MASSACHUSETTS INSTITUTE OF TECHNOLOGY

HAYSTACK OBSERVATORY
MILLSTONE HILL OBSERVATORY
LINCOLN SPACE SURVEILLANCE COMPLEX

NORTHEAST RADIO OBSERVATORY CORPORATION

MIT LINCOLN LABORATORY

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GENERAL INFORMATION

General information about the research facilities and programs at the Observatory and its parent organizations are available on the World Wide Web at the following addresses:

Haystack Observatory
http://www.haystack.edu/haystack

Millstone Hill Observatory
http://www.haystack.edu

Lincoln Laboratory
http://www.ll.mit.edu

Massachusetts Institute of Technology
http://web.mit.edu

NEROC

INTRODUCTION

Nestled among the hilly woods of Westford, Tyngsboro, and Groton, Massachusetts, and surrounded by some of the nation's most prestigious universities and research centers, an array of large radio, radar, and optical instruments are used by scientists and engineers from the Massachusetts Institute of Technology (MIT), the Northeast Radio Observatory Corporation (NEROC), and the MIT Lincoln Laboratory, with the following objectives:

- Study the processes of star formation in the universe
- Probe the central engines of quasars outside our galaxy
- Monitor the Earth's plate tectonic motion and its orientation parameters
- Investigate the atmospheric plasma surrounding our Planet
- Track and image earth satellites and other objects in our space environment
- Provide opportunities for the education of graduate, undergraduate, and pre-college students.

The Haystack Observatory, the Millstone Hill Observatory, and the Lincoln Space Surveillance Complex are parts of a multidisciplinary research facility of MIT in Cambridge, Massachusetts, and the MIT Lincoln Laboratory in Lexington, Massachusetts, and are engaged in the following research disciplines and their application to education:

- Radio astronomy
- Geodesy
- Atmospheric science
- Space surveillance

The radio astronomy program is conducted under the auspices of the NEROC, a consortium of twelve educational institutions in the northeast which includes:

- Boston University
- Brandeis University
- Dartmouth College
- Harvard University
- Harvard-Smithsonian Center for Astrophysics
- Massachusetts Institute of Technology
- University of Massachusetts
- University of New Hampshire
- State University of New York at Stony Brook
- Tufts University
- Wellesley College
- Yale University

The Observatory receives its primary financial support from the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Department of the Air Force (USAF), as well as from other federal agencies, national programs, and industrial sources. The facilities are available for use by all qualified scientists, researchers, and students. Strong scientific and technical collaborations exist between the Observatory's researchers and colleagues in the national and international communities. A vigorous education program exists at the Observatory for students at all levels.

HAYSTACK OBSERVATORY

The Radio Telescope

Construction of the Haystack facility by MIT Lincoln Laboratory began in 1960 as a technological step in the evolution of high-performance microwave systems. Operations began in 1964, and for the first ten years the primary role of Haystack was as a planetary astronomy radar, observing the reflection characteristics and orbital parameters of the Moon, Venus, Mars, and Mercury. Topographical characteristics of the lunar surface were examined with emphasis on the proposed landing sites for the Apollo lander, and similar observations were made in support of the Viking lander on Mars. The “fourth test” of Einstein’s general theory of relativity was also carried out at Haystack by making precise measurements of the round trip travel time of the radar echo from Mercury, which, passing near the sun, was delayed due to the intense solar gravitational field.

In 1970, the Haystack facility was transferred from the Air Force to MIT to be operated under agreement with NEROC to foster and encourage radio astronomy.

A cutaway view of the Haystack antenna showing the Cassegrain subreflector and the hoisting system for the interchangeable equipment boxes.

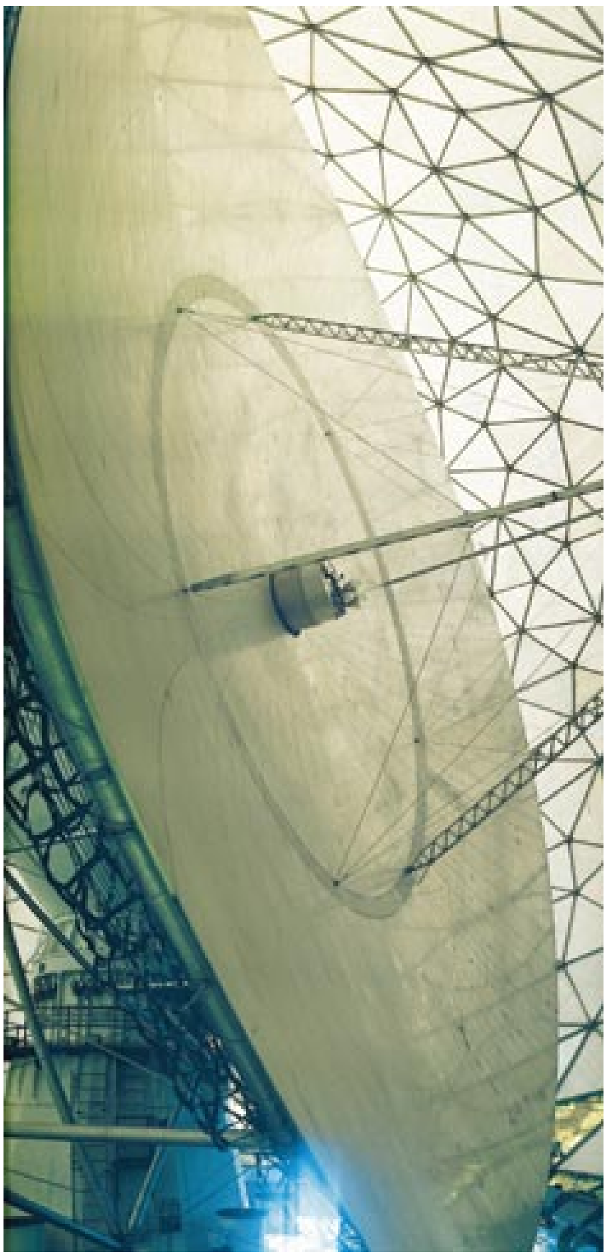
Haystack is renowned for many astronomical discoveries such as the initial detections of various molecular species in interstellar space. Under grants from the NSF for the radio astronomy program, the Observatory is available for observations by qualified scientists and students from all universities and research institutions. As many as 100 investigators, including about 20 graduate students, utilize the facility annually in their research projects.

The Haystack radio telescope is a fully steerable parabolic antenna 37 meters in diameter, enclosed in the world’s largest space-frame radome. The telescope configuration is Cassegrain, where the energy focused by the large primary reflector is redirected by a small subreflector to electronic receivers near the center of the primary “dish.” The Haystack radome is 46 meters in diameter, and its 932 triangular membranes are made of 0.6-mm thick Tedlar-coated dacron cloth manufactured by ESSCO of Concord, Massachusetts. This material has been designed to minimize signal loss across the frequency bands of astronomical interest.

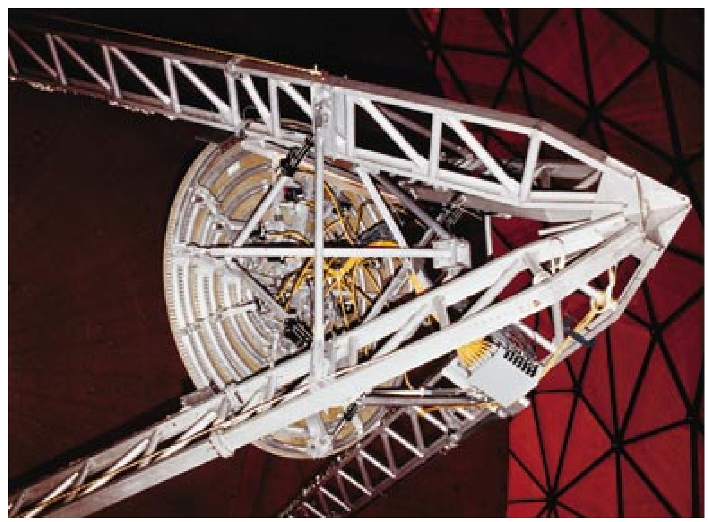
The Haystack antenna was initially designed for operation at a frequency of 8 GHz (one GigaHertz is 1 billion cycles per second). Frontier radio astronomical observations have driven observations towards higher frequencies, which require a more accurate reflector surface, and the main Haystack surface has thus been continually improved since its initial construction. In 1991–1993, the surface was adjusted to a root-mean-square deviation of 0.25 mm from a perfect parabola, the thermal environment in the radome and on the antenna was accurately controlled, and a deformable subreflector was installed, to allow use of the telescope up to a frequency of 115 GHz during cold and dry winter nights. At that frequency lies an important emission line of the carbon monoxide molecule, which traces high-density interstellar gas in the stellar nurseries where new stars form. Astronomers using Haystack can now observe this line, along with other molecular transitions in the 85–115 GHz range, with high resolution – the telescope’s beam size at

100 GHz is 20 arcseconds, or about the size of a basketball at a distance of 2 miles. Recent feasibility studies indicate that it is possible to further improve the telescope's performance by adding an actuated set of light-weight panels and a laser measurement system that could allow operations up to 150 GHz in all seasons and times of day.

The pointing capabilities of the telescope have also been improved to allow its narrow beam to be steered accurately. Good pointing is simplified by the enclosure of the telescope in a radome, which provides protection from snow, ice, wind loading, and direct radiation from the sun. The antenna can be moved at rates of 2° per second about both elevation and azimuth axes. Because of the antenna's usage at a number of frequencies for astronomy, and also as a high-power radar for satellite imaging, it has been designed to use interchangeable electronics modules ("boxes") at the antenna focus, which can be exchanged in a few hours. One module contains the three primary astronomy receivers for use at 20–26 GHz, 35–50 GHz, and 85–115 GHz, and a second contains a radar transmitter and receiver operating at 10 GHz. The astronomical receivers consist of amplifiers or mixers and other components cryogenically cooled to as low as 4° above absolute zero (4 Kelvins). Such low temperatures are required to reduce electronic noise and allow sensitive observations of the extremely weak astronomical signals originating from sources as diverse as planets in our own solar system and quasars at the edge of the universe. A variety of computers control and direct the radio telescope subsystems, and versatile digital processors are available to reduce the data. The first digital correlation spectrometer for radio astronomy was built at Haystack in the early sixties. It was used for the discovery at Millstone Hill in 1963 of the OH (hydroxyl) radical, which was the first molecule to be detected in interstellar space.



The Haystack 37-m diameter antenna surface is made of 96 honeycomb aluminum panels which are set to a root-mean-square tolerance of 0.25 mm.

