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 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 at millimeter wavelengths to observe the center of our galaxy. 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 current goal of the atmospheric science program is to understand the impact of solar disturbances on the earth's upper atmosphere using measurements from the observatory's radars. A strong technology and engineering program supports each of the scientific research disciplines.

Haystack's education program supports the training of students by providing opportunities for them to link their education with research through the disciplines practiced at the observatory. Access to the observatory's telescopes is provided for educational projects, special instrumentation is developed for introducing students to radio astronomy, and training courses and materials are offered to faculty and students. In addition, internship opportunities are made available to graduate and undergraduate students and to local area science teachers.

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 enjoys a close relationship with MIT Lincoln Laboratory, shares some of the facilities, and supports the laboratory's space surveillance program. The observatory receives financial support for its research programs from federal agencies, including the National Science Foundation, the National Aeronautics and Space Administration, 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 the earth's rotation parameters

- A 24-station digital radio array operating at 327 MHz for the measurement of deuterium emission
- An 8-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

Three developments in low frequency radio arrays have been in progress at Haystack during the past year, and include the Deuterium Array, the Mileura Widefield Array, and the Square Kilometer Array.

Figure 1. Deuterium array at Haystack showing the 24 stations each with 24 dual-polarized dipoles, coupled to digital receivers at 327.4 MHz. The trailer contains the RFI detection system, which consists of 12 Yagi antennas pointed every 30 degrees.

A 24-station array operating at 327 MHz constructed at Haystack over the past two years (Figure 1) has been successfully used to detect the radio line of deuterium. The deuterium abundance in the primordial gas formed during the Big Bang is dependent on the baryon-to-photon ratio during nucleosynthesis. The measurements with the Deuterium Array have been made in a direction towards the galactic anticenter, and deep integrations equivalent to 6.5 years from a single station have resulted in a 6-sigma detection of the hyperfine ground state of deuterium in emission from the interstellar gas. A ratio of deuterium to hydrogen of 23 ppm has been obtained from the measurements, in close agreement with the cosmological predictions from cosmic microwave background data, but higher than that obtained from ultraviolet absorption measurements from space observations (Figure 2).

The Mileura Widefield Array–Low Frequency Demonstrator (MWA-LFD) is planned to operate in the frequency range of 80 to 300 MHz, and has been designed for deployment in Western Australia as a collaborative project between US and Australian institutions led by MIT's Haystack Observatory and the Center for Space Research. Partner institutions include the Harvard-Smithsonian Center for Astrophysics, the University of Melbourne, the Australian National University, Curtin University of Technology, and the Australia Telescope National Facility. The MWA-LFD consists of 500 stations, each with 16 dual-polarized dipoles, spread over a 1.5 km region, and will provide an electronically steerable 15–50 degree field-of-view, with sensitivity at the milli-Jansky level and resolution at the arc-minute level. Scientific goals include detection

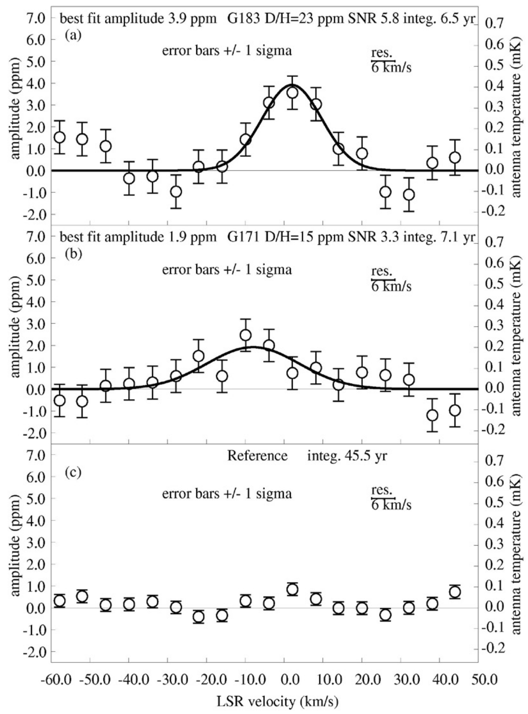

Figure 2. Spectral measurements from the deuterium array towards the galactic anti-center, compared to a nearby region and a reference region out of the galactic plane

and characterization of redshifted HI signals from the epoch of reionization, measurements of radio transients, and probing of heliospheric density, velocity, and magnetic fields using remote radio sensing techniques. A proposal is currently pending at the National Science Foundation (NSF) for support of the US share of the array construction and its operation for scientific experiments.

