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 (CfA), 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 US 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 the Earth's upper atmosphere using incoherent backscatter techniques

Radio Astronomy

Deuterium Array

The 24-station deuterium array observed the deuterium radio line at a frequency of 327.4 MHz in the anti-center region of the galaxy. A ratio of deuterium to hydrogen of 20 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.

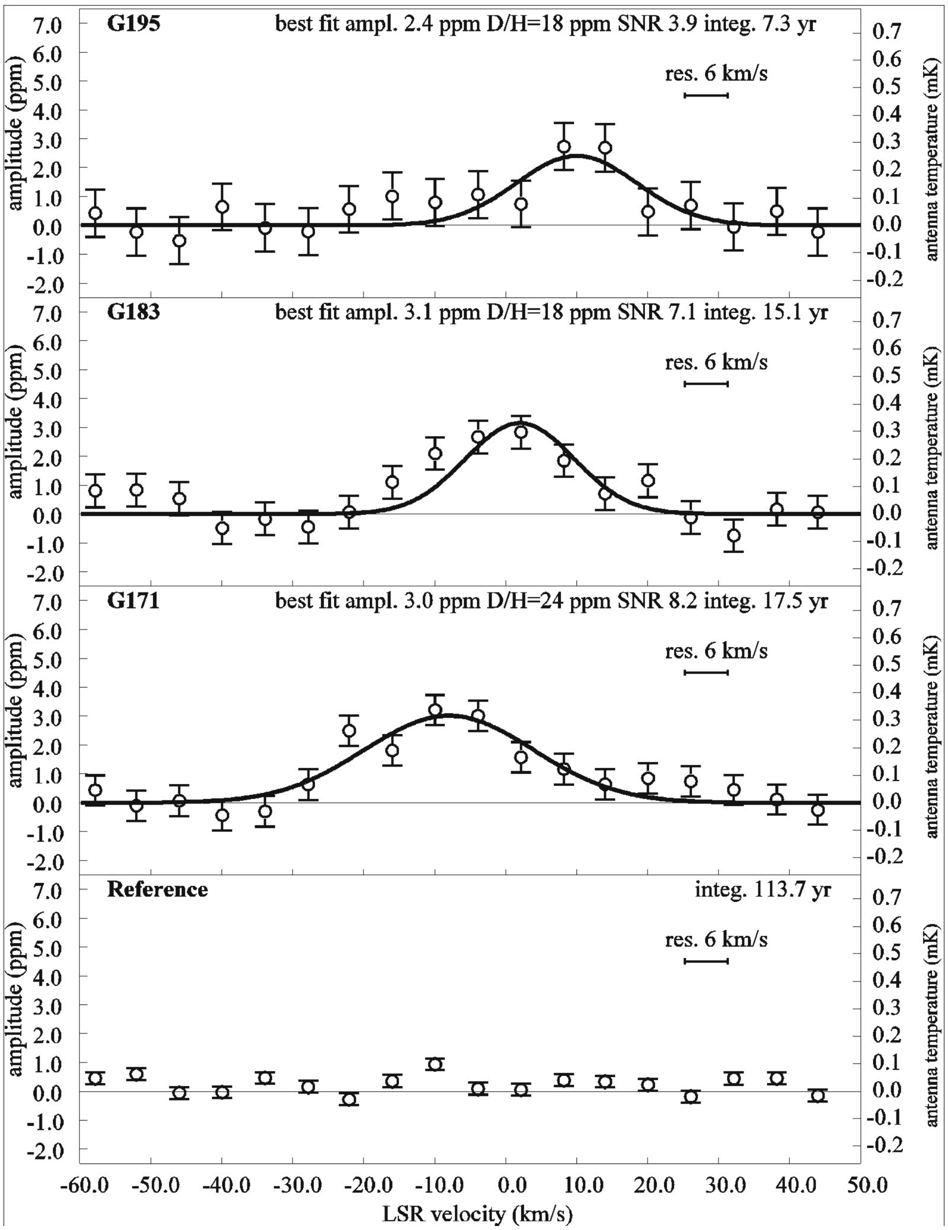

Figure 1. Accumulated spectral measurements from the deuterium array toward the galactic anti-center are compared to a nearby region and a reference region out of the galactic plane. From "Observations of the 327 MHz deuterium hyperfine transition" by A. Rogers, K. Dudevoir, and T. Bania in the Astronomical Journal.

