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, Harvard-Smithsonian Center for Astrophysics (CfA), University of Massachusetts, University of New Hampshire, and Wellesley College. Haystack Observatory also supports the space surveillance program of Lincoln Laboratory, with whom 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 US Department of Defense.

Awards and Personnel

Dr. Alan E. E. Rogers, senior research scientist at Haystack Observatory, has been awarded the International Union of Radio Science (URSI) John Howard Dellinger Gold Medal with the following citation: "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." Dr. Rogers was awarded the Dellinger Medal in a ceremony at the URSI General Assembly in Chicago, IL, on August 10, 2008. We are proud and honored to have Dr. Rogers as a member of the Haystack staff, and extend our warm congratulations.

A planned change in directorship of Haystack Observatory was recently announced by Professor Claude Canizares, MIT vice president for research and associate provost, with the following note:

To Haystack Observatory Community and Friends:

Earlier this year, I announced the selection of Dr. Colin Lonsdale as the new Director of Haystack Observatory, to become effective later in the year pending completion of some major activities associated with his leadership of the Murchison Widefield Array Project (MWA). I am now pleased to report that Colin will formally assume the Directorship on September 1, 2008. I am confident that this will be an entirely smooth transition, as Colin has already worked closely with Alan Whitney, the Interim Director, over the past months. I am also sure that Colin will have the strong support of all members of the Haystack staff and users. I personally look forward to working closely with him in the coming years.

I also want to reiterate recognition of Alan Whitney's extraordinary service to Haystack and MIT as Interim Director and his willingness to continue in that role for an additional half year in order to allow Colin to complete his MWA commitment. As you may know, Alan has recently agreed to become Interim Director of the MWA Project, at the request of the MWA Board. This is yet another great contribution he will make to Radio Astronomy and MIT, one which will maintain Haystack's leadership role in this major, international endeavor. We all wish him the very best in this challenging new role.

Please join me in extending warm thanks to Alan and congratulations to both Alan and Colin in their new positions.

Sincerely yours,
Claude R. Canizares
Vice President for Research & Associate Provost

Research Instrumentation

Facilities used in Haystack's research program include:

- A 37 m diameter radio telescope used for astronomical observations and for 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

Significant progress has been achieved in the development of the Murchison Widefield Array (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 sub-awards have been made to the MIT Kavli Institute (MKI) and CfA. Colin Lonsdale is the principal investigator 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.

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. A major milestone in the antenna development was achieved in mid-2008 with the deployment in Australia of 32 production antenna tiles as a system testbed. Several of these tiles can be seen in Figure 1. The antenna design, developed under the leadership of Brian Corey and in close collaboration with an industrial partner, has been optimized for manufacturability, cost, and ease of installation in a hostile field environment. The finished product has proven to meet cost targets, including installation labor, established three years ago.

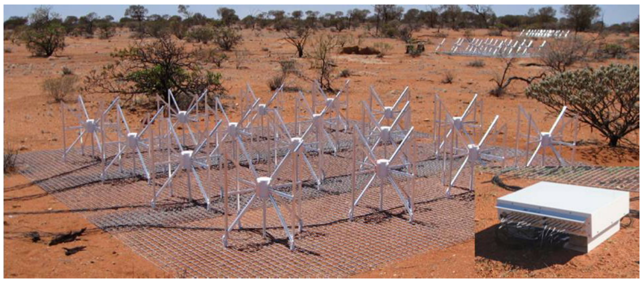

Figure 1. Three antenna tiles of the MWA are visible in this photo from the MWA site in Western Australia. Each tile consists of 16 individual dual-polarization dipoles. In the lower right is a photo of the beamformer that allows the tile beam to be pointed in any direction in the sky.

Six of the installed antenna tiles were outfitted with beamformers and receivers, which allowed data to be collected to produce an image of Centaurus A (Figure 2) using software correlation, though the quality of the image is not nearly as good as will be achieved with the full 512-tile system.

