Haystack Observatory

Haystack Observatory is a multidisciplinary research center located in Westford, MA, which is 27 miles northwest of the MIT campus. The observatory conducts astronomical studies using radio techniques, geodetic measurements using Very Long Baseline Interferometry (VLBI), and atmospheric observations using high-power incoherent scatter radar. An important component of Haystack's mission is the education of students through research opportunities using the observatory's facilities.

Over the past year, the priorities of the radio astronomy program at Haystack have involved the development of radio arrays operating at low frequencies to study the structure of matter in the universe and the advancement of the astronomical VLBI technique to observe our galaxy and other galaxies. The primary objective of the geodetic VLBI research program is to improve the accuracy of measurements of the Earth's shape and orientation in space for better geophysical understanding. The goal of the atmospheric science program is to understand the effects of solar disturbances on the Earth's upper atmosphere using measurements from the observatory's radars and observations from global positioning satellites. A strong technology and engineering program supports each of the scientific research disciplines, and the observatory benefits from extensive overlap in technologies and techniques applied to the various radio science areas of research.

The research program is carried out under the auspices of the Northeast Radio Observatory Corporation, a consortium of nine educational and research institutions that includes, in addition to MIT: Boston University, Brandeis University, Dartmouth College, Harvard University, Harvard-Smithsonian Center for Astrophysics, University of Massachusetts, University of New Hampshire, and Wellesley College. Haystack Observatory also supports Lincoln Laboratory's space surveillance program with which it shares some of the facilities at the Westford site. The observatory receives financial support for its research programs from federal agencies including the National Science Foundation (NSF), the National Aeronautical and Space Administration (NASA), and the Department of Defense.

External Staff Activities

Haystack staff have been engaged in a wide variety of activities in service to the broader scientific and engineering communities. Alan Whitney serves on the Board of Trustees for Internet2. He also served as project director for the Murchison Widefield Array (MWA), and was recognized this year by MIT through an excellence award in the category "Bringing Out the Best: leading others through change." He also holds multiple positions within the International VLBI Service (IVS) organization, including membership on the directing board. Arthur Niell participates extensively in planning and coordination activities of the IVS. Colin Lonsdale has served as a representative of the US on the governing body for the Square Kilometer Array (SKA), and as technical reviewer for SKA subsystems. He is also a member of the MWA board. John Foster is chair of the NSF Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) program. Frank Lind is chair of URSI Commission G, and also serves as chair of the technical advisory committee for the European Incoherent Scatter (EISCAT) 3D phased array radar project in Europe. Larisa Goncharenko is AGU secretary for the Space Physics and Aeronomy section, and has served on the CEDAR science steering committee. She has also served as guest editor for a special issue of the *Journal of Geophysical Research*. Shunrong Zhang is a member of the URSI/COSPAR working group for the IRI ionospheric model. Anthea Coster is guest editor for a special issue of *Radio Science*, has served in coordinating roles for two conferences, and has delivered multiple invited lectures.

Research Instrumentation

Facilities used in Haystack's research program include:

- A 37-m-diameter radio telescope used for astronomical observations and radar measurements; this telescope is nearing completion of a major upgrade, and has been unavailable for use during the past year
- An 18-m-diameter radio telescope, known as the "Westford antenna," involved in VLBI measurements of the Earth's rotation parameters
- A 10-station wideband VLBI correlator used to process global geodetic and astronomical observations
- A 2.5 MW UHF radar that utilizes two large antennas, 46 m and 67 m in diameter, to study the Earth's upper atmosphere using incoherent backscatter techniques
- A 12-m-diameter radio telescope located at Goddard Space Flight Center, used for geodetic and astronomical observations, and to serve as a remote station for the next generation geodetic observing system

Radio Astronomy

Murchison Widefield Array

Work has continued on the MWA project, with the goal of completing a system comprising 512 dipole-based antenna tiles plus supporting electronics in the outback of western Australia. Such a revolutionary instrument can enable studies of the early universe during the formation of the first stars and galaxies, can provide unprecedented diagnostics of solar wind plasma conditions that will aid in space weather prediction, and will be a powerful research tool for a wide variety of radio astronomy investigations in a poorly explored spectral window.

In 2010, the US-based members of the MWA collaboration, led by the MIT Kavli Institute, submitted a proposal to the NSF for the United States' share of array construction, and for two years of operations in pursuit of the cosmology goals. Unfortunately, this proposal was not successful, and all funds for construction must now come from Australia. This requires a descope from 512 tiles to 128 until additional funds can be secured. In addition, the declination of the US proposal severely limits the level of effort that can be maintained at US institutions on this project, including Haystack. The MWA project represents a major, long-term investment for Haystack over the past decade, and the primary goals at this juncture are to help ensure the success of the Australian-funded 128-tile system, and to exploit the still formidable capabilities of that system for unique science. Haystack is seeking funding for this activity, from both US and Australian sources, enabling us to demonstrate the capabilities of the instrument, and setting the stage for future enhancement of the array.

