Haystack Observatory

Haystack Observatory is a multidisciplinary research center located in Westford, MA, 40 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.

The current priorities of the radio astronomy program at Haystack involve 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 Earth's orientation parameters and establish a celestial reference frame for geophysical measurements. 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.

The radio astronomy research program is carried out under the auspices of the Northeast Radio Observatory Corporation (NEROC), a consortium of nine educational and research institutions that includes, in addition to MIT, Boston University, Brandeis University, Dartmouth College, Harvard University, the Harvard-Smithsonian Center for Astrophysics (CfA), the University of Massachusetts, the 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.

Awards and Personnel

Colin Lonsdale assumed the directorship on September 1, 2008, and Alan Whitney stepped down as interim director after 20 months of extraordinary service to the observatory. Alan returned to his position as associate director and became director of the international Murchison Widefield Array project (MWA). Under Alan's able leadership, the MWA project has progressed strongly and now stands poised for major construction. Haystack Observatory is deeply indebted to Alan for his tireless efforts in expertly guiding the observatory through a transition period and for successfully navigating the complexities and challenges of the MWA, maintaining and strengthening the role of MIT and Haystack in a project of great significance and potential for the future of low-frequency radio astronomy.

Dr. Whitney was honored by the US Naval Observatory (USNO) as recipient of the 2008 Superintendent's Award for Distinguished Service. The USNO announcement noted that "Dr. Alan Whitney has distinguished himself as a prominent contributor to the US Naval

Observatory's Very Long Baseline Interferometry and Earth Orientation programs. As the head of correlator development for both the Mark 3A and Mark 4 correlators, he has been instrumental in supplying the US Naval Observatory with the state-of-the-art correlators that process the VLBI data used to determine Earth orientation." We congratulate Alan on this well-deserved honor.

Dr. Shun-Rong Zhang was cited by the *Journal of Geophysical Research—Space Physics*, for excellence in refereeing.

Research Instrumentation

Facilities used in Haystack's research program include:

- A 37-m-diameter radio telescope used for astronomical observations and radar measurements
- An 18-m-diameter radio telescope 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

Radio Astronomy

Murchison Widefield Array

Strong progress has continued in the development of the MWA. The project seeks to deploy 512 dipole-based antenna tiles operating between 80 and 300 MHz for scientific investigations encompassing cosmology, the heliosphere, and the transient radio universe. Haystack Observatory, through NEROC, is the recipient of a four-year, $4.9 million NSF award from which subawards have been made to the MIT Kavli Institute (MKI) and CfA. Alan Whitney, appointed in July 2008 as MWA project director, has assumed principal investigator status on the NSF grant, with Jackie Hewitt (MKI) and Lincoln Greenhill (CfA) as co-principal investigators. The project is international in nature, with multiple Australian university partners as well as the Raman Research Institute in India.

During the past year, work has focused almost exclusively on establishment of a fully operational 32-tile system at the site in remote outback Western Australia, including final designs of most hardware subsystems and hardware correlation, with generation of sky images in real time. Demonstration of this 32-tile prototype system is required before major construction of the 512-tile system can be funded and executed, and such demonstration is anticipated for the second half of 2009.

In addition to the project leadership role, Haystack has responsibility for the development of the antennas and the correlator and support for a number of other subsystems. Over the past year, the design of the antenna tiles and their electronic steering electronics, led by Brian Corey, has been extensively tested and verified through field experiments. In partnership with colleagues across the international project, the installation at the site now includes upgraded infrastructure, digital receiver electronics sufficient to support all 32 tiles, and software correlation capability (Figure 1). In November 2008, a major and highly successful effort was mounted to integrate this full system and to demonstrate proper functioning of many key subsystems. Among the many observations conducted, an image of the sky at a frequency of 150 MHz over an approximately 1,000-square-degree area surrounding the bright radio source Pictor A has been produced (Figure 2). A number of other, fainter radio sources are visible in the field. This and other images and source detections provide strong verification of many complex subsystems, as well as proper functioning of the antenna tiles. An ongoing series of roughly monthly site visits continues to refine and debug the developing prototype array in preparation for installation of the hardware correlator and real-time imaging system and formal completion of the 32-tile project milestone, currently scheduled for autumn 2009.