After the array operated for two years, it was disassembled and stored for possible future deployment in the southern hemisphere where it could be used to measure the deuterium-to-hydrogen ratio in the Magellanic Clouds. The Magellanic Clouds, which are not visible from Haystack, are thought to contain interstellar gas from the Big Bang that has undergone less reprocessing in stars than the gas in the galaxy and should therefore be closer to the "primordial" gas from the Big Bang. Results from the deuterium array were published by A. Rogers, K. Dudevoir, and T. Bania in the April 2007 *Astronomical Journal*.

Figure 2. The deuterium array at Haystack Observatory as it existed from 2004 until July 2006. The trailer contains the radio frequency interference detection equipment.

Experiment to Detect the Global EOR Signature

Preliminary instrumentation consisting of a broadband antenna and a direct-sampling spectrometer was deployed in Western Australia to set some initial limits on the highly red-shifted hydrogen emission from the early universe, expected to lie around 150 MHz. The system, known as EDGES (an Experiment to Detect the Global EOR Signature), is shown in figure 3 as it was deployed at the Mileura station by J. Bowman and A. Rogers. In addition to setting a "first" crude upper limit for the emission from the highly red-shifted hydrogen, the instrument has been used to measure the spectral index of the galactic background in the 100 MHz to 200 MHz band. Further development of the instrument will be needed to reduce the systematic errors that dominate the spectra in order to set more interesting limits, or possibly even detect signals from the epoch of reionization (EOR).

Murchenson Widefield Array

Major progress has been achieved in the development of the Murchenson Widefield Array (MWA), projected for completion in Western Australia by the end of 2008. The project seeks to deploy 500 dipole-based antenna tiles operating between 80 MHz and 300 MHz, for scientific investigations encompassing cosmology, the heliosphere, and the

Figure 3. The EDGES antenna at Mileura Station in Western Australia in December 2006. The antenna and spectrometer cover a frequency range from 100 MHz to 200 MHz.

transient radio universe. Haystack Observatory, through NEROC, has received a four-year, $4.9 million NSF award, from which subawards have been made to the MIT Kavli Institute (MKI) and CfA. C. Lonsdale is the principal investigator on the NSF grant, with J. Hewitt (MKI) and L. Greenhill (CfA) as co–principal investigators. The project is international in nature; partners include multiple Australian universities as well as the Raman Research Institute in India. The international project leader is Lonsdale at Haystack, and the project engineer is R. Cappallo, also at Haystack. The international project office is rounded out by administrative and secretarial support at Haystack and an Australian branch in Melbourne led by R. Sault.

The MWA project was formally launched in June 2006, and the past year has seen rapid progress toward deployment of a 32-tile engineering testbed array at the remote site during the second half of 2007. In addition to taking on the project leadership role, Haystack is responsible for developing the antennas and the correlator and for supporting a number of other subsystems. A major milestone in the antenna development was achieved in March 2007 with the deployment in Australia of the first production prototype antenna tile (figure 4). This design, developed under the leadership of B. 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 cost of the finished product, including labor for installation, is expected to meet targets established three years ago. The first 32 tiles are scheduled for installation at the MWA site in September 2007, and if performance proves satisfactory, the remaining 480 tiles will be ordered early in 2008.

Hardware for the 32-tile system is primarily being procured with funds from an equipment grant to Haystack Observatory from the Air Force Office of Scientific Research (AFOSR) under the Defense University Research Instrumentation Program (DURIP). Ultimately, the DURIP-related equipment will support high angular-resolution studies of solar bursts associated with space weather prediction.

Figure 4. Manufactured antenna tile installed at Boolardy Station, Western Australia. The approximate cost per dipole is $50, and the associated rigid-wire mesh underneath it costs about $15 per dipole.

The MWA correlator is a highly innovative system based on field-programmable gate arrays (FPGAs); the system is 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, R. Cappallo and B. Kincaid have been working on the FPGA functionality for the main computational core of the machine. Known as the "correlation cell," this FPGA code is responsible for efficient multiplexing and pipelining of data for delivery to the high-speed arithmetic units on the chips. A schematic diagram of the correlation cell is shown in figure 5. Each correlator board has eight Xilinx v4SX35 FPGA chips, and each chip hosts 136 correlator cells. The full correlator comprises 64 correlator boards and several subsystems. This work is on schedule for operation of the 32-tile system by January 2008 and delivery of the full correlator system by the end of 2008.

