Haystack Observatory

Haystack Observatory is a multidisciplinary research center located in Westford, Massachusetts, 27 miles northwest of the MIT campus. The Observatory conducts a broad range of radio astronomical studies, geodetic measurements using very-long-baseline interferometry (VLBI), and observations of the geospace environment using high-power incoherent scatter radar, complemented by a variety of other techniques and instruments. An important component of Haystack's mission is the education of students through research opportunities using the Observatory's facilities.

The Observatory research portfolio continues to broaden; the addition and maturation of astro- and geoinformatics programs, the initiation of space-based projects, and research into the Earth's cryosphere are all recent developments. A strong technology and engineering program supports each of the scientific research disciplines, and the Observatory benefits from extensive overlap in technologies and techniques applied to the various radio science areas of research.

Haystack has a number of major, established programs that together provide stable funding that constitutes the bulk of the total budget. Geodetic VLBI, supported primarily by the National Aeronautics and Space Administration (NASA), continues to be a mainstay, and enjoys strong technical overlap and synergy with the astronomical VLBI effort at the Observatory. These programs share technical developments in data recording and correlation. The geodesy program includes a focus on the implementation of next-generation broadband receiver and back-end systems as part of the US investment in the Global Geodetic Observing System (GGOS). The astronomical VLBI program is primarily driven by the Event Horizon Telescope (EHT) project, which relies on Haystack Observatory for a range of correlation, technical, and data analysis functions. Another major program is the geospace science facility effort, supported by the National Science Foundation (NSF), which is centered on the incoherent scatter radar (ISR) instruments on site. This program also supports a range of internal science investigations, provides extensive geospace science community support for users across the country and the world, and includes a significant component of advanced engineering and technical development. Augmenting all these programs is a complement of smaller individual science grants from NASA and NSF, which are a steadily increasing fraction of the budget. Also in the category of established programs is the informatics effort, which effectively combines cutting-edge computer science techniques with practical scientific applications using large radio-based and related data sets.

Haystack also enjoys a close relationship with Lincoln Laboratory and provides extensive engineering and facilities support for a range of Lincoln Laboratory projects and installations at the field site. The Observatory has significant technical collaborations with Lincoln Laboratory, particularly involving innovative CubeSat projects.

The other category of essential Haystack research programs involves future-oriented efforts, which seed the major programs of the next decade and beyond. Haystack is pursuing a rich portfolio of initiatives, from next-generation array radar development to a revolutionary passive, portable imaging array concept, and radio science CubeSat mission proposals to NASA. The Observatory is investing in the development of on-site drone-testing and training facilities, leveraging a favorable location with respect to restricted airspace. Haystack is pursuing advanced general data capture and digital processing architectures, with application to high-performance back-end astronomical instrumentation for the 37-meter telescope and architecturally simplified, low-cost wideband VLBI recording and correlation systems. Staff members regularly and actively survey the relevant technological landscape for developments that can be exploited in a timely way for new radio science capabilities and instruments, and Observatory representatives routinely attend national and international community meetings focused on future technical and scientific developments in radio science.

Strategic Priorities

Strategic planning is an essential, ongoing activity at the Observatory; it is key to efficient coordination of the diverse, yet interconnected and related, research activities. A number of clear research program priorities for the Observatory are being pursued:

- Continued expansion of collaborative efforts with Lincoln Laboratory and with campus researchers.
- The renewal and development of the Northeast Radio Observatory Corporation (NEROC). NEROC is a nonprofit corporation whose board of trustees guides Haystack's radio science programs and appoints the Visiting Committee. The NEROC community, consisting of 12 education and research institutions with interests in radio science, is a potent reservoir of current and potential collaborators, with the significant benefit of regional proximity.
- The development of a world-class applied informatics group. This is a strategic choice with immense potential, capable of amplifying and revolutionizing Haystack research based on radio techniques. Technologically, rapid and inexorable growth in both measurement capabilities and machine intelligence capabilities are pointing strongly in this direction.
- Establishment of a stronger, more diverse astronomical research program, reestablishment of the 37-meter telescope as a competitive research tool, and incorporation of research using national and international flagship facilities.
- Development and eventual construction of a replacement instrument for the venerable megawatt-class ISR facility at Haystack, using advanced low-frequency array technology. This effort, which is well under way, is a potent vehicle for the more general development and scientific exploitation of passive low-frequency arrays of various kinds, for both geospace and astronomical research.
- Maintenance and expansion of Haystack's presence on the web and in the media, for both professional and public communications. The recent addition of a communications officer was made partly to address this pressing strategic need.
- Establishment of a viable program of space-based radio science investigations. The barrier to entry into this field of endeavor is high, but a sustained effort is being mounted in partnership with Lincoln Laboratory and a variety of key collaborating institutions.

Personnel

One of the consequences of the Observatory's growth in recent years, both in research volume and diversity, is added administrative complexity, with increasing burdens on members of the director's office. Haystack has recently added a second financial officer, a communications officer, and an assistant director for administration with expanded responsibilities for the human resources, financial, information technology, and facilities functions of the Observatory.

Other new hires, including software developers, postdoctoral researchers, research engineers, and scientists in geospace and astronomy complement the technical expertise that already exists within the Haystack staff. These new Observatory staff further strengthen all research groups and expand the range of challenges that can be met with confidence.

Finances and Funding

Haystack staff have been extraordinarily productive on the proposal submission front, with 38 funding proposals submitted during the 12-month period covered by this report, involving 14 different principal investigators. Seven of these proposals are still pending; 12 of the remaining 31 proposals were awarded for a success rate of 39%. The success rate was somewhat lower than in recent years, partly because of efforts to break into new fields of research. Haystack financing and staffing remain healthy and the Observatory continues to grow. This success has been tempered by delays in the issuance of some awards because of the uncertain climate in Washington, the need for caution in Observatory hiring for the same reason, more modest growth in research volume than had been projected a year earlier, and the negative effect of such resource limitations on the ability to exploit new opportunities quickly.