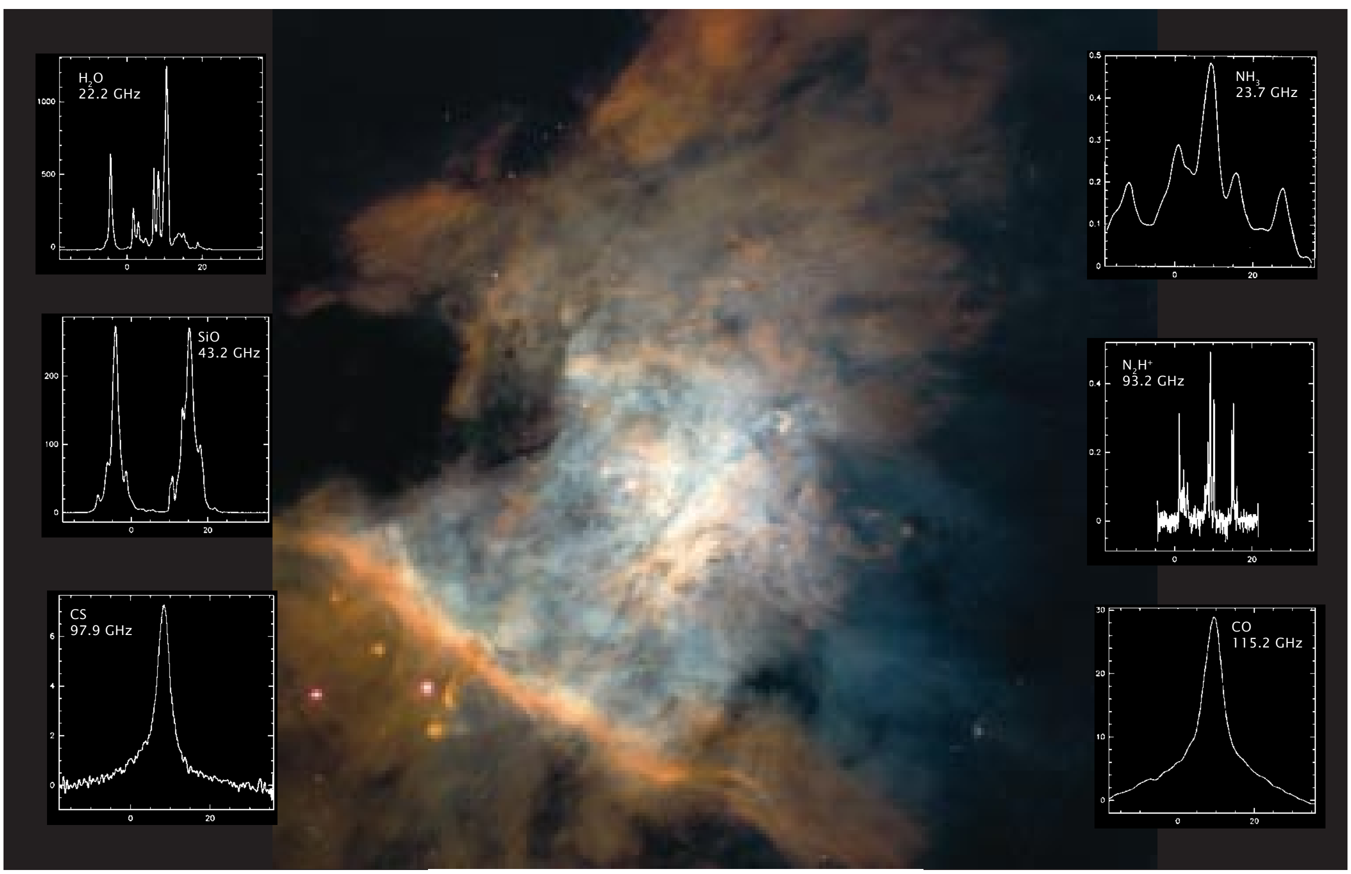


The Haystack antenna subreflector is made of fiber-reinforced plastic with a set of nineteen actuators that precisely control its surface to compensate for residual errors in the primary surface, and that can focus, translate, and tilt the subreflector.

Single-dish Radio Astronomy

The term “single-dish” denotes use of the Haystack telescope when operating alone, in contrast to its use with other antennas as part of a radio interferometer. Most of the single-dish observations at Haystack involve the detection and mapping of emission from molecules in interstellar clouds of gas and dust. Star formation occurs when these clouds contract due to their own self gravity, aided at times by external forces such as shock waves. Understanding the life cycles of stars, their birth, evolution, and eventual death, is one of the fundamental problems of modern astronomy. At Haystack, the main thrust of single-dish research is investigation of the physical conditions in interstellar clouds and the processes of star formation.

One of the best known regions of star formation is in the constellation Orion. This stellar nursery contains vast clouds of gas, some of which are heated by newly formed stars and glow in the optical region of the spectrum, while others are cold and dense and emit primarily in the spectral lines of molecules at radio frequencies. Such spectral lines, which comprise emission at discrete frequencies, result from quantum jumps between molecular energy levels. The pattern observed in frequency from an astronomical object can range from extremely simple to quite complex, depending on the molecule being observed and the number of individual cloud regions contributing to the total emission. By examining the spectral lines from various molecules, or by comparing a number of different lines from the same molecule, it is possible to infer the basic physical parameters of molecular clouds, such as gas density, temperature, and cloud motions. Typical star-forming clouds have temperatures of 10–30 Kelvins (degrees Celsius above absolute zero) and densities of 100–1000 hydrogen atoms per cubic centimeter. Over 80 different molecular species have been discovered to date in interstellar space.

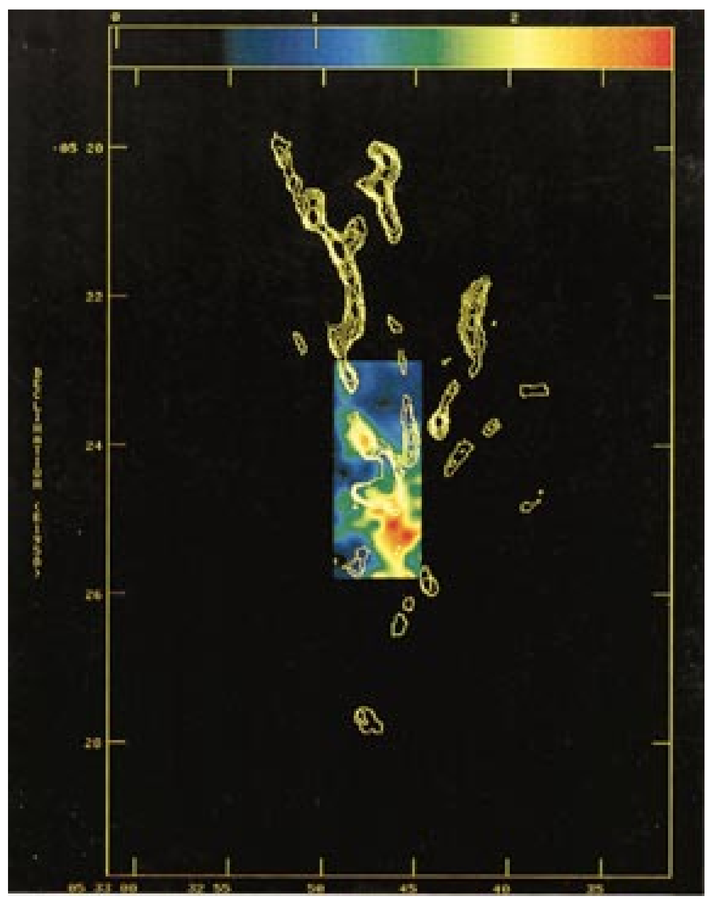


Line spectra in Orion taken in six different molecular species are superimposed on a Hubble Space Telescope image of the nebula M42. The line shapes range from simple to complex, depending on the structure of the molecule observed and the complexity of the gas clouds emitting in that particular species. The line strengths are given in “antenna temperature,” a radio astronomical unit of measurement, and the frequency axis has been converted to its equivalent Doppler velocity range.

Haystack can observe a large number of molecular transitions in the frequency range 20–115 GHz. Some examples, all observed in the Orion region, are shown superimposed on an optical picture of the famous nebula M42 taken by the Hubble Space Telescope. While some interstellar molecules are quite familiar, such as water (H_2O), ammonia (NH_3), and carbon monoxide (CO), others, such as diazenylium (N_2H^+), are more obscure and may be formed more easily in space than on earth. The emission patterns of the six lines illustrated are all quite different, reflecting both the physics of the molecules themselves and the differing physical conditions within the regions where they reside. These effects can usually be disentangled, so that molecular lines are able to provide a sensitive probe of various interstellar environments. In the Orion spectra we find maser emission in SiO and H_2O (which is similar in concept to laser emission except occurring at microwave rather than optical frequencies), emission from diffuse gas caught up in an out-flowing wind from a young star in CO and CS, and emission representing complex transitions from molecules having many "hyperfine" line components in NH_3 and N_2H^+.

Some of the types of structures seen in interstellar molecular clouds are shown here, in an overlay of sky maps obtained with the Haystack radio telescope and with the Very Large Array (VLA). The VLA is an interferometer telescope consisting of 27 separate radio dishes located in New Mexico, and operated by the National Radio Astronomy Observatory. These maps cover essentially the same region in Orion shown previously, but in the molecular emission of ammonia (yellow contours, VLA), and an isotopic species of carbon monoxide (colored rectangle, Haystack). The molecular morphology, tracing cold gas, is in sharp contrast to that seen in visible light, where gas at a temperature of 10,000 K glows as a result of heating by embedded stars. Of note in the molecular images are the "filamentary" structures formed by the cold molecular gas clouds, which are located behind the optical nebula. Over 200 separate pointings of the Haystack telescope were required to build up, pixel by pixel, the carbon monoxide image.

Other recent research programs using the Haystack telescope have included investigations of in-falling gas onto newly forming stars, searches for radio counterparts to the mysterious gamma-ray bursters, and monitoring of radio source fluxes to detect those whose emission flares to high levels of intensity. As a participant in Very Long Baseline Interferometry (VLBI) experiments, the Haystack telescope has also contributed to the discovery of systematic motions in an extragalactic water maser that helped solidify one of the best cases for the existence of a supermassive black hole in the galaxy nucleus of NGC 4258. In the future, the Haystack telescope will participate in space-VLBI experiments associated with the Japanese satellite, VLBI Space Observatory Program (VSOP), as part of an international array of ground-based telescopes operating in unison with the satellite. This satellite will serve to extend earth-limited baselines into space, thus greatly enhancing the measurement angular resolution.

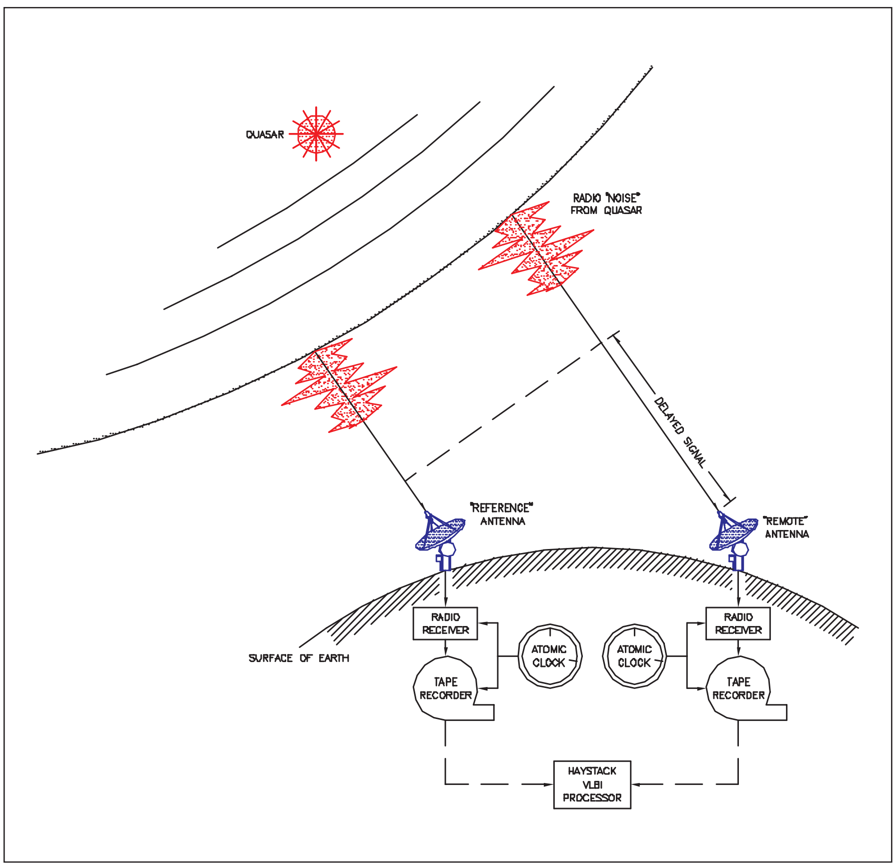


The Orion region mapped in the molecular emission of ammonia (yellow contours) and isotopic carbon monoxide (color image). The molecular picture outlines the structures of cold gas clouds in the Orion molecular complex and is very different from that seen in visual light.

VERY LONG BASELINE INTERFEROMETRY (VLBI)

VLBI is a technique that combines the world's radio telescopes in order to gain many of the advantages of having a giant radio dish as large as the distance, or baseline, separating the telescopes. Radio telescopes in the United States and around the world cooperate in these joint observations of quasars, galaxies, and radio stars. The VLBI technique has been applied to astronomy to allow observations with higher angular resolution than can be obtained from individual radio telescopes operating separately, to astrometry to provide precise measurements of the angular positions of stars and other cosmic objects, and to geodesy to determine motion in the earth's plates and the rotation parameters of our Planet.

VLBI was first demonstrated in the late 1960s. A pioneering group of scientists and engineers from MIT, Haystack, and other radio observatories cooperated to probe the radio energy from the brightest quasar cores and showed that it came from very small but violent regions. Quasars are actually the disturbed cores of distant galaxies. In most quasars, this concentrated activity outshines the host galaxy in both the optical and radio parts of the energy spectrum. Some of this radio emission comes from vast regions that have spilled far outside the host galaxy – by up to 6 million light years, in a few cases, or 50 times larger than the galaxy itself. These radio sources are therefore among the very largest entities in the universe, and are kept running by compact central energy sources whose output dwarfs all man-made and nearly all other natural events.