Figure 1. An antenna tile of the MWA with the electronics hut and office trailer visible in the background, at the MWA site in Western Australia. The system is currently powered by a 35 kVA diesel generator provided by Australian partners. Each tile consists of 16 individual dual-polarization dipoles and an electronic beam forming unit that can steer the tile beam in any direction across the sky (the box on the far side of the tile in this photo). The full MWA will comprise 512 such tiles.

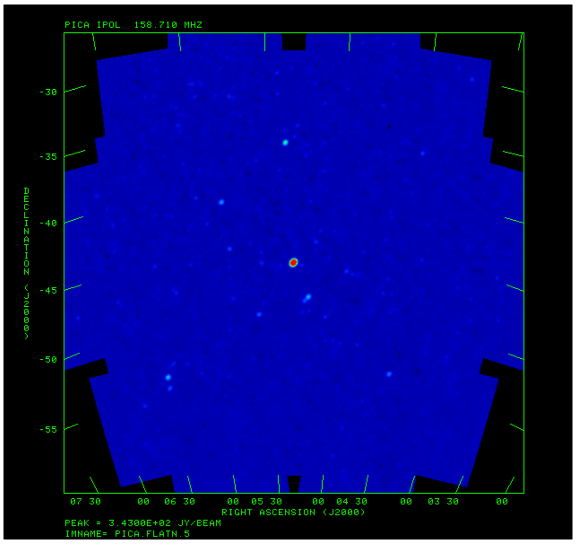

Figure 2. Radio image of a region of sky 30 degrees across made with 26 tiles of the prototype MWA system at the site in Western Australia. The bright central source is Pictor A, with several other fainter sources clearly visible. This image demonstrates nominal performance from several key subsystems and verifies large parts of the system integration.

The MWA correlator is a highly innovative field-programmable gate array (FPGA)–based system capable of delivering 18 tera-complex multiply-and-accumulate operations per second, spread over a half million simultaneous independent signal-pair combinations. The correlator is being developed in close collaboration with Australian groups and in synergy with another radio astronomy project in Australia known as SKAMP. Haystack is responsible for delivery of the entire subsystem, with Roger Cappallo, Bart Kincaid, and Russ McWhirter focusing on the FPGA functionality of the main computational core of the machine. Delivery of the system, which has been somewhat delayed by the challenges of long-distance technical collaboration, is currently anticipated in September 2009.

The overall project seeks to complete physical construction during 2010 and ramp up a commissioning period as field capability grows. Key science investigations involving cosmology and heliospheric measurements will follow the commissioning period.

Astronomical VLBI

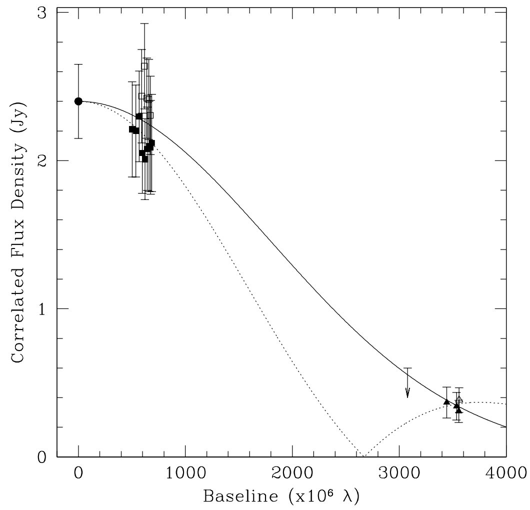

Figure 3. Size determination of the supermassive black hole candidate, SgrA. Correlated flux density is plotted against VLBI baseline length in megawavelengths. Triangles are JCMT-SMT detections, squares are SMT-CARMA detections, and the upper limit is for the JCMT-CARMA baseline. The filled circle denotes the total flux of SgrA* at 230 GHz. The solid curve shows the best-fit circular Gaussian model (35 microarcseconds FWHM), while the dashed line shows that an annulus with an inner diameter of 35 microarcseconds and an outer diameter of 80 microarcseconds (with scattering effects of the interstellar medium included) can also fit the data.*

Using data from the 230 GHz VLBI observations made in April 2007, a team led by Shep Doeleman obtained the first robust size measurement (Figure 3) of Sagittarius A* (SgrA*). SgrA* is a bright radio source associated with a 4 million solar mass black hole at the center of our galaxy. This result is of groundbreaking significance, because the measured size was only 3.7 Schwarzschild radii, which is substantially smaller than the smallest theoretical apparent size of any emitting region centered on the black hole location due to gravitational lensing effects. Therefore, the emission is deduced to be offset from the black hole, as predicted by models of emission from the accretion disk that include the effects of relativistic Doppler boosting. These measurements demonstrate the potential of high-frequency VLBI arrays to probe the immediate vicinity of the black hole and to provide new constraints on the physics of these exotic objects. The result was published in the journal *Nature* and has attracted widespread attention from researchers and the public media alike.