Astronomical VLBI

Astronomical VLBI efforts at the observatory have focused on deploying the new wideband VLBI systems developed at Haystack in several key areas of scientific research. In April 2007, the new VLBI systems were used in a three-station VLBI array to observe active galactic nuclei at 230 GHz. The array included the James Clerk Maxwell Telescopes on Mauna Kea in Hawaii, the Arizona Radio Observatory on Mount Graham in Arizona, and a single 10 m dish of the new CARMA array near Big Pine, CA, with

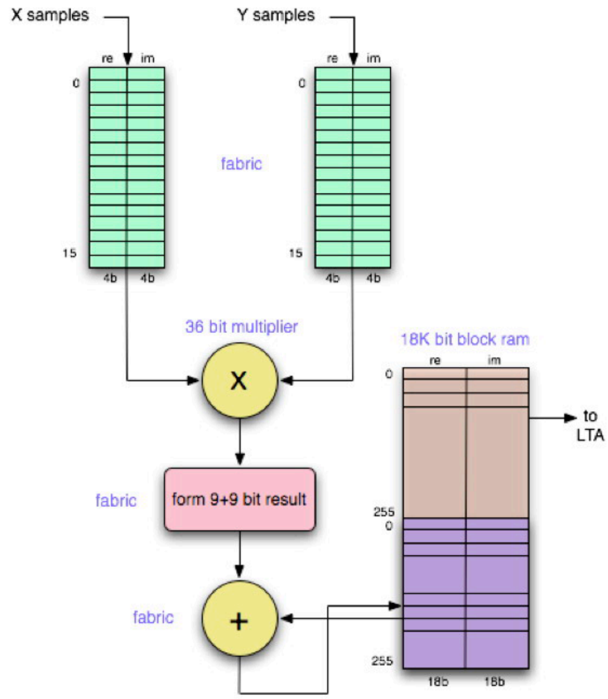

Figure 5. Correlation "cell" as implemented in a Xilinx FPGA chip.

significant support from the Smithsonian Submillimeter Array on Mauna Kea. The successful observing campaign detected eight bright active galactic nuclei on all three baselines—the first time this has been done at this frequency—with angular resolutions of 60 micro arcseconds (about 2,000 times sharper than the Hubble Space Telescope). Of particular interest are robust detections of SgrA*, the massive black hole candidate in the Galactic Center; this evidence will allow the most precise measurements to date of the emission near a presumed event horizon. At lower frequencies, observations made by the observatory's ultra-wide bandwidth VLBI program enabled late-time size measurements of the gamma ray burst GRB030329. The increase of the gamma ray burst size with time has slowed and is now consistent with the original burst expanding into a constant density medium, an important probe of the progenitor object. Limits placed on the proper motion of the gamma ray burst strengthen the idea that the emission is due to a narrow beamed jet of particles. Preparations are under way for new wideband VLBI observations using the Arecibo and Green Bank Telescope baseline to search for faint gravitationally lensed images of quasars. These so-called central images are highly demagnified and should appear within tens of parsecs of the lensing galaxy's center. If wideband VLBI can routinely detect these images, a new window onto the study of galactic centers will be opened.

Square Kilometer Array

Haystack Observatory continues to play a prominent role in the international Square Kilometer Array (SKA) project. This is an ambitious global effort to design and build the next generation radio telescope array that is 100 times more sensitive than any existing instrument. C. Lonsdale is the principal investigator on a NSF award to study advanced

