions modifies the gas-phase chemistry of sodium, thus changing the steady-state concentrations. Recognition of this association is important in that it implies that auroral precipitation simulates an active experiment, where the response to a transient variation in atmospheric parameters can be studied to test understanding of chemical processes. It has also been demonstrated that sporadic E layers formed at high latitudes can cause significant enhancements in the sodium layer.

For lidars located at high-latitude radar sites, a high-priority science objective is to study noctilucent clouds. The Rayleigh lidar at Sondrestrom has been detecting noctilucent clouds since 1994 and the influence of local gravity wave interactions with the clouds has indicated that gravity waves serve to weaken cloud backscatter (Thayer et al. 2003). This is an indication that, although gravity waves drive the large-scale circulation leading to cold summer mesopause temperatures, locally gravity waves can cause the clouds to weaken and dissipate. Radar studies have been pursued to coordinate lidar measurements of noctilucent clouds with polar mesospheric summer echoes; however, the operating wavelength at 1290 MHz may be too high to produce adequate scatter from these structures. The noctilucent cloud measurements by the Rayleigh lidar have also been combined with the resonance lidar measurements of sodium density to illustrate a sequestering of free sodium atoms in the presence of ice clouds (Thayer and Pan 2006).

Passive Optics

The atmospheric airglow and aurora provide unique information about both the neutral and plasma environment. The UAFs have long served as hosts to a variety of passive optical instruments, including scanning photometers, grating (low-dispersion) spectrometers, Fabry-Perot (high-dispersion) interferometers, high-speed video cameras, and multi-spectral imaging systems. The information obtained by ISR and optical instruments is complementary: The ISR senses plasma-state parameters at a given point in space and time, an imaging system senses line-of-sight integrated photon production simultaneously over a two-dimensional field. The complementary nature of radar and optical diagnostics enables investigations that are not possible using traditional single diagnostic approaches, regardless of the origin of the photometric signal (e.g., ionospheric recombination, impact excitation, or thermal excitation).

The meteorological conditions at Jicamarca are not ideal for optical observing, mainly due to the presence of the strong inversion layer at about 1000 m above sea level. However, optical measurements can be performed from other places within Peru where the Instituto Geofísico del Perú and other Peruvian institutions can help with logistical support. Optical measurements have been made from Arequipa for many years with a Fabry-Perot Interferometer. A major upgrade to this system was made in December 2003, yielding an excellent instrument for measuring the speed and direction of the neutral upper atmospheric wind between 225–275 km altitude at night. In order to complement and improve the Arequipa measurements, the SOFDI instrument (Second-generation Optimized Fabry-Perot Doppler Imager) will be set up at Huancayo. SOFDI is a high-resolution multi-etalon Fabry-Perot interferometer designed to measure temperature and winds in the mesosphere, thermosphere, and topside regions from dayglow and nightglow.

At high latitudes, the spectral content of the aurora has long been used to infer characteristics of the incident energy spectrum of electrons. The classic approaches have involved simultaneous measurements at 427.8 nm ($N2^+$) and at 630 nm (O) (i.e., the so-called "red to blue" ratio) to parameterize an effective-incident Maxwellian-particle spectrum. Subsequent studies have incorporated other wavelengths and more sophisticated modeling to attempt to back out other parameters, such as incident heat flux and ion outflow. Photometric measurements of these parameters in the magnetic zenith can be readily compared with temperatures, densities, number fluxes, and incident particle fluxes derived from ISRs. Because optical diagnostics are much less expensive, it is hoped that such coordinated experiments will lead to reliable diagnostics of magnetosphere-ionosphere coupling based on passive optical diagnostics alone.

In the spatial dimension, high-speed video sensors have established that dynamic aurora can vary on time scales <10 ms and over spatial scales <50 m. A true understanding of auroral physics requires that we fully understand the magnetospheric plasma processes supporting this level of variability. Current ISRs are not capable of resolving such scales, but they can resolve bulk plasma properties within which these displays occur. Many theories of fine-scale auroral structure make specific predictions about auroral motions relative to the background **ExB** plasma circulation. The latter can be readily resolved through ISR analysis (preferably tristatic, although monostatic estimates of 100 km horizontal resolution are possible). In this way, the low-resolution radar diagnostic can contribute directly to the analysis of a high-resolution optical sensor.

