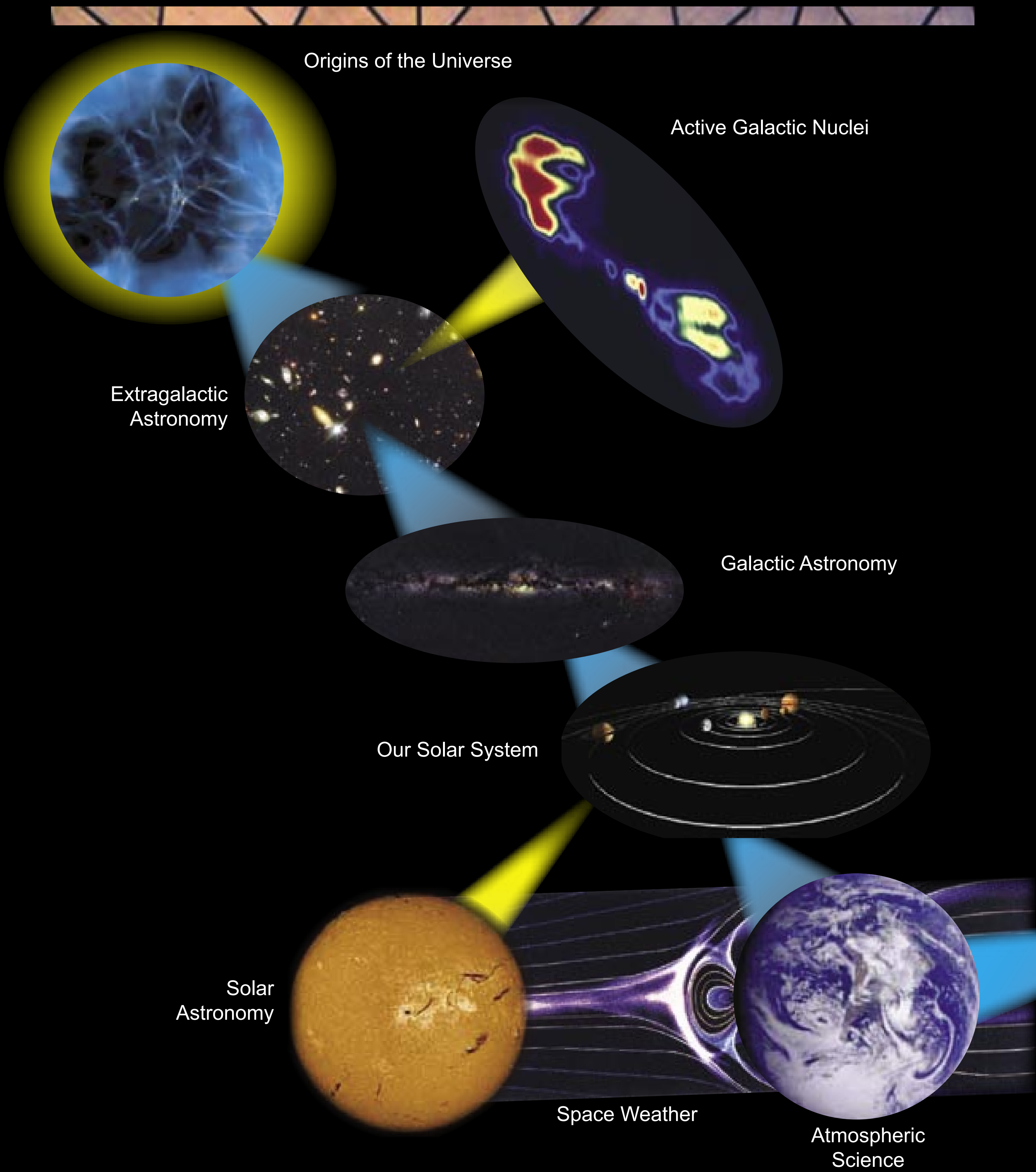
Massachusetts Institute of Technology

Haystack Observatory

www.haystack.mit.edu



Credits top to bottom: N. Gnedin (U. Colorado, Boulder); NRAO/AUI; NASA, Robert Williams and the Hubble Deep Field Team (STScI); Axel Mellinger, University of Potsdam, Germany; Windows to the Universe, at http://www.windows.ucar.edu/ at the University Corporation for Atmospheric Research (UCAR) ©1995-2004; National Solar Observatory/Sacramento Peak; NASA.

Introduction

Haystack Observatory is an interdisciplinary research center of the Massachusetts Institute of Technology (MIT) engaged in radio astronomy, geodesy, upper atmospheric physics, and radar applications.

Our Mission is to

- Study the structure of our galaxy and the larger universe
- Advance scientific knowledge of our planet and its atmosphere
- Enhance technology development to serve radio science and radar sensing
- Contribute to the education and training of the next generation of scientists and engineers

Haystack Observatory was founded in 1970 and occupies 1,300 acres of hilly woodlands in the towns of Groton, Tyngsborough, and Westford, 40 miles northwest of the MIT campus in Cambridge, Massachusetts. A group of 100 scientists, engineers and technical personnel conducts the Observatory's research programs and operations. Haystack receives its primary financial support from the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Department of Defense (DoD).

Science at Haystack: From the Earth to the Limits of the Observable Universe

Current radio astronomy research programs at Haystack focus on important questions that captivate today's astronomers. These inquiries pertain to the origin and evolution of the universe, the powerful variable emissions from galaxies and the black holes they contain, the births and deaths of stars, and the energy mechanisms in and around our Sun.

The science of geodesy allows researchers to make precise measurements of the Earth's plate tectonic motions and its orientation parameters, with emphasis on the study of their variation over short time scales. Haystack's atmospheric science goals are focused on understanding the connections between the Sun and Earth. To do this, Observatory researchers study the effects of solar disturbances on Earth's upper atmosphere.

Haystack's research programs are coupled with major technology and instrumentation efforts that include the development of large telescope arrays and high-power radars, and the application of modern information technology to scientific techniques.

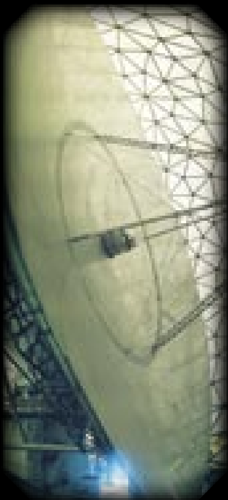
An extensive education program focuses on both undergraduate and graduate student research experiences. It includes training graduate students and post-doctoral scientists through research activities, while undergraduate students take part in the programs through internships and access to the Observatory's telescopes. A broad informal outreach program brings Haystack scientists and technical specialists in contact with local area science teachers and high school students, as well as the public.

Geodetic Studies

Haystack Observatory facilities occupy wooded hills in northeastern Massachusetts. Shown in the photograph are the Haystack 37-meter radio telescope and radar in the large radome (top right), the Millstone Hill incoherent scatter radar antennas (center), the Lincoln Laboratory Millstone Satellite Tracking radar 26-meter antenna (bottom right), and the Firepond optical facility with its 1.2-meter telescope (bottom left).

Research Facilities

Haystack Observatory's primary research facilities include a collection of large radio antennas for astronomical and geodetic Very Long Baseline Interferometry (VLBI) observations and ionospheric radar measurements, a correlator to process VLBI measurements, an optical facility for upper atmospheric measurements, and testbeds for technology development.



Haystack 37-meter radio telescope with a cutaway view of it in its radome.

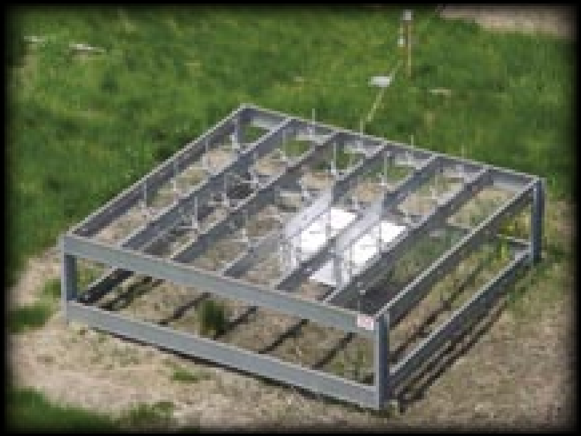
Haystack Radio Telescope. This 37-meter radio antenna performs astronomical observations at frequencies from 20 to 100 GHz, and radar imaging of satellites and space debris measurements at 10 GHz. The telescope is part of a global VLBI observation network, and is available via remote Internet access for educational projects associated with the study of such objects as star-formation regions and maser emissions from molecules in space. A major upgrade of the antenna by MIT Lincoln Laboratory will enable radar operations at 95 GHz to improve the spatial resolution of satellite images. The improvements will also benefit future radio astronomy research through enhanced telescope sensitivity at 100 GHz and above.

Westford Radio Telescope. The 18-meter Westford Radio Telescope antenna is an important link in a global VLBI network of geodetic radio observatories operating at 2.8 and 8.4 GHz that routinely gather data on Earth's plate motions and orientation parameters. The telescope is also used by the Observatory as a test bed for wideband data transmission experiments through fiber networks, and for space communication tests by Lincoln Laboratory.

The Westford 18-meter radio telescope (housed in an inflatable radome) operates with radiometers at frequencies of 2.8 and 8.4 GHz as part of the international VLBI geodetic network.