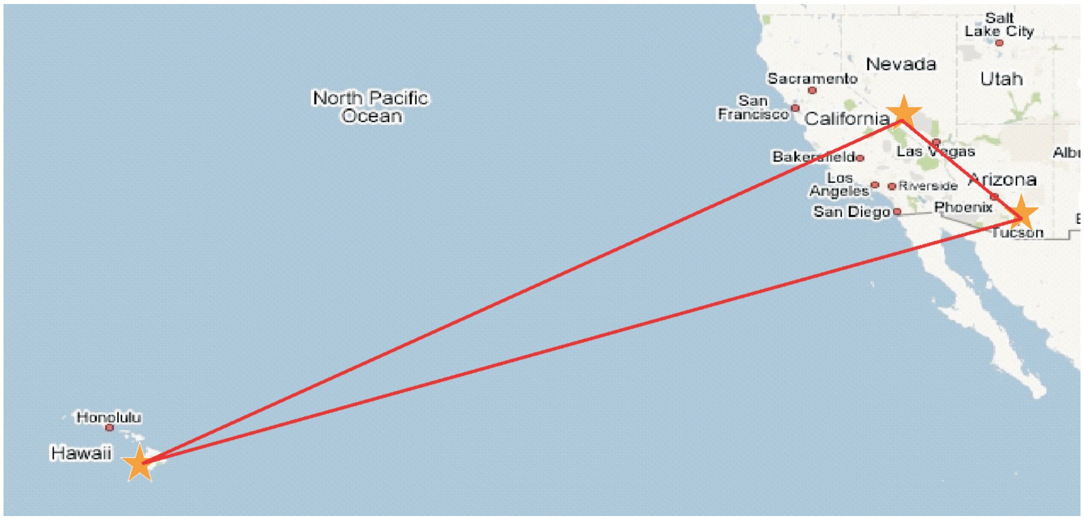

Figure 6. The 230 GHz VLBI experiment included the James Clerk Maxwell Telescopes on Mauna Kea in Hawaii, the Arizona Radio Observatory on Mount Graham in Arizona, and a single 10 m dish of the new CARMA array near Big Pine, CA.

correlation techniques. This project focuses on a new algorithm to pave the way for achieving the extremely high imaging dynamic ranges that will be needed to realize the full sensitivity of the SKA. A postdoctoral associate will join the group in October 2007 to expand and accelerate this work. In addition, MIT, through Haystack, is part of the US SKA consortium. A USSKA proposal to the NSF, led by Cornell University, is expected to lead to funding for SKA technology development over a four-year period starting in November 2007. Haystack is participating in this effort, and will receive funds from the grant to support a postdoc. The focus of the Haystack work will be calibration, imaging, simulation, and correlation architectures.

Instrumentation Development

Drawing on its unique mix of scientific and engineering expertise, Haystack continues to be a leader in the development of next-generation VLBI instrumentation. Recognizing 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 GHz to 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 the 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 about 50. This is done by replacing costly analog filterbank units (which are effectively irreplaceable) by a polyphase filterbank realized through digital signal processing onboard 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 the National Radio Astronomy Observatory and UC Berkeley to develop the final 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 is also developing 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 passed lab tests and will be deployed for field tests in late 2007. 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 hard-disk media. Mark5C, a next-generation system currently under development, 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 able to store data at rates up to 16 Gbits/sec—eight times 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 high-frequency VLBI where atmospheric turbulence decorrelates 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 on 10's of Schwarzschild radii scales.

To leverage all these instrumental developments for VLBI at the highest frequencies (>=230GHz), an extremely stable frequency reference is required. At longer wavelengths (cm), hydrogen masers provide sufficiently stable tones for 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 to 100 times more stable than hydrogen masers over 1- to 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 ~10 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 ALMA, APEX, and ASTE) to be combined into a single VLBI instrument capable of 20 micro arcsecond angular resolution.

For geodetic-VLBI, as mentioned above, a VLBI2010 development program is under way 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 ~2 GHz to 13GHz radio frequency (RF) range with a single feed. A prototype RF system under development includes a cooled feed, low-noise amplifiers, and a wideband optical-fiber transmission system to transmit the entire RF bandwidth to processing equipment on the ground. A demonstration experiment recording four 1 GHz-wide bands within the broadband RF is planned for late 2007. A new 12 m fast-moving antenna will likely be procured in 2008 as a new platform for the broadband system. The Haystack VLBI2010 development program, funded largely by NASA/Goddard Space Flight Center, is part of an international effort to develop a major upgrade to the existing geodetic-VLBI systems.

Atmospheric Science

Atmospheric science research at Haystack during the past year centered on the causes and effects of solar-induced geomagnetic storms in Earth's upper atmosphere. Storm effects at mid latitudes have been observed in detail with the powerful Millstone Hill incoherent scatter radar, and such observations were placed in a global context using correlative observations with spacecraft and the distributed array of GPS receivers. The features of interest for mid-latitude space weather have been related to the causative effects of magnetospheric electric fields and in particular to the subauroral electric fields (SAPS) whose importance has been a major theme of the Haystack work. Large-scale ionospheric disturbances have been shown to be magnetically conjugate and to exhibit a pronounced intensification at American-sector longitudes. These features result in severe ionospheric density gradients that affect communications and navigation systems over the United States. The workings of the coupled magnetosphere-ionosphere system in controlling the development of electric fields in the upper atmosphere is under continued investigation. High-latitude electric fields driven by Earth's interaction with the disturbed solar wind are found to influence the low-latitude ionosphere and innermost regions of the magnetosphere for extended intervals (more than six hours) during large magnetic storms. These initiate a chain of events that leads to a large-scale redistribution of the low-latitude ionospheric plasma throughout the magnetosphere.