Despite this setback for the US members of the MWA project, a Haystack-led effort has yielded the first published science result using data from the field. This work, led by Divya Oberoi, revealed the existence of previously unsuspected low-intensity nonthermal emission from the solar corona above active regions, even when there were no indications of significant burst activity by any other instruments around the globe or in space. The extraordinary high dynamic range imaging capabilities of the MWA design were also demonstrated, exceeding the performance of existing instruments by an order of magnitude, at a fraction of the cost.

The project remains inherently international in nature, with strong US representation on the governing Board, the management team, and various project committees. As the US partners regroup, new funding proposals will be submitted, and the Haystack team remains committed to the advanced instrumentation concepts and the associated scientific opportunities underlying the MWA project.

Astronomical VLBI

Activities within the (sub)mm VLBI group at Haystack focus on extending the VLBI technique to the shortest possible wavelengths to study super massive black holes on Event Horizon scales. At the center of the Milky Way, a compact radio source, SgrA*, marks the position of a 4 million solar mass black hole, which has been the focus of several 1.3mm VLBI observing campaigns. A first round of observations resolved structures on the scale of a few Schwarzschild radii within SgrA*, providing evidence that the bright emission arises in a jet or accretion disk, which is offset from the position of the black hole. Results from recent observations, reported in *The Astrophysical Journal Letters*, show SgrA* to exhibit time-variable structures near the black hole event horizon, confirming the power of short wavelength VLBI to observe matter spiraling in to a black hole. New work, published by Haystack scientists and collaborators at Harvard University and the Canadian Institute for Theoretical Astrophysics, uses the new SgrA* data to considerably tighten constraints on the black hole spin, disk inclination, and orientation on the sky of SgrA*.

The science focus of the group has broadened considerably with the detection of the super massive black hole at the center of M87, a giant elliptical galaxy. While the apparent size of the SgrA* event horizon is the largest known in the universe, the extraordinary mass (~6 billion solar masses) and proximity (48 million light years) of M87 renders its event horizon apparent size only slightly smaller than that of SgrA*. A relativistic jet of charged particles that emerges from the black hole in M87 extends hundreds of thousands of light years from the core, and is the archetype for powerful outflows that return mass and energy to the intergalactic medium. Using a three-station 1.3mm VLBI array, the Haystack group measured a size for the emission at the base of the M87 jet that is only ~4 Schwarzschild radii across. Such a compact size implies that the M87 black hole must be spinning, and that the jet derives its power from extraction of energy from the black hole's rotation (Figure 1). Follow on work will concentrate on using mm VLBI arrays with more telescopes to constrain specific models of relativistic jet genesis.

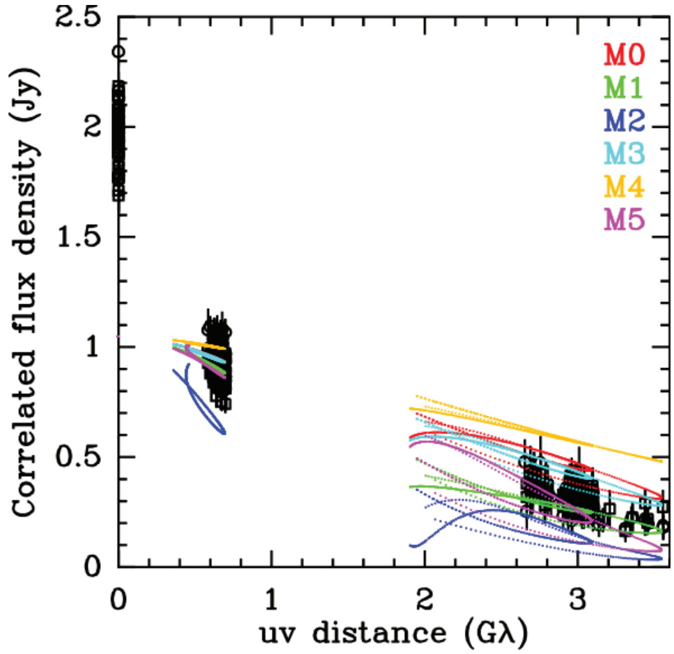

Figure 1. Comparison of 1.3mm VLBI observations of the 6.6 million solar mass black hole in M87 to models of the relativistic jet. Black points show the amplitudes of the VLBI signal. Colored curves show expected amplitudes from various models. Models with high black hole spin (M0, M1, M3, M4, M5) all fit the data, while the sole model for a non-spinning black hole (M2) does not. The size of the base of the jet in M87 determined by the VLBI data is ~5 Schwarzschild radii across, which is smaller than the jet size for a spin 0 black hole. Models courtesy of Avery Broderick and Avi Loeb

In April 2011, the VLBI group undertook an ambitious observing campaign that used newly developed phased array systems at two sites. These systems, designed to combine the collecting area of multiple telescopes into a single VLBI element, were successfully deployed at both Mauna Kea (combining the Submillimeter Array and James Clerk Maxwell Telescope together) and the Combined Array for Research in Millimeter-Wave Astronomy (CARMA) radio telescope array in Northern California (combining seven dishes each 10m diameter). The resulting boost in sensitivity enabled the first polarimetric 1.3mm VLBI detections of SgrA*, opening a new window to studying the plasma near the black hole. This campaign was further notable for carefully scheduled contemporaneous x-ray satellite observations to study flaring events in SgrA* across a wide range of photon energy.

