Haystack Observatory

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

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 sciences 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 (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 Aeronautics and Space Administration (NASA), and the Department of Defense.

Awards and Personnel

Dr. Alan Rogers has been recognized for his pioneering contributions to radio astronomy over a long and illustrious career at Haystack. Now retired, he continues to contribute his formidable expertise and energy to the observatory as a research affiliate. He received the 2008 John Howard Dellinger Gold Medal of the International Union of Radio Science for "his outstanding contributions to instrumentation in radio astronomy and its use to make fundamental discoveries about interstellar masers, superluminal expansion of quasars, deuterium abundance in the galaxy, and plate tectonics." In addition, Alan was awarded the 2010 Grote Reber medal for outstanding and innovative contributions to radio astronomy. The award was presented in recognition of his many pioneering developments in radio and radar interferometry and radio spectroscopy and his application of radio astronomy techniques to society.

Dr. Shep Doeleman was promoted to principal research scientist and leads the astronomical VLBI effort at Haystack. Shep continues to build a major instrumentation and research program aimed at direct imaging of the immediate environment of supermassive black holes. Dr. Phil Erickson was also promoted to principal research scientist, and he has assumed principal investigator status on the major NSF cooperative agreement that funds the Millstone Hill incoherent scatter radar facilities.

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 undergoing a major upgrade, scheduled for completion in 2011, and is currently unavailable for use.
- 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.

Radio Astronomy

Murchison Widefield Array

Work continues on the Murchison Widefield Array project (MWA), which seeks to deploy 512 dipole-based antenna tiles operating between 80 and 300 MHz for scientific investigations encompassing cosmology, the heliosphere, the transient radio universe, and a wide variety of galactic and extragalactic phenomena. The project is a collaboration among Haystack Observatory, the MIT Kavli Institute (MKI), and CfA in the United States; a consortium of Australian universities; and the Raman Research Institute in India. The US teams are supported by a $5.8 million NEROC grant to Haystack that is due to expire at the end of 2010; a new proposal is in preparation, led by MKI, to complete construction and conduct cosmology studies. Other NSF proposals are planned in early 2011, to be led by Haystack, for array operations, continued technical support and development, and noncosmology science. Alan Whitney serves as the international project director, and Colin Lonsdale serves on the MWA board.

During the past year, a major project milestone has been met, involving the end-to-end demonstration of a fully integrated 32-tile subset of the full array (Figure 1). This milestone was established as a requirement for the release of significant new funding in Australia, which is now flowing. Plans for the rollout of the array are well advanced, with major construction scheduled for most of the next 15 months. The array completion will coincide with the installation of major infrastructure elements at the remote site by the Australian Commonwealth Scientific and Industrial Research Organisation, including an environmentally controlled and electromagnetically screened building, a power generation facility, and high-capacity fiber connectivity to the outside world.

A recent highlight has been the successful execution of an ambitious site visit designed to gather significant quantities of science and engineering data with the commissioned

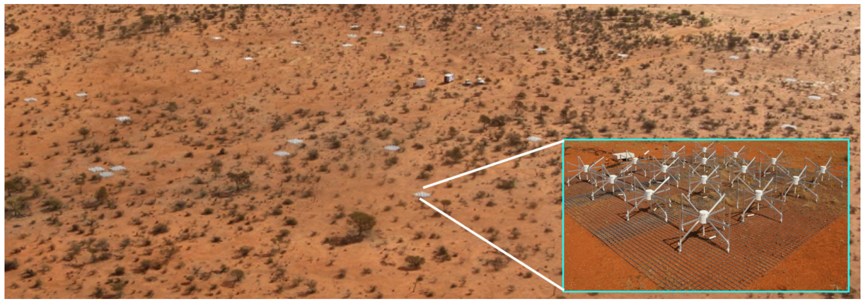

Figure 1. Aerial view of the MWA 32-tile system located on the radio-quiet Murchison Radio Observatory site in Western Australia. The prototype 32-tile system is laid out in a rough circle 300 meters in diameter, and the full system to be completed in 2011 will comprise 512 tiles spread over an area 3 kilometers in diameter. Each tile (inset) 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.