VLBI Correlator. VLBI telescopes generate tremendous volumes of information, which require a correlator to take the data and turn it into a scientifically-useful product. Haystack's correlator, developed on site and replicated at several other VLBI data processing centers around the world, is capable of playing back and processing wide-bandwidth data collected from multiple VLBI telescopes engaged in global geodetic and astronomical network observations. It is equipped with both tape and disk recording systems, and is also used as a research and development test bed for enhancement of real-time data processing and software development.

Deuterium Array. This telescope consists of 24 stations, each equipped with 24 dipole antennas and a receiver tuned to 327.4 MHz, the emission frequency of deuterium, an isotope of hydrogen. The deuterium line being searched by this array is a sensitive indicator of the density of baryons, the particles that make up atomic nuclei. A measurement of this density can then be related to the amount of dark matter in the universe.



A closeup of a station of the Deuterium Array.

Millstone Hill Incoherent Scatter Radar. This facility operates at 440 MHz, with a 46-meter antenna and a 67-meter antenna, using incoherent backscatter techniques to study the Earth's atmosphere above 100 kilometers. The 67-meter radar points to the zenith and monitors atmospheric variations above Massachusetts, while the 45-meter antenna is fully steerable and gathers data about the upper atmosphere from northern Canada to southernmost Florida.

Atmospheric Optical Facility. Haystack's optical facility supports the ionospheric radar measurements program. It includes Fabry-Perot interferometers that observe the emission from atomic oxygen in the Earth's upper atmosphere in order to derive the velocity of its neutral winds.

Millstone Hill Incoherent Scatter Radar antennas.

Atmospheric Optical Facility.

Collaborations

Haystack researchers collaborate with faculty members and staff in various MIT departments and research centers, including the Center for Space Research, the Physics Department, the Computer Science and Artificial Intelligence Laboratory, and the Department of Earth, Atmospheric and Planetary Sciences.

MIT departments maintain other observing facilities located on the land in Westford, Massachusetts, in addition to those that form the Haystack research complex. They include the George R. Wallace Astrophysical Observatory for research and teaching in optical astronomy, which is equipped with 0.6-meter and 0.4-meter telescopes, and a geophysical observatory that utilizes sensitive seismometers to monitor ground motions as part of a global seismic network. The MIT Department of Earth, Atmospheric, and Planetary Sciences operates both facilities. The Haystack Observatory also occasionally hosts instruments from other MIT departments and research centers.

A close relationship exists with MIT Lincoln Laboratory, which shares and supports the research infrastructure at Haystack for space surveillance activities sponsored by the United States Air Force. While some of the site radars are dedicated to the Air Force program, most of the facilities are shared between the astronomical and space surveillance activities, and some of the Observatory's engineering staff contribute to both programs, resulting in an overall cost-effective operation. Lincoln Laboratory uses the Haystack radar operating at 10 GHz, the Millstone Hill Satellite Tracking Radar – a 26-meter antenna operating at 1295 MHz, the Haystack Auxiliary Radar – a 12-meter antenna at 16.7 GHz, and the Firepond Optical Facility.

Finally, Haystack Observatory enjoys excellent collaborative relationships with universities and research institutions in the northeast United States. The Northeast Radio Observatory Corporation (NEROC) is a non-profit consortium of educational institutions that oversees and guides Haystack's radio astronomy program. NEROC includes Boston University, Brandeis University, Dartmouth College, Harvard University, the Harvard-Smithsonian Center for Astrophysics (CfA), MIT, the University of Massachusetts, the University of New Hampshire, and Wellesley College.

NEROC members utilize the Observatory's resources for undergraduate education and for graduate student research. Haystack also provides support to NEROC institutions for their own projects. The Smithsonian Institution recently assembled and tested the Submillimeter Array antenna mounts at Haystack, prior to their installation on Mauna Kea in Hawaii. The University of Massachusetts runs a digital ionospheric sounder at the Observatory, and Boston University operates optical imagers to study upper atmosphere dynamics. Haystack also maintains close relationships with the Harvard-Smithsonian Center for Astrophysics and Brandeis University through various VLBI programs, and with the University of New Hampshire for correlative investigations of the Earth's upper atmosphere using the meteor wind radar in Durham, NH. In addition, several of the NEROC institutions participate in developing the next generation of radio arrays and collaborate with Observatory researchers on these projects.

Haystack Observatory welcomes visiting instruments from other institutions for collaborative research. Currently this includes global positioning satellite (GPS) systems from the University of Texas, optical interferometers from the University of Pittsburgh, and infrared radiometers from Utah State University.

Astronomy

Solar Physics. The nearest star to Earth, our Sun, dominates the radio sky and provides a convenient laboratory to investigate various radio phenomena at high spatial and spectral resolutions. Haystack scientists are studing observational techniques to probe the charged outer layers of the Sun that affect Earth through the solar wind and geomagnetic storms.

Stellar Evolution. Radio astronomers probe the interstellar medium (ISM) by observing molecular "signatures" that provide information about the temperatures, densities, chemical compositions, and velocities of the gases surrounding stars. Star-forming regions are dense with molecular clouds that gravitationally coalesce into hot, young stellar newborns. Scientists at Haystack use single-dish radio astronomy to observe molecules such as methanol (CH_3OH) in large regions containing numerous new stars.

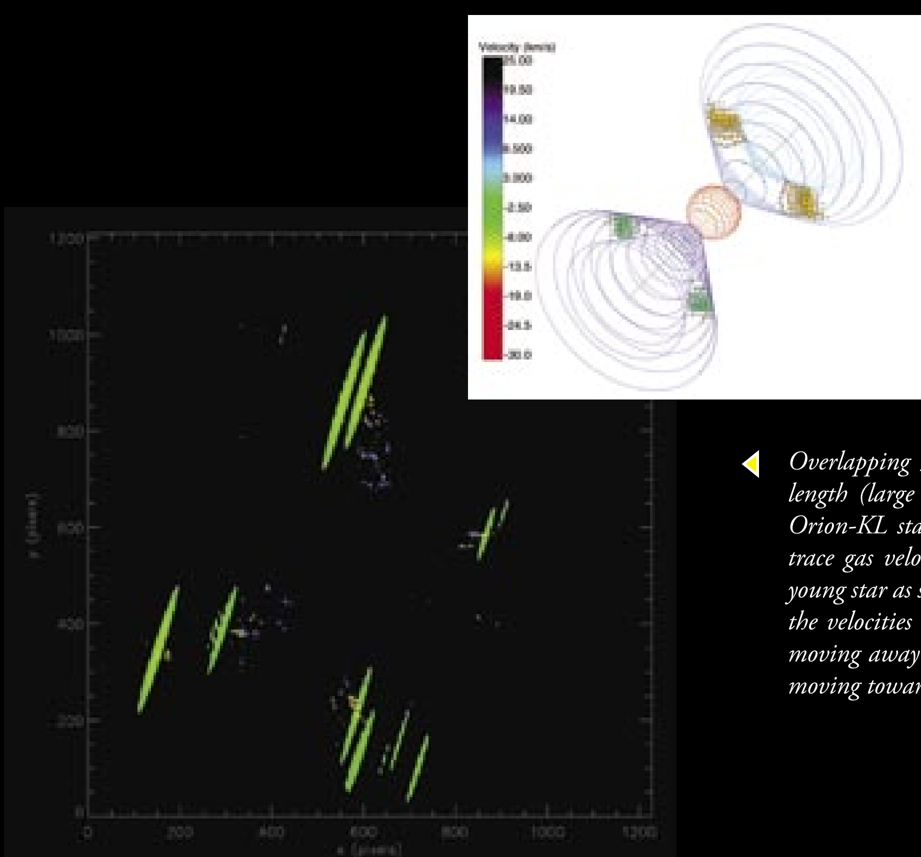
VLBI techniques allow very high-resolution observations of emission from molecules such as silicon monoxide (SiO). These come in the form of masers—regions of gas and dust that send out laser-like beams of microwave radiation towards Earth. Masers can trace the velocities of outflows emanating from young protostars buried in opaque molecular clouds such as those in the Orion nebula.

At the end of its life our Sun will expand as a red giant star, possibly swallowing the inner planets of the solar system. VLBI observations of SiO masers around other red giants such as R Cassiopeiae provide insight into the aging of stars similar to the Sun by allowing scientists to study gas dynamics in their atmospheres.

Galactic Astronomy. The Milky Way Galaxy is home to a vast array of interesting astronomical objects: planets and planetary systems, molecular clouds, star-forming regions, and nebulae. A strong radio source of another kind lies at the heart of our own galaxy, the Milky Way. Sagittarius A (known as Sgr A*) is a very compact object thought to house a black hole. Astronomers at Haystack have made very high-resolution VLBI measurements of Sgr A* that show this mysterious source of radio waves to be no larger than 150 million kilometers across.

