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 undergraduate and graduate students through research opportunities that make use of 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 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, University of Massachusetts, University of New Hampshire, and Wellesley College. Haystack Observatory also supports Lincoln Laboratory's space surveillance program, and the two share the Westford facilities. 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.

Research Instrumentation

Facilities used in Haystack's research program include:

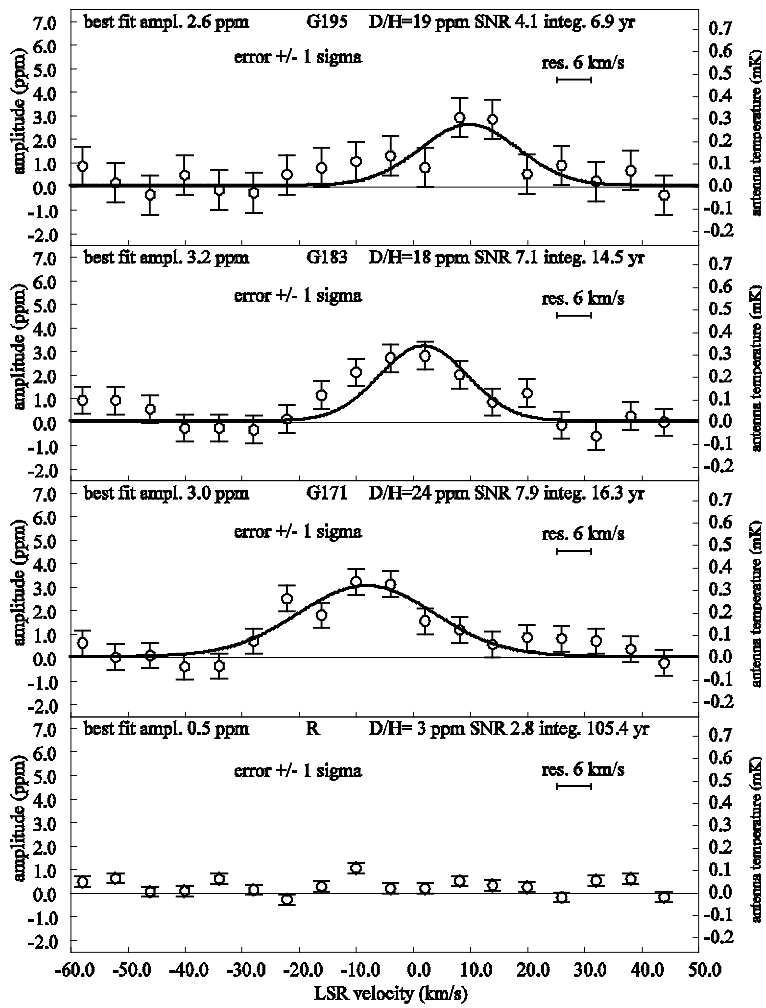
- A 37 m diameter radio telescope used for astronomical observations and for radar measurements
- An 18 m diameter radio telescope involved in VLBI measurements of Earth's rotation parameters
- A 24-station digital radio array operating at 327 MHz for the measurement of deuterium emission
- An eight-station 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 Earth's upper atmosphere using incoherent backscatter techniques

Radio Astronomy

The important developments in radio astronomy at Haystack during the past year include the confirmation of the deuterium line through extended observations with the deuterium array, the formal initiation of the development of the Mileura widefield array, and advances in the application of VLBI technology to the study of galaxies and Earth's plate tectonics and orientation.

This close-up of one station of the deuterium array at Haystack shows the dual-polarized dipoles with beam directors. The trailer in the background contains the radio frequency interference detection system.