32-tile system. Many observations were performed over a 12-day period in late March 2010, including an all-sky survey, multiwavelength imaging of the sun, long integrations on cosmology fields, monitoring for transient radio events, and a variety of tests related to instrument performance. Examples of the results from this site visit are shown in Figure 2. Of particular note is the detection and characterization of type III solar burst and "microburst" radio emissions. The MWA prototype 32-tile array has proven far more sensitive to such emissions than existing solar burst monitoring systems, thanks in part to the interferometric nature of the array, but also to its wide and continuous frequency coverage and high spectral resolution. This allows us not only to investigate much fainter and more numerous events but to do so with excellent time and spatial resolution, yielding multiple science results and anticipated publications, even from these preliminary data.

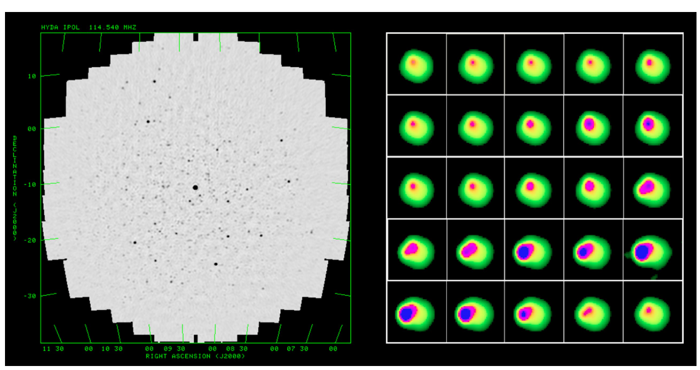

Figure 2. Some results from the prototype 32-tile array of the MWA. The left panel shows an image of the sky centered on the bright source Hydra A. Many dozens of other sources are clearly visible, and the dynamic range of the image is approximately 2,000:1. The field of view is of order 30 degrees across, giving meaning to the term "widefield" in the telescope name. The remarkable radio quietness of the site is underscored by the fact that these observations included a large section of the FM band, which has for decades been a radio astronomy no-go zone due to interference from FM transmitters. The right panel is a time series of solar images capturing a type III solar burst. Each frame is one second apart, and within the span of approximately 10 seconds the emission is seen to vary dramatically, including a large shift in the location of the burst emission on the solar disk.

Current plans call for physical completion of the 512-tile array and supporting digital electronics in 2011, followed by commissioning and a variety of early science observations. The highly demanding deep integrations to look for faint hydrogen line signals from the so-called "epoch of reionization" in the early universe require extensive preparation and a thorough understanding of the system, and are scheduled to begin in September 2012.

Astronomical VLBI

The submillimeter VLBI group at Haystack has focused on analyzing recent 230 GHz VLBI data on Sagittarius A* (SgrA*) collected in April 2009. These new data, collected with a four-antenna VLBI array, represent the highest sensitivity and angular resolution observations of this 4 million solar mass black hole candidate at the center of the Milky Way. Previous observations by the Haystack group detected an event horizon scale structure in SgrA* but could not distinguish between two physically motivated models. In one, the strong gravity of the black hole creates a "shadow" or dim central region in the emission. In the other, the black hole spin and high speeds of luminous material orbiting the black hole conspire to create a more compact emission region that is offset from the black hole position. The April 2009 data used new detections of SgrA* on baselines between Hawaii and California to effectively rule out the shadow model, confirming that the orbiting accretion disk is likely inclined to our line of sight and is preferentially enhanced on the side that is approaching us. A further new result from this work is that the event horizon structure of SgrA* was observed to brighten during one of the three observing days in the April 2009 campaign, demonstrating that high-frequency VLBI can resolve time-variable structures ostensibly due to changes in the accretion flow at the innermost orbits of the black hole. This represents some of the best evidence for event horizon scale variability around a supermassive black hole (Figure 3). As the submillimeter VLBI array continues to add new dishes, it will soon become possible to use high time resolution VLBI data to time the orbits of material close to the black hole, enabling new tests of General Relativity.