Haystack has already implemented strategies to reduce risk and promote growth in the face of chronically tight federal budgets. These strategies include diversification of both projects and sponsors, promotion of synergies in the technological underpinnings of projects to improve agility in response to opportunities, and an aggressive, coordinated, and prioritized proposal-writing program. Such an approach continues to provide the primary defense against agency austerities, whether they are general or targeted at specific agencies and programs. It is being augmented by approaches to a variety of potential nonfederal sponsors, although the Haystack staff recognizes the substantial lead time involved.

Research Area: Geodesy

Haystack Observatory's significant legacy of VLBI technology innovations for geodetic application has continued under group leader Pedro Elosegui.

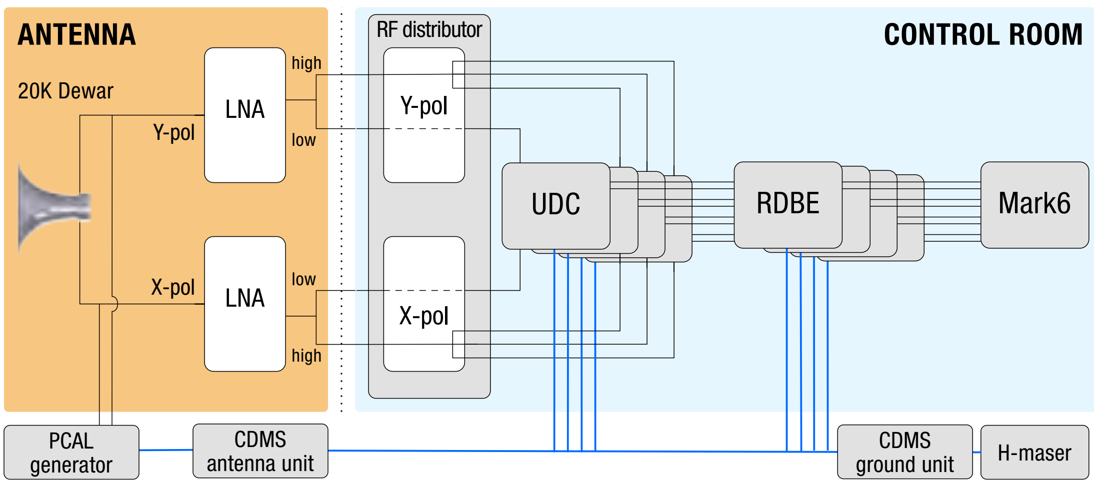
Geodetic Observing System

Under NASA sponsorship, the Haystack geodetic VLBI group continues to develop the advanced system known as the VLBI Geodetic Observing System (VGOS) for the next-generation geodetic VLBI network. VLBI is one of the fundamental space geodesy techniques that are essential to realizing an accurate and stable terrestrial reference frame. The terrestrial reference frame is crucial to advancing our understanding of critical components of the Earth system, such as the global hydrological cycle, which includes the cryosphere and the dynamics of the oceans and the atmosphere; natural hazard warning and prevention; disaster mitigation; sustainable development; and society at large.

VGOS is the VLBI component of GGOS. Under its Space Geodesy Program, NASA is leading the development of a global network of 10 GGOS stations. The NASA network will be expanded with additional stations funded and built by international partners, with the goal of eventually forming a global array of GGOS stations that spans the Earth surface and is homogeneously distributed.

In 2016, Haystack installed the signal chain for the first VGOS station, at the Kōke'e Park Geophysical Observatory (KPGO) in Hawaii. The Haystack-developed VGOS system deployed at KPGO consists of a fast-slewing 12-meter-class antenna coupled with a system of innovative and highly sophisticated signal chain hardware, also designed by Haystack engineers. Central to the VGOS project goals are the Haystack advanced software correlation capabilities, as well as the postprocessing, diagnostic, and quality control software systems.

The first fully operational VGOS system installed at Kōke'e Park Geophysical Observatory on the island of Kauai.



The Haystack-designed antenna signal chain from the feed horn through to the Mark 6 recorder. (LNA = low-noise amplifier; RF = radio frequency; UDC = up-down converter; RDBE = ROACH digital back end; PCAL = phase calibration; CDMS = cable delay measurement system; H-maser = hydrogen maser.)

In June 2017, development began on the second VGOS station. It will be built at the McDonald Observatory at the University of Texas, and will follow the design of the KPGO station.

In addition to the Westford telescope operations in support of VGOS, Haystack continued its routine support of geodetic VLBI through correlation, network support of various kinds, data quality monitoring, and support of UT1 monitoring through a US Naval Observatory contract.