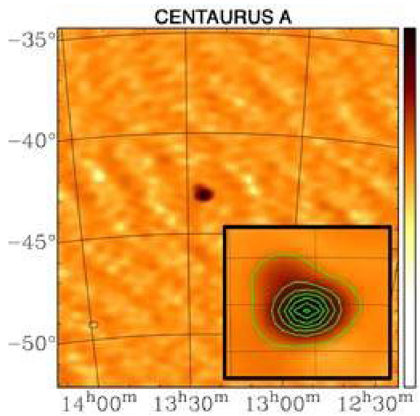

Figure 2. This image of Centaurus A was synthesized from data from six MWA antenna tiles, showing that the system is functioning properly. The image will be of much higher fidelity when the entire 512-tile array is operational in 2010.

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, but in particular, Roger Cappallo and Bart Kincaid created the FPGA functionality for the main computational core of the machine. The first demonstration of this correlator system with a full 32 tile system is scheduled for spring 2009.

Due to some delays in development of some MWA subsystems, as well as some site access issues in Australia, the goal for completion of the entire 512-tile area has been delayed to mid-2010. In addition, a new international management team has been appointed to move the project ahead during the upcoming period of major construction.

Astronomical VLBI

The Observatory has four currently funded NSF awards that focus on developing next-generation VLBI instrumentation. Efforts within these four projects are aimed at high profile science projects that require both the high angular resolution provided by VLBI and the high sensitivity enabled by wideband systems. At centimeter-wavelengths one project has focused on monitoring the size evolution of a nearby gamma ray burst explosion. In published work, Haystack scientists and collaborators have constrained the density profile of the medium, presumably from the progenitor stellar wind, into which the gamma ray burst is expanding. New results from the study of ultraluminous infrared galaxies show that some merging galaxies exhibit multiple sources near their cores that are likely radio supernovae. Study of these supernovae populations is shedding light on the origins of the infrared radiation flux from these sources, which may be due to obscured active galactic nuclei or an intense burst of star formation. At higher frequencies, Haystack led an effort this year to deploy new VLBI recording systems on the Very Long Baseline Array (VLBA), enabling observations of the Galactic Center at 86 GHz aimed at measuring the parallax of SgrA*. Analysis of these observations is underway, but the new wideband systems let the Haystack team attempt high precision astrometry of SgrA* at higher frequencies than previous efforts.

The most exciting result this year was a robust size measurement of Sagittarius A* (SgrA*) using 230 GHz VLBI observations made in April 2007. Careful analysis of the data allowed an international team led by Haystack staff to derive a diameter for SgrA* of just 3.7 Schwarzschild radii (assuming a four million solar mass black hole at the Galactic Center). This represents the best measurement of the intrinsic size of this supermassive black hole candidate, and confirms that high-frequency wideband VLBI will open a new window onto black hole physics through study of the Galactic Center. This result will appear in *Nature* in September 2008. Figure 3 shows the observed and intrinsic size of SgrA* as a function of frequency. The new point at 1.3 mm wavelength shows that the intrinsic size is larger than the scattering disk resulting from the intervening plasma that lies between the Earth and the Galactic Center. Simulation work led by Shep Doeleman and postdoc Vincent Fish show that high-frequency VLBI will be able to discriminate amongst detailed models of the innermost accretion region around the putative black hole.