The VLBI technique involves reception of radio signals at two or more widely separated antennas. Each antenna operates independently, with the timing and frequencies controlled by highly accurate atomic clocks. The signals are recorded, along with time marks, on magnetic tapes at data rates up to a billion bits per second. The tapes are then shipped to a central correlator for processing.

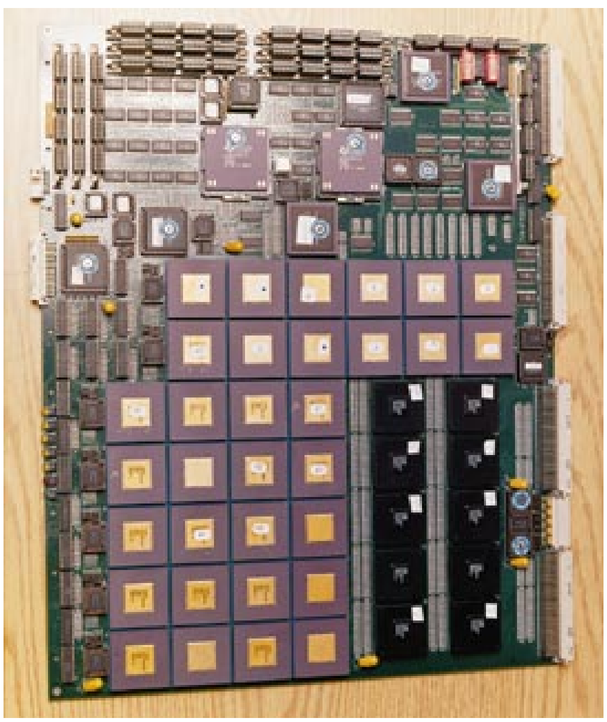
Several technical challenges must be overcome to make VLBI experiments feasible. Because the radio telescopes used are over the horizon from one another – hundreds or thousands of miles – they cannot easily be linked electronically. Instead, computers and video tape recorders have been modified to collect a digitized form of the quasars' radio noise, and the tapes from each telescope are shipped to a central processing site where they are analyzed. Another crucial development has been the hydrogen maser clock, which forms an extremely stable source of time-signals that allows remotely recorded observations to be reconstructed days or weeks after recording. As a result, all telescopes engaged in VLBI now possess these extremely accurate atomic time standards, which are kept synchronized within a few microseconds of Universal Time.

Instrumentation

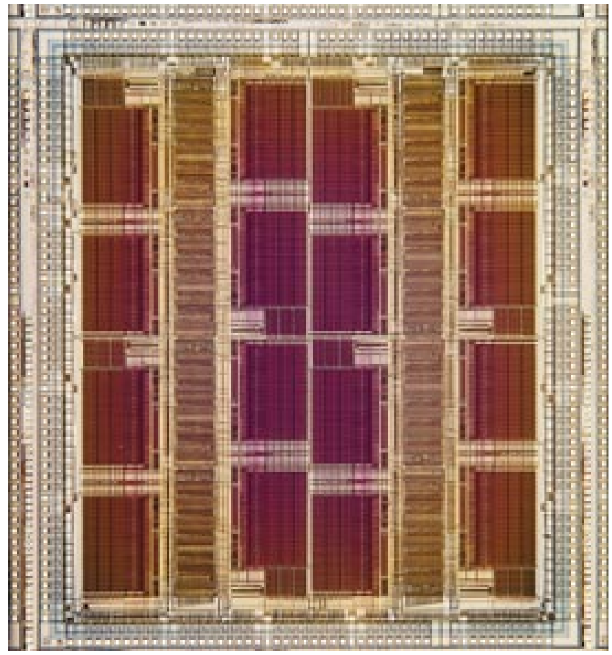
The Haystack VLBI group has played a key role in the development and application of VLBI to research in radio astronomy, astrometry, and geodesy. The Haystack radio telescope was equipped with one of the first hydrogen maser frequency standards. It participated in the pioneering VLBI experiments conducted in 1967 to produce high-resolution astronomical observations, and in 1969 to obtain the earliest geodetic baseline measurements. VLBI science and technology have continued to grow at Haystack since those early days and led to the development of the Mark III correlator in 1978 and the Mark IIIA in 1983, which have since been utilized to process VLBI data collected globally. Exciting astronomical and geodetic data gathered at centimeter wavelengths and longer have been processed with these correlators, including data from the first space-VLBI experiment, which was conducted in 1986. For that experiment, an antenna aboard a NASA data-relay satellite was used to extend the VLBI baseline beyond 2 earth diameters, thus demonstrating the feasibility and importance of such space experiments. The design and development of narrow-track recording heads to expand the volume of data recorded on tapes were completed at Haystack in 1986 and deployed at telescopes worldwide. Haystack engineers then developed advanced data-acquisition systems and longitudinal high-density recording systems for the nation's Very Long Baseline Array, which began operations in 1992.

The Mark III and Mark IIIA processors at Haystack are shown together with playback recorders and computer control and monitoring terminals.

Haystack engineers are presently engaged in the development of the next generation advanced VLBI system – called the Mark IV. This project was initiated by the geodetic-VLBI community, spearheaded by NASA and the U.S. Naval Observatory (USNO), to achieve global millimeter-accuracy measurement by the end of the decade. The result of this commitment has grown into a broad-based international development effort that has reached deep into both the geodetic and astronomical VLBI communities. The new Mark IV system allows an increase in the data recording bandwidth by more than a factor of 4, to over 1 Gbit/sec, which translates to more than a two-fold increase in the sensitivity of VLBI arrays. A concomitant development of thin-film head arrays is also in progress to support further increases in recorded bandwidth. The Mark IV data-acquisition system is now being deployed in both the United States and in the European VLBI Network to support both geodetic and astronomical observations.



The Mark IV digital correlator board utilizes 32 Very Large Scale Integrated (VLSI) chips and allows over 16,000 real lags to be computed at a rate of 64 million samples per second. For VLBI applications, 16 boards will be constructed in each correlator to handle 16 stations at 1 billion bits per second for each station at 32 complex lags. Each board is 50 cm x 40 cm in size, a single one of which will replace an entire rack of Mark IIIA correlator equipment.



The VLSI chip, 1 cm square, was developed specifically for Mark IV by the Haystack Observatory and the University of New Mexico/NASA Space Engineering Research Center, and was fabricated by Hewlett-Packard. Each chip consists of 1 million transistors and operates at a clock rate of 64 MegaHertz (a MegaHertz is a million cycles per second).

The Mark IV system consists of 3 major components:

- Major upgrade to the Mark IIIA data-acquisition system to support Gbit/sec data rates.
- New advanced correlator system to support up to 32 stations at Gbit/sec/station data rates.
- Major field-system and timing upgrades to provide a broad base of data-acquisition system support across a wide variety of VLBI systems.

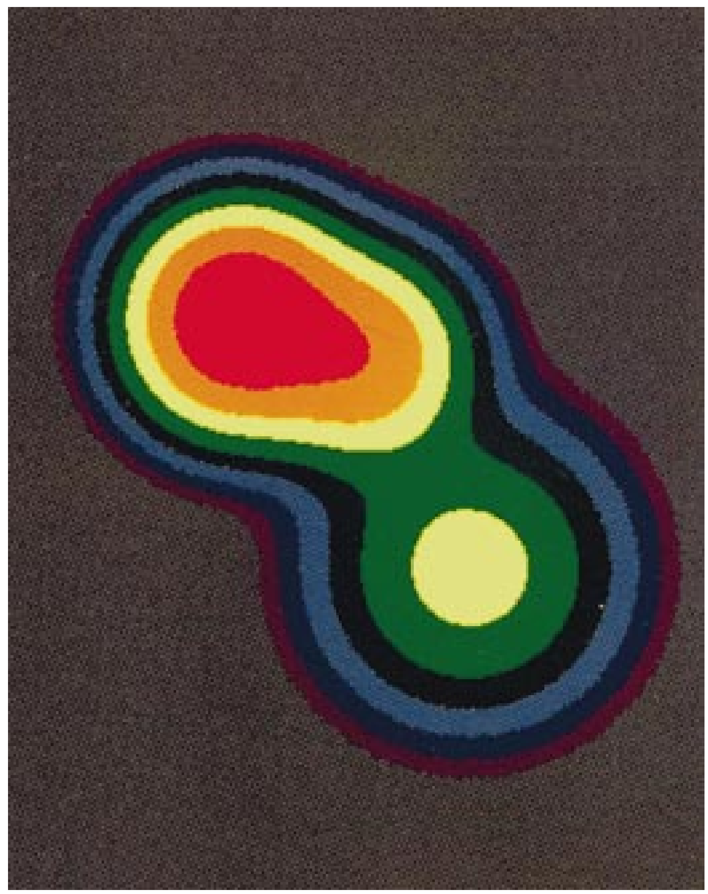
The correlator system to support Mark IV is being developed by the International Advanced Correlator Consortium (IACC), which includes the Haystack Observatory, NASA, USNO, the Smithsonian Institution, the Netherlands Foundation for Research in Astronomy (NFRA), the Joint Institute for VLBI in Europe (JIVE), and the Institute for Applied Geodesy in Germany. Target correlators for this development effort include four large VLBI correlators in the United States and Europe (Haystack, USNO, JIVE, the Max-Planck Institut in Bonn), as well as the Westerbork array in The Netherlands, and the Smithsonian Submillimeter Array to be installed on Mauna Kea, Hawaii.

Astronomical VLBI

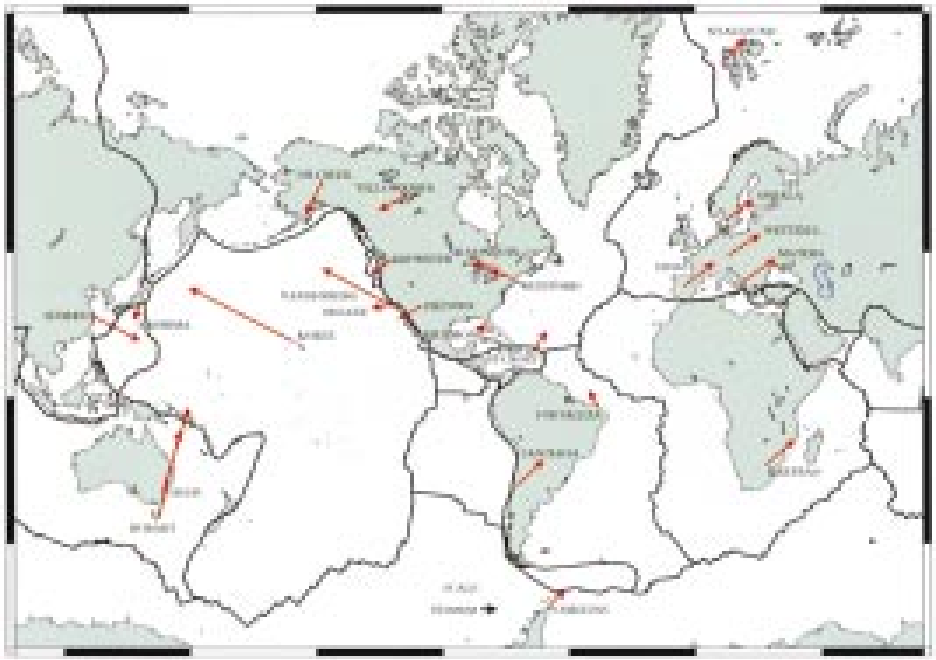
In hopes of understanding how the energetic matter is produced before it travels to the outer radio lobes, VLBI has been brought to bear on the cores of quasars, as well as "radio galaxies," which show the same energy source, but not the optical emission of quasars. A modern VLBI observation, using radio telescopes thousands of miles apart, can form images of these radio sources with great detail. VLBI experiments conducted at the highest frequency (shortest wavelength) yield the highest achievable angular resolution, and present an opportunity to probe the central engines in the nucleus of our galaxy, active galaxies, and quasars. The thrust of Haystack's radio astronomical VLBI program, under sponsorship of the National Science Foundation, is to push the frontier of such observations to wavelengths of 3 mm and shorter, as part of the Coordinated mm-VLBI Array (CMVA) project.