The 24-station deuterium array, recently constructed at Haystack under the leadership of associate director Alan Rogers, continued to observe the deuterium radio line at a frequency of 327.4 MHz. Accumulated signals have confirmed the initial detection of the line. The measurements at Haystack have been made in a direction toward the galactic anti-center, and deep integrations to date equivalent to ~16 years from a single station, have provided solid evidence for the hyperfine ground state of deuterium in emission from the interstellar gas. A ratio of deuterium to hydrogen of 21 ppm has been derived from the measurements, in close agreement with the cosmological predictions from cosmic microwave background data. Determination of the deuterium abundance in the primordial gas formed during the Big Bang is important since it can be related to the baryon-to-photon ratio during nucleosynthesis. Further



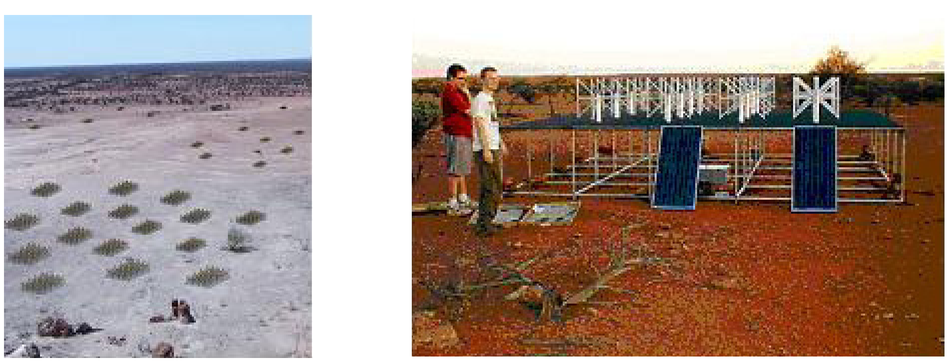
Accumulated spectral measurements from the deuterium array toward the galactic anti-center are compared to a nearby region and a reference region out of the galactic plane.

observations toward the galactic center have been deemed too difficult due to the presence of radio frequency interference, and plans are being considered to conduct such measurements in a radio-quiet site in the southern hemisphere.

The proposed Mileura widefield array – low frequency demonstrator (MWA-LFD) has been funded by NSF under a cooperative agreement with NEROC. Colin Lonsdale at Haystack is the principal investigator. The project involves collaboration with the MIT Kavli Institute for Astrophysics and Space Research, the Harvard-Smithsonian Center for Astrophysics, and several partner institutions in Australia. One of the scientific goals of the MWA-LFD is to observe red-shifted hydrogen from the early universe to detect signals from the epoch of reionization prior to the formation of galaxies and stars. A second goal is to observe solar bursts and heliospheric plasma structure with emphasis on the measurement of magnetic fields due to their influence on the generation of space weather effects in the Earth's environment. The MWA-LFD is planned to operate in the frequency range of 80 to 300 MHz, and will consist of 500 antenna tiles to be deployed over a 1.5 km region in the radio-quiet outback of Western Australia. Each of the tiles will have 16 dual-polarized dipoles and will provide an electronically steerable field of view of ~1,000 square degrees with an overall array sensitivity at the milli-Jansky level and a resolution at the arc-minute level. Deployment of a 32-tile prototype array is planned in late 2007, and the full 500-tile system should be ready by the end of 2008. Scientific observations will follow in 2009–2010.

The MWA-LFD is managed through a project office at Haystack Observatory, and members of the Haystack staff will lead the overall array system design and integration. Haystack staff will be responsible for the development of the antenna and beam-forming systems, the digital correlator that will process the array signals, and the ionospheric calibration system. Several areas of scientific leadership are also being undertaken at Haystack, including the all-sky monitor for radio transients and the observation of interplanetary scintillations and solar bursts.