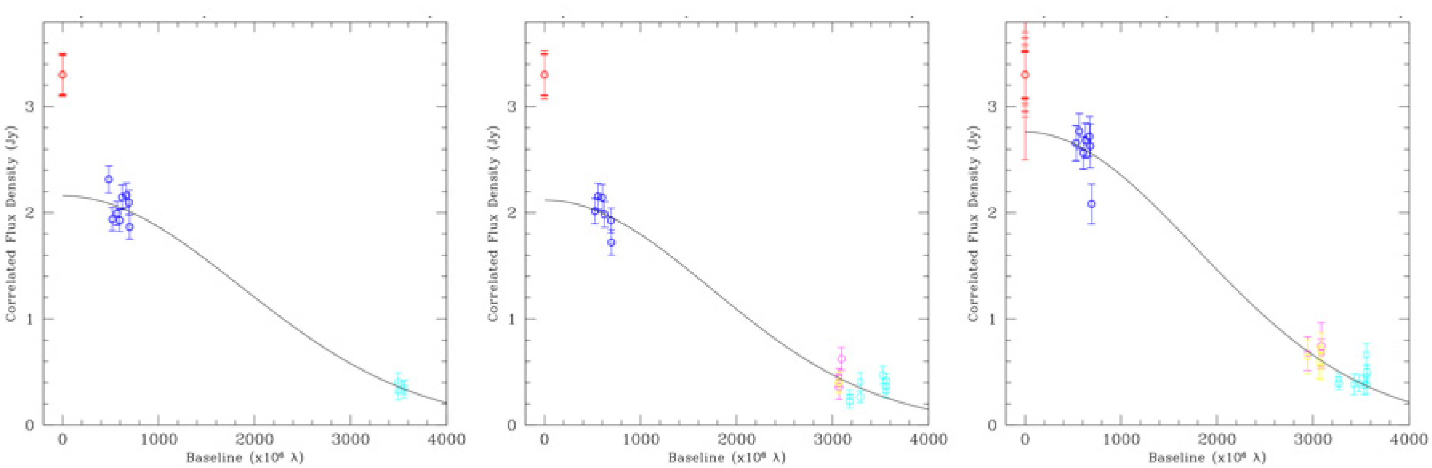

Figure 3. 230 GHz VLBI observations of SgrA in April 2009 show that the small scale structure of the emission surrounding this supermassive black hole brightened during the last of three observing nights. Shown are flux density versus baseline length on (from left to right) April 5, 6, and 7. On April 7, the size of the compact emission was unchanged, but the flux density increased by 30 percent, implying an increase in accretion rate within a few Schwarzschild radii of the black hole.*

In April 2010, the VLBI group mounted a new observing campaign, in collaboration with CfA, to test a phased array system that combines all of the collecting area of the Submillimeter Array on Mauna Kea into a single VLBI element. Results of the test show that the system delivers very high phasing efficiency, and the collaboration has now expanded to include the VLBI group at the University of California, Berkeley, who will transfer the technology to similarly phase up the Combined Array for Research in Millimeter-Wave Astronomy (CARMA) in northern California. The resulting increase in collecting area at both sites will enhance the sensitivity of the submillimeter VLBI array by a factor of 3.

The April 2010 campaign was also notable for including the first successful 230 GHz polarimetric observations. Study of polarized emissions from SgrA* on Schwarzschild radius scales will provide a new probe of the plasma surrounding the black hole. The Haystack group and collaborators at CfA and the Canadian Institute for Theoretical Astrophysics (CITA) published work this year on using nonimaging submillimeter VLBI polarimetry to extract period signals due to matter orbiting the black hole.

Building on these developments, Haystack has continued to organize the concept of a global submillimeter VLBI network called the Event Horizon Telescope (EHT). Last year, Haystack led a submission on this activity to the ASTRO2010 Decadal Review on the EHT. This year, an international meeting that included participants from all EHT collaborating sites and institutes was convened at Haystack, where plans for EHT logistics, technical work, and science were discussed.

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. A Haystack-led project on advanced correlation techniques was completed; this project explored and demonstrated processing algorithms for restricting the field of view of the SKA at higher angular resolutions, thereby greatly reducing data volumes and analysis complexity. It has also been shown that algorithms such as this are likely to be required for maintaining the internal consistency of SKA data sets and enabling the extreme imaging dynamic range required for the full SKA sensitivity to be exploited. 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 the MIT representation on the US SKA consortium executive.

