Haystack Observatory

Haystack Observatory is an interdisciplinary 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. A strong instrumentation development program is conducted at Haystack Observatory to support the various scientific research programs.

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 in the northeast that includes, in addition to MIT, Boston University, Brandeis University, Dartmouth College, Harvard University, the Smithsonian Astrophysical Observatory, University of Massachusetts, University of New Hampshire, and Wellesley College. Haystack Observatory also enjoys a close relationship with MIT Lincoln Laboratory and shares some of the observing facilities in support of the laboratory's space surveillance program.

The current priorities of the radio astronomy program at Haystack include 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 allow sensitive observations of the center of our galaxy. The primary objectives of the geodetic VLBI research program are to improve the accuracy of measurements of the earth's orientation parameters by enhancing the bandwidth of the observations and the application of high-speed data transport and processing technology to allow rapid delivery of the results. The current goal of the atmospheric science program is to understand the impact of solar disturbances on the earth's upper atmosphere over the United States using measurements from the observatory's radars as well as the Global Positioning System.

An important component of the observatory's mission is to support 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 purposes to students nationwide, special instrumentation is developed for introducing students to radio astronomy and radio science techniques, and training courses and materials are offered to interested faculty and students. In addition, internship opportunities are made available at Haystack to graduate and undergraduate students and to local area science teachers.

The observatory receives financial support primarily from federal agencies, including the National Science Foundation, the National Aeronautical and Space Administration, and the Department of Defense.

Instrumentation

The Haystack Observatory instrumentation consists of the following facilities:

- 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.
- 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, augmented by passive optical telescopes.
- A 24-station digital radio array operating at 327 MHz for the detection of Deuterium emission.

Radio Astronomy

A 24-station array operating at 327 MHz for the detection of Deuterium has been completed at the Haystack Observatory during the past year. Deuterium is a most sensitive indicator of the density of baryons, relating to the amount of dark matter in the universe, and its detection at its radio frequency has been elusive due to the inadequate sensitivity of available telescopes. The project, funded by the NSF with MIT contributions, is led by Dr. Alan Rogers. Each station of the array consists of 24 dual-polarization dipoles connected to a very sensitive multi-channel digital receiver. To allow such an array to operate at these frequencies, major effort has been expended to characterize the radio frequency interference (RFI) environment at the Haystack site in a narrow frequency band centered at 327 MHz, and RFI mitigation techniques through frequency excision have been implemented. Test results to date have been most encouraging with integrated spectra showing close agreement with theoretical expectations. Deep integrations with the multi-beam array have now started, and early results on the detection of Deuterium are anticipated by the end of 2004.

One station of the Deuterium array showing the 24 dipoles and digital receiver box.

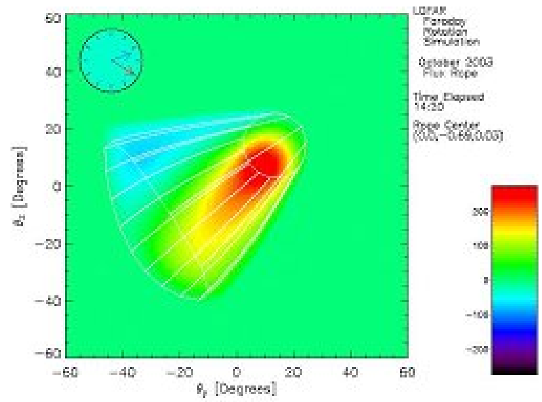
The Deuterium array of 24 stations.