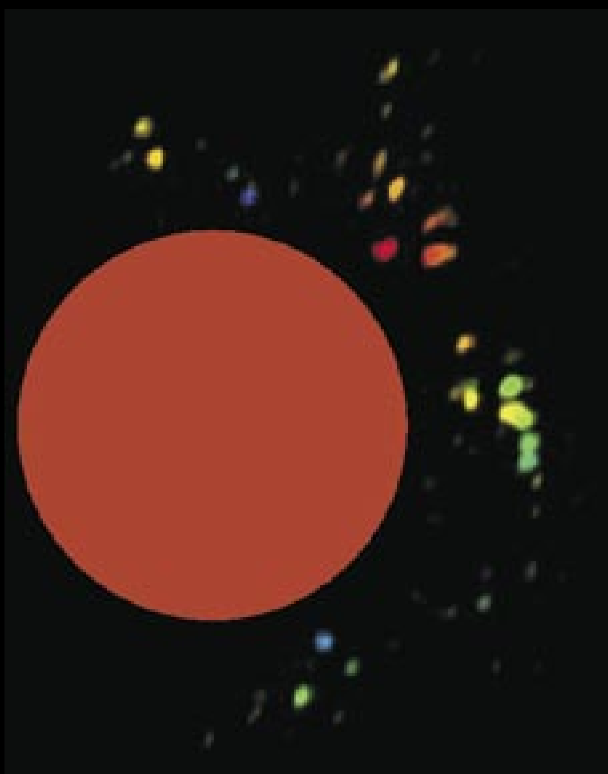
Extragalactic Astronomy. The most active and violently energetic objects are found far from the Milky Way and display strong, point-like sources of radio emissions. Among these are starburst galaxies, active galactic nuclei, and quasars. Very high-resolution images of the starburst galaxy Arp 220 produced at Haystack revealed its emission sources to be the remnants of hundreds of supernovae explosions.

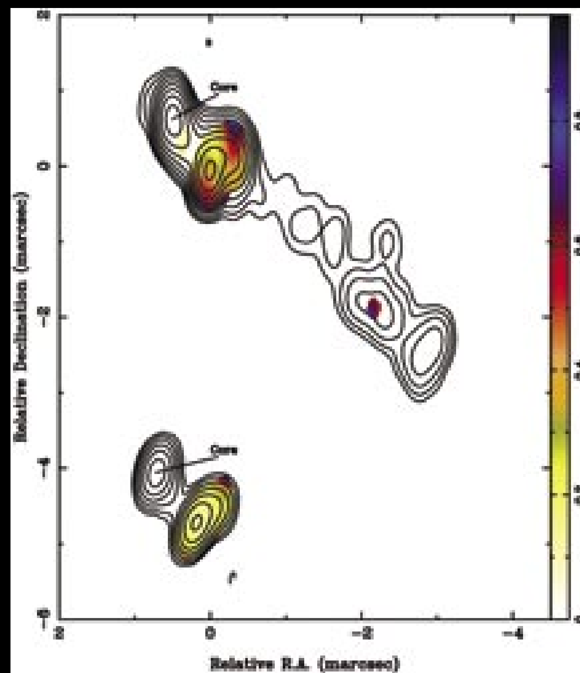
The most energetic objects known in the cosmos are hidden in brilliant, tiny point sources of light called quasars. They lie at the limits of the observable universe and hold the record for energy output. Each second a quasar blasts out as much energy as a supernova explosion. Its violent emissions can only be explained by the presence of a supermassive, rotating black hole at its core. Using high-frequency VLBI, Haystack scientists observe these powerful energy emitters at ultra-high resolution, imaging regions that lie within a light-year of the central black hole.



Overlapping 7-millimeter (small spots) and 3-millimeter wavelength (large green stripes) images showing SiO masers in the Orion-KL star forming region. The masers' spectral fingerprints trace gas velocities in conical shapes emerging from the central young star as shown in the inset. The colors of the masers represent the velocities of the gas. The masers in the upper right cone are moving away from Earth, while those in the lower left cone are moving toward Earth.

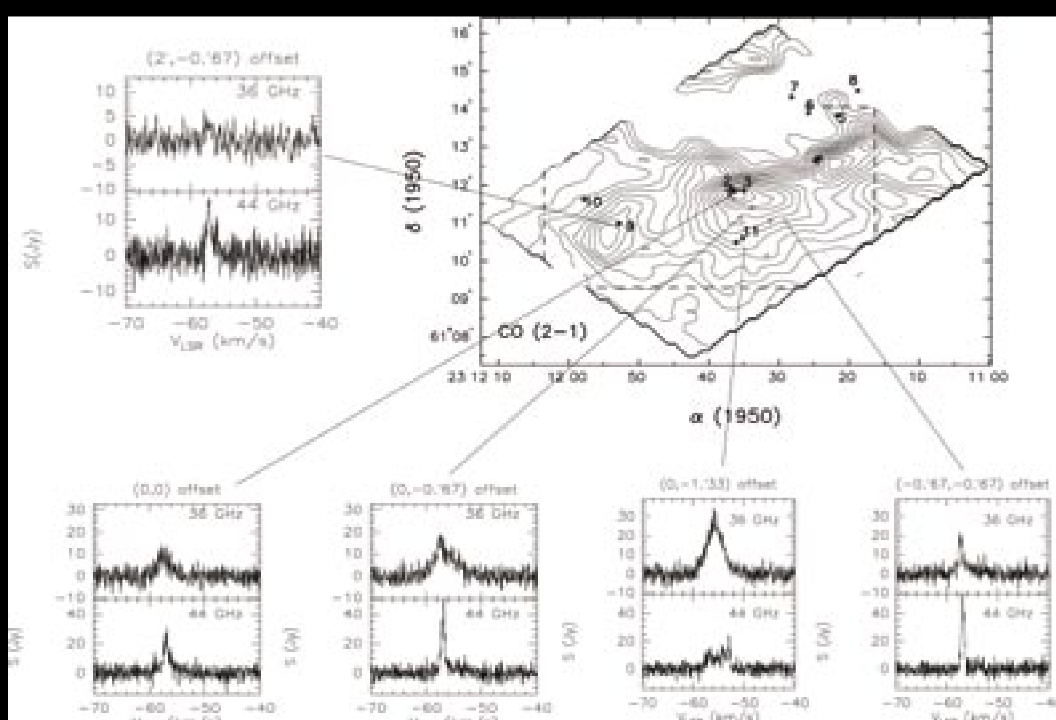
SiO maser spots (rainbow colors) observed at 3-millimeter wavelength show a nearly complete circumstellar ring surrounding the pulsating red giant star R Cassiopeia. The central red disk is a computer-generated image to show the size and orientation of the star with respect to the masers. The smaller red spots are masers moving toward Earth, and blue spots are masers moving away from Earth.





Images of the quasar 3C273 at 7-millimeter wavelength (top) and 3-millimeter wavelength (bottom). Contours represent the strength of the total intensity of radio radiation in the source; colors represent the strength of the polarized radio radiation intensity. Polarized radiation is not visible in the core, implying the presence of a thick cloud of material that surrounds the central black hole, and blocks the polarized radiation from escaping to Earth.

Spectra of methanol masers detected with the Haystack 37-meter telescope. Their positions are identified on a carbon monoxide image of NGC 7538 [C.J. Davis, et al.]. The two spectra at each position are from two transitions of methanol. The line shapes indicate different physical conditions such as temperature and density. The 44 GHz line appears to be from maser emission while the 36 GHz line seems to switch from thermal to maser emission.



Geodesy and Geophysics

Geodesy and geophysics are concerned mostly with what is going on under our feet, so it may seem ironic that these two disciplines are advanced by looking up at the stars! VLBI techniques, which were originally developed for studying radio objects in the universe can, in effect, be turned upside down to do very precise studies of the Earth. By simultaneously collecting data from a single radio source via a worldwide array of radio telescopes, the relative time-of-arrival of signals from that source to each telescope can be determined to within a few picoseconds (3 picoseconds = 1 mm of light travel time). By observing many radio sources spread widely over the sky over a period of 24 hours, data are collected that allow the ultra-precise measurements of the Earth and its orientation in space. The geodetic VLBI techniques in use at Haystack originated more than three decades ago at the Observatory, which continues to lead the way in new developments and improved accuracy in these important research methods.

Geodetic VLBI in Action

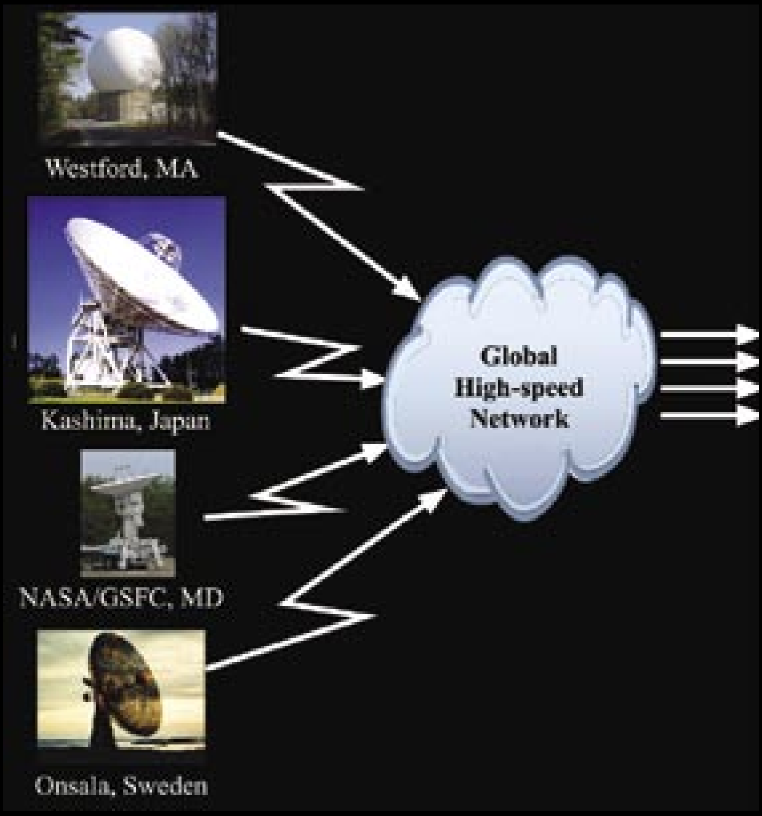
Among the important applications of geodetic VLBI are:

Measuring tectonic plate motions. By determining the relative 3-dimensional position of globally distributed telescopes to a precision of a few millimeters, motions of the Earth's tectonic plates can be directly measured. A 10-year time history of the distance between the Westford antenna and an antenna in Germany shows that the separation of North America and Europe is proceeding at a steady rate of about 17 millimeters per year. Global tectonic motions measured by VLBI also allow scientists to measure changes in the position of the famous San Andreas fault in California, where the Pacific plate slips past the North American plate at the rate of about 5 centimeters per year.