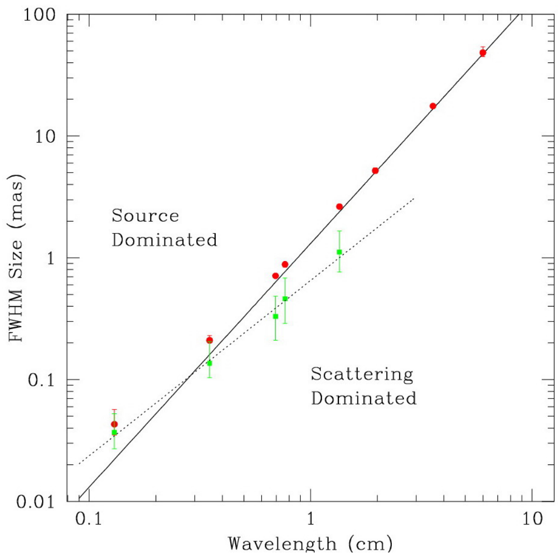

Figure 3. Observed and intrinsic size of SgrA as a function of frequency. Red circles show major axis observed sizes of SgrA* from VLBI observations (all errors are 3σ). Data from 6 cm to 3 mm wavelength are from the literature, and the 1.3 mm data are from the 230 GHz observations. The solid line is the best-fit λ^2 scattering law and is derived from measurements made at λ>17 cm. Below this line, measurements of the intrinsic size of SgrA* are dominated by scattering effects, while measurements that fall above the line indicate intrinsic structures that are larger than the scattering size (a 'source dominated' regime). Green points show derived major axis intrinsic sizes from 2 cm < λ < 1.3 mm and are fit with a λ^{α} (α=1.44+/-0.07, 1σ) power law shown as the dotted line.*

Square Kilometer Array

The international Square Kilometer Array (SKA) effort continues to build momentum, and Haystack is playing a central role in the project through involvement in a Technological Development Program (TDP) led by Cornell University as well as a Haystack-led project on advanced correlation techniques. This last project focuses on the important problem of efficiently and cleanly attenuating image noise from faint source sidelobes in SKA observations. New algorithms to address this problem are required to enable the current SKA design (one based on large numbers of small antennas) to achieve high dynamic range images that match SKA sensitivity. Haystack now has a postdoc working on this as well as a Research Experience for Undergraduates (REU) student who just completed a summer project comparing different algorithmic approaches to the problem. With funds from the TDP, Haystack will continue to fund a postdoc on this project and allow Haystack staff to participate in SKA design studies and to serve on SKA committees.

Instrumentation Development

Drawing on its unique mix of scientific and engineering expertise, Haystack continues to be a leading center in the development of next-generation VLBI instrumentation. In recognition of the fact that modernizing VLBI systems can dramatically increase the sensitivity of existing arrays, Haystack has initiated active and funded programs to address the entire VLBI signal path from antenna to correlator. When deployed on national facility observatories, such as the VLBA, the hardware being designed at Haystack will boost sensitivities by factors of three to four, enabling exciting new science. For geodetic VLBI, a VLBI2010 prototype system is being developed that will span approximately 2–13 GHz to help achieve a goal of 1 mm accuracy for global geodetic-VLBI measurements.

The Digital Backend (DBE) project aims to replace the functionality of an approximately $500,000 floor-to-ceiling rack of analog VLBI backend equipment with a single FPGA chip, housed in a PC-sized chassis. The advance of analog-to-digital converters coupled with the speed of flexibly programmed FPGAs has allowed Haystack, in collaboration with University of California at Berkeley, to develop a working prototype of a fully digital VLBI backend that increases the processed bandwidth of a VLBI station by a factor of four while cutting the cost by a factor of approximately 50. This is done by replacing costly analog filterbank units (which are effectively irreplaceable today) by a polyphase filterbank realized through digital signal processing via an on-board an FPGA chip. Lab and field tests show that the new digital backend is compatible with existing equipment, and provides a low-cost path to upgrade VLBI networks worldwide. Building on this effort, Haystack is now partnering with National Radio Astronomy Observatory (NRAO) and UC Berkeley to develop the second-generation version of the DBE, which will use the latest family of FPGA chips to increase VLBI bandwidths by a further factor of two.

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.