The resolution of the global array operating at 86 GHz (3.5-mm wavelength) as part of the CMVA is about 50 microarcseconds, which corresponds roughly to the angle subtended by the head of a pin in San Francisco as viewed from Boston. Telescopes participating in 3-mm VLBI, in addition to Haystack, include the interferometric arrays at Owens Valley (California Institute of Technology) and at Hat Creek (University of California at Berkeley, University of Illinois, and University of Maryland), and the radio telescopes at Kitt Peak, Arizona (National Radio Astronomy Observatory) and Quabbin, Massachusetts (Five College Radio Astronomy Observatory), at Onsala, Sweden (Onsala Space Observatory), at Bonn, Germany (Max-Planck Institut), at Pico Veleta, Spain (Institut de Radio Astronomie Millimétrique), and in Chile (SEST, Swedish ESO Submillimeter Telescope). Haystack coordinates the scheduling of experiments from all interested astronomers, correlates the data from the various telescopes, and conducts post-processing activities to enable astronomers to develop the high-resolution images of the quasars that are observed.

Recent observations of the compact source at the center of our galaxy, Sagittarius A, using CMVA telescopes have set a new limit on the intrinsic size of the source at one astronomical unit (150 million kilometers), and have produced an improved location of the source. In another experiment, an image of the flaring quasar, NRAO 530, was obtained in April, 1995. This quasar began a period of exceptional activity in late 1994, and its emission tripled in strength at a wavelength of 3.5 mm after over a decade of quiescence. The VLBI image reveals the presence of a core and an evolving emission region that may develop into a jet of energetic material over larger scales. The key aspect of the CMVA program is to track the evolution of this material as a function of time and to improve our understanding of the energy supply process at very early stages.



An image of the flaring quasar NRAO 530 was obtained in a VLBI experiment at 3.5-mm wavelength using the Haystack, Kitt Peak, and Hat Creek radio observatories. The image was constructed from a model of the VLBI data and convolved with a beam size of 90 microarcseconds. The size of the entire field shown in the figure is one thousandth of an arcsecond, or 13 light-years at the distance to the quasar. The component detaching to the southwest (lower right) is seen at only ~1.3 light-years from the quasar core. By contrast, the galaxy hosting the quasar is probably 100,000 light-years across.



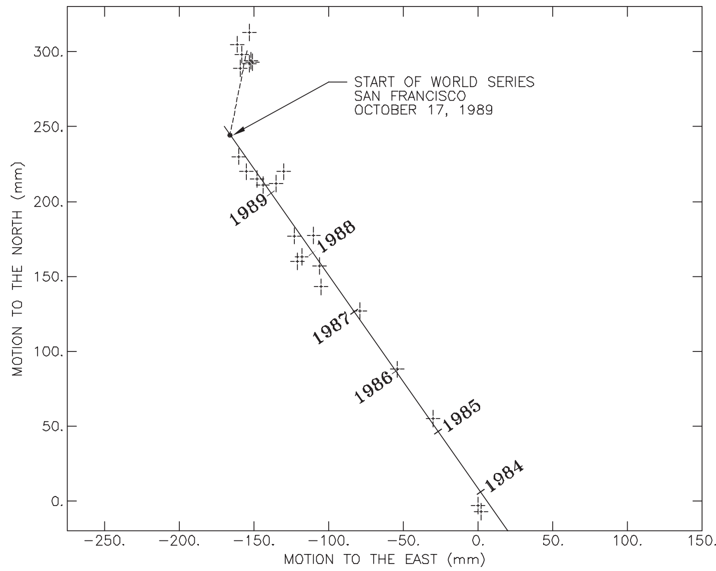
A summary of geodetic VLBI observations showing plate motions relative to the North American plate. The red dots denote sites with measured motions shown by the arrows. Note the motion of the Pacific plate along the North American plate at the San Andreas Fault. The westward velocity is 5 centimeters per year.

The Westford radio telescope is an 18-m diameter antenna enclosed in an inflatable radome (not shown here) and operates with radiometers at frequencies of 2.8 and 8.4 GHz as part of the VLBI geodetic network.

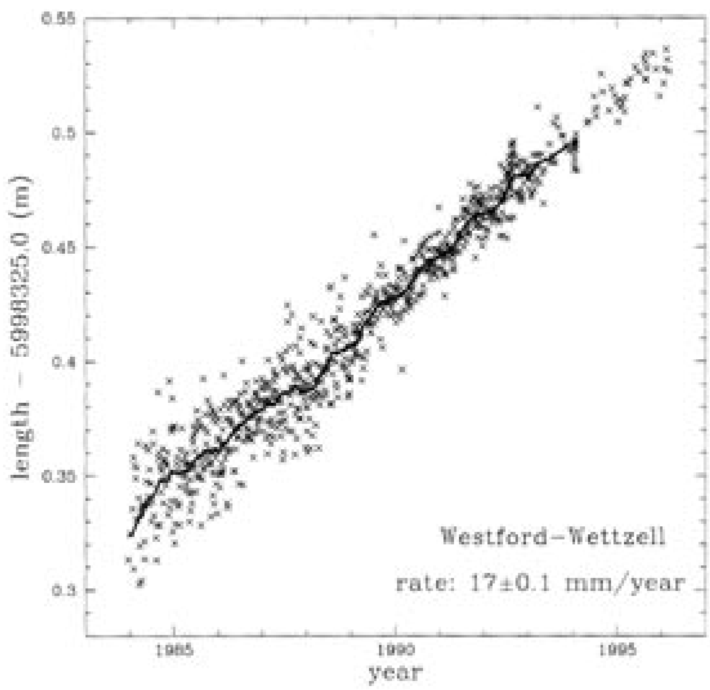
Geodetic VLBI

The development of VLBI was prompted as much by its promise as a tool for studying the shape and rotation of the Earth as for its use in astronomy. NASA's Space Geodesy Project and its predecessor, the Crustal Dynamics Project, in which Haystack Observatory plays a significant role, have led in the development of a global and international network of radio telescopes for geodesy. This network is used for measuring the motion of the Earth's tectonic plates, for defining deformation in zones of major crustal change such as the San Andreas Fault, and for measuring and monitoring changes in the rate of the Earth's rotation and the wobble of the Earth's axis. Our knowledge of the rates of plate tectonic motion from these observations, taken over the past twenty years, surpasses the previous estimates, which are based on geologic data spanning millions of years. The Westford radio telescope is the primary telescope at the Haystack Observatory that participates in these geodetic network observations, and the Haystack correlator shares in the processing of the resulting data. VLBI measurements in California, following the Loma Prieta earthquake, also known as the "World Series Earthquake" of 1989, were the first to show that the motion was not what was expected from the famous San Andreas Fault and thus might be the source of a new threat to the Bay area. Both the Haystack and Westford radio telescopes have been involved in the geodetic VLBI network. They have played crucial roles in the research and development program which has led to the major improvements in geodetic VLBI accuracy over the past three decades.

The current thrust in geodetic VLBI for more accurate measurement of changes in the Earth's rotation rate will help in our understanding of climate change, since the rate is closely coupled to the global wind field. A special measurement program is being organized by NASA to allow Continuous Observations of the Rotation of the Earth (CORE), using seven networks of telescopes around the world. Our goal is to reach measurement accuracies of the order of a few millimeters over baseline lengths of several thousand kilometers by the end of the decade. As VLBI measurement accuracies improve, particularly for the component of motion in the vertical direction, the limits of post-glacial rebound of the Earth's crust will be better determined, and the prospects for global sea-level change can be better evaluated.



Motion of Fort Ord, California, from 1983 through 1989, showing the large northward shift of 50 mm due to the Loma Prieta earthquake in October 1989.



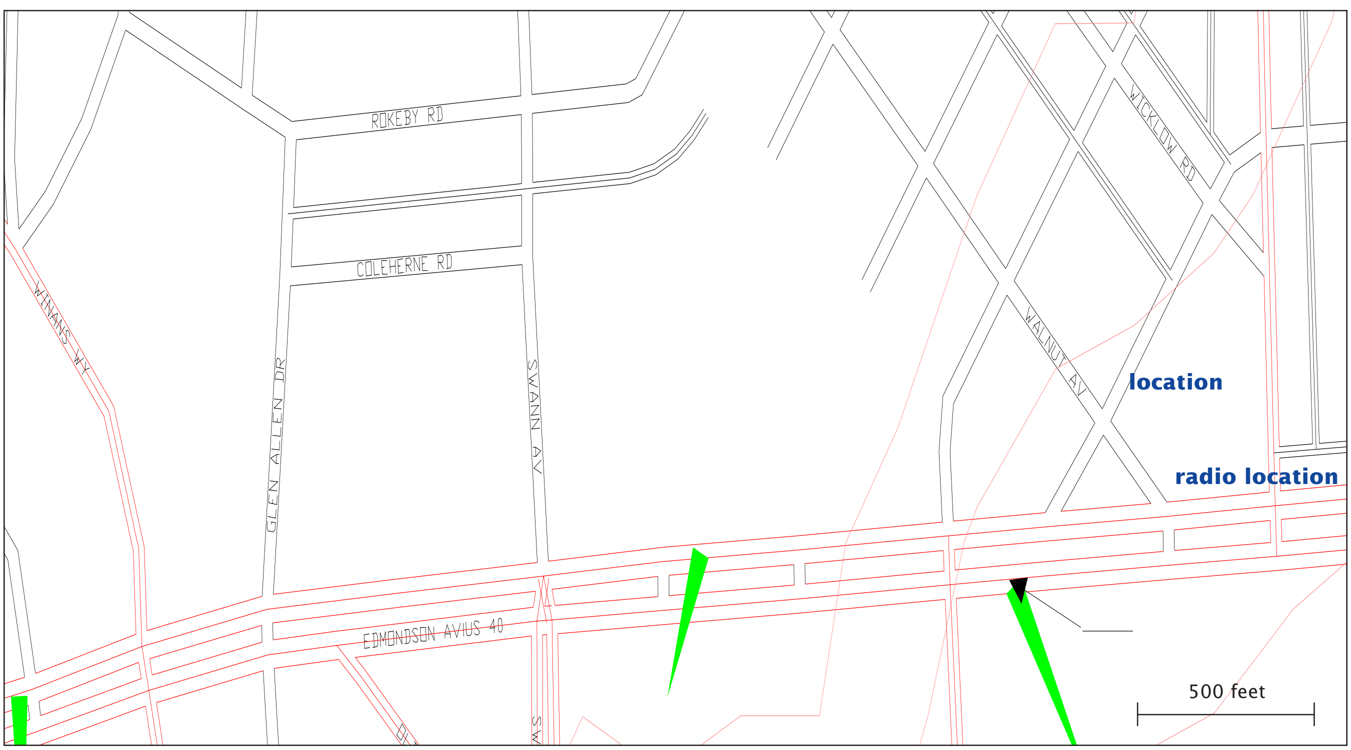
The length of the baseline between Westford, Massachusetts, to Wettzell, Germany, measured by VLBI from 1984 through 1995. The increase in length is interpreted as a measurement of the separation of the European plate from the North American plate with a rate of 17 mm per year. The red line is a 30-day average which shows an unexplained annual variation that is apparent from 1988 through 1993. Before 1988, the data were not accurate enough to see the variation, and beginning in 1994, the measurements were too sparse.

Radio Location Technology

An important illustration of the benefit of basic research to society and commercial enterprise is the spin-off of VLBI technology to the location of mobile telephones. The popularity of mobile "cellular" telephones has generated a demand for technology to locate emergency "911" calls made from these phones. Haystack Observatory has been working with the Associated Group, Inc., to develop a radio location system based upon the time-difference-of-arrival of signals at the "cell sites." The location system, known as TruePosition™, is based on the techniques used in VLBI.

The accuracy with which signals from cellular phones can be located is severely limited by the multiple paths taken by the radio waves as they are diffracted and reflected by the terrain and buildings along the way to the receiving sites. Haystack engineers have developed digital signal-processing algorithms to ameliorate the effects of this "multipath." In 1995, tests made with a prototype of the TruePosition™ system measured the location of calls with a root-mean-square error of about 180 meters. These tests were made in the cities of Philadelphia and Baltimore showing that reasonably accurate locations can be obtained even in an urban environment. Accuracy is expected to improve with a new generation of receivers currently under development. The system works with all existing mobile phones even if the emergency call is made from inside buildings, or with a hand-held model inside a vehicle, in contrast to competing technologies which lack such capabilities.