Measuring "post-glacial" rebound. The last Ice Age, which occurred more than 10,000 years ago, depressed large areas of the Earth's crust under a thick blanket of ice. When that ice melted, the surface began to rebound, a process that continues today and can be measured with geodetic VLBI. Such studies help scientists understand the elasticity of the Earth's surface and the role of its underlying structures.

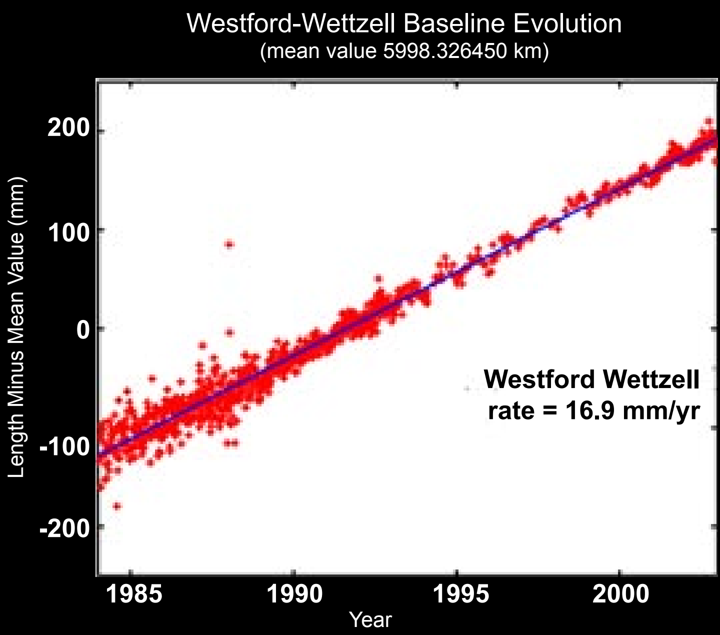
Measuring and monitoring changes in the Earth's rotation and the wobble of its axis. Our planet is perceived to turn at a uniform rate with a steady axis of rotation, but it actually wiggles and wobbles in space and experiences changes in rotation rate every day. While these perturbations are small, they *are* real and VLBI can measure them. These motions are important in understanding the Earth's dynamics and the physical processes that drive them. Many factors influence Earth's motion, among them the action of surface weather, which is a major driver in changes of the planet's rotation period.

Understanding the interaction between Earth's mantle and core. By measuring minute variations of the Earth's motion in space, it is possible to study the dynamic interactions between the material at the boundary between the Earth's solid mantle and its liquid core. Geodetic VLBI is currently the only scientific technique that allows direct observations of the consequences of these interactions, and is thus a very important technique for understanding what is happening deep within the Earth.

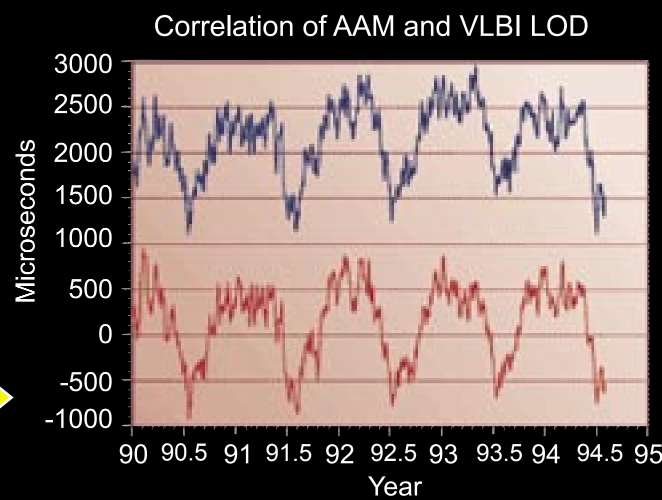


Mark 4 VLBI Correlator

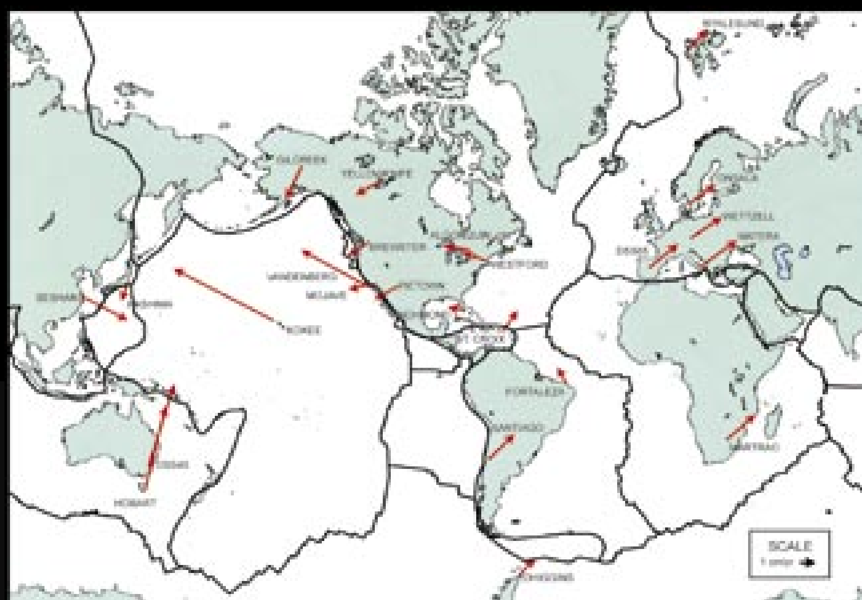
Global high-speed networks allow the direct connection of antennas to a correlator for real-time VLBI data processing. The antennas shown here are among those already connected; more are added each year.



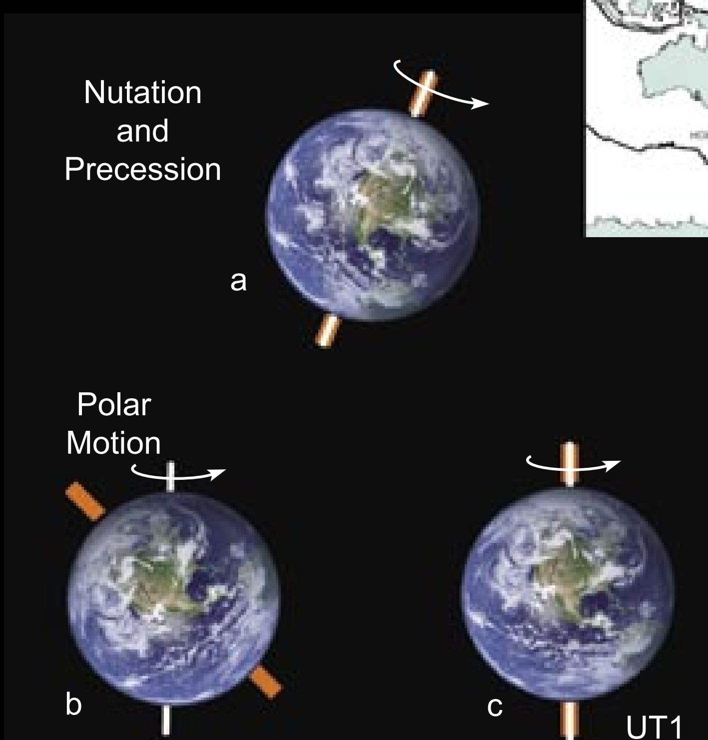
The length of the baseline between Westford, Massachusetts, and Wettzell, Germany, as measured by VLBI from 1985 through 2002. The increase in length is interpreted as a measurement of separation between the European tectonic plate and the North American tectonic plate with a rate of 17 millimeters per year.



Variations of Atmospheric Angular Momentum (AAM, in red) and VLBI length-of-day (LOD, in blue) are strongly correlated over periods of one week to several years. This implies that changes in the Earth's rotation rate are primarily influenced by the Earth's changing weather.



A summary of geodetic VLBI observations showing global tectonic plate motions relative to a net non-rotating reference frame. The red arrows show the direction and speed of the measured motions. Note the motion of the Pacific plate along the North American plate at the San Andreas fault; the westward velocity is five centimeters per year.