Tests of the MWA-LFD antenna system (Figures 3 and 4) have been conducted at Mileura in the past year with the deployment of prototype equipment. The measurements have demonstrated the suitability of the antenna design for the array and the ability of the beamformer to steer the station beam electronically, and have confirmed the low-level radio frequency interference environment at Mileura based on deep integrations with the array's instrumentation. Three antenna stations are now deployed at Mileura for interferometry tests, which demonstrate the phase stability of the system, and are being used to image the galaxy and detect solar radio bursts as validation tests of the design.

The Square Kilometer Array (SKA) is a large array with as many as 1,000 stations and 1,000 km baselines, covering frequencies from 100 MHz to 22 GHz. It is being designed by an international consortium of institutions for development in the next decade. As part of the US SKA consortium, led by Cornell University, Haystack

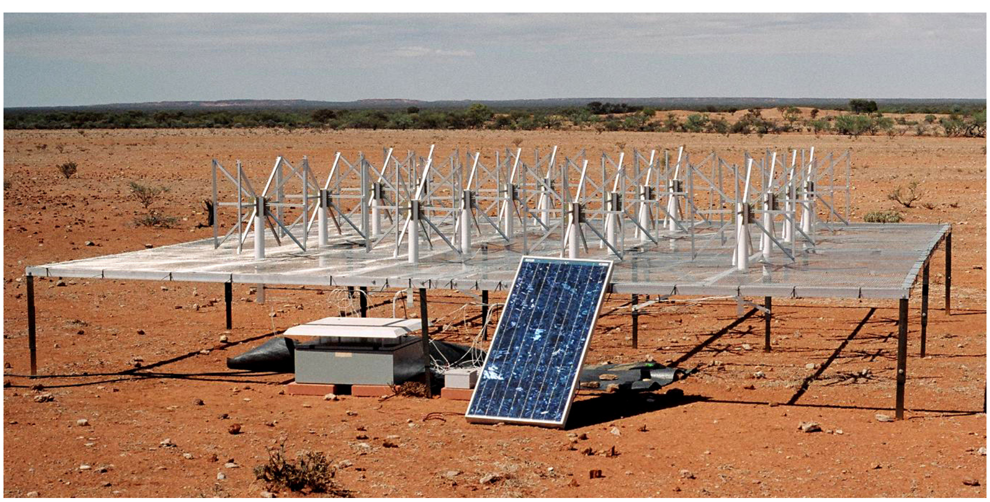

Figure 3. The first completed antenna station with beamformer box and battery-backed solar power supply deployed at Mileura, Western Australia.