Leveraging community interest in such high-resolution black hole studies, Haystack has made progress on organizing the Event Horizon Telescope (EHT), a global VLBI network of (sub)mm dishes. This concept was presented to the ASTRO2010 Decadal Review and received a very favorable mention in the Radio/mm/submm panel report. This panel specifically called out the importance of adding the large collecting area of the new Atacama Large mm Array (ALMA) to the EHT, which, at a single stroke, increases baseline lengths by a factor of two and baseline sensitivities by nearly an order of magnitude. In response, Haystack led an international design effort for a system of coherently phasing all 64 of the ALMA dishes (each 12m in diameter). A Major Research Instrumentation proposal to build and deploy this system was submitted to the NSF in January 2011, and was awarded in August 2011. This challenging and exciting project will transform the current (sub)mm VLBI array into an instrument capable of monitoring the orbits of matter as it circles the SgrA* black hole.

Square Kilometer Array

Haystack has continued to participate in the international Square Kilometer Array (SKA) through involvement in a NSF-funded technology development program led by Cornell University. Haystack staff regularly attended SKA-related meetings and contributed to MIT representation on the US SKA consortium executive. Colin Lonsdale joined the US delegation to the SKA Science and Engineering steering Committee and attended meetings to represent the US low frequency array community. He also served on a SKA aperture array review committee. The recent formal withdrawal of NSF support for US partnership in the international SKA project implies that activity in this area will decrease sharply in the future, though interactions with the SKA community on a variety of scientific and engineering topics of relevance to Haystack projects will continue.

37-Meter Telescope

The iconic Haystack radome-enclosed 37-meter radio telescope is in the final stages of a major upgrade, funded by the Air Force and managed by Lincoln Laboratory. The new dish has a target rms surface accuracy of 100 microns, enabling high efficiency operation at millimeter wavelengths. During 2010, Haystack became a construction zone of extraordinary scope and complexity, with a tight schedule for performing all major structural work, which required removal of the radome cap, before the threat of winter weather returned. Haystack continues to provide extensive support to the primary Lincoln Laboratory team and their industry contractors, and the entire operation has been executed to date with no significant injuries. A photograph of the telescope immediately following installation of the backup structure for the new dish, on September 15, 2010, is shown in Figure 2. Haystack personnel are also under contract to Lincoln Laboratory to install radio astronomy receivers on the new dish, to be used by Lincoln Laboratory to establish and maintain an accurate pointing model for the telescope via sensitive observations of celestial radio sources. As of August 2011, the new telescope is ready for initial tests with radar and radio astronomy instrumentation, and a period of intensive commissioning will follow.

Figure 2. The appearance of the Haystack 37m telescope in mid-September 2010. The old reflector had been removed, and the backup structure and quadrupod of the new reflector had been installed. Following this, the radome cap was reattached, the radome panels were replaced, and the reflecting surface panels were then attached to the backup structure in a weatherproof environment.

Upon completion, the radio astronomy receivers will also be used to help reestablish Haystack astronomy and education programs that have been put on hold by the upgrade project. Up to 30% of the telescope time will be available for this purpose, by prior arrangement, and a variety of investigations will be made possible by the dramatically improved performance characteristics of the new dish. A new high-performance wide-band spectrometer, developed by Haystack under a grant from the NSF, will augment the astronomical capabilities of the telescope. Arrangements for handling the shared use of the telescope are under active discussion by Lincoln and Haystack representatives.

VLBI Instrumentation Development

Haystack Observatory has long been known for its expertise in VLBI data acquisition technology. That tradition has continued with the creation of a new digital back end, and high data rate recorder. These are being used in two applications: with existing antennas for very high frequency VLBI to study the radio emission from Black Holes, and with a new relatively small antenna to push the accuracy of geodetic VLBI.

Fast-Slewing Antenna

Haystack Observatory's geodetic VLBI program has led the design and implementation of instrumentation improvements needed to realize the goal for the next generation geodetic VLBI system of approximately 1 mm. Essential to this realization is the use of fast-slewing antennas to reduce the errors due to the atmosphere. In order to provide proof-of-concept, Haystack procured a 12 meter radio telescope from Patriot Antenna Systems, which was installed at the Goddard Geophysical Astronomical Observatory in Greenbelt, Maryland, in the fall of 2010 (Figure 3). The broadband Instrumentation associated with the antenna, which is described below, provides the high sensitivity that allows the use of such a relatively small antenna for the geodetic project. The 12-m antenna and associated electronics form the VLBI component of the prototype Global Geodetic Observing System fundamental station being developed for NASA's Space Geodesy Project.