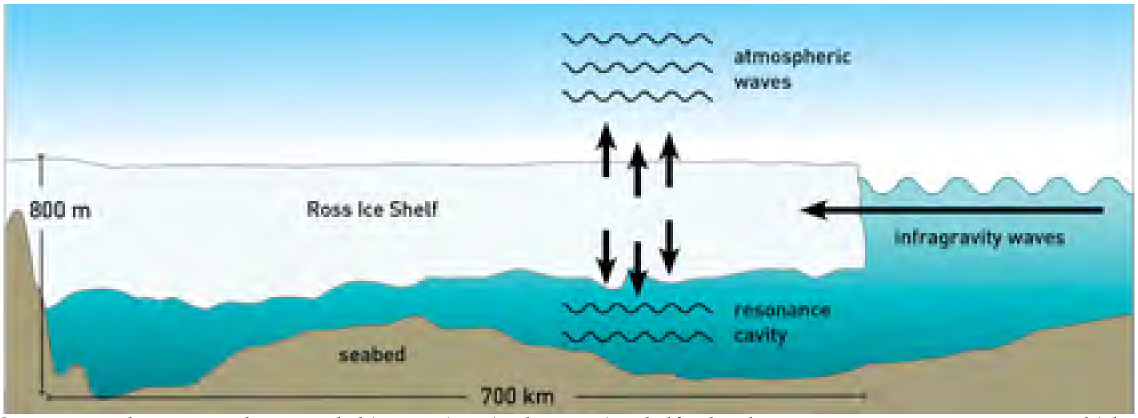
Haystack has embarked on a forward-looking series of internal workshops aimed at identifying technologies and techniques with the potential to revolutionize VLBI systems and bring new levels of flexibility and measurement accuracy to the geodetic VLBI community. This effort is intended to help shape the vision for systems that will succeed the VGOS network, in a manner that leverages and overlaps with an installed base of VGOS systems around the world. Among the topics being explored are lower-cost antennas, improved cryogenic systems, novel observing strategies, better methods for estimating water vapor in the troposphere, correlation systems that are easier to port and maintain in the face of evolving computing platform architectures, and more sophisticated data reduction and analysis approaches to make better use of the inherent information content of the data.

The annual International VLBI Technology Workshop for 2016 was hosted at the Observatory; representatives from 17 countries attended. Haystack continues to hold a leading role in coordinated international efforts to pursue a joint vision for advanced future systems in the service of geodetic science.

The 9th IVS Technical Operations Workshop was held in April–May 2017 at the Observatory. This biennial meeting, a major international gathering of 80 VLBI technologists and practitioners, focused on problem solving, hands-on training sessions, and direct communication initiatives with personnel across stations, the International VLBI Service for Geodesy and Astrometry (IVS) Coordinating Center, and the correlator locations.

Polar Geodesy

Initial polar geodesy efforts are focusing on the cryosphere, including precision measurement of ice movements with deployable GPS-based systems. Such work is relevant to the high-profile topics of global climate and sea level change. A specific initiative is the NSF-funded development of an air-droppable penetrator system intended to allow dense instrumentation of Antarctic ice shelves with broadband seismometers and GPS receivers to monitor the response of the shelves to ocean forcings, with satellite communication for near-real-time data download to a central repository. Such a system would eliminate the challenging logistics currently faced in obtaining such measurements, replacing those logistics with efficient aircraft-based deployment. The manner in which the ice shelves behave, and the mechanisms by which they collapse, “uncorking” the land glaciers and triggering major ice sheet collapse and associated sea level rise, is a critical cryosphere-ocean research topic.



Ocean-cryosphere-atmosphere coupled interactions in the Ross ice shelf, whereby storms generate ocean waves, which force vibrations in the ice shelf, which may generate detectable responses in the atmosphere, from the mesosphere up to the thermosphere and ionosphere. Infragravity waves are thought to be an important factor for the possibility of floating ice shelves disintegrating, permitting land-based glaciers to flow quickly into the sea.

Research Area: Geospace

Geospace research is a major component of the Haystack portfolio, encompassing investigations from the Sun to the lower atmosphere and everything in between. Traditionally, the emphasis has been on the ionosphere and the workhorse instrument has been the large and powerful on-site ISR facility. In recent years, however, the research of the group has broadened to include a wide variety of measurement systems and techniques, supported by a complement of relatively modest science grants from multiple agencies and programs led by principal investigators.

Radio Array of Portable Interferometric Detectors

The Radio Array of Portable Interferometric Detectors (RAPID) is an NSF-sponsored innovative, portable, and flexible low-frequency radio array developed in collaboration with the University of Cambridge and the Jet Propulsion Laboratory. The individual antennas in the array use per-element software-defined radios and a flexible software signal processing architecture to enable the study of a wide range of natural phenomena with radio imaging techniques. Among the many potential RAPID uses are investigations of ionospheric phenomena, solar radio emissions, the galactic synchrotron background, and ultra-high-energy cosmic rays. The scalable array will initially consist of 50 small, low-gain antennas operating over a frequency range of 48 to 615 MHz, and will be available for community use when completed in fiscal year 2018. At the time of writing, procurement of the hardware components for the major array was being initiated.

RAPID has already resulted in several generations of increasingly integrated prototype hardware that use commercial software radios for a wide range of data acquisition needs of scientific investigations by facility users. Most recently, the RAPID team successfully installed multiple prototype systems at the Jicamarca Radio Observatory in Peru.

RAPID prototypes being installed in Peru by Haystack scientists and students from the MIT International Science and Technology Initiatives Program; note the base design, which includes solar power panels, with storage for batteries, receiver electronics, and data storage systems, and a variety of auxiliary systems, such as wifi and satellite communications, GPS units, and more. The bases also act as the shipping container and can be stacked on pallets.

Madrigal

The atmospheric and geospace sciences group continues to actively develop the Madrigal distributed database, a standard in the upper atmospheric community that was originated at Haystack in the early 1980s. Madrigal has become the community standard interaction portal for all coupling, energetics, and dynamics of atmospheric regions (CEDAR) data, representing a large fraction of the historical and current US (and some international) ground-based geospace observational repository. From July 1, 2016, to June 30, 2017, the CEDAR Madrigal site—a community-based archive hosted at the Observatory—served data to 216 unique users across the space science community; the Millstone Madrigal site, which stores data from the Haystack facilities, served 228 unique users.

The next software release, Madrigal 3.0, has completed development and testing and is available to the outside world as a beta release. The final deployment of Madrigal 3.0 at full production capability is planned for FY2018.

UHF Radar

Over the past year, the Millstone Hill ultra high frequency (UHF) radar system, operated for decades by the Haystack Observatory under a cooperative agreement with NSF, was used for numerous, extensive observations. The space science community continues its significant use of Millstone Hill in its capacity as an NSF geospace facility. Maintenance of the transmitter system to ensure continuing operation is ongoing. Updates to core ISR and derived data product software are in current development. Several derived data sets have significant scientific potential and have attracted a number of in-progress scientific studies.