Sponsorship of the Associated Group, Inc. has also fostered support for the development of radio astronomy and geodesy at Haystack through post-doctoral appointments such as the Berkman fellowship named in honor of the Chairman of the Associated Group, and for cost-sharing contribution to Haystack's educational initiatives.



A small sample of locations obtained during TruePosition™ demonstration "drive test" in Baltimore, Maryland, in 1995.

MILLSTONE HILL OBSERVATORY

The Massachusetts Institute of Technology maintains an extensive upper atmosphere research facility at Millstone Hill as a part of the interdisciplinary program at the Haystack Observatory. Investigations of the mid- and high-latitude ionosphere and thermosphere are carried out in support of national and international programs using the high-power UHF incoherent scatter radars at Millstone Hill, together with the optical and radiowave instrumentation clustered around them. Combined radar and optical observations are used to study the coupled chemical and physical processes occurring in the terrestrial atmosphere and ionosphere.

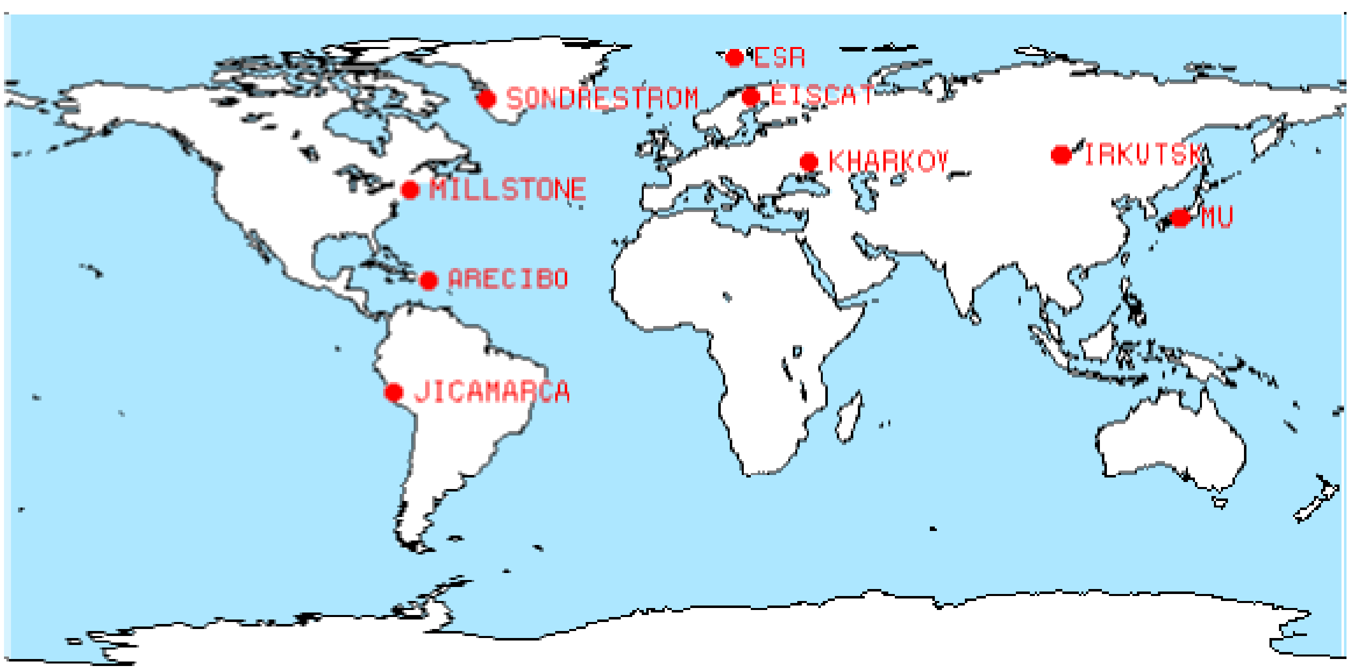
In order to improve our understanding of Earth's near-space environment, the role of the upper atmosphere in shaping Earth's long-term weather patterns and climate, and the variability of the high-altitude medium due to solar activity, it is necessary to understand the atmosphere's role as an absorber and transformer of solar energy. In addition, Earth's upper atmosphere represents a natural laboratory for the study of complex plasma and gas-phase interactions.

Millstone Hill incoherent scatter radars use a 68-m zenith-directed dish and a 46-m fully steerable antenna.

Global variability in the earth's ionosphere and upper atmosphere is associated with sun/earth coupling phenomena over a wide range of temporal scales. Solar-cycle variations in the sun's output and activity alter the temperature, density, and ionic composition on a ten-year time scale. Longer-term solar variability, on a time scale of centuries, is being investigated as a contributor to global climate change. On a time scale of several days, ionospheric storms are driven by large-scale changes in the solar wind. They result in enhanced energy dissipation, expansion of auroral phenomena and processes to middle latitudes, and large-scale changes of neutral atmospheric characteristics. On a scale of several hours, magnetospheric storms called substorms, involve a localized release of energy in the magnetotail and its dissipation in the nightside ionosphere.

Effects of storms and substorms spread rapidly through the magnetosphere-ionosphere-atmosphere system. Enhanced electric fields induce ionospheric irregularities and scintillations, which affect radio-wave propagation. Injected particles alter the inner radiation belt and lead to spacecraft charge build-up creating hazards for astronauts. Enhanced turbulence creates radar clutter, which affects ground and space-based radars. The observations conducted at Millstone Hill contribute to the National Science Foundation's program for the study of the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR), the National Space Weather Program, and the Geospace Environment Modeling program. The location of Millstone Hill in the heart of the New England academic community helps make it a center for collaborative and student research.

The research emphasis of the Atmospheric Sciences Group at Millstone Hill encompasses a broad range of topics involving processes and dynamics of the Earth's thermosphere, ionosphere, and magnetosphere, as well as investigations of plasma waves and magnetic storm effects. Radar and optical data are deposited in the CEDAR database at the National Center for Atmospheric Research (NCAR) for community use. A visiting-scholar program for ionospheric researchers from the Former Soviet Union brings a strong international involvement to Millstone Hill.



The Millstone Hill incoherent scatter radar operates as a part of a global array of incoherent scatter radars for studies of ionospheric climatology and large-scale structure.

Millstone Hill as an Upper Atmosphere Research Facility

Millstone Hill has evolved over the past two decades as a broad-based observatory capable of addressing a wide range of investigations in atmospheric science. The incoherent scatter radar facility has been supported by the National Science Foundation since 1974 for studies of the earth's upper atmosphere and ionosphere. The scientific capability of the facility was greatly expanded in 1978 with the installation of a fully steerable 46-meter antenna to complement the 68-meter fixed zenith pointing dish.

The favorable location of Millstone Hill at sub-auroral latitudes combined with the great operational range, afforded by the steerable antenna, permit observations of the ionosphere over a latitude span from the polar cap to near the equator. Since 1982, Millstone Hill has been a part of the ionospheric radar chain which extends from Sondre Stromfjord, Greenland, through Millstone Hill at mid-latitudes, beyond Arecibo, Puerto Rico, at low latitudes, to the Jicamarca facility at the magnetic equator in Peru.

Extensive database and real-time support capabilities have been developed to augment the atmospheric sciences program at Millstone Hill. Ease of access to the data from remote sites and an interactive experimental capability have been emphasized in order to fully support cooperative and multi-instrument ionospheric experiments. A modern digital data acquisition system was designed to be monitored and controlled remotely making a "telescience" capability a basic feature of the system. Using a standard data structure, which incorporates experiment description and status information, a distributed data acquisition system is being implemented that permits radar or other data to be interpreted and processed by any computer.

Atmospheric optical observing instruments were added to complement the radar in 1988 and are housed in a dark-sky facility located on a remote portion of the Haystack Observatory property. Other universities have also located complementary instruments at the site. The coordination of these instruments for collaborative studies is conducted by the Millstone Hill Experimenters' Working Group. The research instrumentation currently collocated with the Millstone Hill Observatory includes:

• Incoherent Scatter Radars	*Massachusetts Institute of Technology* Frequency: 440 MHz, Peak Power: 2–5 Megawatts 68-m zenith and 46-m steerable parabolic antennas
• Digital Ionospheric Sounder	*University of Massachusetts at Lowell* Frequency: 0.5–30 MHz 60-m rhombic transmit antenna; directional receiving array
• Meteor Wind Radar	*University of New Hampshire* Frequency: 36.8 MHz; Peak Power: 30 Kilowatt Dual receiving array antennas
• Fabry-Perot Interferometers	*MIT and the University of Pittsburgh* Aperture: 100 mm; wavelength: 630 nm Aperture: 150 mm; wavelength: 558, 630, 845 nm
	Boston University Aperture: 150 mm; wavelength: 630, 845, 1080 nm
	University of Wisconsin Aperture: 150 mm with CCD; wavelength: 630 nm
• All-Sky Imager and Spectrometer	*Boston University* Image intensified TV camera; wavelength: 558, 630 nm
• Infrared Radiometer and Spectrometer	*Utah State University* Wavelength: 1–1.7 μm

Millstone Hill Incoherent Scatter Radars

The Millstone Hill UHF radar consists of two 2.5 MW 440-MHz transmitters, a fully steerable 46-meter antenna, a zenith-directed 68-meter fixed antenna, and dedicated computer and database facilities. Principal operational support derives from the National Science Foundation Upper Atmosphere Facilities Program for incoherent scatter investigations of large-scale processes in the thermosphere, ionosphere, and magnetosphere.

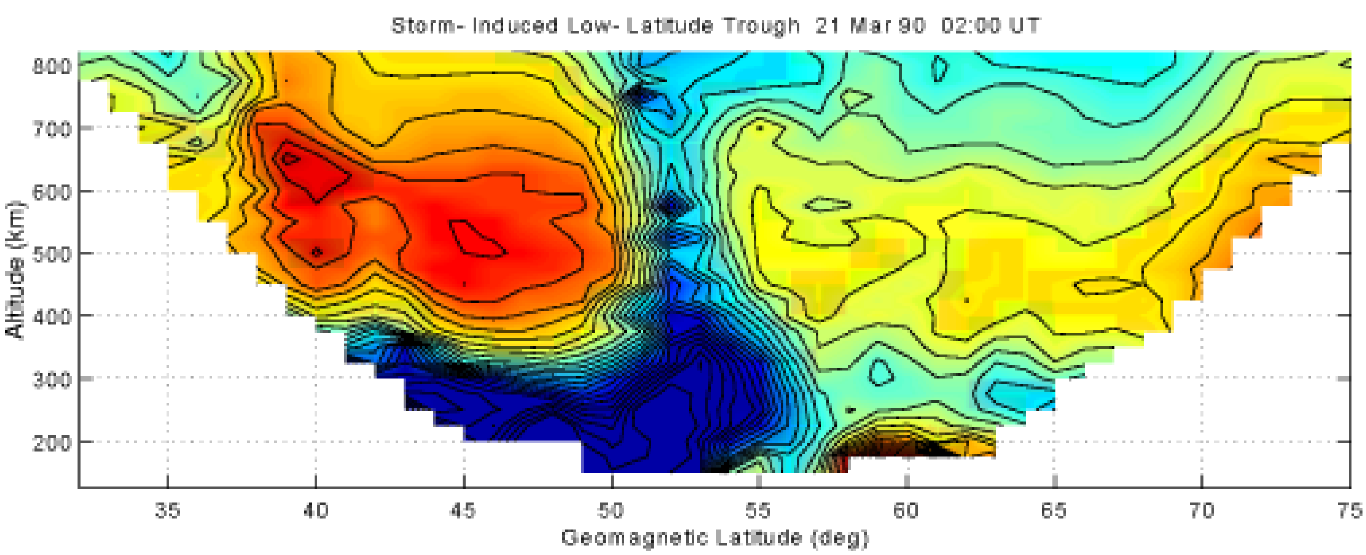
The Millstone Hill radar uses incoherent or Thomson backscatter from ionospheric electrons to deduce fundamental parameters of the Earth's ionosphere and upper atmosphere. These include electron and ion temperatures, electron densities, plasma drift velocities, and ion composition. These parameters are also used to derive information about the neutral gas temperatures and motions, as well as about the electric fields in the ionosphere. The incoherent scatter technique provides observations of many of these parameters over an altitude range extending from less than 100 km to 1000 km or more.