Figure 3. The new 12-meter antenna in Greenbelt, MD, forming part of the new VLBI2010 geodesy system being developed at Haystack.

Wideband Radio Frequency Signal Acquisition

The enabling technologies that have led to the development of the new antenna system are the wideband feeds and low noise amplifiers for signal reception, and the high-speed digital signal processing and data storage for signal processing. The instantaneous RF bandwidth adopted for the next generation receiver is a factor of 10 greater than that of the current geodetic VLBI systems. To implement this capability, Haystack has been collaborating with Chalmers University of Technology (Gothenburg, Sweden), Onsala Space Observatory (OSO; Onsala, Sweden), and the California Institute of Technology (Caltech) in an effort to develop an extremely broadband front-end for the 12m radio telescope. Two different feeds are being evaluated at Haystack by two different techniques: a) measurements in an antenna chamber; and b) direct measurement on the 12-m antenna. The feeds are the "Eleven" antenna designed at Chalmers and fabricated at OSO (see last year's report) and the more promising quadridge feed horn (Figure 4), which was developed at Caltech. Each feed is followed by ultra low noise amplifiers from Caltech. When cooled to 20K in Dewars designed and built at Haystack, these feeds and LNAs have attained a noise temperature of less than 25K at the output of the Dewar over the frequency range 3 GHz to 10 GHz. The performance is somewhat degraded before the signals are digitized and recorded, but the goal of 50K appears achievable.

Figure 4. The "quadridge" feed horn being developed and tested for the VLBI 2010 geodesy system at Haystack. This horn is being adapted for geodesy use through a collaboration with Caltech.

Wideband Signal Processing

To take advantage of the wideband frontend (previous section), a flexible local oscillator (also called an UpDown Converter) was developed at Haystack that allows selection of a 2 GHz band anywhere in the range approximately 2–12 GHz Flexibility is needed in order to select bands that are most free from radio frequency interference (RFI) but also optimize the delay precision for each observation.

Each UDC passes the down-converted radio frequency (RF) signal from two orthogonal polarizations to a digital back end. A new digital back end (DBE) has been developed jointly with the National Radio Astronomy Observatory (NRAO; Socorro, NM) that is capable of producing packetized two-bit samples at a data rate of four Gigabits per second (Gbps). The DBE hardware, which is based on the University of California, Berkley's CASPER project's Reconfigurable Open Architecture Computing Hardware and is thus designated RDBE, was designed primarily by NRAO, while the firmware and software were implemented primarily by Haystack. The modularity of the RDBE firmware has enabled the initiation of a second version of the RDBE with a data throughput of eight Gbps that is currently under development.

Data from either of these DBEs can be recorded on either the Mark5C at up to 4 Gbps or on the new Mark6, which is currently under development, at up to 16 Gbps.

Mark 6 VLBI Data System

The demand for greater VLBI observation sensitivity continues to push required data-acquisition and playback rates to higher and higher levels. The current Mark5-generation of data systems tops out at sustained 4 Gbps per system. However, near-term demands are for 8 Gbps, pushing to sustained recording and playback at 16 Gbps within about a year. These rates are required to support both astronomical mm-VLBI studies of the black hole at the center of our Galaxy, and 1-mm global measurement precision demanded by the next-generation geodetic-VLBI system, both of which are active programs at Haystack.

In order to meet these needs Haystack Observatory, in collaboration with the Earth and Space Data Computing Division at NASA's Goddard Space Flight Center, has embarked on an effort to design a 16Gbps VLBI data system. Unlike its Mark 5 predecessor, the Mark 6 system is based almost entirely on commercial-off-the-shelf hardware, the only exception being in the continued use of customized 8-disk modules that are similar to the disk modules used in the Mark 5 system which provide the necessary portability demanded by the VLBI application. We are partnering with Conduant Corporation of Longmont, CO, who also partnered with Haystack on the Mark 5 system, for development of specific items to support the custom Mark 6 disk modules, and who will also act as the manufacturer and distributor of Mark 6 system for the global VLBI community.

The cost of the Mark 6 system will be comparable to the Mark 5 system, but the data-rate capability will be four times greater. This will help to significantly reduce the cost to support the new demand for higher dates. The Mark 6 system is expected to be available for operational use late in 2011.

Atmospheric Science

Radar Operations

The Millstone Hill UHF radar facility executed approximately 1000 hours of observations, supporting experiments divided between a regular program of internationally coordinated World Day observations and site-specific or regionally coordinated experiments measuring characteristics of the midlatitude and subauroral ionosphere, thermosphere, and plasmasphere. The space science community made heavy use of Millstone Hill as a NSF facility instrument, with 23 external users from a number of institutions. In addition to synoptic experiments measuring the mid-latitude ionosphere, science investigations included coordinated regional convection / HF radar backscatter and UHF incoherent scatter observations, meteoroid head echoes, natural and enhanced plasma lines for precise electron density measurements, passive airglow optics comparisons focusing on neutral and ionized atmospheric coupling, ionospheric perturbations caused by STS shuttle launches, and long duration probing of planetary wave and stratospheric warming effects coupling the lower, middle, and upper atmosphere. In 2010–2011, many of these studies have directly involved graduate students and faculty members from Stanford University, Virginia Tech, Boston University, and Cornell University.