Another array project, previously called the Low Frequency Array (LOFAR), has undergone major change in the past year. The planned array, consisting of 100 stations each with 130 dipole antennas, was specified to operate in the 10−240 MHz frequency range and was aimed at sensitive observations for various astronomical studies, including the measurement of the structure of the universe during the early epoch of reionization and the detection of astronomical transients. The project was a formal partnership with the Netherlands Foundation for Radio Astronomy (ASTRON) and the Naval Research Laboratory (NRL), and was led by Dr. Colin Lonsdale in collaboration with Professor Jacqueline Hewitt of the MIT Center for Space Research and the Department of Physics. A key component of the array development was the selection of a site for the array where the radio-frequency interference from man-made sources was minimal and where the logistics of implementing an array spaced over 400 km were affordable. An international committee including members from all three partner institutions evaluated three candidate sites and ranked them as follows: western Australia, southwest United States, and the Netherlands. The international steering committee for LOFAR approved the selection of Western Australia as the optimum site and negotiations began with the Australia Telescope National Facility (ATNF) for the implementation of the array at the selected site.

In early 2004, funds from the Dutch government were secured by ASTRON for the array, but were constrained by a requirement for constructing the array in the Netherlands as part of an economic development project to support regional agriculture and geophysics. ATNF and MIT withdrew from the LOFAR project and continued on the path toward developing the array in western Australia and operating over the 80 to 300 MHz range. Proposals are currently in preparation for the acquisition of the necessary funds from NSF to construct an initial demonstrator in western Australia, called the Mileura Widefield Array, in the next three years. NRL is exploring alternative paths with a group of universities in the southwest United States for the development of another array in New Mexico, and discussions are underway towards the potential sharing of some of the MIT-based array technology for this development.

Prototype array of low-frequency dipoles designed to operate at 80–300 MHz.

During the past year, studies at Haystack Observatory and at the Center for Space Research have shown that an array operating at low frequencies can provide some valuable measurements of the structure of coronal mass ejections (CME) from the sun that are critical to the understanding of space weather effects. These effects can disrupt radio communications, jeopardize satellite electronics, alter satellite orbits, and potentially disrupt power grids on earth. The studies demonstrated the ability of the array to precisely determine the density and velocity of plasma structures in the solar wind using interplanetary scintillations, and to measure the magnetic field strength and its orientation as the CME travels from the sun to the earth using Faraday rotation of radio sources. The orientation of the magnetic field determines the effectiveness of the CME to couple with the earth's magnetosphere and cause space weather effects. The success of these studies has led to the establishment of heliospheric science as one of the key drivers for the Mileura Widefield Array, and the measurement requirements are being considered in the design of the array.



Simulations of Faraday rotation from a Coronal Mass Ejection observed during the October 2003 solar storm event.

Based on the success of an astronomical VLBI experiment conducted last year using a small network of radio telescopes operating at 1.3 and 2 mm wavelength, a new project led by Dr. Shep Doeleman has proposed the application of Haystack's advanced recording technology using a larger network of international telescopes. The aim is to record data at 2-4 Gbits/sec using Haystack's Mark 5 disk-based system, thus greatly enhancing the sensitivity of VLBI experiment so that precise measurements of the structure in the center of our galaxy can be made at millimeter wavelengths. Application of this advanced technology using large telescopes at centimeter wavelengths, such as Arecibo, Green Bank, and Effelsberg, Germany, has also been proposed by Colin Lonsdale to investigate star formation in luminous infrared galaxies. Haystack is anticipating the initiation of the work in the next year under NSF support.

Instrumentation Development

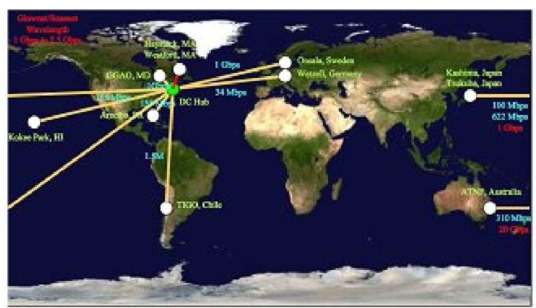
The most exciting development during the past year has been the initiation of the upgrade of the Haystack antenna and radar system. Under a program sponsored by the US Air Force, Lincoln Laboratory has awarded a contract to L3 Communications/ESSCO for the replacement of the 37-m reflector with a new dish with much improved surface tolerance. This will allow observations in the 100 GHz band with an electrical efficiency that is a factor of 3-4 higher than currently achievable at that frequency. In addition, a new radar system operating at a frequency of 95 GHz with wider bandwidth than the current 10 GHz radar will be installed to allow imaging of small satellites with fine resolution.