Multispectral and hyper-spectral imaging bridge these two examples by acquiring spatial, spectral, and temporal information simultaneously. This approach constitutes a major frontier in optical aeronomy. In the aurora, for instance, auroral morphology is thought to be related to the functional form of the causative particle distribution function, information that can be evaluated through multispectral observations. Multispectral analysis is also valuable for studying airglow structures associated with neutral gravity waves, drifting plasma patches, and thermospheric tidal oscillations. Recent improvements in detector technologies (such as electromagnetic CCDs and InGaAs detectors) continue to expand the achievable resolution of these sensors. As such, their scientific efficacy at the UAFs will continue to increase.

APPENDIX C: PLANNED UPGRADES AND ENHANCEMENTS TO EXISTING FACILITIES

All of the facilities have developed plans for upgrades and enhancements over the next five to ten years. Such improvements must be undertaken only after careful consideration of science priorities and budget realities. At some point, continued investment in aging equipment has to be weighed against the cost of replacement using newer, more robust technology. Nevertheless, cost-effective upgrades to existing facilities can greatly enhance their scientific usefulness in the near term.

At Arecibo, a project is underway to rebuild the HF heating facility using the 1000-foot dish and wire antennas. Surplus transmitters have been obtained from a decommissioned Over-the-Horizon Radar site in Maine, greatly reducing the cost of building the new heater. When completed, the Arecibo heating facility will have a tremendous advantage over other heating facilities because the diagnostic observations can be carried out with the most sensitive ISR in the world.

The Jicamarca Radar is continuously improving its observational capabilities by taking advantage of low-cost radars and antennas that can be deployed and operated with few impediments. The most important upgrade for Jicamarca in the near term, however, is the electronic phase shifters that will allow the radar beam to be redirected quickly, with no mechanical reconfiguration of the antenna. In the past, redirection of the Jicamarca beam took several hours. The new capability will allow observers to interleave coherent and ISR observations to almost simultaneously measure ionosphere drifts and electron and ion density and temperature profiles.

Along with partners, including the NSF, Jicamarca is considering constructing a new heating facility for carrying out ionospheric modification experiments. Should it go forward, the research would make use of surplus transmitters and perhaps a small array of crossed-dipole antennas, similar to the antennas at HIPAS. The Jicamarca site has ample room for a heating facility. The additional power required is available from the local substation with some modification, and frequency allocation poses no special problems. The main impetus for the new facility is the equatorial electrojet and the prospect of generating VLF radiation by modulating the E-region conductivity. VLF radiation was first demonstrated in the 1980s at Jicamarca through underdense heating with the main 50 MHz radar. We expect VLF generation in the equatorial electrojet by overdense heating to be particularly effective, since radiation associated with the small but significant vertical current there couples most efficiently into the Earth/ionosphere waveguide. Furthermore, the day-to-day consistency of the equatorial electrojet and absence of absorption common in the auroral zone are attractive from a reliability point of view. Heating experiments at Jicamarca could pave the way for a dedicated equatorial VLF transmitter elsewhere.

The diagnostic array at Jicamarca, which includes the 50 MHz ISR, the AMISR prototype UHF radar, the SOUSY MST radar, numerous other small radar and radio propagation instruments, and optical instruments nearby, make the site well suited for investigations of other well-known heater-related phenomena. These include Langmuir turbulence, stimulated electromagnetic emission, artificial field-aligned irregularity generation, artificial periodic inhomogeneity generation, and artificial airglow. Research in these areas yields information not only about heating physics, but also about the background ionosphere.

A number of other lines of investigation would be new to the dip equator. The persistent mesospheric echoes seen over Jicamarca are weaker relatives of polar summer mesospheric echoes, and valuable insights into both would come from contrasting their behavior during ionospheric modification experiments. Insights into the saturation of Farley-Buneman waves would likewise stem from controlled heating experiments in the equatorial electrojet.

The Millstone Hill Observatory upgrade and enhancement paths focus on two areas. Efforts are underway to extend the operating life of the MISA, whose wide coverage area is central to Millstone's mid-latitude science capabilities. A cost-effective program of antenna and foundation structural repair over the next decade will mitigate further material degradation. Upgrades to the MISA control system are also under consideration to ensure that operations can be conducted with minimal impact to antenna drive and support systems. Additionally, the radar transmitter hardware has components more than 40 years old, which will require refurbishment or replacement in the future.