In addition to the NSF award, Haystack Observatory received an equipment grant from the Air Force Office of Scientific Research (AFOSR) under the Defense University Research Instrumentation Program (DURIP). The purpose of the grant, with director Joseph E. Salah as the principal investigator, is to augment the MWA-LFD with additional antenna tiles beyond 1.5 km in order to increase the angular resolution of the array for solar burst imaging and precise localization. The proposed deployment will

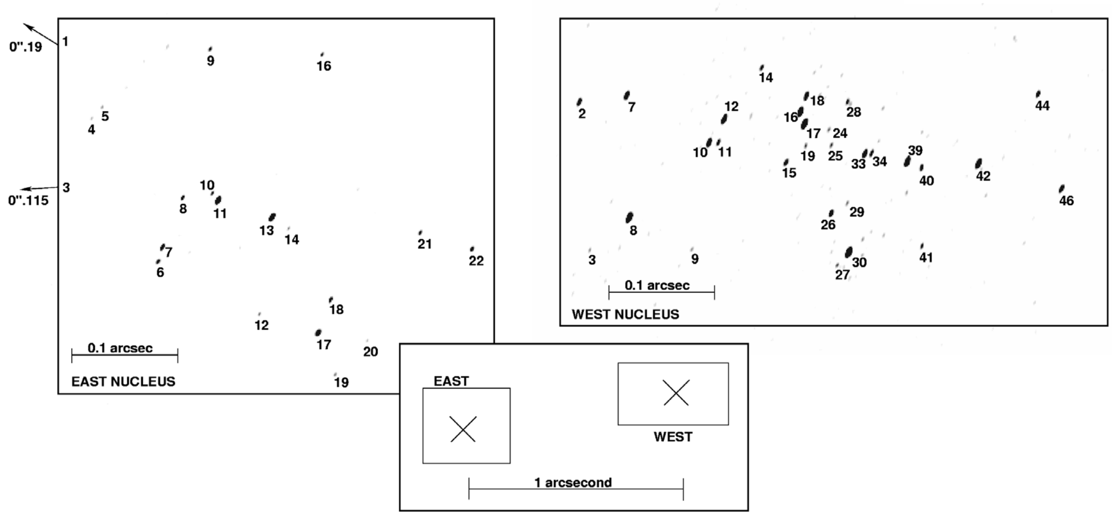


Artist's rendering of array in field at Mileura with close-up of a prototype antenna tile.

result in an angular resolution of 2 arc-minutes and is aimed at developing a linkage between the solar bursts and the initiation of coronal mass ejections in the solar wind. The AFOSR DURIP grant will support the construction of the prototype 32-tile system at Mileura to begin observations of solar bursts. The prototype array will also be used as a test bed for signal processing and software algorithms.

The next large radio array being planned by the international radio astronomy community is the square kilometer array (SKA)—an array of as many as 1,000 stations covering baselines as long as 1,000 km and frequencies in the range of 100 MHz to 20 GHz. The MIT array performance simulator (MAPS), developed at the Haystack Observatory to investigate configurations and design tradeoffs for large radio arrays, will now be used to evaluate the potential of field-of-view shaping using the array's massive signal processor. Under a new NSF grant awarded to Lonsdale and colleagues at the Haystack Observatory, MAPS will be used to develop the shaping algorithms that will then be tested using data from existing smaller arrays.

In astronomical VLBI, preparations have been initiated to observe the galactic center at 1.3 mm wavelength. Tests were conducted during the past year under the leadership of Sheperd Doeleman using the Smithsonian's sub-millimeter array (SMA) and the Caltech Sub-millimeter Observatory on Mauna Kea, Hawaii, and the Arizona Radio Observatory on Mount Graham. Hydrogen masers, digital back-end systems, and wideband Mark 5 recorders were deployed at these telescopes, and test observations were made on calibration sources and the galactic center. At present, the sources are believed to have been resolved across the long baseline, and additional experiments are planned next year that will include short baselines possibly involving the combined array for research in millimeter-wave astronomy (CARMA) telescopes in California. In addition, Lonsdale and his collaborators conducted observations at 18 cm wavelength to image the nucleus of the ultra-luminous infrared galaxy (ULIRG), Arp 220, with a linear resolution of ~1 parsec, using the very long baseline array, the Green Bank telescope, Arecibo, and five