As part of the upgrade, the astronomical radiometers and radar systems will be combined in one equipment box enabling rapid change in the mode of operation. It is expected that the antenna upgrade will be completed in three years, with operations starting in 2007 after an estimated six months of downtime. As part of this major upgrade project and to satisfy USAF requirements, steps have been taken to transfer ownership of the Haystack antenna to the USAF; it had been owned by MIT since 1970 when it was transferred by the USAF to MIT for radio astronomical observations. 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.

Haystack's Mark 5 recording system, developed under the leadership of Dr. Alan Whitney, has been formally adopted worldwide as the standard recording system at VLBI telescopes. The system is based on magnetic-disk recording, and is now available commercially through Conduant Corporation, CO. Currently, 100 Mark 5 systems have been installed and are operating at 20 radio telescopes and four VLBI correlators for data playback and processing. Haystack researchers plan to continue further improvements to the Mark 5 system to further enhance bandwidth to 2 Gbits/sec, and to improve the efficiency of processing at correlators. In addition, the Mark 5 system is now being used under NASA sponsorship to transport data using fiber optic networks in order to avoid shipping costs, increase the data processing turn-around, and react promptly to events during experiments.

The real-time application of VLBI data transport, called "e-VLBI," has continued at Haystack Observatory under the leadership of Dr. Alan Whitney and Dr. David Lapsley, in collaboration with the MIT Laboratory for Computer Sciences and Lincoln Laboratory, under both NSF and NASA sponsorship. Protocols for the sharing of the fiber networks with other applications on a non-interference basis have been developed and tested. Tests of the e-VLBI system have been successfully conducted during the past year with telescopes in Australia, Japan, Europe and within the United States.

Haystack's Mark 5 data system used for disk-based recording and e-VLBI.

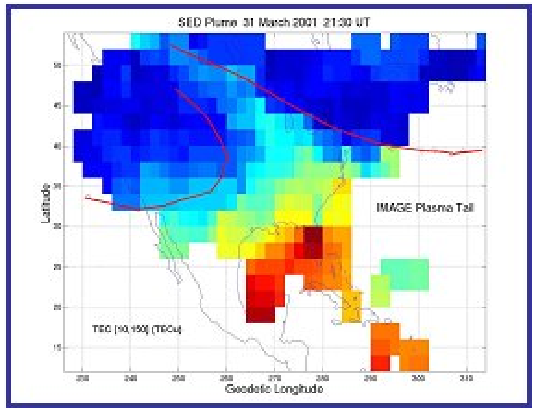


The e-VLBI system of radio telescopes connected through a fiber optic network.

Two studies have been initiated in the past year with Haystack staff involvement and leadership to outline future instrumentation developments in VLBI. The first is charting the future of astronomical VLBI in the United States and preparing recommendations for the upgrade of the nation's Very Long Baseline Array operated by the National Radio Astronomy Observatory. The second, under the auspices of the International VLBI Service, is developing a roadmap for geodetic VLBI and the necessary upgrades to telescopes and processors.

A new radio frequency interference monitor is also being developed at Haystack to acquire a data base on interference levels in the frequency range from 30 to 1500 MHz. The system will be tested around the observatory and at nearby locations, and then the design will be made available to other institutions nationwide for replication. Under support of the NSF, such a system will be useful to monitor conditions involving wireless systems and to evaluate RFI effects on radio astronomy bands. Commercial spectrum analyzers are being evaluated as part of the development in order to simplify the replication.

Atmospheric Science



Plume of electron density over North America observed with the GPS receiver network during a geomagnetic storm.