A capability to receive the Millstone Hill radar echo bistatically at a distant location is now available using a data acquisition system and receiver at the Algonquin Observatory antenna in Canada. A program of joint experiments with the University of Western Ontario is investigating simultaneous coherent and incoherent scatter probing of the E-region of the ionosphere (100–150 km altitude), as well as bistatic mid-latitude plasma convection observations.

Radiowave Instruments

Since 1987, the University of Massachusetts-Lowell has operated a digital ionospheric sounder, the Digisonde 256, at Millstone Hill using a 60-m vertical rhombus antenna for transmission and four spaced crossed-loop antennas for reception. Routine ionogram soundings are made every 15 minutes, normally followed by 5 minutes plasma drift observations. The ionograms are used to derive electron density profiles in real time. The critical frequency parameters obtained from the ionograms are used to calibrate the incoherent scatter electron density profiles. The Digisonde is also used to determine the three-dimensional plasma velocity.

The University of New Hampshire Meteor Wind Radar, located in nearby Durham, New Hampshire, is a 30-kilowatt high frequency, or HF, coherent pulsed



Electron density observed over a 30-degree span of latitude by the Millstone UHF radar indicates the large-scale ionospheric structure which occurs at mid-latitudes during geomagnetically disturbed conditions.

radar system operating at a frequency of 36.8 MHz. Two transmitting and receiving antenna arrays are used to obtain northward and eastward components of the neutral wind at altitudes of 80–100 km based on observations of meteor trails. Each receiving system utilizes two interferometers to measure the direction of the meteor trail reflection point. The radar is computer controlled for unattended operation and operates routinely with the Millstone Hill radar as part of the mesosphere, lower-thermosphere study initiatives.

Optical Instruments

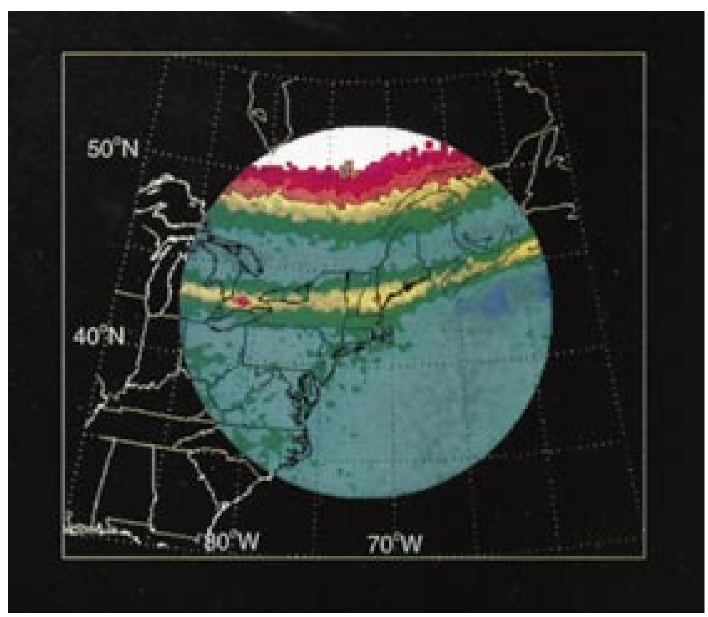
An MIT Fabry-Perot Interferometer is operated every night, observing emissions at a wavelength of 630 nanometers (a nanometer is a millionth of a millimeter) from the F-region of the ionosphere, a layer that spans roughly 200–500 km in altitude. The data are analyzed for winds and temperatures and, since May 1989, have been sent regularly to the CEDAR database for community access and usage. The observations reveal gradients in both meridional and zonal winds, and in conjunction with a similar instrument at the University of Pittsburgh, have shown the presence of large vertical atmospheric motions.

Haystack Observatory atmospheric optics facility is situated in a dark-sky location.

The Boston University Fabry-Perot Spectrometer is capable of measuring a wide variety of visible and near-infrared airglow emissions over a wavelength range of 550–1100 nm. A unique combination of detectors provides additional sensitivity needed for operation at near-infrared wavelengths. The instrument includes a six-element filter wheel permitting multiple emission measurements in a single evening.

The Wisconsin Triple-Etalon Fabry-Perot operating with charge-coupled device (CCD) has been located at Millstone Hill Observatory since early 1995. It is capable of both daysky and nightsky observations of the atomic oxygen red line emission at 630 nm. Winds and temperatures in the thermosphere are obtained and complement the radar data.

The core instrument of the Boston University Imaging System is an image-intensified CCD system optimized for low light levels using an all-sky camera. A filter wheel makes available 630 nm, 558 nm, and 777 nm observations on a routine basis. Operations involve a 14-day period each month centered on the day of the new Moon. In this mode, over 900 nights of observations have been made with visible structures such as diffuse auroral light or stable auroral red arcs, in addition to background airglow.



All-sky red-line imagery at a wavelength of 630 nm made with the Boston University imager locates a mid-latitude stable auroral red arc directly poleward of Millstone Hill.

Haystack Observatory post-doctoral researcher combines the latest instrument and computer techniques to investigate upper-atmospheric processes.

The proximity of the MIT Lincoln Laboratory Firepond facility, which supports the operation of a 1.2-m steerable optical telescope and several high-power laser systems, provides an excellent opportunity for atmospheric lidar experiments. Lidar is the analog of radar using light waves instead of microwaves as the transmitted energy. A 25-Watt Nd-YAG laser was operated on the Firepond telescope in the Summer of 1996 in a collaborative program with Clemson University, South Carolina. The experiment demonstrated that Rayleigh scatter can be obtained from neutral molecules in the Earth's stratosphere and mesosphere covering altitudes from 30–100 km. These measurements, which are used to determine the density and temperature of this atmospheric region, complement the set of data available from the radar and passive optical instrumentation outlined above. A future capability to measure laser Doppler velocities in various directions can yield the full wind vector velocity. The full set of instruments at Millstone Hill can then probe in detail the structure and dynamics of the entire middle and upper atmosphere from about 30 km to 1000 km.

The laser beam of 800 milli-Joule intensity emitted from the Firepond 1.2-m optical telescope in experiments to demonstrate the capability of the system to study the structure of the stratosphere and mesosphere.

LINCOLN SPACE SURVEILLANCE COMPLEX

The Lincoln Space Surveillance Complex (LSSC) consists of three high-power steerable dish radars – the **Millstone Hill Radar** (MHR), the **Haystack Radar**, and the **Haystack Auxiliary** (HAX) **Radar**. The LSSC is operated by MIT Lincoln Laboratory for the U.S. and Air Force Space Commands. LSSC's primary mission of satellite surveillance entails tens of thousands of precision satellite tracks and thousands of high-resolution radar images each year. Crucial coverage of domestic and foreign satellite launches is provided along with supporting analysis. Extensive data collection on man-made orbital debris is accomplished with the Haystack and HAX radars. Support for other sponsors includes orbital debris studies for NASA, and missile tracking for the Ballistic Missile Defense Organization (BMDO) and the Navy on rocket shots from Wallops Island, Virginia.

Millstone Hill Radar (MHR)

The MHR transmits at an L-band frequency of 1295 MHz at a peak power of 3 MW (MegaWatts) using a 26-m diameter antenna atop a 25-m pedestal. High power and sensitivity allow for routine tracking of satellites, rocket bodies, and debris in the geosynchronous belt (40,000 km) and beyond. In 1957, MHR was the first radar to track a man-made object in space (Sputnik) and in the early 1960s became the first computer-controlled radar. Today, MHR is a highly automated instrument, allowing a single operator to accomplish the high-priority Space Command requirements of orbital catalog maintenance, status monitoring, and satellite launch coverage. Precise calibration and sophisticated orbit modeling help MHR produce the most accurate data in the Space Surveillance Network.

Originally constructed as a Ballistic Missile Early Warning System prototype operating at UHF, MHR has been upgraded in the 1960s with the installation of the current parabolic reflector, monopulse feed, and a 3-MW L-band transmitter. In the early 1970s, MHR deep space tracking capabilities were developed, which led to the world's first capability to actively track satellites in geosynchronous orbit.

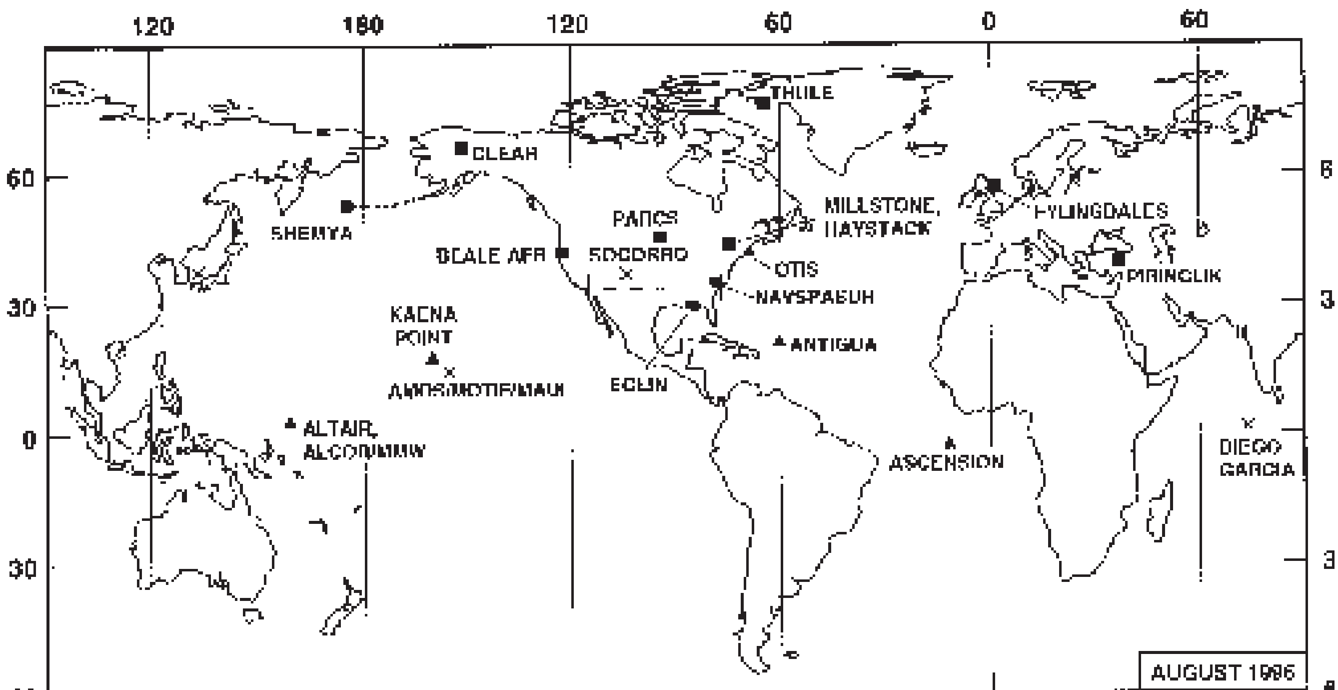
MHR includes an extensive suite of advanced, and often unique, equipment. The transmitter uses two CPI X-780 four-cavity Klystron tubes and is driven by a 1-kW solid-state driver. Typical operations are at 2 MW of peak power. The antenna is a 26-m diameter parabolic reflector with Cassegrain optics employing a 3-m diameter hyperbolic secondary reflector and unique 12-horn monopulse feed. Antenna motion ranges from 0–90° elevation with unconstrained travel in azimuth for full hemispherical coverage. The transmitted radar signals have right circular polarization. Received signals are right and left circular sum channels and left circular elevation and transverse error channels. Real-time radar control and signal processing are done in a pair of redundant Harris Nighthawk

The 26-m diameter antenna of the Millstone Hill L-band satellite tracking radar.

Capacitor bank and L-band transmitter.

computers comprising dual 32-bit processors. Communication with the Space Surveillance Network is maintained 24 hours a day on redundant hardware. All message traffic is logged to the database. A comprehensive history of observations from MHR and the rest of the Space Surveillance Network provides a valuable resource to analysts.