During the past year, a new front-end amplifier design for the UHF radar system was implemented, produced, and tested using a MIT Haystack in-house approach. A custom enclosure was created, and the new front-end amplifiers were successfully transitioned to production use, with a notable improvement in receiver system temperature. This design also provides a good starting point for future designs employing thermoelectric and cryogenic cooling to improve system sensitivity. Ganesh Rajagopalan, Haystack research engineer and former head of electronics at the Arecibo Observatory, brings extensive receiver cryogenics and low-noise amplifier experience to assist in this development.

Software

The geospace group continues the transition to a modern cloud computing architecture for both software and hardware. The new system is based on Apache CloudStack and GlusterFS (a scalable network file system), and is implemented with approximately 100 cores and 960 terabyte storage. The system is also now accessible using a virtual private network, allowing secure remote access. Many of these advanced features are unique to the NSF-supported suite of geospace facilities, such as Millstone Hill.

A newly developed data format for disk storage and retrieving radio signals achieved a significant milestone. Digital RF 2.0 is built on native hierarchical data format 5 standards, making use of existing libraries and tool sets. It was developed jointly for the Millstone Hill geospace facility and RAPID magnetic resonance imaging applications. The design provides many advantages for users, including very fast data recording; a logical, self-contained, and self-describing file format; clear and simple programming language interfaces for Python and C; efficient access to multiple channels of stored data; and cross-platform accessibility, among other benefits. The updated digital RF 2.0 file format, along with Haystack-developed application programming interfaces and expanded documentation, was released to the community under an open source license in June 2017.

Further insights into total electron content (TEC) behavior within the Alaskan sector are expected from a new global navigation satellite system (GNSS) receiver that was installed as part of a supplement to an NSF award. A GNSS receiver was placed at Venetie, Alaska, approximately 250 kilometers north of Fairbanks, with the aim of increasing the density of TEC and differential TEC measurements in the important auroral/subauroral region. The work is in collaboration with the University of Fairbanks.

Research Area: Astronomy

Event Horizon Telescope

The EHT is an array of observatories operating in campaign mode at 1.3 mm wavelength. The primary goal of the EHT project is to observe and image nearby supermassive black holes with enough resolution to see the lensed photon ring and shadow predicted by general relativity. Sagittarius A* (Sgr A*, the black hole in the center of the Milky Way) and M87 (a nearby giant elliptical galaxy that launches a powerful jet from its central black hole) are the primary targets, because these are the two black holes for which the achievable angular resolution is sufficient to delineate structural details on event horizon scales. The EHT is also a potent instrument for observing the innermost jet structures in many other active galactic nuclei.

In addition to sites in Arizona, California, and Hawaii that were used for early demonstration observations, the EHT has undertaken test and commissioning observations using VLBI telescopes in Mexico, Spain, Chile, and at the South Pole. These additional locations are important because they provide a wide range of baseline lengths and orientations, an essential prerequisite to reconstructing model-independent images of Sgr A* and M87.

The most significant sensitivity increase has come from the inclusion of the Atacama Large Millimeter/submillimeter Array (ALMA) in EHT observations. Haystack leads an international team that has phased up the array as a single VLBI site. When all antennas are phased, the sensitivity of ALMA is equivalent to a dish of more than 80 meters in diameter, making phased ALMA the most sensitive millimeter-wavelength aperture on the planet.

An EHT experiment already exceeds a petabyte for a typical observing run, and data rates continue to expand. The Haystack correlator was upgraded in early 2017 to handle the large data volume anticipated for the significant EHT VLBI run that took place in April 2017. The April 2017 run was the first opportunity for science to use phased ALMA, yielding sufficient sensitivity to enable attempts at true imaging of the black hole structures in Sgr A* and M87.

For Sgr A*, the effective resolution of the longest baselines in the EHT array will be about half the angular diameter of the shadow predicted by general relativity. Making an image of the shadow with higher resolution thus enables a test of general relativity: is the shadow nearly circular and of the predicted size? Haystack is leading the way in developing new image reconstruction software that makes use of compressed sensing techniques and robust VLBI observables to reliably extract structural information on the smallest possible scales.

Most of the data from the April 2017 run have been successfully received and correlated; the remaining data will arrive at Haystack in late 2017 once air transportation is again available from the South Pole telescope. Once the data are processed, the resulting images in early 2018 will be the first made of a black hole, and extensive international media attention is expected.