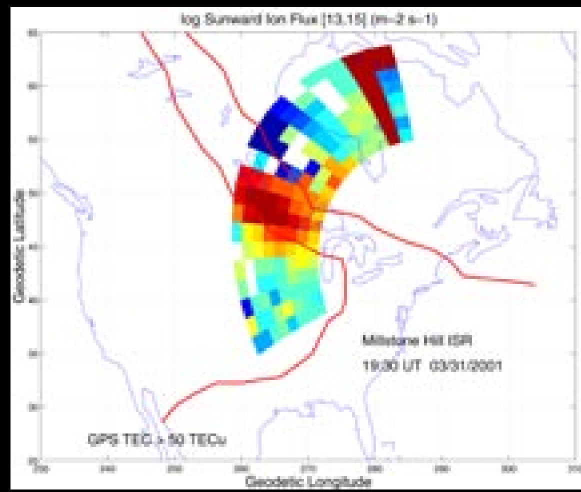


Earth Orientation Primer. The north and south geographic poles (in red) are imaginary fixed points on the Earth that define latitude. The spin axis (in white) is the line about which the Earth rotates at a particular instant. At some time in the past the poles were defined to coincide with the spin axis. Changes in the Earth's orientation are described in three ways, greatly exaggerated here for clarity. (a) Nutation and precession are the periodic and long-term motion of the spin axis in space with respect to the distant quasars. (b) Polar motion describes the motion of the N and S poles about the spin axis. Over time the poles are spiraling away from the spin axis. (c) UT1 describes the non-uniform daily rotation of the Earth; at any particular time, the rotation angle of the Earth differs from what would be predicted if the rotation rate was exactly constant.

Atmospheric Science

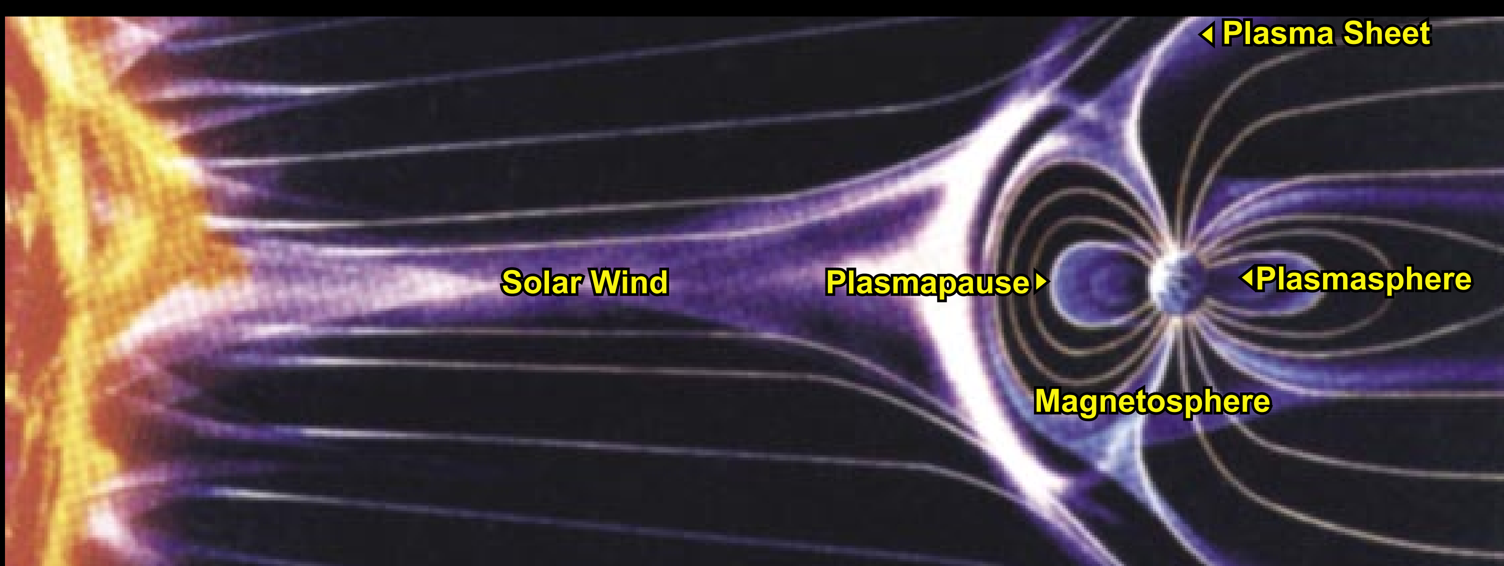
Earth's atmospheric blanket and the protective bubble of the magnetosphere shelter everything on the planet from the most energetic wavelengths of the Sun's radiation. Haystack Observatory's Atmospheric Sciences Group studies all levels of the atmosphere using incoherent scatter radar (ISR) techniques. The group has been operating for more than forty years, collecting ionospheric measurements spanning a range of latitudes covering most of Eastern North America. The radar's extensive field of view for ionospheric observations encompasses the full extent of mid-latitude, sub-auroral and auroral features and processes. The unique location of Millstone Hill near the Earth's plasmapause, combined with the wide reach of the Millstone Hill Steerable Antenna, have made it a premier facility for mid-latitude ionospheric research, magnetospheric studies, and thermospheric measurements. In addition to improving our fundamental understanding of the near-Earth environment, this research has immediate relevance to the welfare of people and our technological society since it contributes to the development of improved space weather alerts and storm predictions.

Regions of the magnetosphere are coupled along magnetic field lines to the ionosphere, which causes it to behave almost like a viewing screen for processes occurring in the magnetosphere. This greatly extends the scope of the Observatory's investigations. Explosions on the Sun create storms of radiation that release energetic particles which travel outward with the solar wind to Earth. The solar wind, in turn, interacts in complex ways with Earth's magnetic field, leading to geomagnetic disturbances that can seriously impact satellites, power grids, and communications systems. Solar wind-driven magnetospheric phenomena can cause almost immediate disturbances in the mid- and low-latitude ionosphere. During one such event the interplanetary magnetic field, which is carried by the solar wind, oscillated between southward and northward with a period of about two hours. The Millstone Hill incoherent scatter radar detected similar periodic oscillations in all mid-latitude ionospheric F-region plasma parameters. The close link between the solar wind and the ionosphere could well be related to the penetration of the interplanetary electric field into the ionosphere. This interaction between the solar wind and mid-latitudes plays a very important role in the space weather effects detected.



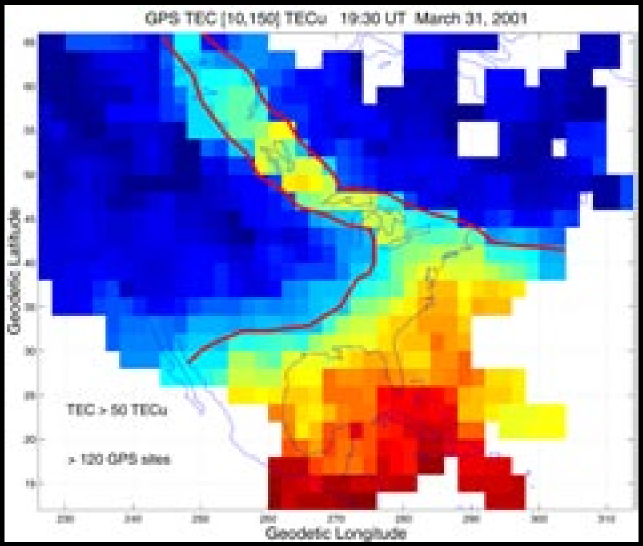
Ion velocity measurements using incoherent scatter radar track the movements of ions through the upper atmosphere as a result of the interaction between the Earth's magnetosphere and the solar wind.

The Millstone Hill radar frequently observes storm-enhanced density during the early stages of magnetic storms. These and related phenomena are now much better understood as a result of a multi-sensor approach utilizing data from the radars, Global Positioning Satellites (GPS), imaging satellites, and the Super Dual Auroral Network (SuperDARN) coherent radars. Total electron content measurements from a worldwide network of GPS receiving sites reveal plumes of plasmaspheric material streaming toward north polar regions. Simultaneous ion velocity measurements by the incoherent scatter radar show that this material moves at speeds of a kilometer per second. During strong space weather events, material in the upper ionosphere is redistributed from lower latitudes through middle latitudes and ultimately to the rarified atmosphere over the polar regions, moving material from over South America to the north slope of Alaska in as little as 30 minutes.

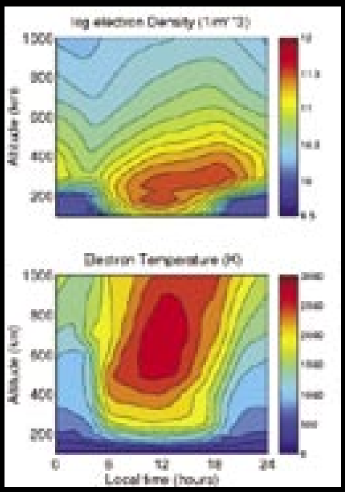


In addition, geomagnetic storms have a major influence on the Earth's thermosphere (the neutral atmosphere at altitudes ranging from about 100 to 1,000 kilometers). Haystack Observatory leads community-wide efforts to better understand space weather's role in the activities observed in this region during solar storms. Observatory research shows that during major geomagnetic disturbances, the tidal pattern of neutral winds in the lower thermosphere at middle latitudes is heavily disrupted and becomes dominated by the ion-driven convection.