37-Meter Telescope

The iconic Haystack radome-enclosed 37-meter radio telescope is undergoing a major upgrade, funded by the Air Force and managed by Lincoln Laboratory, with the goal of creating a high-performance 90 GHz imaging radar capability. Most of the original, 45-year-old telescope structure is being replaced, and as of mid-2010 the work is proceeding rapidly. Photographs of the activity on site are shown in Figure 4. Haystack personnel are engaged in support for the upgrade operation in a variety of ways, and Haystack is under contract to Lincoln Laboratory to install radio astronomy receivers on the new dish, to be used by Lincoln to establish and maintain an accurate pointing model for the telescope via sensitive observations of celestial radio sources.

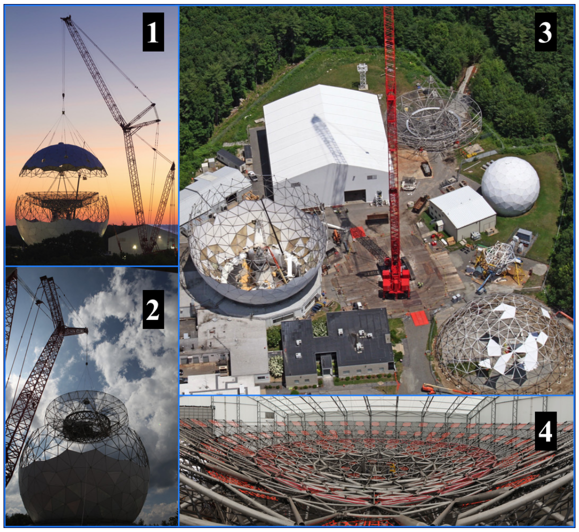

Figure 4. Photos of the Haystack 37-meter telescope upgrade, courtesy of Colin Lonsdale (Haystack) and Joe Usoff (Lincoln Laboratory). Panel 1 shows the removal of the radome cap on May 28, 2010, with the approximately 435-foot-high crane on site. The cap will be replaced after the new dish is installed. Panel 2 shows the removal of the old dish backup structure on June 4, which was scrapped. Panel 3 is an aerial view of the site following the old dish removal, showing the crane, the empty radome, the radome cap in the process of having its fabric covering replaced, and the old dish before it was dismantled. The main Haystack offices are at bottom left. Part of the new telescope structure can be seen just above the radome cap, and the new dish backup structure is inside the large white temporary building, the contents of which are shown in panel 4.

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 percent 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 wideband spectrometer, developed by Haystack under a grant from NSF, will augment the astronomical capabilities of the telescope.

VLBI Instrumentation Development

Fast-Slewing Antenna

Haystack Observatory's geodetic VLBI program is spearheading instrumentation advancements needed to realize geodetic VLBI's global position uncertainty goals for the next-generation station. An essential and major element of this realization is the incorporation of fast-slewing antennae that will enable the next-generation station to perform as many as 1,400 observations per day, a quantity previously unheard of. As such, Haystack has procured a suitable 12-m radio telescope from Patriot Antenna Systems (Figure 5) that is scheduled for installation in the fall of 2010 at the Goddard Geophysical Astronomical Observatory in Greenbelt, MD. As part of NASA's recently funded two-year space geodesy project, this 12-m radio telescope will be incorporated into the first fully integrated Global Geodetic Observing System station in the world.

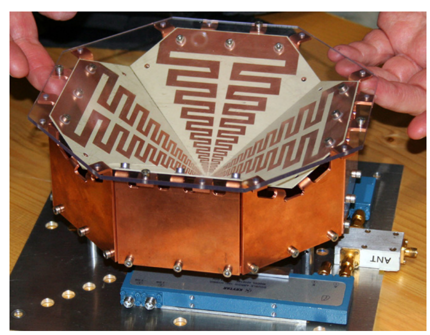

Figure 5. A Patriot Systems 12-meter antenna of the type being acquired for geodetic use. This photo is of a similar antenna installed at Arecibo for other purposes.

Wideband Receiver

Figure 6. Photo of the cryogenic "Eleven" feed being considered for the 12-meter geodetic antenna system.