After the backend stage, VLBI data must be recorded at very high data rates. The Mark5A and Mark5B data recorders, developed at Haystack, have moved VLBI recording from expensive magnetic tape recorders to industry driven hard-disk media. A next-generation system, dubbed Mark5C, is currently under development which will record a sustained rate of 4 Gbps, with data arriving through a 10 Gigabit Ethernet standard interface. A new program, funded by the NSF, will build on the Mark5 effort to develop a 'burst-mode' recorder that will be capable of storing data at rates up to 16 Gbits/sec—a factor of eight higher than currently possible. This new recorder is aimed at VLBI science applications that cannot increase signal-to-noise ratio by integrating for long time intervals and must record as much data as possible in a short time. An example is millimeter-wavelength VLBI where atmospheric turbulence de-correlates the VLBI signal over times significantly longer than about 20 seconds. The proposed architecture will use commercial off-the-shelf components and established industry high-speed data protocols to speed development and prototyping. It is expected that these new burst-mode systems will be used within two years to make high-sensitivity observations of the massive black holes in active galactic nuclei with a resolution of a few 10s of Schwarzschild Radii.

To leverage all these instrumental developments for VLBI at the highest frequencies (≥230 GHz), an extremely stable frequency reference is required. At longer wavelengths (cm), hydrogen masers provide sufficiently stable tones that allow widely spaced VLBI sites to maintain phase coherence and operate as a single "Earth-sized" telescope. Above 230 GHz, 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 (CSO) for VLBI use. 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 is designing a phase-locked loop system that will harness the stable approximately10 GHz signal output from the CSO and generate 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 Atacama Large Millimeter Array, Atacama Pathfinder Experiment and Atacama Submillimeter Telescope Experiment) to be combined into a single VLBI instrument capable of 20 micro arc second angular resolution.

For geodetic-VLBI, as mentioned above, a VLBI2010 development program is underway with the goal of increasing global measurement precision to 1 mm. Many of the instrumental building blocks, such as DBE, flexible radio frequency converter, 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 (RF) range with a single feed. A prototype broadband system has been developed, including cooled feed, low-noise amplifiers and a wideband optical-fiber transmission system to transmit the entire RF bandwidth to processing equipment on the ground. Several successful demonstration experiments using the Westford antenna at Haystack Observatory and the Goddard Geophysical and Astronomy Observatory antenna at NASA Goddard Space Flight Center (GSFC) (Figure 4) have been conducted, and more are planned as the system matures. A new 12 m fast-moving antenna will likely be procured in 2009 as a new platform for the broadband system. The Haystack VLBI2010 development program, funded largely by NASA GSFC, is part of an international effort to development a major upgrade to the existing geodetic-VLBI systems.

Figure 4. A prototype broadband frontend system being installed on the 5 m GGAO antenna at NASA GSFC. This advanced system is part of a program whose goal is to make global geodetic-VLBI measurements with a precision of 1 mm.

Atmospheric Science

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

Stratospheric Warming

Haystack researchers organized an Incoherent Scatter World Day observing campaign in early 2008 to study the thermospheric and ionospheric response to stratospheric changes during a large stratospheric warming event. Alternating regions of 100 K warming and 50 K cooling were observed above the Millstone Hill facility, with warming in the lower thermosphere and cooling above 150 km altitude. The seasonal trend, solar flux, and geomagnetic activity do not account for the observed upper-atmosphere temperature variations, suggesting an association with stratospheric warming which is being investigated by an international collaboration. This study demonstrates a link between the state of the lower atmosphere and the ionosphere which has not been considered before and indicates that ionospheric variability as part of space weather should be considered in conjunction with stratospheric changes.

Ionospheric Response to the Greenhouse Effect

Increasing concentrations of greenhouse gases are expected on theoretical grounds to lead to a cooling of the upper atmosphere. Due to the close thermal coupling of the neutral and ionized components of the upper atmosphere the effects of this cooling are also expected to be seen in the ionospheric ion temperature. The long-term Millstone Hill incoherent scatter radar dataset in the Madrigal Database is a unique resource for verifying this prediction. Temperature data from 1978 to 2007 were analyzed to provide a direct estimate of the temperature trend. The long-term trend in ion temperature at 375 km was found to be -4.7 K/year with a 95% confidence interval of -3.6 to -5.8 K. This is the first direct confirmation of the predicted cooling in the upper atmosphere.