Images of the east and west nuclei of Arp 220 shows the location of the point sources that were detected. The relative location of the diffuse continuum emission peaks in the two nuclei is shown in the inset.

other large radio telescopes in Europe. The image resulted in a background of 5.5 μJy/beam root-mean-square—the most sensitive VLBI image ever obtained—and revealed 49 point sources in the field with flux densities between 60 and 1200 μJanskys. Comparison with an image from 12 months earlier reveals at least four new sources that are believed to be new radio supernovae. If these represent all supernovae exploding during this interval, the rate of four supernovae per year in Arp 220 implies that the star formation is sufficient to power the entire observed far infrared luminosity of the ULIRG.

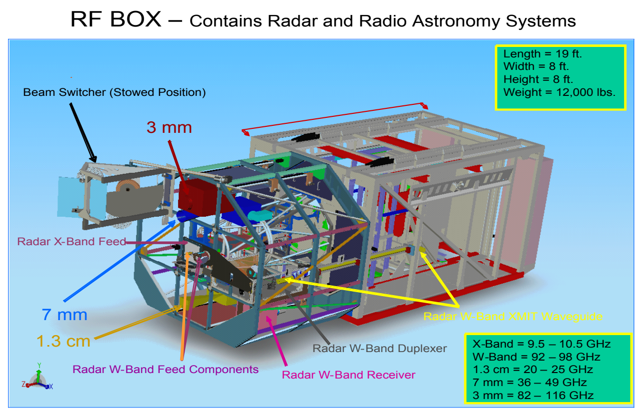
Instrumentation Development

Instrumentation development at Haystack Observatory during the past year has concentrated on VLBI wideband data recording systems and high-speed data transport. In addition, instrumentation for the Haystack 37 m antenna is undergoing a major upgrade. The emphasis in Haystack's VLBI instrumentation program has been on the improvement of observing sensitivity through increased measurement bandwidth for both astronomical and geodetic applications. The Mark 5 technology, developed at Haystack Observatory in collaboration with Conduant Corporation, is based on magnetic disks and currently supports recording data rates up to 1,024 Mbps. The system employs two independent eight-pack disk modules which, when populated with individual disks of 250 GB capacity, provides a total Mark 5A capacity of 4 TB. At present, there are more than 150 Mark 5 systems deployed at telescopes and correlators worldwide. While Haystack staff continues to provide support for these deployments, progress has also been made on doubling the data rates to 2,048 Mbps. Tests of advanced prototype systems were carried out successfully this past year. The Mark 5 systems in the field are due to be upgraded to the higher data rates in the coming year. The projected path for further enhancements of bandwidth is through the use of fiber-optic networks to transport wideband data from telescopes to the VLBI correlator. For this "e-VLBI" project, Haystack Observatory has been pioneering the development of data transport protocols, working to establish interface standards at telescopes, and conducting demonstration experiments with telescopes in Europe and Japan that exploit the available network systems. Real-time data rates up to 512 Mbps have been achieved, and the plan is to continue to expand available capacity. Associate director Alan Whitney and his collaborators received the Internet2 Exemplary Applications Award for this work.

Demonstration of e-VLBI wideband data transport from international radio telescopes to the correlator at Haystack Observatory for real-time processing.

Concomitant with the increased data rates, modernization of VLBI equipment is under way to replace analog filters with digital polyphase filter banks based on field programmable gate arrays that provide increased stability and precise performance. Under a new grant from NSF and with support from NASA, a digital back-end system is being developed by the Haystack VLBI group in collaboration with the Space Sciences Laboratory at the University of California, Berkeley. In geodetic VLBI, the modernization program being undertaken at Haystack as part of NASA's VLBI2010 program includes the development of broadband feeds to allow observations at frequencies up to 15 GHz, thus avoiding the interference-plagued frequencies around 2 GHz where the measurements are currently made.