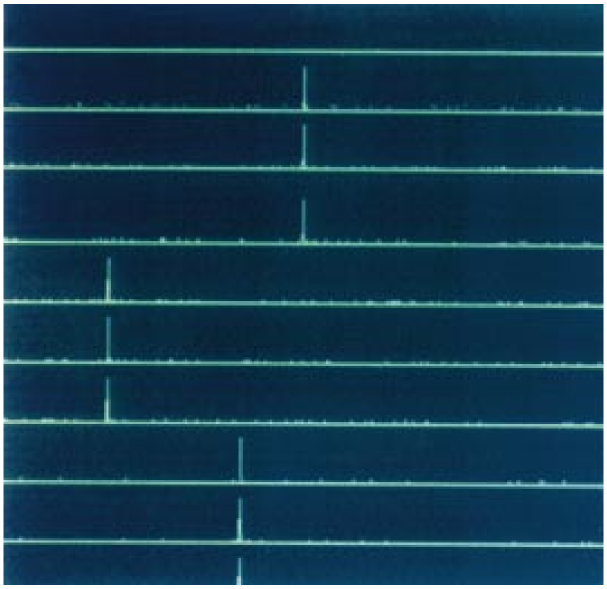
MHR is part of the deep space surveillance network, which includes radars: ALTAIR in the Marshall Islands, FPS-79 in Pirinclik, Turkey; optical sites: Ground Based Electro-Optical Deep Space Surveillance (GEODSS) telescopes in New Mexico, Hawaii, and Diego Garcia in the Indian Ocean; and Deep Space Tracking System (DSTS) passive radar sites in New York and England.



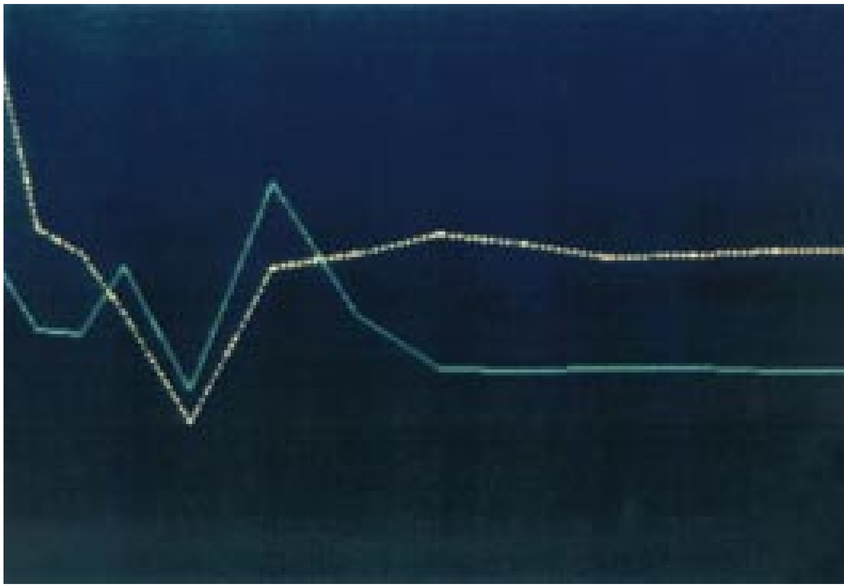
The U.S. Space Surveillance Network.

As a contributing sensor to the Space Surveillance Network, MHR provides approximately 18,000 deep-space satellite tracks per year and coverage for an average of 2–3 satellite launches per week, including pre-mission planning, radar coverage of critical events, and searches, as needed. Software tools and analysis techniques are used to support the entire Space Surveillance Network for searching, tracking, correlating, and identifying unknown objects. Real-time capabilities include:

- *cluster resolution*: Closely spaced objects are resolved in range and Doppler and cross-tagged objects are sorted out.
- *automatic status monitoring*: Signature returns of targets (e.g., peak and mean radar cross-section, spin period) are compared to historic values and alerts automatically sent to Space Command, if characteristics change.
- *break-up analysis*: Correlation, coverage, orbit prediction.
- *data-driven processing*: Polarization and coherency of target returns are automatically processed in the most efficient way to get maximum information from the returned signal.



Range-Doppler display used for real-time cluster resolution of closely spaced geosynchronous satellites.



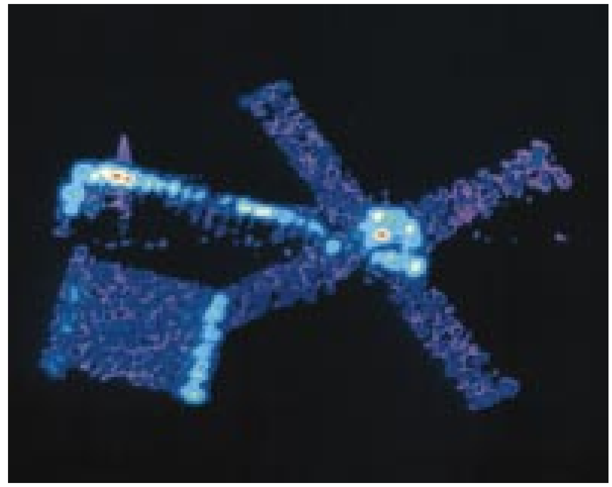
Automatic monitoring of satellite signatures for payload status monitoring.

The Millstone complex also encompasses additional radar equipment including a large steerable 46-m diameter UHF radar. This radar is primarily used for ionospheric research as described earlier, but is also maintained as a backup to the L-band system. All MHR real-time control systems for satellite tracking – scheduling, tracking, data processing, operator displays, creation of observations, database manipulations, and communications – function with both the L-band and UHF system.

Haystack Radar

The Haystack Radar utilizes the 37-m Haystack antenna and operates at a frequency of 10 GHz (X-band) with 1 GHz of bandwidth, allowing for the generation of radar images with 25-cm resolution in range and cross-range. Satellites to geosynchronous distances are imaged in near real-time on a graphical workstation using Lincoln Laboratory-developed software. These high-resolution images are used by the Air Force Space Command to assess payload structure, mission, and status. The radar is operated on a schedule of about ten to twelve weeks per year and is used approximately 600 hours per year to collect data on orbiting space debris. The Haystack Radar and its auxiliary system, HAX, have been the major contributors to understanding the space environment for debris in the 1–10-cm size regime.

The Haystack Radar is capable of tracking both near-earth and deep-space satellites with orbits ranging from 200 km above the earth's surface out to geosynchronous (40,000 km) and beyond. The antenna provides 68 dB of gain with a beamwidth of 0.06 degrees, and is capable of moving in azimuth and elevation at about 2 deg/sec with full hemispheric coverage. Typical pointing accuracies are about 0.4 millidegrees. The transmitter produces 400 kW of peak power and 140 kW of average power.



Simulated radar range-Doppler image.

Originally constructed in 1964, the Haystack radar system has undergone many upgrades since then to maintain a state-of-the-art system. A Gould SEL/9780 functions as the main real-time computer, while some functions such as timing and displays are driven by other workstations. A right circularly polarized wave is transmitted and both right and left circularized polarized signals are received. The monopulse tracking feed also provides azimuth and elevation error signals so that returns are processed in four identical channels.

The collocated radomes of the Haystack Radar and Haystack Auxiliary (HAX) antennas.

The Haystack Radar equipment box in its test dock, showing the monopulse tracking feed.

Future upgrades will include a new real-time computer, array processor, and recording system. Asteroid tracking capabilities are currently being tested in preparation for future planetary radar applications.

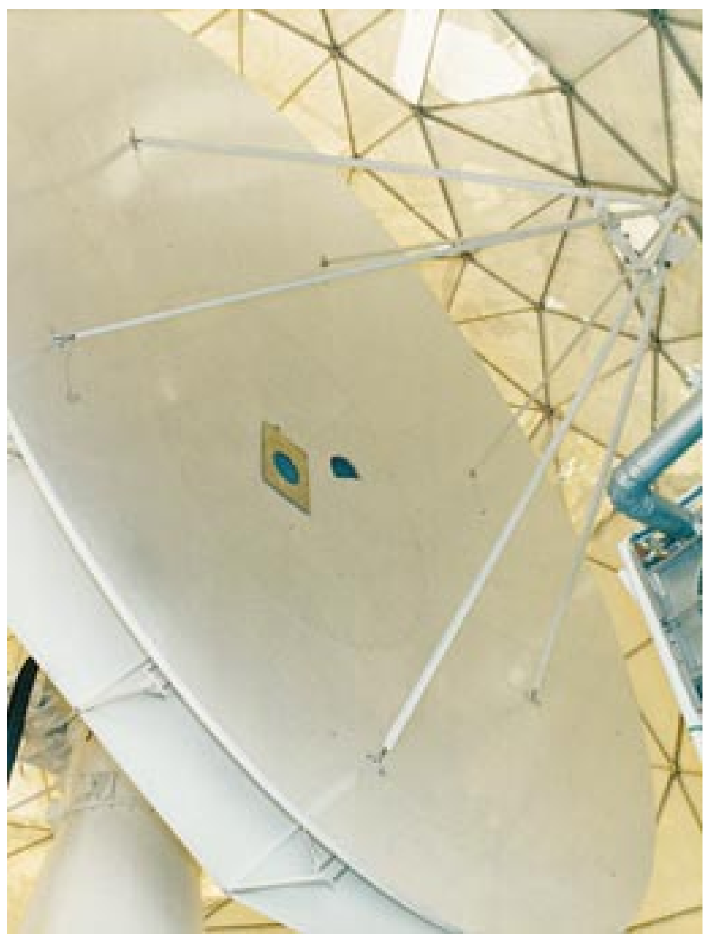
The Haystack satellite tracking and radar control console.

Haystack Auxiliary Radar (HAX)

The HAX radar has a 12-m diameter antenna inside a radome and operates at 16.7 GHz in the Ku-band. HAX is truly an auxiliary to Haystack, sharing a Processing and Control System, which incorporates common hardware and software for waveform generation, master timing, receiver processing, real-time computer, displays, and controls.

The HAX radar transmits a 2-GHz bandwidth pulse and produces radar images with 12-cm resolution. HAX is a state-of-the-art radar with a quasi-optical beam waveguide system and an antenna surface maintained to 0.018" rms resulting in a 64-dB antenna gain. The antenna is extremely agile and is able to move at rates of 10 deg/sec with full hemispherical coverage.

The HAX radar was built in 1993 by Lincoln Laboratory to augment satellite imaging and space debris data collections. The need for HAX was motivated by the limited availability of the Haystack radar for both imaging and debris work. Like Haystack, HAX is used to track satellites to produce range-Doppler images for U.S. Space Command and is used in a beam-park mode to conduct measurements of space debris down to sizes of 1 cm. The combination of Haystack and HAX provides year-round availability for Space Command imaging requirements.



The 12-m diameter antenna of the Haystack Auxiliary (HAX) Radar.

EDUCATIONAL ROLE AND CONTRIBUTIONS

As an integral part of their pursuit of advanced research, the MIT staff at the Haystack Observatory and Millstone Hill has been dedicated to the education of graduate, undergraduate, and pre-college students. With the availability of a unique research facility in astronomy, geodesy, atmospheric science, and radar applications, the Observatory presents a special opportunity for training students in research as part of their education. This linkage of research and education has been established as a high-priority national goal to improve the preparation of students for careers in science and engineering. These pre-college outreach programs for middle and high school students in the local area fulfill the Observatory's commitment to the goal of enhancing interest by young students in science, engineering, and mathematics, and contribute to the neighboring towns and State wherein the Observatory resides. In addition, Observatory resources have been made available to science teachers at all levels in the local area. The Observatory has also been opened to visitors and to the larger public community to increase the appreciation and benefits of scientific research to society.

An MIT undergraduate student works with high school students from Groton and Westford on the derivation of the rotation rate of the Sun from observations of sunspots.

Graduate Student Education

Graduate-level projects have always been a major important aspect of this university-associated Observatory. Students from MIT, the NEROC institutions, and universities nationwide use the Haystack radio telescope, the VLBI correlator, and the Millstone Hill radars and optical instruments for the acquisition and processing of observations as part of doctoral thesis research projects. About 20 graduate students per year utilize the Haystack and Millstone Hill facilities for such purposes and some reside at the Observatory for substantial portions of their graduate research programs. Several hundred graduate students have received their training at these facilities, and it is expected that this important contribution to education will continue in the future.