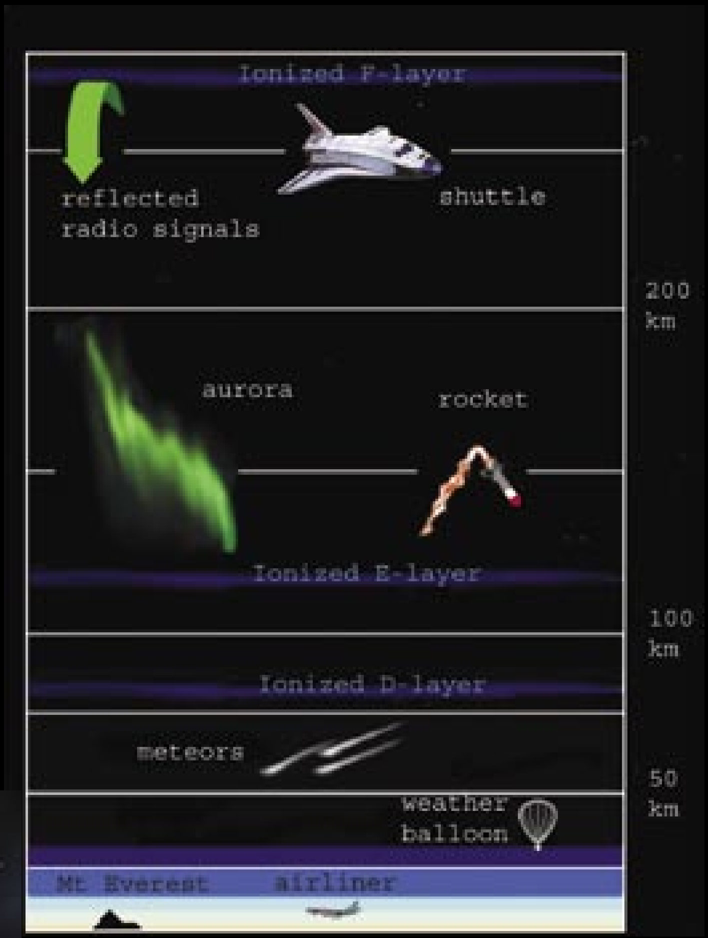
Improved specifications and predictions of the ionosphere and thermosphere system are important objectives of the U.S. National Space Weather Program. Regional and local models can be more useful than global models, which often smear out features unique to a particular region like eastern North America. Based on the long-term Millstone incoherent scatter radar database, which covers nearly three solar cycles, Haystack scientists have developed a series of empirical models of electron density, electron and ion density, and vector ion drift in local areas. The Haystack Observatory Web site provides open and easy access to these simulations. Based on the techniques developed for the Millstone data sets, similar models have been constructed for other incoherent scatter radars, with the ultimate goal of combining them into regional models for North America and Western Europe.



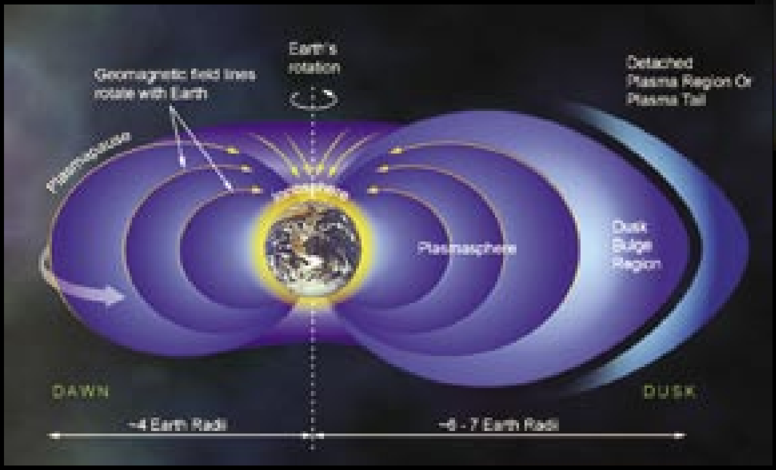
Global Positioning Satellites (GPS) and their ground-based receiving sites tracked the total electron content above the North American continent during a solar storm and revealed plumes of plasmaspheric material streaming toward northern polar regions.



The Millstone Hill empirical models provide climatological averages of ionospheric electron density and temperature.



The various layers of the Earth's atmosphere. The Millstone Hill radar probes these layers in an effort to chart changes brought about by interactions with the solar wind.



The Earth's plasmasphere is a torus-shaped region contained within our planet's magnetosphere.

Array Technology and Applications

Scientists at Haystack use advanced technologies to develop new radio arrays to observe in the unexplored, low frequency regime of the radio electromagnetic spectrum, in the hope of expanding the potential for new discoveries. Current radio telescopes and arrays are limited in their sensitivity when operating at frequencies below about 400 MHz. In addition, observations at these low frequencies are hampered by radio frequency interference (RFI) from a variety of sources, among them cellular telephones, car ignitions, answering machines, broadcast television, and radio transmitter signals. New digital technology allows researchers to excise this noise from the data, and permits the long integration times needed to detect weak astronomical signals.

The Deuterium Array. Deuterium, often called "heavy hydrogen," is an isotope of hydrogen having one proton and one neutron, and emits at a frequency of 327.4 MHz. The detection of deuterium is considered to be one of the most important goals in radio astronomy, because measurement of hydrogen abundances vs. deuterium abundances will provide a gauge of the amount of dark matter in the universe. In theory, as the primordial fire of the "Big Bang" cooled, neutrons and protons combined to form deuterons—the nuclei of deuterium atoms. When the density of the deuterons was high, nuclear reactions continued and the deuterons went on to form helium and other heavy atoms. The primordial abundance of deuterium is determined by the competition between the nuclear reaction rates as elements form, and the universal expansion rate. As the infant universe expanded, the deuteron density should have decreased, leaving more deuterium and less helium. At optical wavelengths the characteristic signatures of deuterium are confused by nearby fingerprints of hydrogen. At radio wavelengths however, the signatures are easily identifiable.

Station with active crossed dipoles and beam directors. An RFI monitor system is shown in the background on the roof of the trailer.

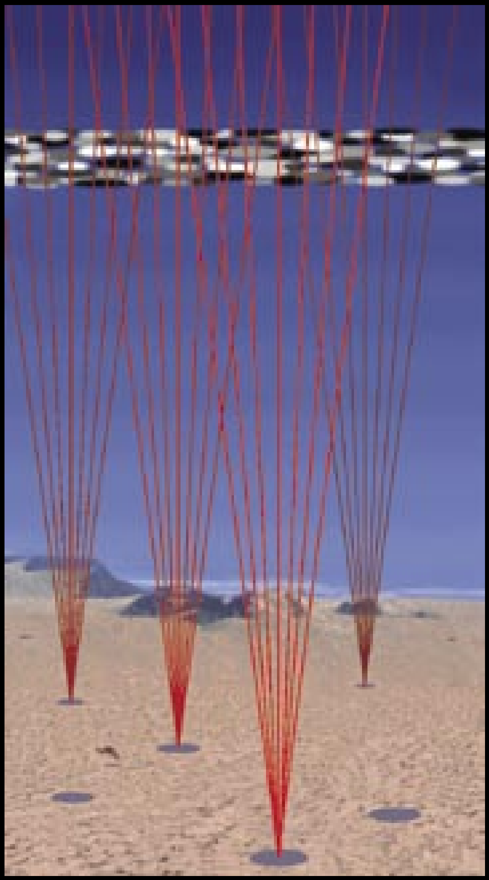
48-channel receiver.

Stations of the Deuterium Array.

MWA: Mileura Wide-field Array. Building on the experience of designing and implementing the Deuterium Array, Haystack scientists are extending their expertise to include the low-frequency radio regime below 300 MHz. This technology development arises from worldwide scientific interest in exploiting an essentially unexplored part of the electromagnetic spectrum. Haystack's antenna designs, correlator architecture, data simulation package, and calibration schemes are being implemented in the design of low-frequency interferometric arrays such as the Mileura Wide-field Array (MWA) in radio-quiet Western Australia and the larger Square Kilometer Array (SKA) that is expected to be built in the next decade.

An artist's conception of a small portion of the MWA in Western Australia.

MWA Science Drivers. The revolutionary design of the MWA will enable astronomers to probe a variety of scientific regimes never before studied. One of the most exciting science drivers is the study of the Epoch of Re-ionization (EOR), the time in the early universe when neutral hydrogen was ionized, leaving behind a transparent universe containing the first stars and quasars. Signatures of this process should be readily detectable within the frequency range covered by the MWA. This capability will make it the first instrument to not only detect the EOR, but to characterize the three-dimensional structure of the universe as the first stars and quasars formed.



The ray paths (in red) from individual MWA sub-arrays (grey disks) will overlap, permitting high-precision tomography of the ionosphere above the array.

The universe is filled with variable bursts of energy called transients, and astronomers cannot predict where or when they will occur. The constant wide-field capability of the MWA will catch a variety of transient sources at low-radio frequencies such as gamma-ray burst afterglows from distant quasars, flares from active galactic nuclei, and giant pulses from pulsars. The system will feature buffered storage so that astronomers will have a look-back capability as they track transient events.

Another science driver for the MWA is located close to home. When our Sun emits a strong coronal mass ejection (CME), satellite transmissions, cellular telephones, pagers, and airline communications are interrupted. The CMEs also cause interplanetary scintillations of radio-emitting sources. The MWA will be optimized for detection and study of those effects. By studying CMEs, especially the orientation of their intrinsic magnetic fields, scientists will better understand their effects on Earth, and possibly learn to predict them.