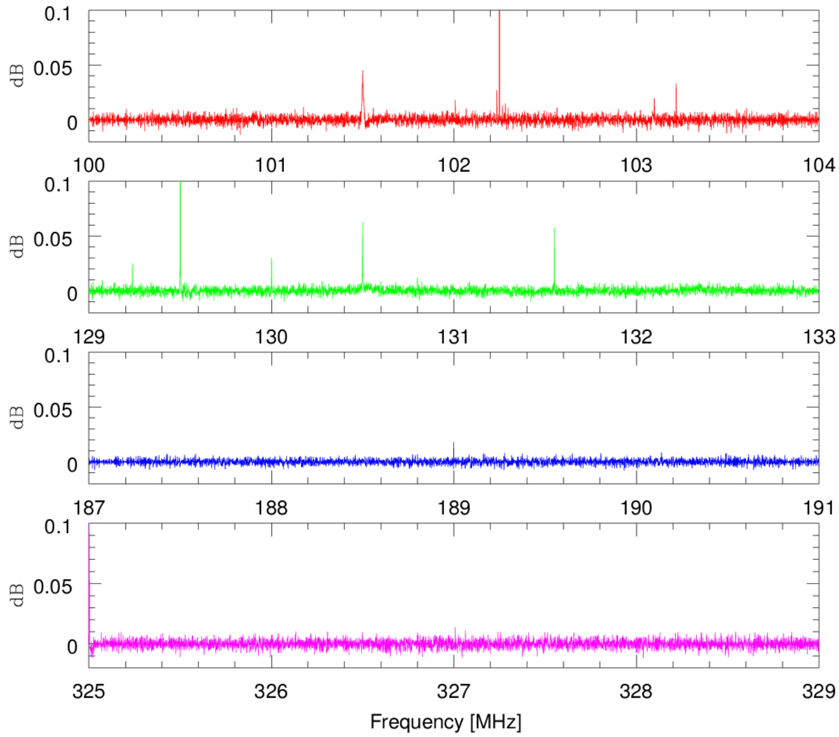

Figure 4. Spectra in four bands obtained with the initial antennas at Mileura, with deep integrations of 30–60 minutes. The scales are in dB relative to the system noise, which is dominated by the sky background. These data have been median-filtered to remove the bandpass shape, and the three displayed peaks at 102.25, 129.5, and 325.0 MHz are clipped for clarity.

Observatory has been engaged in studies of signal processing technology for the large array, investigation of imaging and computational strategies, and development of the MIT Array Performance Simulator (MAPS), which has been applied to array configuration and calibration studies. A proposal for detailed design and prototyping of SKA components, submitted by the US SKA consortium, is currently pending at the NSF.

Instrumentation Development

Instrumentation development at Haystack during the past year has been concentrated on the upgrade of the Haystack 37-m antenna and on VLBI wideband data recording and high-speed data transport.

The upgrade of the Haystack antenna as part of a new radar capability at 95 GHz has progressed during the past year under a program sponsored by the US Air Force (USAF) and the Defense Advanced Research Projects Agency through Lincoln Laboratory. L3-Communications/ESSCO, in collaboration with SGH Inc., has completed the design of the new antenna (Figure 5), and manufacturing of the backstructure and surface panels is in progress. The design of the antenna is expected to achieve an rms surface accuracy of 0.1 mm, yielding an effective aperture efficiency of 45%–50% at 100 GHz, including losses from the radome that covers the antenna. The radome material will likely be replaced with Gore-Tex™ as part of the upgrade, resulting in reduced losses in the millimeter-wavelength band and opening the possibility for observations at frequencies well above the antenna design frequency of 100 GHz. While the upgrade is motivated primarily by radar observations at 95 GHz for wideband satellite imaging, the new antenna will provide an enhanced capability for focused research and educational projects in radio astronomy at Haystack, particularly if we are successful in improving the receiver and signal processing through the addition of a wideband focal plane array system.

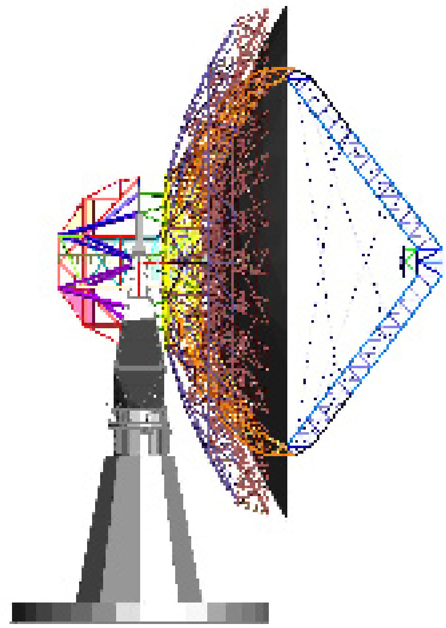

Figure 5. Schematic of the new Haystack antenna structure, which will consist of a steel transition structure connected through thermal slip joints to an aluminum torque ring that holds the entire backstructure and supports the subreflector quadrupod. A total of 432 aluminum panels will form the antenna surface.

An equipment box on the antenna will integrate both the radar receivers at 10 and 95 GHz, and the astronomy radiometers at K-band (20–25 GHz), Q-band (35–50 GHz), and W-band (85–115 GHz). The astronomy radiometer feeds will be offset from the center axis and the subreflector will be tilted to provide alignment. A relatively rapid switching capability between the various receivers and radiometers will allow operations to be changed efficiently between radar and astronomy modes.