The instantaneous bandwidth requirement imposed on next-generation receivers is also a factor of 10 greater than that of the legacy systems. As such, Haystack is collaborating with the Chalmers University of Technology (CUT; Gothenburg, Sweden), the Onsala Space Observatory (OSO; Onsala, Sweden), and the California Institute of Technology (Caltech; Pasadena, CA) in an effort to develop an extremely broadband receiver front end for the 12-m radio telescope. This front end is based on the "Eleven" antenna (Figure 6) designed at CUT and fabricated at OSO, and ultra-low-noise amplifiers designed at Caltech and fabricated by Northrop Grumman Space Technologies. The integration and cryogenic performance of these components is expected to provide a receiver that possesses an instantaneous bandwidth and sensitivity unparalleled by any radio telescope in the entire global geodetic VLBI network. This development is anticipated to revolutionize the global geodetic VLBI infrastructure so that the aforementioned global positioning requirements can be realized. Furthermore, the operational bandwidth of this receiver will provide far more flexibility over the narrowband legacy systems and will enable compatibility with ever-evolving high-speed digital backend (DBE) recorder technology.

Data Recording Systems

Haystack Observatory has long been known for its expertise in VLBI data recording hardware and continues to be at the forefront of such emerging technologies. Collaborations with the National Radio Astronomy Observatory (Socorro, NM) continue, and through this cooperation Haystack is on the cusp of providing a new 8-Gigabit-per-second (Gbps) continuous/16-Gbps burst-mode DBE recorder to the VLBI community. The availability of this device will improve sensitivity by nearly a factor of 6 over the current geodetic observations. This recorder comprises two main components: the DBE, which digitizes/packetizes the data and transmits them using Internet protocols, and the Mark5C, which receives the packets and records them to hard disk.

The DBE portion of the recorder is based on the Reconfigurable Open Architecture Computing Hardware (ROACH) of the University of California, Berkeley, CASPER project; the software/firmware was designed in-house with the interest of modularity in mind. Maintaining this modularity has allowed Haystack to develop a very flexible data recording system that will allow the device to provide much more functionality than was possible in the legacy hardware, and this feature will undoubtedly sustain the global VLBI community's interest in Haystack's recording technology.

The Mark5C recorder is based on the Conduant Corporation's 10-Gbps Ethernet network and StreamStor® hardware. Similar to its Mark5A/B/B+ predecessors, the Mark5C also makes use of commercial off-the-shelf hard disk recording media, the cost of which greatly benefits from economies of scale. The Mark5C, however, differs from its predecessors in that it will make use of networking technology to transfer data from the digitizer to the recorder as opposed to an independently developed architecture. Much like the cost of hard disk media, the data throughput of recorders built on network technology also benefits from economies of scale; 40- and 100-Gbps Ethernet technologies are rapidly evolving. Since radio astronomical techniques are always limited by data throughput, this has been an area of active research in the past but now involves little engineering cost on the part of Haystack.

Frequency Standards

This year, as part of the millimeter VLBI astronomy program, a frequency standards and metrology group from the University of Western Australia came to Haystack to install a liquid helium cryogenic sapphire oscillator (CSO; Figure 7). The stability of the CSO exceeds that of historical hydrogen maser VLBI frequency standards by one to two orders of magnitude, potentially providing an alternate means to extend the VLBI technique to frontier 1.3-mm and 0.8-mm wavelengths. Over time scales of 1 to 300 seconds, use of the CSO as a VLBI frequency reference can reduce coherence losses due to phase fluctuations to negligible levels. The Haystack VLBI group has completed the design, construction, and testing of a custom receiver that locks a high-quality 10 MHz quartz oscillator to the 11.2 GHz native output tone from the CSO. To ensure long-term stability, the quartz oscillator is also locked to a GPS clock. The combination of CSO and GPS conditioning results in a standard 10 MHz frequency reference, suitable for use by any VLBI site, that has excellent stability characteristics over all time scales. Now that the CSO concept has been proven in the laboratory, Haystack is working with our Australian colleagues to use the new receiver in conjunction with closed-cycle refrigerator-cooled sapphire oscillators that can be installed at remote VLBI sites for unattended operation.