Research has continued on studies of the coupling between earth's ionosphere and magnetosphere, with emphasis on the effects of solar storms. The Millstone Hill incoherent scatter radar and a global network of GPS receivers have been used to investigate large plumes of enhanced plasma that are observed across North America creating large density gradients and space weather effects. The research, conducted under the leadership of Dr. John Foster and with sponsorship from NSF and NASA, has traced the source of these plumes to the magnetosphere. A major highlight of the studies has been the investigation of very large geomagnetic storms that occurred at the end of October and early November 2003. These storms caused large disturbances in ionospheric density and temperature, electric fields, and plasma drift velocity in the earth's upper atmosphere. To aid in the studies of such phenomena, long-duration, uninterrupted experiments are now being planned with radar observations lasting at least one month. Analysis of a prototype 30-day campaign that was conducted by Dr. John Holt using the Millstone Hill zenith-pointing antenna demonstrated the feasibility and importance of long duration experiments. Such experiments have been enabled by the availability of a new workstation-based digital data acquisition system that has been put into operation during the past year.

The refurbishment and upgrade of the Millstone Hill steerable antenna have been initiated during the past year. Ownership of the zenith-fixed and steerable antennas and the UHF transmitter that form the Millstone Hill ionospheric radar have been transferred from the USAF to MIT to allow the upgrade to be completed, and a memorandum of understanding allows access to the radar by Lincoln Laboratory for its space surveillance studies.

Work is continuing at Haystack in support of NSF's Advanced Modular Incoherent Scatter Radar (AMISR) under Dr. John Holt's leadership. Haystack is contributing to the development of the digital data acquisition and data base system for this new radar, in collaboration with SRI International that is leading the development. It is expected that the first face of a phased-array radar will be installed next year at Poker Flat near Fairbanks, Alaska, with two other faces to be installed at Resolute Bay in 2006–2007 to begin studies of the dynamics of the earth's polar cap region. In the long-term, it is anticipated that such a phased array will replace the mechanical antennas at Millstone Hill.

A new project, called Intercepted Signals for Ionospheric Science (ISIS) has been initiated at Haystack in the past year under the leadership of Dr. Frank Lind. A major equipment grant was received from the Air Force Office of Scientific Research (AFOSR) under the Defense University Research Instrumentation Program (DURIP) to allow the design and construction of a set of distributed stations in the northeast and northwest United States. The instrumentation will include GPS receivers, digital receivers for passive radar observations, and scintillation monitors, all linked through the internet to a central digital processing and data base system at Haystack. It is expected that such an array will be a prototype for the development of distributed arrays of scientific instrumentation for upper atmospheric research as recommended in a recent National Research Council decadal study for solar and space physics.

Educational Programs

Strengthening undergraduate education through research in radio astronomy using the facilities of the Haystack Observatory continued successfully during the past year. Sharing national access to the Haystack 37-m telescope for education in radio astronomy, development of new materials and their dissemination through the World Wide Web, and short courses to college faculty have been provided. A new digital receiver has been designed to allow the introduction of radio interferometry to undergraduates, using two or more small radio telescopes (SRT).

Radio interferometry using two small radio telescopes.

The SRT continues to be installed at colleges nationwide, and there are now more than 100 kits that have been assembled for undergraduate research and training. In addition, tests at pre-college levels have shown that the SRT can be an important and useful method for educational outreach. Through the use of a transportable SRT, radio astronomy has been introduced at several local area high schools and used for public outreach at local area museums and public events.

The small radio telescope mounted on a transportable trailer for pre-college and public outreach.

Finally, research internships for undergraduates have been provided at Haystack Observatory as part of NSF's Research Experiences for Undergraduates (REU) program. Eight 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 (RET) program at Haystack using the research disciplines of the observatory to introduce their students to science and to build a relationship with the observatory to enhance their educational curricula.

Joseph E. Salah
Director

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