Both Arecibo and Millstone use the same transmitter technology, and the recent acquisition of surplus klystrons from Clear Air Force Station has given both facilities an ample supply that under current usage rates will last for five years or more. After that, however, new klystrons will have to be purchased. New technologies may make it more practical at that point to replace the entire high-power generation subsystem, or to replace the entire radar system with phased arrays. If the former is chosen, commercially available UHF klystron based transmitters are available today that are robust and reliable, and no significant technical barrier exists for their continued use by the UAF community.

Millstone Hill has also begun to investigate the development of the Millstone Advanced Radar System (MARS), a next generation phased array architecture. MARS is a broadband phased array design that includes highly integrated, all digital receiver/exciters at the individual radar element level backed by supercomputing signal processing resources. The design allows for full amplitude, waveform, and polarization control over a wide frequency range. These features allow retention of the wide field of coverage and scanning capabilities, which are crucial for observations of subauroral/plasmasphere boundary layer physical processes, and they maintain maximum spatial coverage with a single ISR system. When combined with simultaneous transmit capability across multiple International Telecommunications Union (ITU) radar bands and broad receive frequency capability, MARS is designed to be an inherently multirole instrument with ionosphere/upper atmosphere radar, radio astronomy, lower atmosphere, and heliosphere applications. Considerable beamforming and signal processing challenges exist, but these have successfully been addressed by the U.S. defense community for hundreds of antenna beams. Millstone Hill is working with MIT Lincoln Laboratory on technical studies to enable MARS as a ~1000 beam system. Of particular note is the possibility that technical solutions in this design space could be applied to the Jicamarca phased array at 50 MHz if manufacturing unit costs were low enough.

The Sondrestrom Facility will undoubtedly need a new klystron within the next five years. Only two klystrons remain on site, and one is only marginally operational. A solid-state high-voltage modulator recently installed at Sondrestrom has made the radar system compatible with commercial, off-the-shelf klystrons more easily acquired than the previous models, which are no longer being manufactured.

SuperDARN is being upgraded with the addition of new radars and the implementation of new antenna designs, electronics, and improved data-processing techniques. A pair of radars under construction in the Canadian high arctic will extend observations into the polar cap and provide complementary measurements of plasma convection in support of AMISR operations at Resolute Bay. Radars are also under construction in Antarctica. Although these projects are mostly under the direction of non U.S.-based SuperDARN colleagues, the new radars will be incorporated into SuperDARN and their data product will be accessible to the U.S. community as a facility resource.

The UAF SuperDARN facility is leading an effort to establish SuperDARN radars at mid-latitudes. A prototype radar built in 2005 at NASA's Wallops Flight Facility in Virginia demonstrated that the technique makes valuable observations in the mid-latitude ionosphere under a variety of conditions including storm-time disturbance. Near-range plans include the construction of an interferometer array that will allow for determination of the vertical angle of arrival of the backscattered returns. A collaboration between JHU/APL, Virginia Tech, and the University of Leicester enabled the construction of a radar at Blackstone, Virginia, in time to participate in the main phase of the NASA THEMIS mission. There are plans to assemble a longitudinal chain of SuperDARN radars beginning with Wallops and Blackstone that will extend SuperDARN capabilities to other mid-latitude sites.

The new radars in the high arctic and at mid-latitudes employ a new, less expensive wire antenna that was designed at JHU/APL. The UAF-supported SuperDARN facility is crafting new phasing and beam control electronics that will significantly enhance functionality over the old designs. It is expected that the electronics and possibly the antennas at the older radar sites will eventually be replaced with the new designs. Enhancements in the digital signal processing are also under development, with an eye to exploiting increased computer capabilities to more finely resolve signal characteristics. One example is the realization of sub-second temporal resolution in the measurement of ionospheric plasma velocities (Greenwald et al. 2008).

Traditionally, plans for upgrades and enhancements to existing facilities have been made with little coordination across the radars. However, budget constraints often make it impossible to initiate all the projects, and certainly the support of one upgrade impacts the ability to start another. Planning and coordination among the radars is highly desirable to ensure that decisions about upgrades are made with all issues considered. A working group composed of facility staff members may be necessary to enforce this coordination and ensure that radar upgrades are made with the best scientific and technical input. Ultimately, NSF is responsible for making the decisions about which upgrades will be funded. As competition for limited funding increases, proposed upgrades and even repair and maintenance projects may have to undergo peer review. A well-thought-out process for prioritizing upgrades that involves the facility staff will minimize the necessity for additional review.