Photograph of a prototype MWA dipole designed and built at Haystack.

Data Transport and Signal Processing for VLBI

Today's VLBI experiments collect prodigious amounts of data, requiring modern data transport and digital-signal-processing techniques to transform this information into a scientifically useful form. Haystack Observatory has long led the way in developing systems to enhance the capabilities of VLBI and the science it enables.

Data Transport. Continuous data rates of up to 1 Gbps (i.e. 1 billion bits per second) per telescope are now common in VLBI, with rates expected to progress up to 10 Gbps within a few years. The massive data streams from each of twenty widely separated telescopes must be collected and combined together into usable form for scientists to analyze.

The Mark 5 disk-based VLBI data system was developed at Haystack Observatory to meet the challenge of managing these large data rates. Until the Mark 5, VLBI data were almost universally recorded on magnetic tapes that were physically shipped to a central processor. Today, users of the Mark 5 system can select from two data transport methods: recording on inexpensive magnetic disks, or transmission over global high-speed networks.

More than 100 Mark 5 systems are now in use worldwide at telescopes and correlators. These systems, combined with more than 5,000 disks of total storage space exceeding a petabyte (1 petabyte = 1,000 terabytes = 1,000,000 gigabytes), are available to meet VLBI storage requirements.

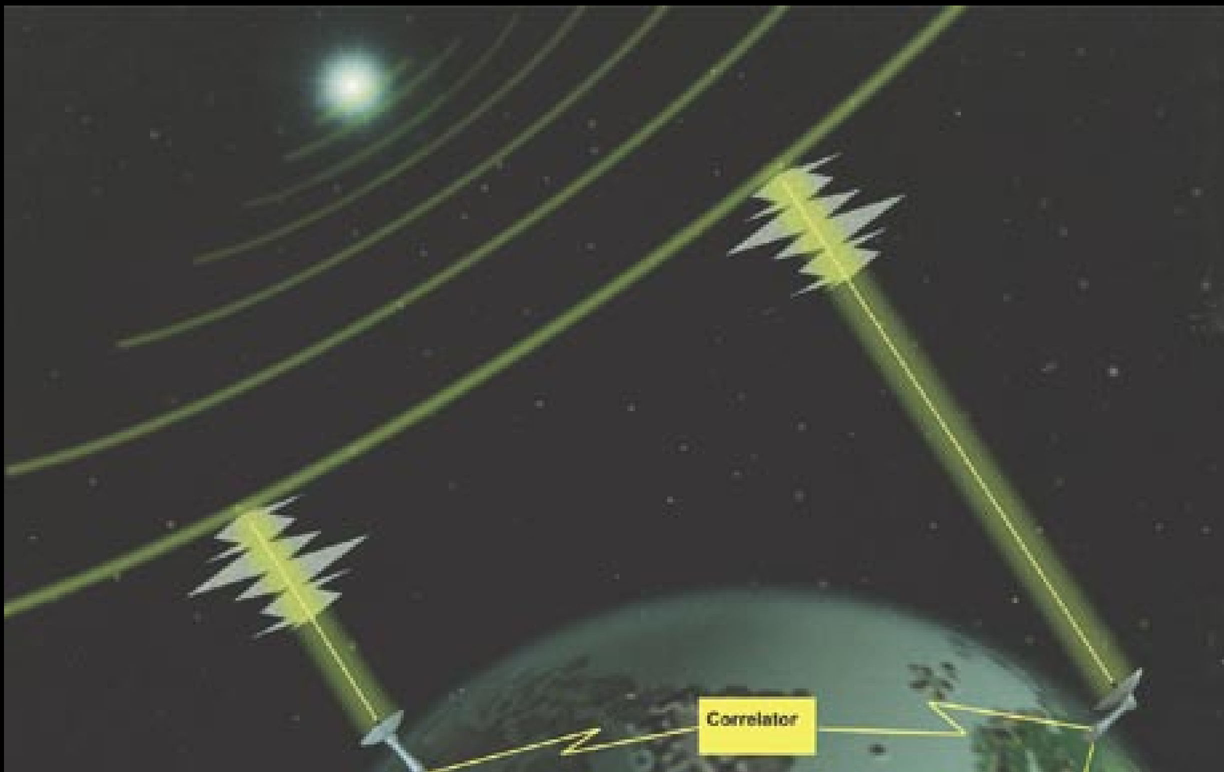
Increasingly, VLBI data are traveling over global high-speed networks, dubbed "e-VLBI." This allows fast turnaround for processing, leading to quicker diagnostics, and more timely response to observing conditions and transient radio phenomena, all of which help to produce better science.

Signal Processing. VLBI data collected at individual telescopes are nothing more than pure random noise, with a small component coming from target radio sources. The rest comes from receivers, the atmosphere and other unavoidable signal sources. Huge amounts of signal processing are required to extract the weak correlated-signal components common to all the telescopes. Correlation processing extracts these signals from the target source, and is the first in a series of complex processing steps leading to the final scientific result.

As part of the International Advanced Correlator Project, in collaboration with other U.S. and European institutions, Haystack Observatory has developed and operates a 16-station Mark 4 VLBI correlator. The Observatory's role was to produce the critical signal-processing core of the correlator, based on a large custom correlator chip designed especially for the task. The Mark 5 VLBI data system has now been connected to the Mark 4 correlator to realize even more powerful processing capabilities that will carry VLBI through the next decade.

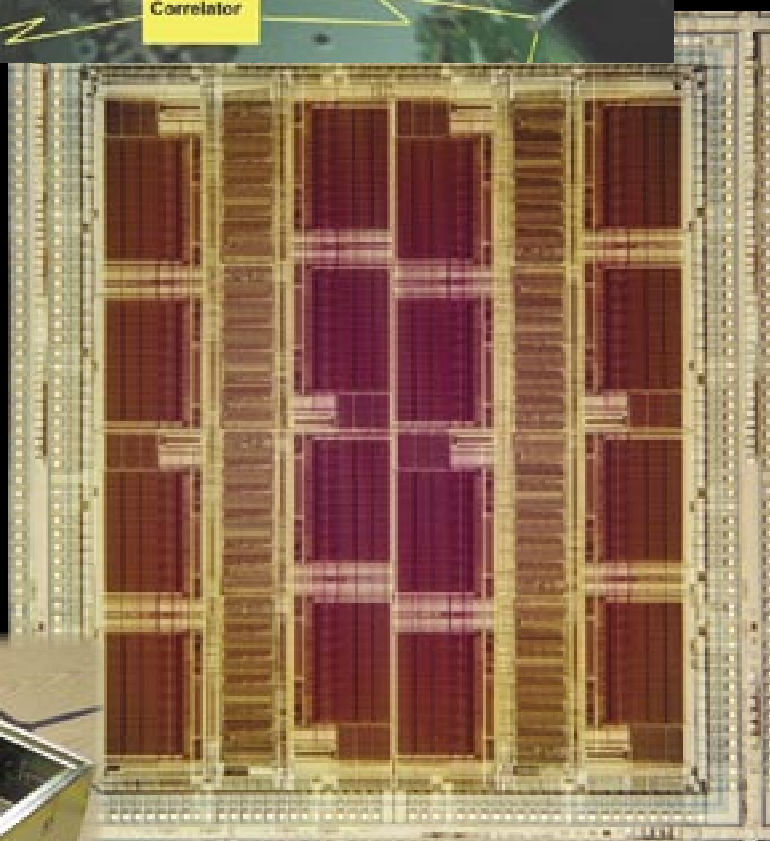
Technology spin-off. VLBI techniques have been successfully applied to the location of E-911 calls from cellular phones using measurements of differences in the signal time-of-arrival at cell phone towers. Haystack developed the algorithms and processing systems for such a network solution for the location of emergency calls from cell phones to an accuracy better than 100 meters, with particular emphasis on improving accuracy by reducing the effects of multipath propagation. The program was sponsored by TruePosition, Inc., and Haystack engineers worked collaboratively to bring this system into practical reality, thus demonstrating the spin-off of basic research using VLBI to the benefit of society. The TruePosition™ system is now in use by several cell phone companies.

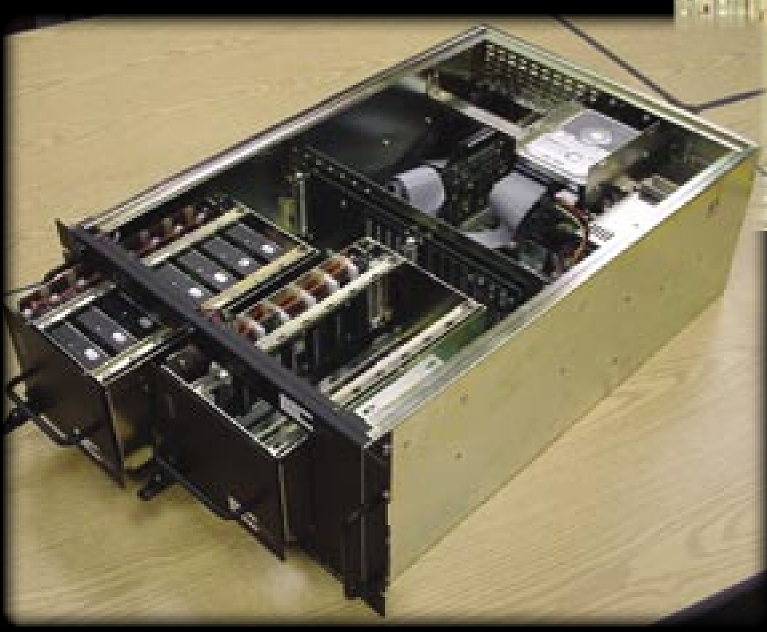
The Mark 4 VLBI correlator, with its seven tape drives for data playback. These drives are now being replaced with the Mark 5 disk-based system.