Following on from this work, theorists have argued that this is the best evidence yet for the existence of a true event horizon, given the lack of infrared emission that would be expected from infalling material if a solid surface existed outside the predicted radius of the event horizon. In a series of modeling papers by Shep Doeleman, Vincent Fish, and collaborators, it is shown that nonimaging observations, feasible today, can strongly constrain the circum–black hole conditions by detection of periodicities resulting from emitting material in orbit around the black hole. In addition, the capabilities of current and near future millimeter VLBI arrays have been explored in terms of their ability to constrain black hole spin and orientation parameters and to thereby exploit this new and exciting observational field.

In April 2009, a new 230 GHz VLBI campaign was mounted, with roughly doubled sensitivity compared to the April 2007 observations. This sensitivity boost was enabled by the ongoing technology and instrumentation development program at Haystack and by the phased array work being pursued collaboratively with the Smithsonian Astrophysical Observatory. Once again, many robust detections of SgrA* were obtained at high angular resolution, and further constraints on models of the emission will be developed through detailed data analysis.

During the new observing campaign, a second object, M87, was observed. The black hole in this object is far more massive than that in our galaxy, but also far more distant. The net result is that the angular resolution of the VLBI array in terms of Schwarzschild radii is almost as high as that for SgrA*. Strong detections of M87 were made, demonstrating that extremely compact emission associated with supermassive black holes is common and, perhaps, ubiquitous. This further cements the importance of this emerging and powerful observational technique enabled by technology enhancements spearheaded at Haystack. A proposal for development of a global millimeter array to pursue this science in the next decade, dubbed the Event Horizon Telescope, was submitted to the National Academy's Astro2010 Decadal Survey on Astronomy and Astrophysics.

Square Kilometer Array

Haystack continues to participate in the international Square Kilometer Array (SKA) through involvement in a technology development program (TDP) led by Cornell University, as well as a Haystack-led project on advanced correlation techniques. In addition, Dr. Alan Rogers serves as chair of the international SKA engineering advisory committee. The advanced correlation technique project seeks to develop and demonstrate a method for restricting the field of view of the SKA at higher angular resolutions, thereby greatly reducing data volumes and analysis complexity. Extensive data sets were acquired from the MERLIN telescope in the UK in support of this project, and are under detailed investigation. The TDP work focuses on data processing architectures and correlation techniques as part of the broader US and international project. Haystack staff regularly attend SKA-related meetings and contribute to MIT representation on the US SKA consortium executive.

37-Meter Telescope

After an extended period of review and assessment, the replacement upgrade of the Haystack 37-meter telescope by Lincoln Laboratory with Air Force sponsorship has resumed and is on track for completion in 2012. At the time of this writing, the physical replacement of the old structure with the new is scheduled for summer 2010. The new dish will feature excellent high-frequency performance and will open up new possibilities for astronomy-based research and education. Haystack Observatory will have access to the telescope when the radar system is not operating, and transfer of the radiometer systems to the new antenna is ongoing under a grant from Lincoln Laboratory to Haystack. In addition, a high-performance spectrometer for the telescope has been developed under a grant from NSF, which will enable high-resolution, wide-band spectroscopy with the new dish. The upgraded telescope has important potential as a sensitive aperture in high-frequency VLBI arrays looking at black holes and other astronomical targets.

Instrumentation Development

Haystack continues to be a leading center in the development of next-generation VLBI instrumentation and is pursuing programs to address the entire VLBI signal path from antenna to correlator. When deployed on national facility observatories such as the Very Long Baseline Array (VLBA), the hardware being designed at Haystack will boost sensitivities by factors of 3 to 4, opening new scientific possibilities. The new systems are enabling sensitive and groundbreaking experiments at millimeter wavelengths and angular resolutions of a few tens of microarcseconds, while a "VLBI2010" prototype system is being developed for geodetic VLBI that will span approximately 2 to 13 GHz to help achieve the goal of 1-mm accuracy for global geodetic VLBI measurements.