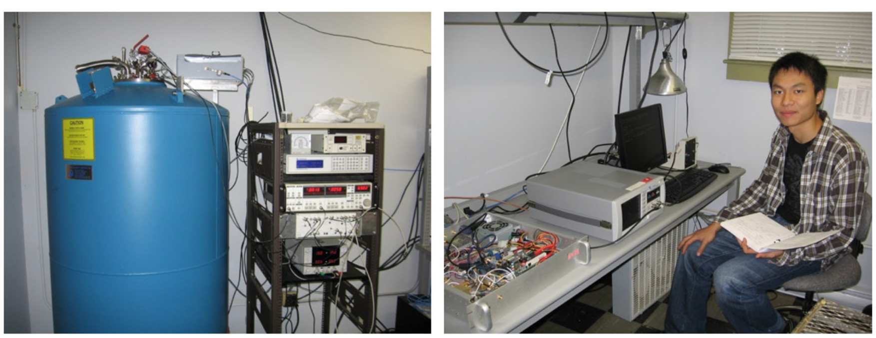

Figure 7. Left: The liquid helium cryogenic sapphire oscillator installed at Haystack Observatory by University of Western Australia collaborators. The blue dewar houses the sapphire crystal, and instruments to servo the crystal temperature and frequency are in the rack. Right: The Haystack-built receiver that converts the native 11.2 GHz tone from the CSO into a standard 10 MHz VLBI reference. NSF REU student Tao Mai (Columbia University) is shown with the receiver (open chassis) and measurement equipment.

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.

Stratospheric Warming

The coupling of the ionosphere to processes in the lower atmosphere remains an elusive and difficult problem—rapidly changing external drivers from the overlying magnetosphere mask variations related to lower atmospheric sources. A superposition of unique circumstances (the current deep solar minimum and a record-breaking stratospheric warming event) enabled the Atmospheric Sciences group to gain new insights into the causes of such ionospheric perturbations. In an article published by Haystack's Larisa Goncharenko and colleagues, a large (50 to 150 percent), persistent variation in the low-latitude ionosphere was found to occur several days after a sudden stratospheric warming event. A general circulation model was used to interpret these observations in terms of large changes in atmospheric tides resulting from their nonlinear interaction with planetary waves, which are strengthened during sudden warming events.

The large magnitude and persistence of the ionospheric perturbations, together with the predictability of sudden stratospheric warming events several days in advance, presented an opportunity to investigate these phenomena in a systematic manner and may eventually lead to a multiday forecast of low-latitude ionosphere conditions.

The article by Goncharenko et al. was featured in *Geophysical Research Letters*, appeared on the American Geophysical Union's most popular papers list, and was selected as an editor's choice by the *Space Weather* journal. A feature article on this research effort ("Phantom Storms: How Our Weather Leaks into Space") was published in 2009 by *New Scientist* magazine. This effort resulted from a collaboration between the Atmospheric Sciences group and professor Alan Plumb of the MIT Department of Earth, Atmospheric, and Planetary Sciences (EAPS).

Distributed Instruments

The current research goal using distributed instrument systems is to experimentally investigate the midlatitude plasmasphere boundary layer to characterize its electron density gradients, perturbations, flows, and electric fields. A secondary goal is to develop and investigate the capabilities of distributed arrays of small radio instruments. 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 number of graduate and undergraduate students have also used the instrumentation as part of educational and research projects.

Geospace System Science

In keeping with an increased emphasis in our NSF Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) program, the Atmospheric Sciences group is continuing to expand its leadership role in community investigations of geospace system science. The group completed a pair of NASA-supported research projects addressing storm-time ionospheric electrodynamics processes and their impact on the geospace system. Our emphasis has been on understanding the complex coupling and feedback processes that interconnect Earth's lower atmosphere with the overlying ionosphere/thermosphere and space plasma regimes of the magnetosphere. The following research questions were addressed:

- What are the causes and characteristics of the redistribution of the equatorial ionosphere in the American sector?
- What determines the duration and strength of penetration electric field events?
- How do the conjugate E- and F-region conductivities influence these effects?
- Do such storm-time perturbations exhibit seasonal or longitude dependencies?
- Are low-latitude ionospheric perturbations geomagnetically conjugate?
- What processes are involved in the large-scale redistribution of the low-latitude ionosphere near sunset during the large storms of the recent solar cycle?

Regional DASI

Distributed array of small instruments (DASI) systems, highlighted in the last Decadal Survey of Solar and Space Physics by the National Academy of Sciences, offer a dynamic new approach to further space science research. DASI incorporates global networks of interactive, autonomous, and smart sensors along with the use of advanced cyber infrastructure to help geoscientists assimilate, explore, and understand observations obtained from disparate databases.