Research Activities

The research activities of the atmospheric sciences group at Haystack Observatory concentrated on several areas of scientific investigations in topics at the forefront of the space science community's emphasis on system science, multiscale atmospheric coupling, and fine scale and mesoscale ionospheric perturbations.

Geospace System Science

In keeping with an increased emphasis and new System Science strategic direction in our NSF CEDAR program, the Atmospheric Sciences Group continues to expand its leadership role in community investigations of geospace system science. Our emphasis has been on understanding the complex coupling and feedback processes interconnecting Earth's lower atmosphere with the overlying ionosphere/thermosphere, and space plasma regimes of the magnetosphere. These science foci align well with CEDAR and NASA missions and directions in the Geospace system. One specific example is the group's mission science team involvement in the major two satellite NASA Radiation Belt Storm Probes mission, scheduled for launch in late 2012 with primary mission activities through 2016 and beyond. In the CEDAR community, Haystack project activities focus on the long term Millstone Hill observational and science record, and the study of mesoscale, system-level phenomena, an NSF CEDAR strategic priority.

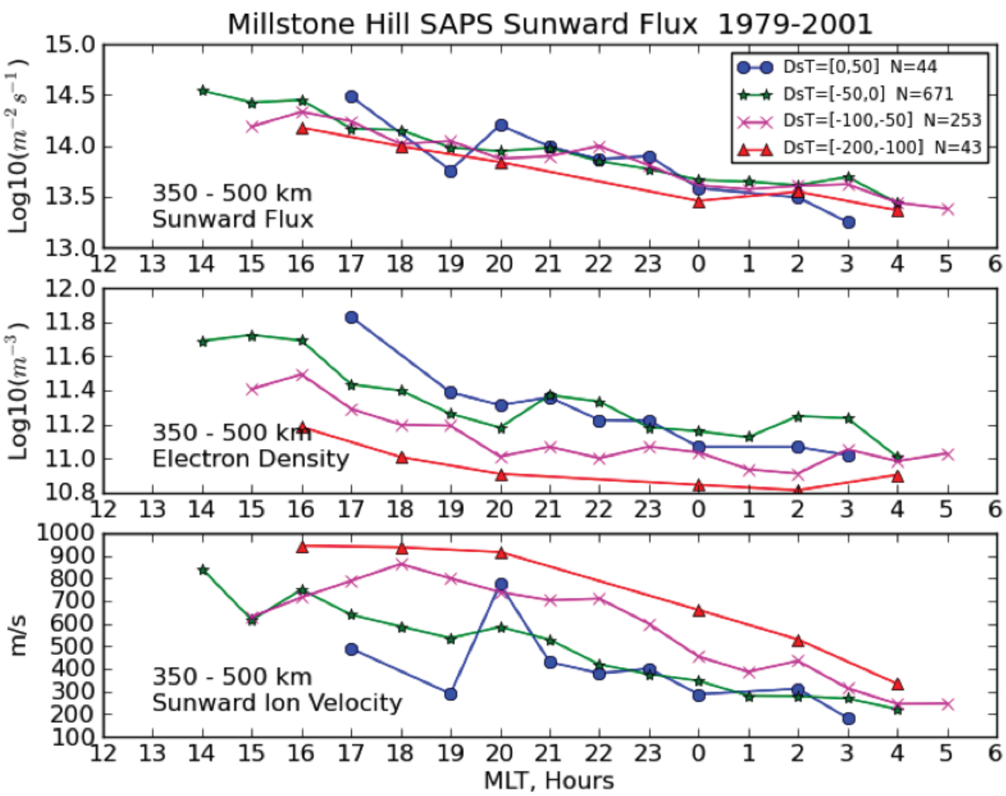

Figure 5. Statistical observations of mid-latitude sunward F region horizontal ionospheric flows driven by the sub-auroral polarization stream (SAPS), a disturbance time electric field feature in the sub-auroral plasmasphere boundary layer region. Over 1100 individual SAPS measurements were taken from a 10,000+ radar scan database assembled by Millstone Hill over more than two solar cycles. The results show an unexpected invariance of sunward flux to the level of system disturbance measured by the DsT index. From Erickson et al (2011).

Dynamic Atmosphere-Ionosphere Coupling

Dynamic coupling of the atmosphere-ionosphere system is a complex interdisciplinary problem. Current thinking suggests that the upward propagation of internal atmospheric waves (planetary waves, tides, gravity waves) from the lower atmosphere is an essential source of energy and momentum for the thermosphere and embedded ionosphere.