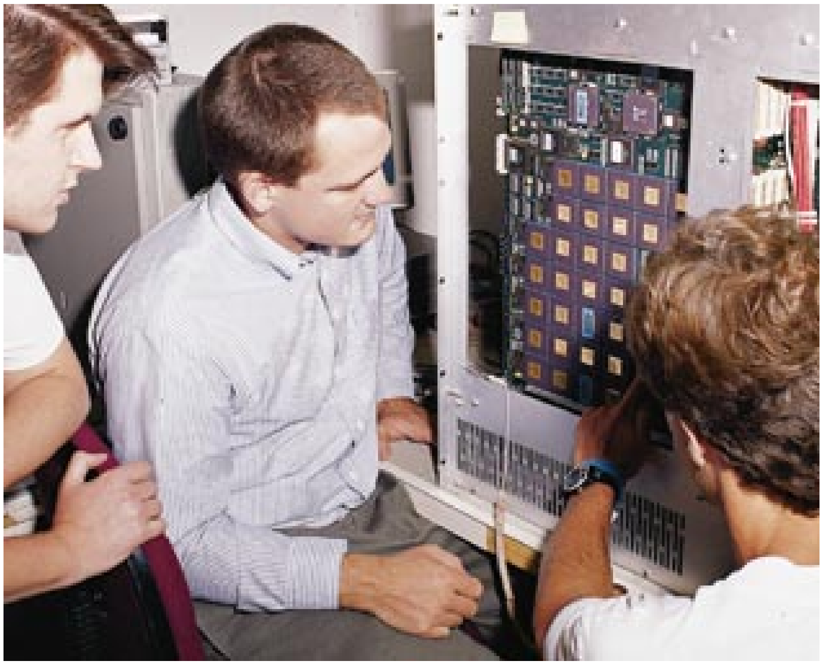
Haystack staff members lend support to these students to facilitate their work and assist in their training through the hands-on use of the instrumentation. On some occasions, the students become involved in the construction and testing of a hardware subsystem required for their project. Such instrumentation development is an important ingredient in graduate education, and the Observatory provides special support for such work.

Undergraduate summer interns from Wellesley College and Boston University are introduced by a Haystack engineer to the observing procedures at the telescope control console.

Undergraduate Student Education

During the past few years, there has been a growing fraction of undergraduate students from several area colleges who come to Haystack to utilize the instrumentation as part of undergraduate projects and honors thesis research. Some university faculty members integrate projects at Haystack as part of undergraduate courses. The Observatory hosts many visits by undergraduate classes from area universities where the students spend a major portion of the day learning about the instrumentation and on-going research projects in astronomy, space geodesy and atmospheric science, and observe data being taken or processed.

A formal summer internship program for undergraduates has been developed at Haystack since 1987. Grants from the NSF Research Experiences for Undergraduates (REU) Program, and from other NSF, NASA, and USAF research grants and contracts at Haystack, support stipends for ten to fifteen undergraduates annually who spend three months at Haystack under the mentorship of MIT staff at the Observatory. The students are selected from over 100 applicants nationwide. They work on research projects in astronomy, geophysics, atmospheric science, and engineering, attend special seminars and learn about the instrumentation at the facility. Over 150 students have participated in the program to date, and their work often results in published material, conference papers, or technical reports.

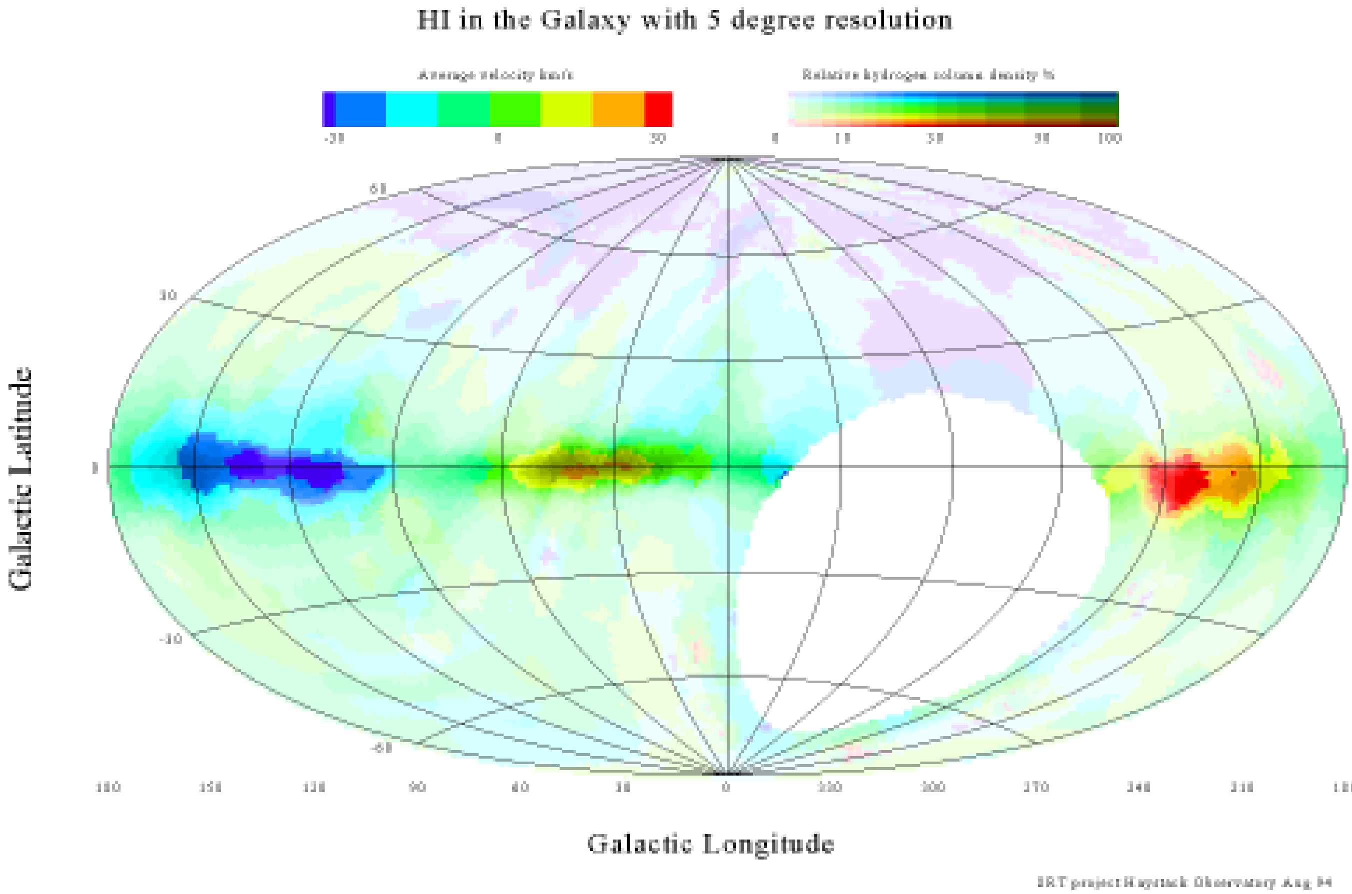


Undergraduate summer interns from Caltech, James Madison University, University of Oklahoma, and the University of Washington work on engineering projects under development at Haystack for the VLBI Mark IV correlator and high-data-rate recorder.

A 3-m diameter small radio telescope using a TV satellite dish has been developed at Haystack as an educational tool for radio astronomy.

Emphasis is now being placed on making capabilities fully accessible nationwide to research by undergraduates who are pursuing degrees in science or engineering. Students will be involved in radio astronomical observations designed to give them the thrill of discovery, as well as challenge them to apply their knowledge of physics and engineering to problems in radio astronomy. Radio astronomical measurements present unique challenges in data collection and interpretation, which require students to draw on a wide range of concepts learned in undergraduate physics and engineering courses.

A capability for remote operation of the Haystack radio telescope is being developed to allow undergraduate students to carry out projects, such as surveying the dense gas cores in our Galaxy as signposts for the birth of new stars, and monitoring the emission from interstellar water masers. In conjunction with this program, a smaller radio telescope is being made available for students to construct and use at their own institutions. A prototype system of such a telescope operating at several frequencies has been recently constructed at Haystack, and used successfully to map the hydrogen gas in our galaxy. Through this program, students will learn the techniques used in radio astronomy and communications, design their own experiments, develop new observational methods, and study regions of star formation and the evolution in our galaxy.



An all-sky radio map of hydrogen in the Milky Way galaxy was obtained at a wavelength of 21 cm using the 3-m small radio telescope.

Pre-college Science Outreach

A Young Scholars outreach program, sponsored by the National Science Foundation, is conducted annually at the Haystack Observatory. Students in middle school and entering high school participate in a three-week summer program aimed at exciting them about science using hands-on research projects in astronomy, geodesy, and atmospheric sciences. The students use the telescopes to map celestial objects and exploit the databases in a dedicated computer laboratory in order to study the earth's plate tectonics. They also conduct balloon and rocket experiments to learn about the earth's atmosphere. Moreover, discussions are held with the students on ethics and careers in science and engineering, scientific debates are carried out, and star observing parties are organized, as well as field trips to scientific facilities. Each student is then assigned a project and staff mentor as part of a follow-up effort during the academic year that culminates in a student conference at Haystack in the Spring. A total of 60 students selected from a large number of applicants in local area schools participate annually in this program. Since its inception in 1990, over 250 students have participated in this important program.

A strong contact also exists with local area science teachers who participate in special sessions at international conferences. Special groups, such as the Boston Physics Teachers Association and the New Hampshire Science Teacher Association, visit the Observatory, and meet with the staff to discuss science and mathematics education for their students through the disciplines that are practiced at the Observatory. Educational materials have been acquired at Haystack and made available for teachers to borrow and use in their school programs. Finally, the Observatory staff volunteer to visit interested science classes and participate in class projects. Through these efforts, mentoring activities are offered by the staff to local area students at all levels.

Community Outreach

A final important element of the Observatory's educational program is the interaction with the neighboring communities. Public open house visits to the Observatory are held in the Fall every year, and include lectures on scientific topics. Organized groups (scouts, clubs, societies) are hosted for similar visits during evening hours and weekends. In the past two years, over 2,000 visitors have come to Haystack. In other public endeavors, the Observatory staff collaborate with nearby science museums for the development of special demonstrations. They also interact with the Amateur Telescope Makers of Boston at the Westford site, who organize public star-watching visits and support the Young Scholars program. Such outreach activities are an important contribution towards enhancing appreciation and support for science in the United States.

Young Scholars and teachers from 20 middle schools in the local area around the Haystack Observatory work with MIT staff on various science projects during the summer. The program culminates in a symposium where the students display the results of their special projects carried out during the academic year under staff mentorship.

INFRASTRUCTURE AND OTHER FACILITIES

While each of the facilities described has its particular functions and the special equipment needed to perform them, provisions have been made to allow all the sites to operate jointly and cooperatively. Whether the instrumentation is used for tracking payloads launched aboard rockets, for providing diagnostic measurements on satellite experiments, or for conducting space and atmospheric observations, the powerful combination of these valuable instruments makes the overall facility an important national resource for basic and applied research. The ability to provide mutual support in both hardware and personnel makes the overall research complex far more valuable than the individual facilities could be independently.

The infrastructure provided by the MIT facility at Haystack and Millstone Hill has allowed several other facilities to carry out research and educational projects at the Westford site.

MIT Lincoln Laboratory operates the Firepond Research Facility for the development and testing of laser radar techniques to track and image satellites and other objects of interest visible to the site. Programs associated with adaptive optics and high-power lasers have been conducted at the facility. The Laboratory also utilizes the Westford radio telescope for conducting atmospheric propagation experiments for space communications applications.

The MIT Department of Earth, Atmospheric and Planetary Sciences operates the George R. Wallace Astrophysical Observatory for research and teaching in optical astronomy. The Observatory consists of two optical telescopes with 0.6-m and 0.4-m diameters. Also part of the Department's research and education programs in geophysics is the George R. Wallace Geophysical Observatory, which contains sensitive seismometers to monitor ground motions as part of a global seismic network.

The MIT Center for Space Research operates a ground terminal as part of the High Energy Transient Satellite – the goal is to study and determine the location of gamma-ray bursts.

The Smithsonian Astrophysical Observatory is assembling the Sub-millimeter Array Telescope at the Haystack Observatory and will test its performance prior to its permanent installation on Mauna Kea, Hawaii. The array will consist of six 6-m diameter antennas operating at wavelengths of 0.35–1.3 mm, or frequencies of 230–860 GHz.

The Amateur Telescope Makers of Boston, a group of 300 amateur astronomers, are hosted by MIT at the Westford site. They construct telescopes in their clubhouse and conduct observations on a regular basis, and help with the Young Scholars educational outreach program.

Moreover, the Site hosts visiting researchers from academic institutions, national laboratories, and international organizations for various temporary tests and measurements using Global Positioning System (GPS) receivers, laser trackers, and optical instruments.

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