The radar observing program has concentrated on supporting International Polar Year (IPY) activities, including a yearlong campaign to take regular coordinated observations at all similar facilities around the world. The Millstone radar is operating on a regular biweekly interval throughout the IPY. Such intensive campaign data are being combined with long-term atmospheric radar and optical observations taken at the Haystack/Millstone complex to develop climatologies of upper-atmospheric characteristics. The associated modeling capabilities developed at Haystack are being been applied to data sets obtained at other facilities and incorporated into the Haystack Madrigal database.

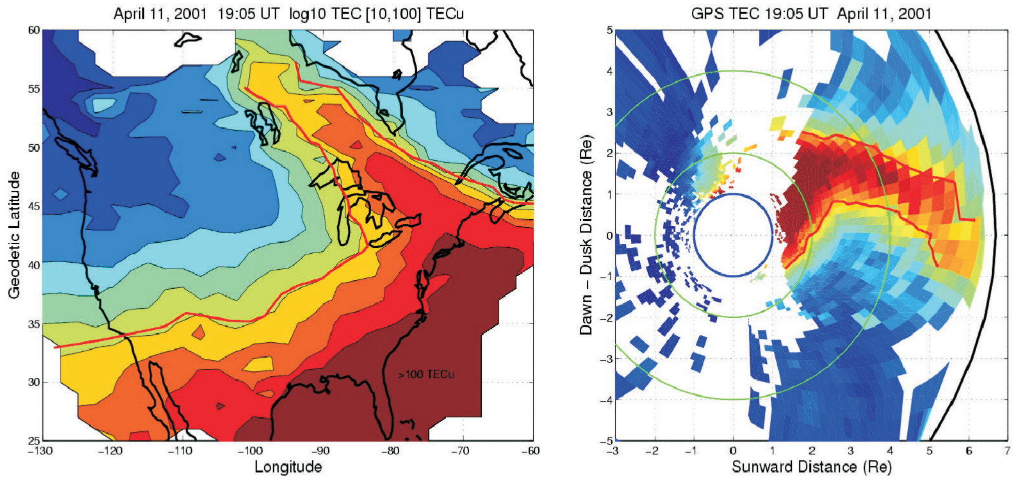

Figure 7. A map of total electron content (TEC) derived from GPS observations reveals a dense plume of ionospheric storm-enhanced density spanning North America (left). Heavy lines mark the > 70 TECu contours showing the extent of the plume at this time. At right, these data are projected to the magnetospheric equatorial plane where they map to a large-scale erosion plume of plasmaspheric material extending sunward to the dayside boundary of the magnetosphere. The ground-based ionospheric observations with radar and GPS map out the magnetospheric disturbance.

The distributed elements of our Intercepted Signals for Ionospheric Science (ISIS) radio-receiving network have been deployed at collaborating institutions under the direction of F. Lind. Data are being received in real time for ISIS sites at the University of Washington, Cornell, Sienna College, and Dartmouth, as well as from the Haystack installations in Westford and Greenbank, WV. The digital receivers and processors are used to perform upper-atmosphere diagnostics through the analysis of signal perturbations along trans-ionospheric propagation paths. Using FM radio stations as source-signal transmitters, the ISIS receivers operate as passive (receive-only) radars for meteor and ionospheric-irregularity backscatter experiments.

Educational and Outreach Programs

Haystack Observatory has completed the development of an inexpensive two-element system based on off-the-shelf components and small satellite dishes to introduce radio interferometry to community college faculty and students. Two community college collaborators are currently beta testing the units and developing educational materials to support the system. A summer student has been testing a three-element interferometer with the small dishes to study the feasibility of solar observations and has developed data analysis tools.

The small radio telescope interferometer with the digital receiver and GPS timing has been operating at the site. Summer students have used the system to observe the sun and the HI line. While the receiver is not being reproduced commercially, the Haystack system is available for remote use.

Figure 8. The very small radio telescope system at Haystack Observatory uses low-cost commercial satellite-TV dishes and receivers.

Research internships for undergraduates have continued at Haystack as part of NSF's Research Experiences for Undergraduates program, which has been funded for another five years. During the past summer, eight students worked with staff on research projects associated with radio astronomy and atmospheric science.

Science teachers from four local high schools also participated in NSF's Research Experiences for Teachers program at Haystack using the observatory's research to introduce their students to science and to enhance their educational curricula. Finally, under an NSF award, a special exhibit on waves in space opened at the Children's Discovery Museum in Acton, MA. Educational activities held in association with the exhibit included presentations from Haystack scientists.

The Solar Storms to Radio Waves exhibit at the Acton Discovery Museum in Acton, MA.

Alan R. Whitney
Associate Director

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