Over the past three years, Haystack has worked with collaborators to design and build a first-generation fully digital VLBI backend. By leveraging the rapid increase in capability of field programmable gate array (FPGA) technologies, this project demonstrated that the functionality of older VLBI backends whose cost was in the area of $500,000 could be replaced with wider bandwidth digital versions at approximately 1/50th of the cost. Digital backend (DBE) prototypes have now been used to make the highest angular resolution observations of the supermassive black hole at the center of the Milky Way Galaxy. Building on this success, the Haystack VLBI group is capitalizing on the continued growth in commercially available FPGA chips to work on a new backend system in partnership with the University of California, Berkeley, and the National Radio Astronomy Observatory (NRAO). The DBE2, which utilizes the Virtex5 family of FPGA chips, will double the bandwidth of the DBE and output VLBI data using the industry standard 10-Gigabit Ethernet high-speed data protocol. This advance will allow recording of VLBI data on commercially available arrays of hard disks, further lowering the cost of VLBI systems.

An additional method of increasing the sensitivity of VLBI arrays is to combine the collecting area of multiple radio telescopes to function as a single large aperture. To do this, cosmic signals from radio telescopes that are in close proximity have to be processed to correct for geometric path delays in real time and over wide bandwidths. Only after this is done can the signals be coherently added and recorded on VLBI systems. Haystack is collaborating with the Smithsonian Astrophysical Observatory on flexible digital systems that can combine up to eight antennas, and initial field tests of the new instrument have been successful. When deployed, the phased array processors will provide sensitivity increases of nearly a factor of 8 on critical interferometer baselines for high-frequency VLBI work.

In parallel with the DBE project, Haystack has also developed a flexible radio frequency converter that provides a connection between the DBE and virtually any telescope receiver output. The converter is built around a broadly tunable synthesizer that can match the telescope receiver frequency band and mix it down to the input band of the DBE. The converter prototype has been deployed for ongoing field testing. The versatility of this new converter module makes it ideal for new broadband geodetic VLBI systems, as well as for submillimeter VLBI sites that typically have very high-frequency receiver outputs.

The Mark5C VLBI recorder is under development at Haystack and is specifically designed to interface with the DBE2 backend. When taken together, the DBE2 and Mark5C will provide a complete VLBI system that will operate at sustained data rates of 4 Gigabits per second. Haystack is responsible for the Mark5C software systems that will enable it to record older data formats, as well as the new VLBI Data Interchange Format (VDIF) that specifies transfer of VLBI data over 10-Gigabit protocols. In partnership with NRAO, Haystack is developing the Mark5C in part to upgrade the VLBA, a national facility instrument dedicated to VLBI observations. When complete, the DBE2/Mark5C upgrade will provide an increase in the bandwidth of the VLBA by a factor of 8 and deliver a significant new capability to the broad astronomy community.

Another NSF-funded program is building on the Mark5 effort to develop a "burst-mode" recorder that will be capable of storing data at rates up to 16 Gigabits per second. This new recorder is aimed at VLBI science applications that for technical or astrophysical reasons must record as much data as possible in a short time. An example is millimeter-wavelength VLBI where atmospheric turbulence decorrelates the VLBI signal over times significantly longer than about 20 seconds. The architecture uses commercial, off-the-shelf components and established industry high-speed data protocols to speed development and prototyping.

To leverage all of these instrumental developments for astronomical VLBI at the highest frequencies (230 GHz or above), an extremely stable frequency reference is required. At lower frequencies, hydrogen masers are sufficiently stable to allow widely spaced VLBI sites to maintain phase coherence and operate as a single "Earth-sized" telescope. At 230 GHz and above, the stability of most masers is insufficient for this task. Haystack is collaborating with the University of Western Australia's Frequency Standard and Metrology Lab to adapt extremely stable cryogenic sapphire oscillators (CSOs) for VLBI use and to develop a pulse-tube cooling system for CSOs. These resonators are 10–100 times more stable than hydrogen masers over 1–100-second integration intervals, making them ideal for high-frequency VLBI where integration times are limited by the atmosphere. Haystack has designed a phase-locked loop system that harnesses the stable, approximately 10 GHz signal output from the CSO and generates a GPS-conditioned 10 MHz tone suitable for controlling all systems at a VLBI site. This development, coupled with the new burst-mode systems, will allow new submillimeter facilities (including the Atacama Large Millimeter Array, the Atacama Pathfinder Experiment, and the Atacama Submillimeter Telescope Experiment) to be combined into a single VLBI instrument capable of 20-microarcsecond angular resolution.