37-Meter Telescope

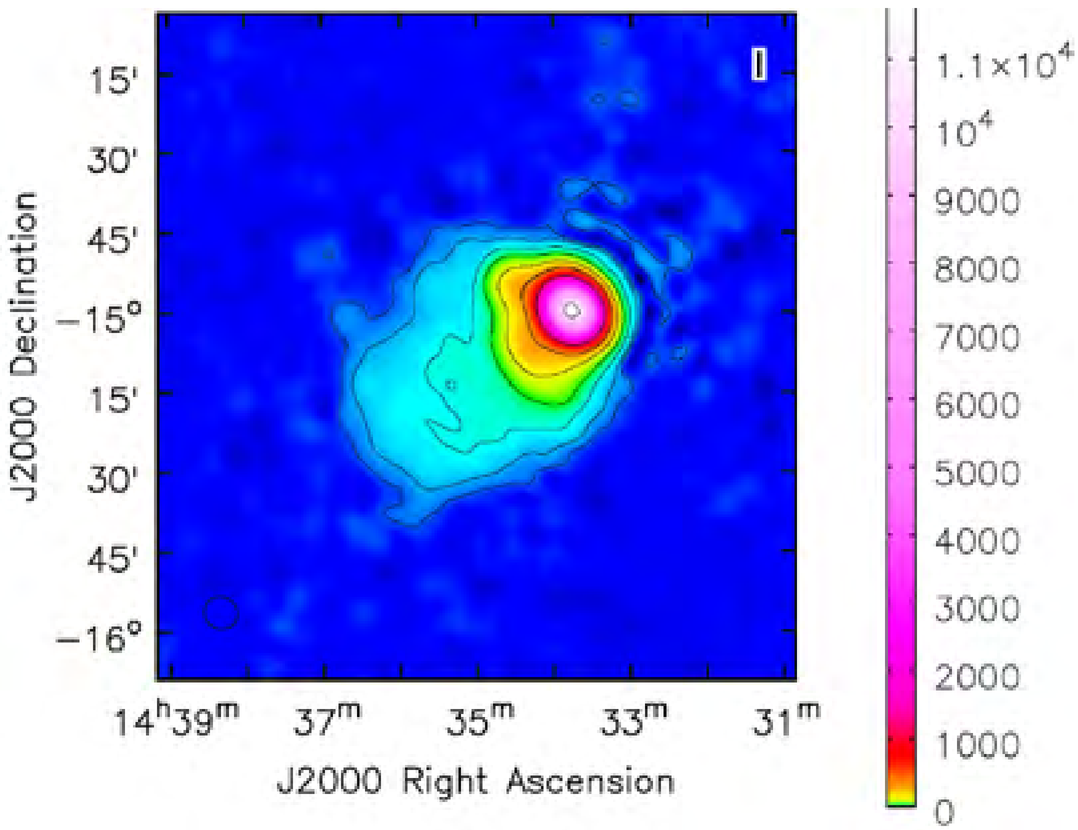
Work continues on the program to make the 37-meter telescope available for remote observations to support undergraduate astronomy classes across the country, with Lynn Matthews as principal investigator; this is supported by an award from the NSF Department of Undergraduate Education. This program is similar to one that made the 37-meter telescope available outside MIT before the upgrade. Many of the universities and astronomy departments that participated in the earlier program have signed up for the new one.

To support scientifically and educationally meaningful remote operations on the telescope, a significant amount of necessary development has begun, along with refurbishment of the radio astronomy receiver systems on the telescope. Establishment of routine astronomy operations also requires close coordination with the Lincoln Laboratory, and the development of protocols for scheduling and coordination of telescope control. The telescope will be available for astronomy users mostly during the nighttime hours and on some weekends. As of this writing, observing capability has been restored to the telescope at the K, Q, and W bands. Significant work is in progress on back-end instrumentation, interfaces with analysis software, and the development of a suitable remote user interface that meets both the educational needs of participating departments and Lincoln Laboratory's safeguards and controls.

The longer-term goal, pending efforts to secure a corresponding funding award from NSF, is to develop advanced, innovative instrumentation for the telescope that will render it competitive with other major high-frequency dishes around the world and support a significant research operations budget. To this end, Haystack is exploring advanced signal handling and processing architectures aimed at radical simplification of the system by exploiting both industry advancements and synergies with other Observatory technical development programs. The team seeks to conduct this effort in collaboration with the National Radio Astronomy Observatory and international groups. Such collaboration could lead to the participation of the Haystack dish in astronomical VLBI networks, the creation of an extremely wideband spectroscopic capability for the telescope, and the replication of similar systems for other telescopes around the world.

Low-Frequency Studies

Research using the Murchison Widefield Array in Western Australia has continued under the sponsorship of the Air Force Office of Scientific Research. This instrument, which was largely designed by Haystack, is unique in its ability to produce high-fidelity images with very small amounts of observing time and frequency range. This capability is being exploited for solar imaging, which, at the low frequencies involved (80–300 MHz), probes both thermal and nonthermal emissions from the solar corona. Recent tests demonstrate the ability to achieve imaging dynamic ranges approaching 105:1, which is three orders of magnitude better than other current arrays. These dynamic ranges open a rich landscape of scientific investigations of both the Sun and the interplanetary medium, with relevance to space weather prediction. Construction of a data reduction pipeline for the several petabytes of raw data that have been collected to date is continuing.



High dynamic range image of the Sun at ~150 MHz, with a ratio between the peak intensity and the background fluctuations of 67,000:1. This image was created from a single 40 KHz frequency channel and a single 0.5 s time sample, illustrating the extraordinary imaging capabilities of the MWA. The dynamic range exceeds that of competing instruments at this low frequency by nearly three orders of magnitude.

In addition, plans are being made to use the RAPID array, developed under the geospace program, to perform groundbreaking observations of the powerful Jovian decametric emission. For the first time, observations will include spatial information to complement the highly complex time, frequency, and polarimetric behaviors of this phenomenon.

Also in the category of low-frequency research is the experiment to detect the global EoR signature (EDGES), the goal of which is to detect and characterize absorption and emission from the 21-cm line of neutral hydrogen in the early universe, redshifted into the 50–150 MHz frequency range. This is an extremely challenging experiment that uses a single small antenna with high-precision calibration to separate the weak signal of interest from a range of much stronger emissions of both natural and man-made origin, and the interactions of those stronger signals with the instrument response. Multiple generations of hardware, software, and analysis techniques are helping to improve the sensitivity of EDGES over time to the cosmological signal.

The EDGES antenna and ground screen deployed in the Western Australian desert, near the Murchison Widefield Array. The large mesh ground screen is shaped to minimize reflections from the transition from mesh to soil, and to maintain the required exquisitely smooth spectral response of the instrument.