Telescopes connected through high-speed fiber networks to a correlator allow data to be transmitted in real-time from telescopes to correlator. "e-VLBI" is expected to become the dominant form of VLBI data transport over the next decade.

Details of a single Very Large Scale Integration (VLSI) correlator chip used in the Mark 4 VLBI correlator, containing ~1,000,000 transistors. This chip is being used in six major correlator projects in Europe and the U.S., including the Smithsonian Institution's Submillimeter Array (SMA) on the summit of Mauna Kea in Hawaii.





The Mark 5 VLBI data system, jointly developed by Haystack Observatory and Conduant Corporation, records data on removable magnetic-disk modules at sustained data rates to 1 Gbps. The system can also be used to move VLBI data over high-speed global networks directly from telescopes to correlators around the world.

Advanced Radar Techniques

The Haystack Observatory Atmospheric Sciences Group actively pursues technological advances in the acquisition, reduction, archiving, and dissemination of incoherent scatter radar (ISR) data. Much of this activity proves useful for other types of instruments and data. The overarching principle behind Haystack's hardware and software development efforts, as well as data distribution, has been the concept of free and easy availability. The open-source movement, well known for Linux, the Apache Web server and other large software projects, has been both an inspiration and a source of tools for realizing this idea.

Hardware designs, software, data, empirical models and documentation are available at: http://www.openradar.org, http://www.openisr.org and http://www.openmadrigal.org. They have several elements in common. First, there is a Web-accessible Concurrent Versions System (CVS) archive of all software. It provides version control of software development, a mechanism for parallel software advances by multiple users, and a means for distributing software source code via the Web. Second, there are mailing lists for developers and users. These have proved to be efficient means of communication between developers, and in the case of Haystack's Open Madrigal database system, the user mailing list has been a useful conduit for suggestions to improve access to the data. Third, extensive documentation is available through each of the Web sites.

The Open Radar Initiative (Open ISR) develops reliable and reusable technology for radio science applications. It provides a resource for the development of radio science systems, reduces the duplication of effort in the community, provides a means for distributing innovative techniques, and lowers the expense and difficulty of developing new experimental systems. The initial focus of the initiative is to produce a set of hardware and software components that can be combined to construct and modernize ionospheric radars. Components are being designed for use in incoherent scatter, coherent scatter, and passive radar systems. Many of the hardware and software elements will also be useful in other scientific systems such as riometers, sounders, beacon tomography systems, and radio telescopes. In particular, Haystack Observatory is developing an array for "Intercepted Signals for Ionospheric Science" or ISIS. It will consist of a series of nodes each of which is a coherent radio system capable of operating as a flexible multi-function radio science instrument. Haystack Observatory is also a partner in NSF's Advanced Modular Incoherent Scatter Radar project led by SRI International, and much of its work will be directly incorporated into this state-of-the-art phased array radar.

One important goal of Open ISR is to develop reliable and reusable software for the analysis and interpretation of incoherent scatter radar data. The Inscal analysis program and a number of related analysis programs are available through http://openisr.org. Other users are invited to contribute software they have written. Eventually the Open ISR project should allow researchers to verify the robustness of results from the different analysis systems each radar system uses. In addition, programs to calculate derived parameters, such as neutral temperatures and winds, are being included in the Open ISR CVS archive.

Madrigal is a robust World Wide Web-based system capable of managing and serving archival and real-time data in a variety of formats from a wide range of instruments. Data can be accessed from the Madrigal sites at Millstone Hill, USA; EISCAT, Norway; SRI International, USA; Cornell University, USA; Jicamarca, Peru; the Institute of Solar-Terrestrial Physics, Russia; and the Chinese Academy of Sciences, using standard Web browsers. Direct remote access to Madrigal from several popular programming languages, such as Python and MATLAB is also supported.

The Open Madrigal initiative dates back to 1980, when Haystack Observatory began to support an on-line incoherent scatter database. The Observatory continues to maintain and develop the Madrigal database, which now contains information from a variety of upper-atmosphere research instruments. The entire database can be freely downloaded and installed, and individual software routines can be extracted from the Madrigal CVS archive. The basic data format is the same as that used by the NSF-supported Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) program, which maintains a CEDAR Database at the National Center for Atmospheric Research (NCAR), and files can be easily exchanged between the two sites.

Artist's conception of the Advanced Modular Incoherent Scattar Radar (AMISR).

Educational Activities

Education is a priority at MIT Haystack Observatory, from the training of students at all levels to special programs for teachers. Staff members volunteer many hours of time and energy to the Observatory's educational programs.

Graduate students from several institutions around New England use the facilities at Haystack and work with the staff on cutting-edge research projects. At the undergraduate level, students are exposed to research in radio astronomy through a Small Radio Telescope (SRT) developed at Haystack and commercially available as a kit. Many of these units are installed on college campuses around the world, allowing students and their teachers to acquire a hands-on introduction to radio astronomy techniques through observations of atomic hydrogen in the Milky Way and radio emission from the Sun. Through the continuing development of the SRT and its capabilities, Haystack is now bringing the techniques and science of radio interferometry to the undergraduate classroom.

Undergraduates without access to research-grade radio science facilities who wish to pursue more extensive projects have remote access to the Haystack 37-meter telescope. Students from around the United States have used it to study emissions from a variety of molecules in space including ammonia, methanol, and silicon monoxide. In addition, observations using the 37-meter dish have been integrated into undergraduate curricula at all levels—from demonstration experiments in basic astronomy courses to laboratory experiences and research projects at more advanced levels.

Since 1987, Haystack Observatory has been part of an NSF-sponsored Research Experiences for Undergraduates (REU) program that allows selected undergraduates to spend the summer at Haystack working closely with scientist mentors. The students participate in research projects, prepare extensive reports, and present their results at national conferences.

The successful REU program led to the establishment by NSF of a Research Experiences for Teachers (RET) program in 1999. The RET program at Haystack invites two teachers from local high schools to spend the summer at the Observatory and learn about the ongoing research. The experience results in high school lesson plans that the teachers take back to their classrooms. Once the lesson plans are tested, they are posted on the Haystack Web site for use by the larger community. Several workshops have been run at the Observatory to introduce other teachers to these resources; in addition, a transportable SRT is available for educators to borrow and use with their classes.

Students from Shawsheen Valley Technical High School put together a Small Radio Telescope kit.

A Haystack REU student presents a poster on the results of her research conducted during the summer internship.

A teacher from Chelmsford High School operates the Haystack 37-meter telescope remotely from her classroom.

College faculty attending an annual workshop at Haystack on undergraduate astronomy education examine a trailer-mounted SRT.

Two SRT units set up for an interferometer experiment.

Public Outreach

In addition to formal educational programs, scientists and technical specialists at Haystack are actively involved in outreach activities to inform the public about the research specialties at the Observatory. They use their scientific knowledge and technical expertise to create programs that introduce people to radio astronomy and atmospheric science. Haystack scientists take an active role in planning and participating in events held at public museums, local libraries, schools, and Haystack Observatory itself. These include such activities as Astronomy Day at the Museum of Science, Boston, and the Art and Astronomy program at the Chelmsford Public Library. The Observatory hosts a semi-annual Open House and conducts tours for special visitors, including the MIT Alumni Association and classes from local high schools and colleges. Visits by school groups are particularly important in meeting Haystack's commitment to the enrichment of students, and activities are carefully tailored to the age and learning level of the visiting classes. Other students come to the Observatory as part of summer courses held at local universities, and some high school students are individually mentored by staff members to encourage their interest in science. In another commitment to public outreach in science, Haystack Observatory has for many years provided the Amateur Telescope Makers of Boston – an amateur astronomy club – use of a building on the observatory grounds to observe the sky, build optical telescopes, and host public star parties. Through all of these activities, Haystack staff members create a lasting connection with their local communities while sharing a love of learning, and the excitement of scientific research and discovery.

Students from the MIT Chandra Science Summer Program working on a multi-wavelength matching game at Haystack Observatory.

Haystack Observatory scientist describing the operation of the SRT to a group of students from the MIT Chandra Science Summer Program.

Children experiment with telescopes during the Family Adventures in Science and Technology Program at the MIT Museum.

Students observe the Haystack 37-meter telescope in action inside its radome.

Learning about the Observatory during "Astronomy Day" activities at the Museum of Science, Boston.

ACKNOWLEDGMENTS

Contributions to this brochure were provided by Joanne Attridge, John Foster, Anne Gorczyca, John Holt, Heidi Johnson, Madeleine Needles, Carolyn Collins Petersen, Preethi Pratap, Joseph Salah, and Alan Whitney. The assistance of Mark Delilse (Lincoln Laboratory Publications) is gratefully acknowledged.

Credit for the cover photo of the Haystack radome panels: © Wenyon & Gamble, 2000.

1 September 2004

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