The Atmospheric Sciences group is leading an effort to implement a regional DASI based around existing capabilities in North America. Currently deployed instrumentation includes the new midlatitude SuperDARN facilities, the recently updated optics facilities at Haystack Observatory, the global network of GPS receivers, the network of coherent ionospheric radio receivers, the ISIS instrumentation, Canadian optical and magnetometer arrays, the Millstone and Sondrestrom incoherent scatter radars, and the Advanced Modular Incoherent Scatter Radar (AMISR). The new Geospace Science Center at Haystack is envisioned as the centralized hub for integrated processing and community access to the DASI instruments and experiment and analysis activities. The Atmospheric Sciences group's Madrigal database collects, stores, and provides relatively easy access to these data. The Haystack staff is organizing workshops aimed to plan science-driven experimental campaigns that address the common field of view of the North American instrument arrays.

Among the science topics emerging are:

- Storm-time coupling of ionospheric plasma between the midlatitude and auroral zones
- Quiet-time electric fields in the subauroral ionosphere and inner magnetosphere
- Magnetosphere-ionosphere coupling in the inner magnetosphere
- Planetary waves and tides in the midlatitude atmosphere
- Causes and effects of traveling ionospheric disturbances over North America
- Causes and effects of ionospheric irregularities at midlatitudes
- Neutral winds and the coupling of atmospheric layers

Technical Initiatives

Millstone Hill Geospace Science Center

A one-year effort is under way to implement a Geospace Science Center at the Millstone Hill facility for use in the control, operation, and science integration of Upper Atmosphere Facilities program 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, a radio frequency interference screened receiver room, an electronics laboratory, and a computing facility capable of supporting a significant grid computing system.

The center 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. It will also 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, as well as a key way to involve the larger community in facility science efforts and provide science opportunities involving facility instrumentation.

Critical Maintenance

In December 2009, the wear plates in the Millstone Hill Steerable Antenna (MISA) elevation drive assembly failed after approximately 20 years of operations, preventing a full range of antenna motion. A repair design study was performed by Simpson Gumpertz & Heger and a local engineering contractor completed the repair work in June 2010, allowing a return to full operations. A supplement request covering a portion of the repair cost has been submitted to the NSF Upper Atmosphere Facilities program and is currently pending.

Collaborations with Lincoln Laboratory

The Atmospheric Sciences group collaborated with MIT Lincoln Laboratory and the Woods Hole Oceanographic Institute (WHOI) on developing a low-cost and high-precision GPS measurement capability on ocean platforms (e.g., floats and buoys). A low-cost GPS platform of this type would provide data for real-time applications with significant societal relevance, including space weather monitoring, tsunami detection and warning, and improvements in severe storm intensity and landfall estimates.

After a series of discussions with WHOI, a Lincoln Laboratory Advanced Concepts Committee (ACC) proposal to produce a prototype demonstrator system was organized and prepared. The demonstrator would be a springboard for larger efforts. Although the ACC proposal was not successful, the project has a high degree of relevance to society, and alternate sources of funding are being pursued.

Educational and Outreach Programs

Haystack Observatory continues development of the Very Small Radio Telescope (VSRT) under a Phase II grant from NSF. The VSRT, an adding interferometer intended for physics and astronomy laboratory demonstrations, can be assembled from inexpensive, commercially available parts. Five VSRT beta test institutions are currently involved at the university level: Bridgewater State University, the University of North Carolina at Greensboro, Southeast Missouri State University, Union College, and Bucknell University. The VSRT is also being used at several local high schools.

The participant at Bridgewater, Dr. Martina Arndt, developed a document describing the assembly and basic operation of the VSRT. Two participants in the Research Experiences for Teachers (RET) program, Michael Doherty at Andover High School and Stephen Minnigh at Nashua High School South, developed an educational unit for the VSRT including hands-on physics activities for students at the high school and lower college levels. Another beta tester, Jonathan Marr at Union, has been developing additional laboratory exercises suitable for an upper university-level radio astronomy course.