Astronomy with Facility Instruments

Lynn Matthews has been leading two programs to study radio emissions from nearby stars. The first employs spectroscopic imaging observations of the 21-cm line of neutral hydrogen to trace the extended mass-loss histories of dying, Sun-like stars known as asymptotic giant branch (AGB) stars. Data obtained from the Very Large Array (VLA) have revealed highly extended (parsec scale) hydrogen emissions around a number of AGB stars, as well as clear signatures of the interaction between these stars and their interstellar environments. Evidence of gaseous ejecta has also been discovered in association with two Cepheid variables, consistent with significant mass occurring during the Cepheid evolutionary phase.

Colin Lonsdale and collaborators are pursuing a multifaceted research effort into luminous active galaxies. These rare objects are thought to be in a transitional state between a massive burst of star formation in the nuclear regions, and the emergence of an active nucleus powered by accretion onto a supermassive black hole. This work involves observations with the VLA, the Very Long Baseline Array (VLBA), ALMA, and the Multi-Element Radio-Linked Interferometer Network (MERLIN) telescope in the UK, with additional studies in other wavebands. Vincent Fish, Colin Lonsdale, and Jansky Fellow Kazunori Akiyama are using the VLBA and the Global Millimeter VLBI Array, as well as the EHT capabilities, to study radio jet launching and collimation processes in bright radio galaxies and quasars.

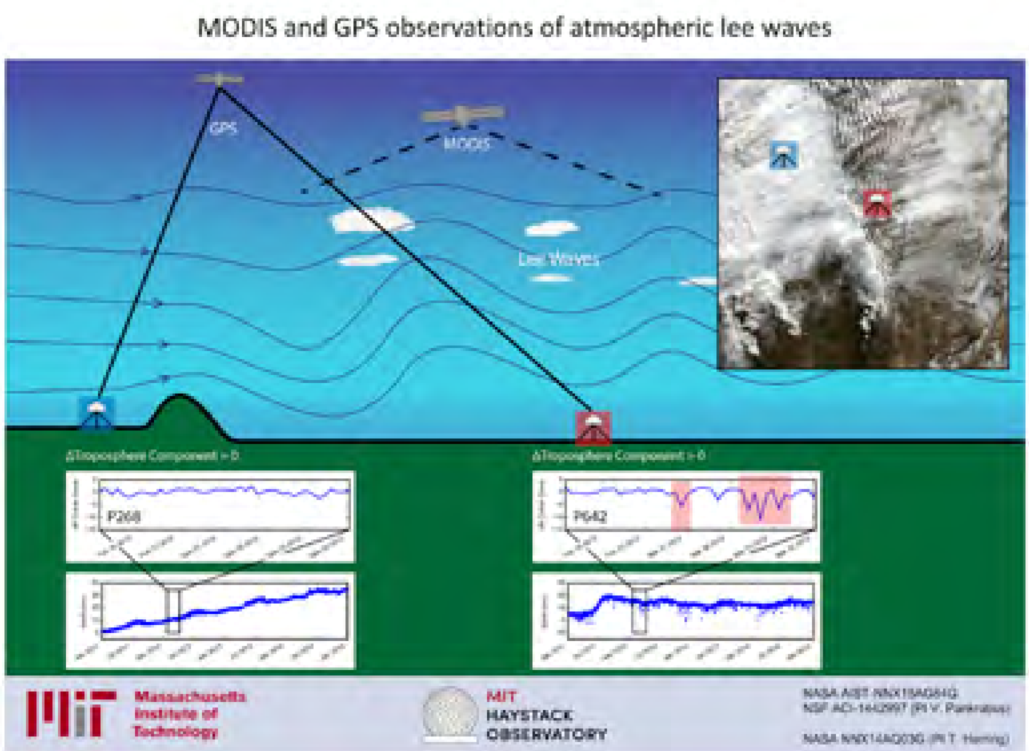
Research Area: Astroinformatics and Geoinformatics

An important and rapidly expanding area of Haystack Observatory research, led by Victor Pankratius, is the emerging field of informatics. As the volume and information content of scientific data in general, and radio science data in particular, increase drastically in response to the use of digital devices following Moore's law, the capacity of scientists to extract scientific understanding optimally from those data is being overwhelmed. Traditionally, close familiarity with data from acquisition through to final reduction, analysis, and interpretation has been a hallmark of competence in experimentalists. However, in the near term, and in many contexts, this approach will no longer be consistent with finite human cognitive capacity, and machine assistance will be mandatory. This transition, already under way, will proceed swiftly, making the field of informatics and machine-assisted discovery a key innovation frontier.

Haystack is investing heavily in forward-looking techniques and software infrastructures to support machine-aided discovery, concentrating on effective ways to present scientists with various kinds of preprocessed and filtered information. The challenge is to blend the comprehensive data sifting, pattern-matching, and processing capabilities of computers with the physical knowledge, context, and capacity for insight of scientists, through an interactive interface.

Driven by technological and scientific developments in so-called Big Data, informatics research represents a deliberate and important strategic departure from traditional core research fields at Haystack. Radio science provides extraordinarily fertile ground for such innovations because of dramatically and swiftly expanding data volumes inherent to the technological status of the field. The informatics infrastructures under development will also generate opportunities for expansion into other fields. The Observatory will pursue such opportunities on a case-by-case basis, depending on perceived synergies and efficiencies, and will not restrict such research to an artificially narrow radio science mission. The informatics research is interdisciplinary in nature and creates new capabilities that can have a fundamental impact in several science areas.

For example, airflow over mountains can produce gravity waves called *lee waves*, which can generate atmospheric turbulence. Because this turbulence poses dangers to aviation, it is critical to identify such regions reliably in an automated fashion. By using both optical imagery and radio propagation data from GPS signals, and applying novel machine-learning techniques, the reliability of lee wave patterns can be enhanced.