With strong Haystack involvement led by Larisa Goncharenko, our recent understanding of the relationship between the neutral atmosphere and the ionosphere has been dramatically altered due to studies of stratospheric sudden warmings (SSW). Analysis of experimental data collected during unprecedented observational campaigns using all available incoherent scatter radars and other ground-based instruments revealed that a SSW event couples all atmospheric layers from the ground to the thermosphere and from the poles to the equator. A significant number of upper atmospheric effects have been associated with this coupling, and in particular, a strong daytime ionospheric response to stratospheric sudden warmings is found in the low-latitude ionosphere. There is potential for using the connection with the ionosphere for forecasting the occurrence and evolution of electrodynamic perturbations at low latitudes, which has remained an unsolved problem for several decades.

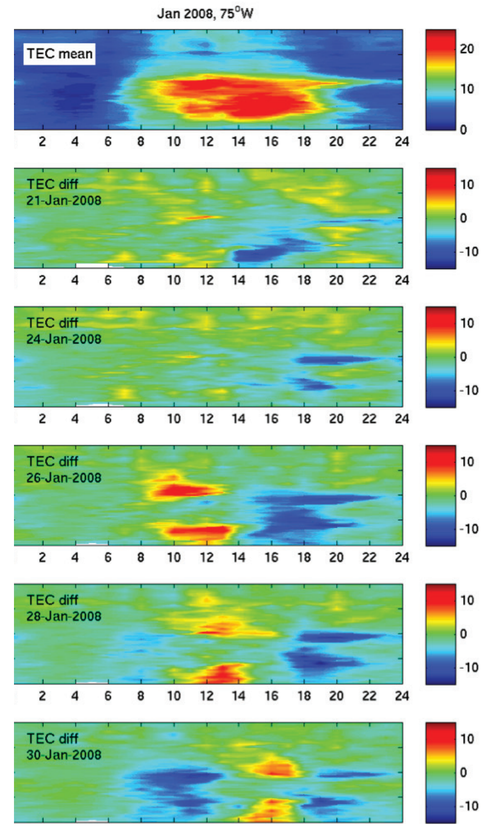

Figure 6. Total electron content (TEC) variations at 75W in local time and latitude observed during the January 2008 stratospheric sudden warming (SSW) event. Top panel shows 10-day mean TEC prior to SSW. Lower panels show difference in TEC from the mean state during the SSW. Both the observed semidiurnal variation and its rapid phase change contribute to the extreme day-to-day variability of the equatorial ionospheric anomaly. From Goncharenko et al. [2010].

Long-Term Upper Atmosphere Trends

Investigations by Haystack researchers continue into long-term trends in the terrestrial upper atmosphere using Millstone Hill and other incoherent scatter radar observations. This type of study directly addresses the topic of long term variations in the upper atmosphere, and climate system modeling. A height profile of long-term trends in ion temperature and other parameters at noon in the 100–500 km height range was determined for Millstone Hill. These studies show a cooling trend in ion temperature in the F2 region and higher altitudes, increasing with height, and an apparent warming at fixed heights in lower regions. Qualitatively, climate change models predict surface warming to be accompanied by high altitude cooling, as observed. The Millstone results are confirmed through a related study using data from Sondrestrom, a high latitude site. The cooling rate derived from the two radar observations at 250 km is ~ 1% per decade. This is significantly larger than current theoretical modeling results of exospheric temperature trends, and has yet to be quantitatively reconciled with the observational record.

Technical Initiatives

Antenna System

Two activities focused on the 46-meter-diameter Millstone Ionospheric Steerable Antenna (MISA), a centerpiece of the group's UHF radar system. The MISA's field of view encompasses the entire eastern half of the US, and allows a unique measurement capability spanning the full range of tropical, midlatitude, and subauroral ionospheric and thermospheric processes. The antenna is nearly 50 years old, having been designed by Stanford Research Institute in the early 1960s and transferred to Haystack in 1977–1978 from Sagamore Hill Radio Observatory in Wenham, MA.

MISA Upgrade

A major project is underway to replace completely the MISA wiring, conduit, and pointing system. After more than 40 years in the New England weather, the antenna's wiring, control, and pointing systems were in need of replacement. The upgrade activities are on schedule and the antenna is projected to return to active service in the fall.

Distributed Instrument Arrays

The research goals of the group using distributed instrument systems are to experimentally investigate the plasmasphere boundary layer (PBL) over a range of geomagnetic conditions, and to develop and investigate the capabilities of distributed arrays of small radio instruments for observations of the mid-latitude ionosphere. Spatially distributed radio sensors are a powerful method for investigating the PBL region because they provide simultaneous coverage of wide spatial regions with high time and spatial resolution. ASG technical development has focused on two networks of distributed instrumentation: assimilation of data from the global GPS network and the Intercepted Signals for Ionospheric Science (ISIS) Array (distributed software radio sensors).

A major geomagnetic event was observed in August 2010 that resulted in the first full array observations of E-region irregularities in the PBL region using the ISIS Array. Since that time signal processing improvements have greatly increased system sensitivity and allowed the first observations of monostatic detection of a Geophysical target (meteor trail) using our systems. This is a significant step in increasing the capabilities of such Geophysical passive radar systems. ISIS array assets are also currently being used by students at Dartmouth for AM radio spectral monitoring and at the University of Washington for passive radar using HDTV signals.