For geodetic VLBI, as mentioned above, the VLBI2010 development program is under way with the goal to increase global measurement precision to 1 mm. Many of the instrumental building blocks, such as DBE, flexible radio frequency converters, and Mark5C, are common to astronomical VLBI development. The hallmark of the VLBI2010 project is the development of a "broadband" system that covers the entire approximately 2–13 GHz radio frequency range with a single feed. A prototype broadband system has been developed, including a cooled feed, low-noise amplifiers, and a wideband optical-fiber system to transmit the entire radio frequency bandwidth to processing equipment on the ground. Several successful demonstration experiments using the

18-m Westford antenna at Haystack Observatory and the 5-m antenna at the NASA Goddard Geophysical and Astronomical Observatory (GGAO) in Maryland (Figure 4) have been conducted, and more are planned as the system matures. A new fast-moving 12-m antenna has been procured and will be installed at GGAO. It is expected that VLBI fringes will be obtained by the end of 2009. With speed of observation being a key performance parameter for the VLBI2010 goals, the burst mode recording system mentioned above is expected to significantly enhance system capabilities by reducing the time required for integration of each target source. The Haystack VLBI2010 development program, funded largely by NASA, is part of an international effort to develop a major upgrade to the existing geodetic VLBI system.

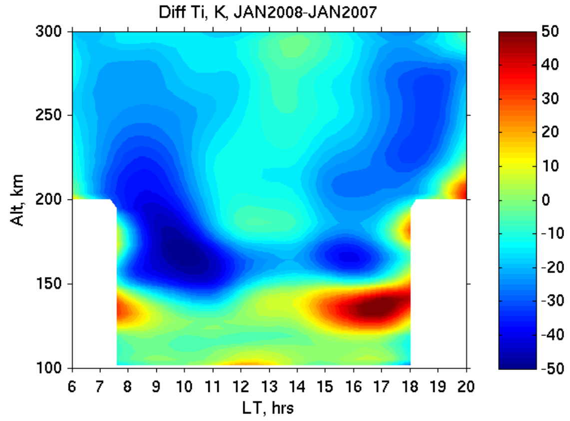

Figure 4. Variation in midlatitude Millstone Hill ion temperature observed during stratospheric warming as compared to baseline data. A warming is observed in the lower thermosphere at approximately 120–140 km, accompanied by a 20–75 K cooling above approximately 140 km. It is well established that stratospheric warming is accompanied by mesospheric cooling. These observations show for the first time that areas of warming and cooling extend to altitudes of the upper thermosphere (approximately 300 km).

Atmospheric Science

The research emphasis for the atmospheric sciences program at Haystack Observatory during the past year focused on coupling processes and trends controlling the various regions of Earth's upper atmosphere.

Lower-Upper Atmosphere Coupling

Community researchers have previously proposed that lower atmospheric processes account for some degree of ionospheric variability. In the first ionospheric study of its kind, Haystack researchers and colleagues from Jicamarca Radio Observatory examined episodes of sudden stratospheric warming that occurred in January 2008 and compared the results with temperature fluctuations in the ionosphere and thermosphere as recorded by multiple incoherent scatter radar (ISR) facilities. At Millstone Hill and other middle latitudes, ionospheric variations were detected that were not linked to seasonal trends, solar flux, or geomagnetic activity but rather to fluctuating temperatures in the stratosphere, demonstrating a previously unobserved link between the lower atmosphere and the ionosphere. A very unexpected result of the study is an observation of large changes in equatorial and tropical latitude plasma densities and velocities, even though sudden stratospheric warming is a high-latitude event. This observed lower atmosphere control of wide-area daytime ionospheric conditions has major practical space weather implications and demonstrates that studies of space weather should consider ionospheric variability in conjunction with stratospheric changes. A number of journal articles, special issues, conference sessions, press conferences, and general public media articles featuring Haystack authors have already resulted from this work.