Magnetosphere-Ionosphere Coupling—Cold Plasma Redistribution

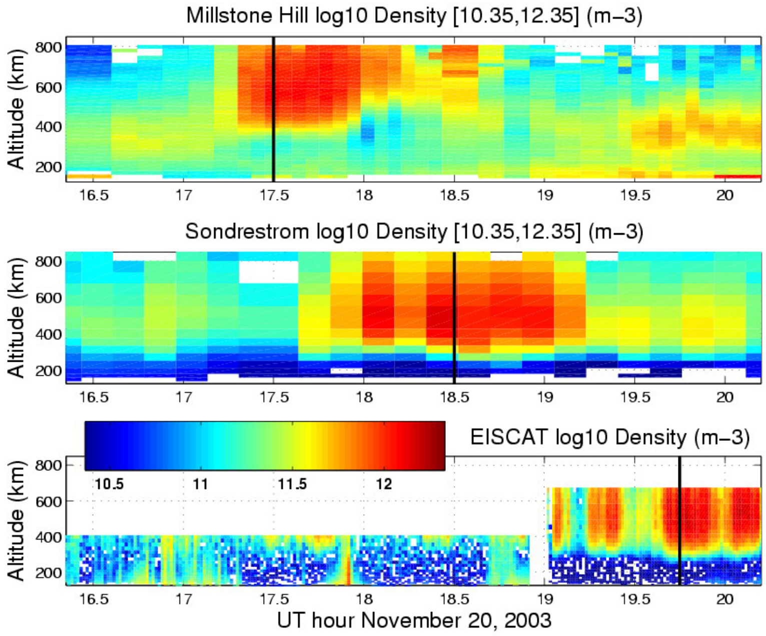

Figure 5. Combined total electron content (TEC) and plasma circulation streamlines are displayed in polar projection. Vertical GPS TEC observations binned by lat/long at 350 km altitude are displayed with the simultaneous, independent convection pattern derived from combined radar and satellite observations. A plume of low redistributed ionospheric plasma is seen to extend continuously from its low-latitude source across the polar cap..

The workings of the coupled magnetosphere-ionosphere system in controlling the development of electric fields in the upper atmosphere are under continued investigation. These initiate a chain of events that results in a large-scale redistribution of the 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 is investigating the processes involved in this ionosphere-magnetosphere coupling. These studies reveal how this process leads to the formation of a polar tongue of ionization spanning the high-latitude region from noon to midnight (see Figure 5).

Technical Initiatives

During the past year an effort to develop the The Millstone Advanced Radar System (MARS) has been initiated in discussions with Lincoln Laboratory and the submission of a pre-proposal to the NSF. In concept, MARS will address a wide range of fundamental scientific topics in the atmospheric sciences from the lower atmosphere through the upper atmosphere and into the heliosphere and near-solar environment. The MARS project has a unifying theme of adaptive active and passive radio measurement over the full sky. The project will be implemented in close collaboration with Lincoln Laboratory. The expected transfer of advanced technical capabilities to the scientific community will greatly lower the overall risk associated with implementation of the MARS project. It is expected that the MARS project will result in a facility with an order-of-magnitude greater user base than the existing Millstone Hill UHF radar. It would also provide the opportunity to more closely couple the facility to Lincoln Laboratory and to the MIT campus. Program development and community outreach efforts for the MARS project continue and funding to support a formal design study will be pursued in the next year.

The atmospheric sciences group is collaborating with Lincoln Laboratory and the NRAO on a study of geophysically imposed variations in the characteristics of radio signals transiting the ionosphere. The project employs a high-gain 43-meter telescope at NRAO in Green Bank, WV, to observe orbiting, radio-bright satellite beacons to yield detailed measurements of electron density fluctuations. The experiments will examine beacon signal amplitude and polarization distortion dynamics imposed by fine scale ionospheric irregularities. Such results will be of great interest to low frequency radio astronomy array efforts such as the MWA, as calibration of heliospheric and astronomical observations requires very accurate and dynamic removal of ionospheric effects.