Geospace Science Center

Efforts are continuing to fully bring online a Geospace Science Center (GSC) at the Millstone Hill Facility for use in the control, operation, and science integration of Geospace Facilities program (NSF/GF) resources, distributed arrays of small instruments, and small satellite missions.

The GSC will form a key point of community interaction with a the Defence and Systems Institute (DASI) system in the eastern half of North America.

The GSC's workshop facility has been fully online since fall 2010 with dedicated displays, computers, and meeting space for small focused workshops of up to 16 people. Several workshops have already utilized this space, and it is available to the wider NSF community. The GSC features modernized radar control with full operations expected in the first half of 2012, with a set of display consoles and computers suitable for the simultaneous operation of multiple instruments, a screened receiver room, an electronics laboratory, and infrastructure to support significant grid computing systems. A one-year effort is underway to implement a GSC at the Millstone Hill Facility for use in the control, operation, and science integration of Upper Atmosphere Facilities program (NSF/UAF) resources, distributed arrays of small instruments, and small satellite missions. This center will provide a modernized control and receiver area for the Millstone Hill UHF radar, a set of display consoles and computers suitable for the simultaneous operation of multiple instruments, an RFI screened receiver room, an electronics laboratory, and a computing facility capable of supporting a significant grid computing system.

The GSC will enhance facility capabilities for supporting a wide range of science and educational activities as well as the interactive operational requirements of the next generation of Geospace science instrumentation. The GSC will form a key point of community interaction with a DASI system in the eastern half of North America. Distributed instruments are a natural focus of facility outreach and collaboration, and are a key way to involve the larger community in facility science efforts and provide science opportunities involving facility instrumentation.

Madrigal Distributed Database

The Atmospheric Sciences Group has been actively pursuing the development of the Madrigal distributed database, a standard in the upper atmospheric community originating at Haystack in the early 1980s. Haystack recently won an award to move the NSF CEDAR database to a Madrigal platform and to continue Madrigal development. While this Madrigal development will be managed by Millstone Hill, there has also been a great deal of community involvement, including strong collaboration with the Jicamarca facility in Peru. Significant new developments and regular releases of this important resource for the radar community continue at a vigorous pace.

Software Radar

The group's technical efforts continue to produce production quality, calibrated software agents (signal processing, control, Madrigal distributed databases) within the generic Millstone Hill MIDAS-W Software Radar platform. These developments directly contribute not only to Millstone Hill and NSF community radar operations but also to future next generation phased array radar designs where scalability is essential.

Community Outreach and Collaborations

Several Haystack personnel traveled to Jicamarca, Peru, home to another NSF Geospace Facility incoherent scatter radar, to conduct a weeklong Software Radar workshop in October 2010. Significant collaboration with the Jicamarca facility is ongoing.

In 2011, a successful conclusion was reached in a long-standing project collaboration with Lincoln Laboratory Group 92 and the National Radio Astronomy Observatory on the detailed polarization and scintillation properties of transionospheric satellite beacon signals. Important geoscience and technical results were obtained, and the group looks forward to future collaborative opportunities of this type.

EISCAT 3D

A major effort is currently underway in Europe to take the next technological step in Geospace Radar systems. EISCAT 3D will be the most advanced system of its kind implemented to date and will provide the basis for significant scientific advances in our understanding of the near space environment. The all-digital radar system will be located in Scandinavia and will be capable of three-dimensional volumetric imaging of the Geospace environment. The system will contribute greatly to international capabilities for studies in space plasma physics, magnetosphere-ionosphere coupling, impacts of the lower atmosphere on the ionosphere, dusty plasmas, long term monitoring of upper atmospheric climate and trends, and real time diagnostics for Space Weather applications. Haystack Observatory is now participating in the technical development of this instrument in an advisory role as part of a collaboration with our EU colleagues and the EISCAT Scientific Association. Members of the Haystack staff (Frank Lind, Phil Erickson) have made significant contributions to this effort, and Frank Lind is the chair of the EISCAT 3D Technical Advisory Committee.

China Initiatives

John Foster and Shunrong Zhang visited China earlier this year for discussions with a number of Chinese institutions and researchers concerning opportunities for expanding US-China (and MIT) cooperation and collaboration in ground-based upper atmosphere and space weather research. Host institutions supported their time in China, including the Center for Space Science and Applied Research of the Chinese Academy of Science, and the Polar Research Institute of China. A focus of the discussions has been an international expansion of the Meridian Chain Project, envisioning a globe-circling set of geospace observatories which would include stations in the Americas, and which complements established US priorities. We have also hosted a visit to Haystack in June 2011 by two members of PRIC who lead SuperDARN HF radar efforts in China, and a future visit to MIT by a high-level delegation from the Chinese Academy of Science is planned.