Ionospheric Cooling during Extreme Solar Minimum

The current extended solar minimum presents an unprecedented opportunity to characterize the background, baseline state of the ionized and neutral upper atmosphere during quiet conditions. Theoretical predictions show that increasing concentrations of greenhouse gases lead to a cooling of the upper atmosphere. As a result of the close thermal coupling of the neutral and ionized components of the upper atmosphere, these effects should also be seen in ionospheric ion temperatures. The ISR technique is the only ground-based method yielding direct ionospheric temperature information. In ISR experiments performed at the Millstone Hill facility during the International Polar Year (IPY) interval, Haystack researchers showed direct evidence of an ion temperature drop (thermal cooling) in conjunction with the ISR multidecade data set used as a reference. Regression analysis revealed that even after solar flux and magnetic activity variations are removed, ion temperature values between 100- and 500-km altitude are much lower during the IPY interval than in previous solar minima, with the trend becoming more significant with increasing height. This is the first direct confirmation of this cooling, and future research will probe links between temperature decreases and overall climate change.

Geomagnetic and Manmade Ionospheric Disturbances

A Haystack multiauthor study of ionospheric response to geomagnetic and solar wind disturbances in November 2004 explored the effects of an unusual multihour period during which solar wind conditions directly drove changes in the equatorial, midlatitude, and high-latitude ionosphere. Results from coordinated multiple ISR and GPS observations showed a dramatic expansion of an important zone of magnetosphere-ionosphere interactions from its normal location north of Millstone Hill to encompass the tropical ionosphere just above Puerto Rico, with large ionospheric structuring and motion consequences. Another study explored the manmade production of large-scale ionospheric variations from the exhaust gases of a large Titan rocket launched from Kennedy Space Center in Florida. Severe upper atmospheric perturbations seen simultaneously by optical emission from the thermosphere and by GPS diagnostics showed up to 50% depletion in ionospheric total electron content over the eastern United States within 30 minutes of launch. The results dramatically illustrate the existence of time-dependent large, regional manmade space weather effects with potential impacts on commercial communications and navigation systems.

Cold Plasma Redistribution and Magnetosphere-Ionosphere System Effects

Electric fields resulting from the coupled interaction of the magnetosphere-ionosphere system result in a large-scale redistribution of low-latitude ionospheric plasma throughout the magnetosphere. Previous studies of ionospheric redistribution from mid to high latitudes developed using the MIT Millstone Hill incoherent scatter radar and supporting observations with spacecraft and the distributed array of GPS receivers have been extended to include the access and impact of such ionospheric material to the overlying magnetosphere. Two NASA-sponsored programs support these studies, and a continuing series of radar experiments with the new Alaskan phased-array radar are investigating the processes involved in this ionosphere-magnetosphere coupling. Two recent Haystack studies examining more than 1,000 radar scans from 20-plus years of Millstone Hill ISR data have developed statistical patterns of ion velocity and ionospheric conductance within these coupling regions. This information is a unique observational resource and results have generated significant interest within the modeling community exploring energy balance and transfer between these two crucial parts of the near-Earth space system.

Technical Initiatives

Geospace Science Center

This year the Atmospheric Sciences group initiated the development of a Geospace Science Center at the Millstone Hill facility for use in the control, operation, and science integration of Upper Atmosphere Facilities program (UAF) resources, distributed arrays of small instruments, and small satellite missions. The 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, a radio frequency interference screened receiver room, an electronics laboratory, and a computing facility capable of supporting a significant grid computing system. By implementing a science integration center capable of supporting a range of modern, distributed scientific instruments, Haystack will directly contribute to efforts for coordination and integration of science and technical activities across the UAF facilities. We anticipate that the center will serve as an important point of community interaction for people who use UAF-supported instruments to collaborate and achieve a greater understanding of the near space environment. An open operations and control center at the MIT Millstone Hill facility will also provide easy access to the Millstone Hill UHF radar facility for researchers, students, and visitors and will form a regional and national center suitable for workshops, educational events, remote instrument operations, and experimental campaign coordination. In addition, the center implementation will form a key point of community interaction with a Distributed Array of Small Instruments system in the eastern half of North America. Distributed instruments are a natural focus of facility outreach and collaboration, as well as a key way to involve the larger community in facility science efforts and provide science opportunities involving facility instrumentation. The Geospace Science Center will help the community exploit distributed instruments in an effective manner.