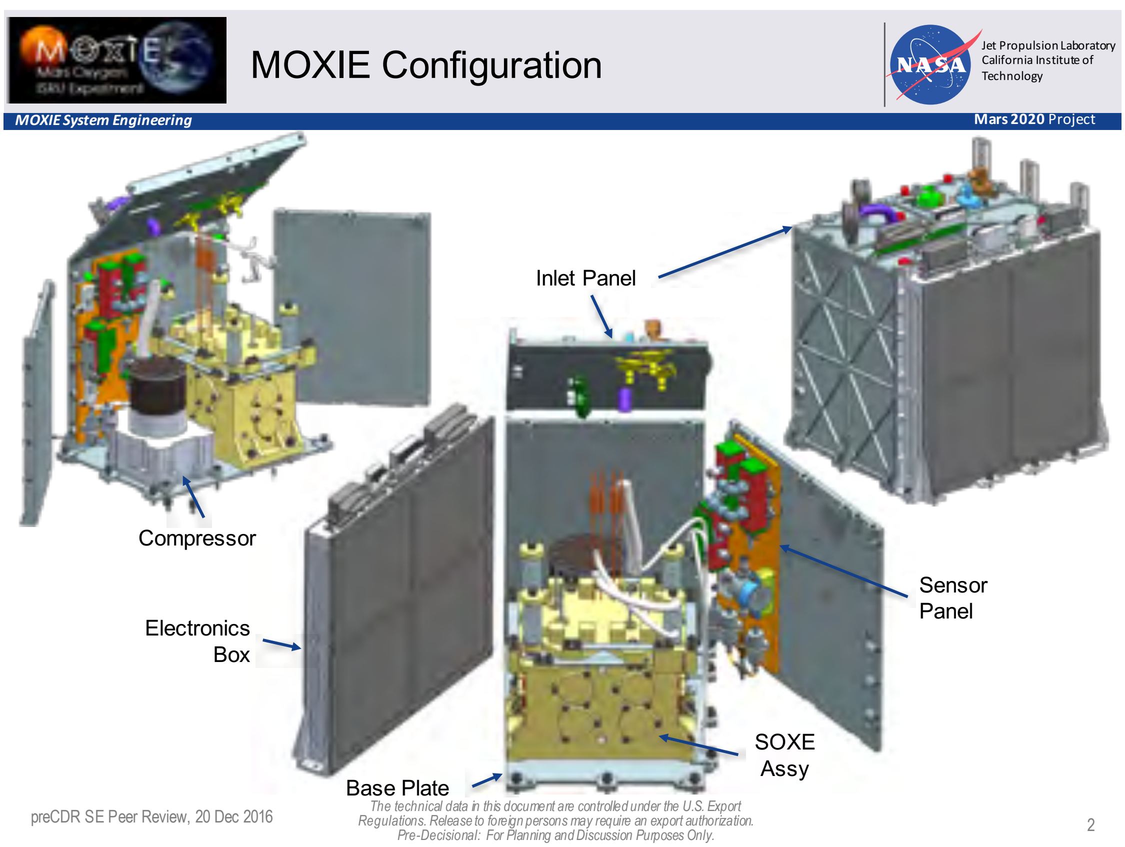
An example of atmospheric lee waves downstream of the Sierra Nevada mountains. The top right panel shows the optical imagery and the locations of two GPS receivers. The lower panels show MODIS (moderate resolution imaging spectroradiometer) data (top) and GPS data (bottom), and the P642 detection of waves is strengthened by the fusion of the two datasets.

Research Area: Space Science

From a research perspective, space-based science offers Haystack the opportunity to observe otherwise inaccessible parts of the radio spectrum, notably 10 MHz and lower frequencies; to examine ionospheric phenomena from above as a complement to measurements from below; to extend astronomical VLBI observations to longer baselines and very high or low frequencies; and to engage in planetary science from deep space probes. From a funding perspective, engagement in NASA-sponsored programs diversifies Haystack's grant portfolio as a buffer against changing NSF fortunes. From a strategic perspective, space-based science offers the opportunities for collaborations within MIT, Lincoln Laboratory, and outside organizations such as the NASA laboratories.

The nascent space-based effort aims at a mix of instrument technology development, exploration of mission concepts, participation in mission science teams, and contributions to full missions, particularly those involving CubeSats and SmallSats, which are growing in acceptance as university-based mission platforms. Haystack is also poised to use its facilities as elements of mission ground support and to provide coordinated ground-based observations.

An in situ resource utilization prototype led by Michael Hecht for NASA's Mars 2020 mission, the Mars oxygen in situ resource utilization experiment (MOXIE) will demonstrate the conversion of atmospheric carbon dioxide to oxygen on the Martian surface.



The configuration diagram for MOXIE.

The technical development of MOXIE hardware largely resides at the Jet Propulsion Laboratory. MIT is responsible for overall investigation leadership, scientific definition, laboratory characterization activities, and interpretation and publication of results. Led by Haystack, MOXIE includes faculty co-investigators from MIT's Aeronautics and Astronautics and Nuclear Engineering departments and their students. The focus of the effort has been to develop and validate a design for the solid oxide electrolysis (SOXE) component of the system, which will effectively convert dry carbon dioxide to oxygen, is robust against the Martian environment, and is insensitive to the frequent on/off cycling that will be experienced during the mission. After numerous iterations, this effort has been successful and the SOXE is ready for production.

Haystack has also proposed to NASA a CubeSat mission to study auroral radio emissions at low frequency. This mission, the Auroral Emission Radio Observer, employs a novel vector sensor on a single polar-orbiting satellite to provide spatial information on such emissions for the first time. The project is led by Phil Erickson, and involves collaboration with Lincoln Laboratory, the Department of Aeronautics and Astronautics, Dartmouth College, Morehead State University, and Merrimack College. Other proposals awaiting a decision include the development (with Lincoln Laboratory and the Department of Earth, Planetary, and Environmental Sciences) of a vector sensor for planetary radar and low-temperature spectroscopy.