In support of the International Polar Year, the MIT Millstone Hill and other high-latitude radars operated on a regular frequent schedule from March 2007 through March 2008. A major goal of this effort was to provide a unique dataset for testing and improving physics-based models of the ionosphere and thermosphere. The large volume of data and model output presents a formidable data handling problem. To help address this problem the Haystack group developed a level-4 Madrigal data product by least-squares fitting tensor-product spline functions to the data, producing a regular grid in both altitude and time.

Haystack has been a partner organization in the construction and user interface to new NSF Advanced Modular Incoherent Scatter Radar at Poker Flat, AK. Installation of a real-time Madrigal data-handling system has been achieved and several student/user workshops arranged to introduce the capabilities of and access to the new facility to the research community.

Education

The Atmospheric Sciences group produced the first Haystack Observatory educational YouTube video: Space Weather FX (http://www.youtube.com/watch?v=fZ-L-pS0syc), addressing space weather, Earth, Sun, GPS, atmosphere, science, and education.

Educational and Outreach Programs

Haystack Observatory has completed and tested the Very Small Radio Telescope (VSRT) that introduces radio interferometry to students. The laboratory experiments and observations of the Sun were developed at Haystack and tested by faculty at Middlesex Community College in Bedford, MA, and Roane State Community College (RSCC) in Tennessee. Based on the successful

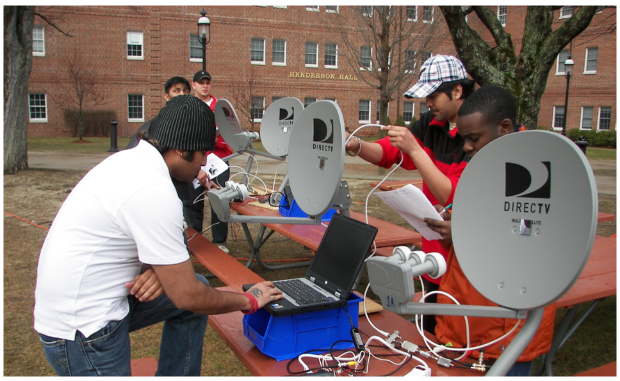

Figure 6. Students at the Middlesex Community College in Bedford, MA, use the VSRT interferometer to measure the diameter of the Sun.

implementation in the community college setting, a Phase II grant from the NSF has been awarded to disseminate these systems into a four-year college setting. Preliminary testing has been conducted by Dr. Martina Arndt of Bridgewater State College. Materials that Dr. Arndt has developed will be tested in her classroom this fall. Figure 6 shows students at RSCC using the VSRT system.

Figure 7. High school students from Chelmsford High School evaluating their ozone spectrometer system, which is based on the VSRT system developed at Haystack Observatory.

A single-antenna VSRT has been developed by Alan Rogers as an 11 GHz spectrometer that is able to measure emission from ozone in the mesosphere. This relatively low-cost system is being beta-tested at a high school in Chelmsford, MA (Figure 7). New, potentially publishable results from this system are being analyzed and documented.

The REU program continues to provide undergraduate students with summer internships. Eight students are completing their projects in astronomy and atmospheric sciences this summer. Science teachers from five local high schools participated in the NSF's Research Experiences for Teachers program at Haystack. Three of the teachers are helping to develop the VSRT into a learning tool that could be used with high school students. The others published a unit on space weather, "Caught in the Solar Wind," on the Haystack website for other teachers to freely use.

Public outreach programs at Haystack have been extremely successful in the last year. In addition to open house events, tours for high school students, and programs at local venues, staff members have been actively involved in efforts such as workshops for the National Science Teacher Association Conference held in Boston in 2008 and a series of science talks at the Science Discovery Museum in Acton, MA. Under a NASA grant, production of a video podcast (vodcast) series, *Space Weather FX*, was begun. The series will help to introduce students and the general public to the concept of space weather and the effects that storms on the Sun can have on the Earth's ionosphere. Based on the success of this project, another vodcast was produced to introduce the science and technology being developed for the Murchison Widefield Array.

Alan R. Whitney
Director

More information about the Haystack Observatory research and education programs can be found at http://www.haystack.mit.edu/.