Satellite Beacon Ionospheric Diagnostics

The Atmospheric Sciences group continues to collaborate with Lincoln Laboratory and the National Radio Astronomy Observatory in Green Bank, WV, on a study of geophysically imposed variations in the characteristics of radio signals transiting the ionosphere. The project employs a high-gain 43-m telescope at NRAO Green Bank to observe orbiting, radio-bright satellite beacons for high-precision measurements of electron density fluctuations. The experiments examine beacon signal amplitude and polarization distortion dynamics imposed by fine-scale ionospheric irregularities. Initial results are promising and of great interest to low-frequency radio astronomy array efforts such as the Murchison Widefield Array as calibration of heliospheric and astronomical observations requires very accurate and dynamic removal of ionospheric effects.

Radar Performance Enhancements

Development of a thermoelectrically cooled low-noise amplifier to improve radar performance and sensitivity was initiated. The goal of this effort is to replace the existing UHF radar front-end amplifiers with more advanced units that are vacuum isolated and cooled to low temperature using thermoelectric cooling. This has the potential to nearly double the sensitivity of the radar while still accounting for the unique characteristics of operation in a high-power radar system. The cooling will stabilize variations in the radar system temperature to better than one degree kelvin. It also avoids the cost and difficulty associated with more traditional cryogenic solutions. Significant analysis, design, finite element simulation, and mechanical engineering have been completed for this project. The project has been tightly coupled with a Research Experiences for Undergraduates (REU) program effort and will continue over the coming year to fabrication, testing, and integration into the Millstone Hill UHF radar system.

Educational and Outreach Programs

Haystack Observatory continues development of the Very Small Radio Telescope (VSRT) under a Phase II grant from NSF. Five VSRT beta test institutions are currently involved, namely Bridgewater State College, the University of North Carolina at Greensboro, Southeast Missouri State University, Union College, and Bucknell University

The participant at Bridgewater, Dr. Martina Arndt, has developed an assembly document and a basic operation manual. These materials will be combined with a VSRT unit containing hands-on physics activities for students at the high school and lower college levels, developed by participants in the Research Experiences for Teachers (RET) program, to create a user's manual.

The single-antenna 11 GHz spectrometer version of the VSRT developed by Alan Rogers that measures ozone emission in the mesosphere has been renamed MOSAIC (Mesospheric Ozone System for Atmospheric Investigations in the Classroom). The systems at Haystack Observatory and Chelmsford High School (North Chelmsford, MA) now have taken 18 months of data, and a paper on the results has been accepted by the *Journal of Atmospheric and Oceanic Technology*. Four of the beta test institutions listed above are also testing the MOSAIC units; three are installed and taking data, and the fourth unit will soon be installed.

MIT teamed with SRI personnel to run a successful Advanced Modular Incoherent Scatter Radar (AMISR) workshop at Haystack for 20-plus international and US students in the summer of 2009.

The REU program at Haystack, now in its 19th year, continues to provide undergraduate students with summer internships. Nine students are completing their projects in astronomy and atmospheric sciences this summer. Science teachers from five local high schools participated in NSF's RET program at Haystack. Three of the teachers are helping to develop the VSRT into a learning tool that can be used with high school students. The others created a "Versatile System for Learning about Radio Telescopes" unit that has been tested in the classroom and will be revised for publishing on the web so that other teachers can freely use it. The RET projects at Haystack and their products

Figure 5. RET participants working with the MOSAIC system for detection of the 11 GHz ozone line in the mesosphere. The system was developed by Alan Rogers (left). This extremely inexpensive system is capable of gathering research-quality data of significant scientific interest in a high school setting.

are attracting widespread interest, and materials have been distributed to educators in India, to an Italian program that trains African scientists, to participants in a conference in Zambia, and to educators in England.

Public outreach programs at Haystack continue to be active and successful. In addition to regular open-house events, tours for high school students, and programs at local venues, staff members have been actively involved in efforts such as hosting tours and events for Cub Scouts (including "cubmobile" races), providing science camp support and presentations, and job shadowing for high school students. The Atmospheric Sciences group is leading the production of a series of educational videos suitable for computer (YouTube, iTunes) and podcast viewing: Space Weather FX (http://www.youtube.com/watch?v=fZ-L-pS0syc), addressing space weather, earth, sun, GPS, atmosphere, science, and education. Other new media efforts involved space weather programs within the International Year of Astronomy podcast series and popular media articles in conjunction with professional science writers. Haystack has also had a presence in mainstream media, with Shep Doeleman interviewed by the BBC and the Discovery Channel on his black hole work. In addition, the local CBS TV channel aired a short segment on Haystack and some of our projects.

Colin J. Lonsdale
Director

More information about Haystack can be found at http://www.haystack.mit.edu/.