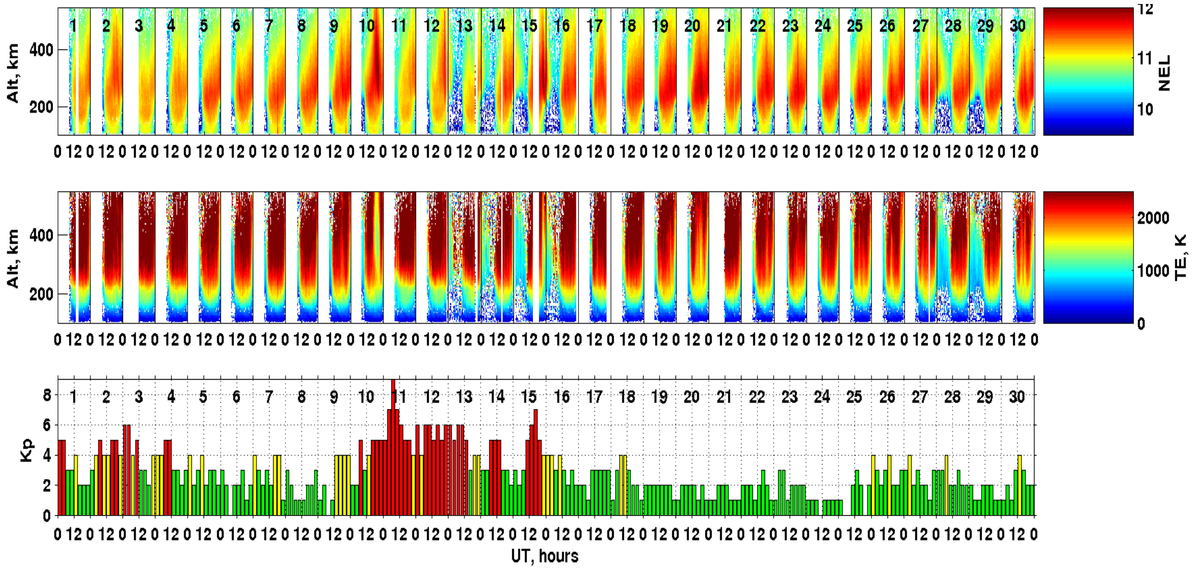
The Department of Defense program through Lincoln Laboratory to upgrade the Haystack antenna for an imaging radar capability at 95 GHz has progressed during the past year. The design has been completed and the manufacture of antenna components has begun. The upgraded antenna is expected to achieve nearly 50 percent effective aperture efficiency at 100 GHz, including radome losses. Haystack Observatory engineers led by Joseph Carter have supported this upgrade project and worked on the integration of three radio astronomy radiometers (22, 43 and 100 GHz bands) into the same equipment box that carries the radar receivers, thus allowing rapid and efficient switching between the various systems. In addition to a new radiometer at 100 GHz based on high electron-mobility transistor (HEMT) technology, a new wideband digital spectrometer is being designed under a recent NSF major research instrumentation grant. The spectrometer will cover 15 GHz bandwidth and will be capable of observing three independent spectral lines in the 100 GHz frequency range. This should allow efficient surveys of star-forming molecular clouds to be conducted. It is projected that the antenna upgrade will be completed in late spring 2008 and will be followed by a commissioning and calibration phase, with radar operations and astronomical observations resuming in fall 2008.



Schematic of the integrated equipment boxes for the upgraded Haystack antenna showing the location of the astronomical radiometers and radar receivers.