In order to satisfy USAF requirements, ownership of the Haystack antenna was transferred in the past year to the USAF. Under a memorandum of understanding, access to the upgraded antenna will continue to be made available to MIT and NEROC institutions for astronomical research and education. The Haystack antenna is not expected to be operated as a general astronomical facility, but will support targeted research projects in radio astronomy and education. Dismantling of the present antenna, assembly of the new antenna, and replacement of the radome panels are expected to start in early 2006, followed by a period of alignments and tests. It is currently projected that the antenna will be completed by the end of 2006, and the astronomy commissioning phase will start in early 2007.

The emphasis in Haystack's VLBI instrumentation program has continued to be on the improvement of observing sensitivity through increased measurement bandwidth using the Mark 5 data system (Figure 6). For astronomical studies, the goal of the recently initiated Ultrawideband VLBI (UVLBI) program is to enable the world's largest telescopes to acquire and record data at rates up to 4 Gbps, with the goal of achieving VLBI image noise levels of a few μJy/beam. Such sensitivity, coupled with

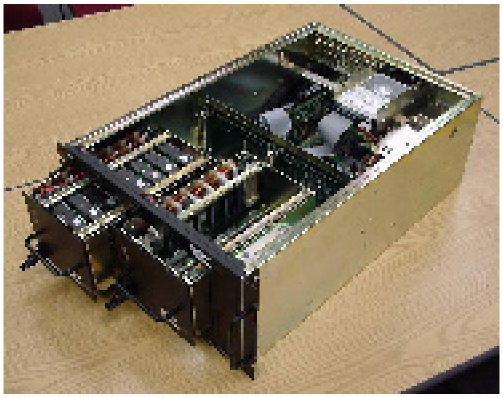
Figure 6. The Mark 5 disk-based data system.

VLBI's angular resolution, will open new scientific frontiers such as the detection and eventual imaging at millimeter wavelengths of the SgrA* source in the center of the galaxy, imaging of starburst-related clusters of faint radio supernovae in the obscured nuclei of luminous infrared galaxies at centimeter wavelengths, and other projects such as the search for faint third images of gravitational lens systems and measurement of fading radio emission from gamma-ray bursts. In geodetic VLBI applications, the increased bandwidth provided by the Mark 5 system improves the measurement precision of earth's orientation parameters and allows the use of smaller antennas as part of the geodetic VLBI network.

The Mark 5 technology, developed at Haystack Observatory in collaboration with Conduant Corp., is based on magnetic disks and currently supports recording data rates up to 1,024 Mbps. While the Mark 5A system represents a two-fold increase over the maximum allowed using Mark 4–style tape recorders, it avoids the difficult maintenance challenges of the tape-based system and expensive replacement of recording headstacks, and allows growth towards higher data rates. The system employs two independent 8-pack disk modules which, when populated with individual disks of 250 GB capacity, provides a total Mark 5A capacity of 4 TB, with further growth anticipated as disk capacity increases further. At present, there are over 120 Mark 5A systems deployed at telescopes and correlators worldwide, and about 1,000 disk modules currently exist for VLBI experiments, representing well over 2 PB of storage. Work is progressing on the next generation system—the Mark 5B, which is targeted at increasing recording rates to 2,048 Mbps, providing full compatibility with the VLBI standard interface, eliminating the need for external formatters at telescopes, and replacing station units at Mark 4 correlators. It is noted that, due to its reliability, the Mark 5 playback system has resulted in much more efficient processing at the correlators. Finally, the Mark 5 system is providing an important interface for rapid transfer of data from telescopes to correlators using global fiber-optic networks. Current experiments in e-VLBI have achieved data transfers at near 1 Gbps within the US and across both the Atlantic and Pacific oceans. Protocols for network sharing and for interface standardization are currently under development in collaboration with researchers at MIT's Computer Science and Artificial Intelligence Laboratory.

Atmospheric Science

Emphasis of the research in atmospheric sciences at Haystack has continued on studies of the coupling between earth's ionosphere and magnetosphere, with particular focus on solar storms. Interactions of coronal mass ejections from the sun during these storms interact with the earth's magnetosphere and can cause space weather effects such the disruption of communications and power grid systems as well as satellite orbits and digital systems. The Millstone Hill incoherent scatter radar and a global network of GPS receivers has now been used to expand the investigation of large plumes of enhanced plasma observed across North America (Figure 7). These create large density gradients that cause the space weather effects on signal communications. The plumes have been found to travel from the equator towards and across the polar cap, and have been related to plasma interactions in the earth's magnetosphere through observations from satellite imagers.