Posters describing the VSRT have been presented at professional society meetings. Also, Haystack staff have demonstrated the VSRT at several meetings, including the AMISR workshop at Haystack, Women in Science Day at the Boston Museum of Science, and a joint meeting of the New England sections of the American Physical Society and the American Association of Physics Teachers in Durham, NH.

Haystack has 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, Chelmsford High School, and Haystack and have been collecting data for up to two and a half years. The MOSAIC project, which has already resulted in a scientific publication in the *Journal of Atmospheric and Oceanic Technology*, allows students to engage in authentic inquiry-based learning by participating in scientific research.

Science teachers from four local middle and high schools participated in the RET program at Haystack in 2010. Two of the teachers returned to revise their unit, "Meet Me in the Mesosphere: Investigation of Atmospheric Processes for Classroom Studies," based on their experience using the materials in class during the school year. In addition, two of the teachers are working on a new unit to teach portions of the high school physics curriculum using the Haystack-developed MOSAIC system. As always, materials developed under the RET program are free for use and easily accessible via the web. Copies of the RET materials on CD media were also distributed by Anthea Coster, invited speaker at the Second Workshop on Satellite Navigation Science and Technology for Africa, for teachers without high-speed Internet access.

The NSF Research Experiences for Undergraduates (REU) program at Haystack, now in its 20th year, continues to provide undergraduate students with summer internships. Eight students participated in the 2010 REU program in scientific and technical projects in astronomy and atmospheric sciences. Each year atmospheric science students attend the CEDAR workshop. Several students from the 2009 REU program presented posters on their research at meetings of the American Astronomical Society and the American Geophysical Union. Two students from the 2008 and 2009 REU programs (Marc Miskin and Farzan Beroz) are coauthors with Phil Erickson of an article submitted to the *Journal of Geophysical Research-Space Physics* describing the results of a statistical study of midlatitude ionospheric redistribution.

Haystack staff 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 (UROP) on a project on the study of black holes using millimeter-wavelength VLBI. Shep is working with a third MIT UROP student on a technical development project on millimeter VLBI in collaboration with staff at CfA. Anthea Coster is mentoring Jennifer Williams, a rising senior in physics at Siena College, on a project to determine biases in using GPS data to estimate the total electron content of the ionosphere. Jennifer has presented a paper on her research at a meeting of the International Union of Radio Science and a poster at a CEDAR workshop. Anthea is also working with professor Hugh Gallagher from the Department of Physics and Astronomy at the State University of New York at Oneonta, who serves as primary advisor to two other undergraduate students who have presented at CEDAR on their research using Haystack GPS data.

Haystack again teamed with SRI International personnel to run a successful AMISR workshop at Haystack. A total of 25 students (21 graduate and four undergraduate students, including several from NEROC universities) and five senior staff/advisors attended the July 2010 workshop. Attendees came from 23 universities and institutions from the United States, Canada, Argentina, and Finland. Haystack staff served as organizers as well as lecturers on the theory and practice of incoherent scatter radar as a probe of ionospheric variations.

Haystack Observatory continues to maintain educational ties with graduate students at other universities. Phil Erickson presented a series of lectures at Boston University as part of professor Joshua Semeter's radar remote sensing class. Josh is the director of the Center for Space Physics and an associate professor in the Electrical and Computer Engineering Department. Phil is in talks with multiple students regarding potential collaborations with Haystack for their research projects. Phil also serves as an external reader on the graduate committee of Elizabeth Bass, a PhD candidate in electrical and computer engineering focusing on meteoric influx into the upper atmosphere. Finally, both Phil Erickson and Anthea Coster are working with Ryan Volz, a first-year graduate student at Stanford University, on high-power large-aperture meteor radar observations in collaboration with professor Sigrid Close of the Department of Aeronautics and Astronautics.

The Atmospheric Sciences group at Haystack has completed a series of educational videos suitable for computer and podcast viewing. Space Weather FX (http://www.haystack.mit.edu/swfx/) is an eight-part series addressing connections between the Earth and the sun, space weather, GPS, and incoherent scatter radars. The series is freely available at the Haystack website, iTunes, YouTube, and MIT TechTV.

Although onsite public outreach programs at Haystack have had to be scaled back during construction, Haystack offers tours and open-house events when possible. 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.

Colin J. Lonsdale
Director

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