Atmospheric Science

In the past year, the research program in atmospheric sciences at Haystack has emphasized measuring the variability in Earth's ionospheric structure and dynamics using long-duration incoherent scatter radar observations. Two 30-day campaigns of near-continuous observations have been conducted using the Millstone Hill UHF radar in collaboration with other radars in Europe, Greenland, Peru, Puerto Rico, and Japan. The measurements have distinctly shown the variation of ionospheric and neutral densities and temperatures due to solar influences, tidal fluctuations, and coupling with



Electron density (top) and temperature (middle panel) as a function of altitude observed during September 2005 with the Millstone Hill incoherent scatter radar. The bottom panel shows changes in Earth's magnetic field indicating the presence of disturbances.

other regions of the Earth's upper atmosphere. In addition, using data from the global network of GPS receivers, the Atmospheric Sciences Group at Haystack Observatory under the leadership of John Foster and Anthea Coster has explored the causes of large plumes of enhanced plasma that are observed across North America. The group has related these plumes to electric field interactions with the Earth's magnetosphere. The large density gradients created by the plasma plumes are found to cause space weather effects on signal communications. Using the large data set of observations gathered over the past 40 years at Millstone Hill, empirical models of the Earth's ionosphere have been developed under the leadership of John Holt and are now being extended to other radars with long data records. These data are also providing an excellent base for the verification of results from global atmospheric models. Moreover, the long records have allowed the initiation of studies of long-term trends in the upper atmosphere. Global models have predicted substantial cooling in Earth's upper atmospheric temperatures as a result of increases in anthropogenic minor species in the lower atmosphere. Some evidence for this cooling is emerging from the investigation of the long-term trends in the radar data and is being currently verified.

The ISIS mobile data acquisition system, developed for bistatic observations with incoherent scatter radar, passive radar, and distributed GPS receivers.

A mobile radar data acquisition system and a powerful centralized signal processing and analysis system have been completed under a program called Intercepted Signals for Ionospheric Science (ISIS) supported by the NSF and AFOSR and led by Frank Lind. A set of seven data acquisition systems have been constructed for deployment in the northeast and northwest US in collaboration with NEROC institutions and the University of Washington. In the past year, the first deployment of the system was successfully carried out by Phil Erickson at the Green Bank 43 m antenna and was used to gather bistatic scatter signals from pulses transmitted from the Millstone Hill UHF radar in order to determine drift velocity vectors of the ionospheric plasma. The ISIS instrumentation is planned to include GPS receivers, digital receivers for passive radar observations, and scintillation monitors, all linked through the internet to the central digital processing and database system at Haystack. The ISIS array is considered as a prototype for the development of larger distributed arrays of scientific instrumentation for upper atmospheric research that will expand the spatial coverage of global observations in a cost-effective manner.

Educational and Outreach Programs

Haystack Observatory has completed the development of a digital receiver with GPS timing designed by Rogers for use with the small radio telescope (SRT). The receiver is aimed at undergraduate education in radio astronomy. An interferometer with three SRTs using the digital receivers has been installed at Haystack and placed in operation for observing solar bursts. Beta tests of the SRT interferometer have also commenced at Guilford College, and the design has been transferred to CASSI Corporation to explore the feasibility of commercial replication. Haystack has also been awarded an NSF grant to develop an inexpensive two-element system based on off-the-shelf components and small satellite dishes to introduce interferometry to community college faculty and students. A course on radio astronomy principles and techniques is held annually at Haystack Observatory under the leadership of education officer Preethi Pratap for faculty from small colleges. Training is provided in the use of the Haystack telescopes.

Research internships for undergraduates have continued to be provided at Haystack as part of NSF's Research Experiences for Undergraduates (REU) program—now in its 20th year at the observatory. Eight students have worked with staff during the past summer on research projects associated with radio astronomy and atmospheric science. Local area science teachers from four high schools have also participated in NSF's Research Experiences for Teachers (RET) program at Haystack using the observatory's research to introduce their students to science and to build a relationship with the observatory to enhance their educational curricula. A special workshop was held at Haystack to expand the impact of the program to 16 other local area science and mathematics teachers. Finally, under an NSF award, a special exhibit on "waves in space" is being developed in collaboration with the Children's Discovery Museum in nearby Acton, MA.

Joseph E. Salah
Director

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