Educational and Outreach Programs

Haystack Observatory has developed a Very Small Radio Telescope (VSRT) under a Phase II grant from the NSF. The VSRT is an adding interferometer intended for physics and astronomy laboratory demonstrations and can be assembled from inexpensive, commercially-available parts. Five VSRT beta test institutions are currently involved at the university level. Haystack has also created the Mesospheric Ozone System for Atmospheric Investigations in the Classroom (MOSAIC), an array of single-telescope systems using direct-broadcast satellite dishes to observe the 11 GHz line of ozone in the mesosphere. MOSAIC systems are installed at three of the VSRT beta test sites. In the past, Haystack also developed the Small Radio Telescope that was highly replicated and placed into effective educational use at hundreds of sites in the US and around the world. The development of inexpensive, innovative instrumentation for both educational and research use, preferably both in a synergistic way as with the MOSAIC system, is a Haystack priority, and efforts to establish a robust funding base for this work continue.

The long-standing NSF Research Experiences for Undergraduates (REU) program at Haystack continues to provide undergraduate students with summer internships. Ten students participated in the 2011 REU program in scientific and technical projects, with four in astronomy and six in atmospheric sciences. Each year's atmospheric science students attend the CEDAR workshop. Several students from the 2010 REU program presented posters on their research at meetings of the American Astronomical Society (AAS) and American Geophysical Union. Haystack REU students have an excellent track record in their professional careers even after the program ends. For instance, Marshall Johnson won a Chambliss Astronomy Achievement Award from the AAS, and two recent students (Rachel Nancollas and Vicki Hsu) were awarded NSF Graduate Research Fellowships. Most students go on to do graduate study in STEM fields, while some opt for engineering jobs in industry after graduation.

Science teachers from local middle and high schools participate annually in the Research Experiences for Teachers program at Haystack. In 2011, teachers from Watertown and Wakefield, MA, worked on "Climate and Weather Change Concepts in the Lower and Upper Atmosphere," and will develop an educational unit for use in the classroom, based on their work at Haystack. In 2011, a pre-college program was field tested at Haystack, with excellent results. Four Puerto Rican high school students were selected based on their performance in the AGMUS SRDC program. These students participated in research projects with Haystack mentors and REU students. After seven weeks, the students presented posters and talks on their research at a local symposium. Overall, the pre-college students gained valuable experience by conducting scientific research and communicating their results.

Haystack staff members also mentor undergraduates outside the REU program. Shep Doeleman and Vincent Fish are working with two MIT undergraduates (Jeremy Steeger and Jessica Ruprecht) participating in the Undergraduate Research Opportunities program on a project on the study of black holes using millimeter-wavelength VLBI.

From 2007–2010, Haystack staff members have been organizers, lecturers, and leaders of a highly successful Advanced Modular Incoherent Scatter Radar (AMISR) workshop series in coordination with SRI International personnel. NSF management requested that the school's scope in 2011 be expanded to include both AMISR phased array radars and conventional single antenna systems such as Millstone Hill. Under a revised support grant, a larger but once again highly successful international one-week Incoherent Scatter Radar workshop in July 2011 was conducted in Kangerlussuaq, Greenland (near the site of the Sondrestrom ionospheric radar) for graduate and advanced undergraduate students. Haystack personnel were instrumental in organizing activities and logistics along with curriculum development and hands-on teaching. A total of 12 instructors included three Haystack ASG staff along with lecturers from Boston University, SRI International, Luléa Technical University in Kiruna, Sweden, and Sodankyla Geophysical Observatory in Sodankyla, Finland. In addition to several NSF personnel, other attendees came from 32 universities, including two from MIT EAPS, with representation from the United States, Canada, Norway, Sweden, Finland, UK, Ethiopia, Brazil, India, Germany, South Korea, Ireland, Peru, Argentina, and Russia. The school has now grown to be the world's premier, focused teaching opportunity aimed at introducing the powerful incoherent scatter technique to students at multiple educational levels, and in the process cultivating new users of ionospheric radar facilities, such as Millstone Hill.

Haystack staff served as lecturers in a number of capacities this past year. At the request of the EISCAT director Dr. Esa Turunen, Phil Erickson gave a weeklong series of lectures in April 2011 as part of a joint European "Erasmus Mundus" master's degree program concentrating on space science and technology. The lectures on General Radar Theory were given in Kiruna, Sweden to more than 40 students from over 15 countries as part of a Luléa Technical University core module emphasizing atmospheric radar and optical observations, and we expect to repeat this on an annual basis. In a similar vein, Anthea Coster gave multiple tutorial lectures for a diverse audience at the International Space Weather Institute summer school in November 2010 at Bahir Dar, Ethiopia.

Haystack Observatory continues to keep up educational ties with graduate students at other universities, such as Boston University, University of Washington, Stanford University, Rhodes University, and Siena College. Haystack staff members regularly serve on graduate student dissertation committees

Although on-site public outreach programs at Haystack were scaled back during construction associated with the upgrade of the 37m telescope, Haystack is now resuming tours and open house events, with the first one scheduled for September 2011. As in past years, staff members have been involved in other outreach activities, such as events for Cub Scouts (including "cubmobile" races) and job shadowing for high school students.

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