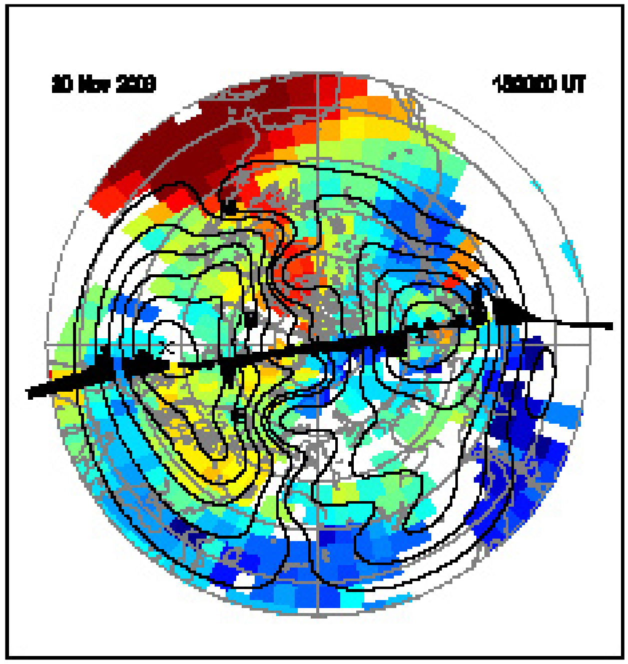

Figure 7. Detection of a plume of ionization in the upper atmosphere propagating from the equator across the polar cap during a geomagnetic storm caused by an intense solar flare. The observations of total electron content shown in the map were obtained from a network of GPS receivers.

A new project, called Intercepted Signals for Ionospheric Science (ISIS), has resulted in the completion of a mobile data acquisition system and a powerful centralized signal processing and analysis system at Haystack. Following tests of the mobile receiver with the Millstone Hill incoherent scatter radar, the data acquisition system will be installed at the Green Bank 43-m antenna to gather bistatic incoherent scatter and coherent scatter signals transmitted from the Millstone Hill UHF radar. These measurements are expected to provide drift velocity vector measurements of the ionospheric plasma. A set of distributed stations using the ISIS data acquisition system are then planned to be replicated for placement at other locations in the northeast and northwest United States, and a collaboration with institutions at these locations has been initiated to facilitate the fielding of the ISIS array and for training students in remote sensing techniques. It is expected that the ISIS instrumentation will 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. In the longer-term future, it is anticipated that the ISIS array will be 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 approach.

Educational Programs

Haystack continues the development of the Small Radio Telescope (SRT) for undergraduate education in radio astronomy (Figure 8). The SRT has so far been replicated at about 120 institutions across the US and the world. The current focus is on SRT radio interferometry for which a new digital receiver operating at 1400–1600 MHz with GPS timing has been

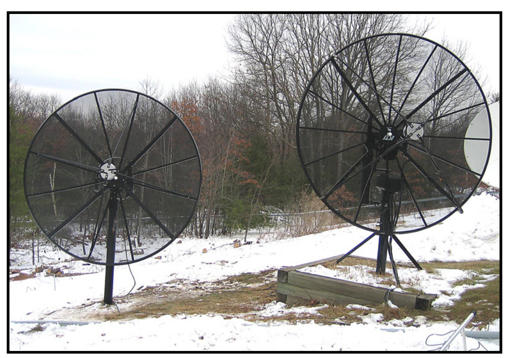

Figure 8. A two-element radio interferometer for educational projects using Haystack's small radio telescopes.

constructed and tested during the past year. This project provides the capability for education in 'unconnected' radio interferometry such as used in VLBI. The Haystack SRT interferometer system is planned to become remotely available in the future for educational purposes for students and faculty nationwide, and will be capable of supporting baselines of tens of meters to a few kilometers.

Finally, research internships for undergraduates have been provided at Haystack Observatory as part of NSF's Research Experiences for Undergraduates program. Seven students have worked with staff during the past summer at Haystack 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 program at Haystack using the research disciplines of the observatory to introduce their students to science and to build a relationship with the observatory in order to enhance their educational curricula.

Joseph E. Salah
Director

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