Teaching and Outside Activities

Haystack staff members have been engaged in a wide variety of activities in service to the broader scientific and engineering communities:

- Arthur Niell served on multiple IVS committees and is a member of the directing board. He is also a member of the technical and scientific advisory committee for the Spain–Azores Atlantic Network of Geodynamical and Space Stations (RAEGE) project for geodesy.
- Pedro Elosegui served on the steering committee for the Ice, Climate, Economics—Arctic Research on Change Program, sponsored by the European Union.
- Lynn Matthews chaired the review of global 1-mm VLBI proposals for the Event Horizon Telescope Consortium. She also served as a proposal reviewer for the Giant Metrewave Radio Telescope and refereed manuscripts for several major journals.
- Victor Pankratius participated in an advisory role in the NSF "Intelligent and Information Systems for Geosciences" workshop in March 2015 in Washington, DC. Pankratius also served on the scientific organizing committee for the International Astronomical Union's Astroinformatics Symposium in Sorrento, Italy, in 2016.
- Colin Lonsdale served on the Murchison Widefield Array board, and on the interim board for the EHT Consortium.
- Larisa Goncharenko's activities included NSF review panels, serving as an International Space Science Institute team lead for whole-atmosphere studies, and chairing many conference sessions. She also served as lead for a NASA "Living With a Star" focused science topic team in whole-atmosphere coupling.

- Shunrong Zhang is also a lead for the International Space Science Institute's Beijing studies of the upper atmosphere and a key member of a NASA "Living With a Star" focused science topic team examining the topside ionosphere. Zhang has convened major CEDAR and American Geophysical Union (AGU) science sessions, is a member of the international scientist committee for the upcoming Chinese electromagnetics satellite mission, and continues as a key member of the International Reference Ionosphere project's science board.
- Phil Erickson and John Foster continued on the mission science team for multiple instruments on the NASA Van Allen Probes twin spacecraft. The mission was launched in late August 2012. Erickson and Foster are also co-authoring a number of chapters in a major International Space Science Institute text focused on the scientific foundations of space weather.
- Anthea Coster served on a number of committees in 2016, including a NASA heliophysics graduate fellowship board and the AGU Africa Space Science Award Committee. She was elected a fellow of the Institute of Navigation in January 2016. She also served as a program organizer for the Beacon Satellite Symposium.
- Phil Erickson co-convened major CEDAR/GEM and AGU sessions on mid-latitude dynamics and serves on the Science and Program Committee for NASA's Ionospheric Connection/Global-Scale Observations of the Limb and Disk Geospace Observations and Analysis Opportunities. He has also been a guest editor at both AGU's *Journal of Geophysical Research: Space Physics* and the European Geosciences Union's *Annales Geophysicae*.
- Michael Hecht and Pedro Elosegui co-taught a two-semester MIT capstone course on space penetrators. Victor Pankratius co-taught Astroinformatics for Exoplanets with Professor Sara Seager (Department of Earth, Planetary, and Environmental Sciences).
- Phil Erickson continued his annual week-long series of guest lectures as part of the Erasmus Mundus Space Masters program at the Swedish Institute of Space Physics in Kiruna, Sweden.
- Members of the atmospheric sciences group also participated in the 2016 International Incoherent Scatter Radar workshop, held at Sodankylä, Finland.
- A focused community workshop on space science use of data from the Defense Meteorological Satellite Platform satellite constellation was held at Boston College on October 20–21, 2016, co-sponsored by Haystack Observatory.

Education and Public Outreach

Twice a year, Haystack holds an open house, featuring a lecture, an extended question-and-answer session, and a tour of the 37-meter telescope. Recently, this has been augmented by hands-on demonstrations and informal interactions with various staff members, as well as by the display of a range of informational posters. These events are popular; attendance is managed through registration, with a typical attendance of about 150 people.

The Observatory also hosts numerous tours for schools, student groups, prominent researchers from various institutions, MIT alumni groups, and many others. Each year, a scouting "cubmobile" race takes place on the Haystack access road. Many inquiries and questions from the public are routinely fielded by the new full-time Haystack communications officer. The maintenance of excellent relationships between Haystack and the surrounding communities is an explicit priority for the Observatory.

Students from the Winsor School (Boston) visit the 37-meter antenna radome.

In April 2017, Haystack's Open Radar group hosted a well-received radar workshop for NEROC and Pennsylvania State University.

Haystack's geospace group continues an active outreach relationship with the Nashoba Valley Amateur Radio Club, the local amateur radio group, including hosting visits and lectures, attending their field events and monthly meetings, participating in experiments making use of amateur radio science expertise, and fostering technical discussions that enhance both Haystack's scientific work and radio enthusiasts' knowledge of the latest research developments. Nashoba Valley Amateur Radio Club members and the Open Radar workshop attendees attended a joint meeting in April 2017.

An animated discussion at the joint meeting between the local amateur radio club (Nashoba Valley Amateur Radio Club) and a group of students at the Open Radar workshop.

Members of the Haystack staff continue to be featured in the popular media, including local television and radio stations, science websites, magazines, and newspapers. Certain high-profile projects at the Observatory, notably the EHT work and MOXIE, attract a high level of media attention. Staff members regularly appear in articles and interviews with media, including the BBC, NPR, WGBH Radio, *National Geographic*, the Smithsonian Channel, and numerous prominent traditional and online news sources.

Each summer, Haystack hosts seven to 10 undergraduate students from around the country, an activity that is anchored by an award from the NSF Research Experiences for Undergraduates program. This is a long-standing and highly developed Observatory program that involves many staff mentors in supervision of 10-week research projects for the students, as well as an extensive series of lectures spanning the full range of Haystack scientific and engineering investigations. In 2016–2017, steps were taken to increase the diversity of the program in terms of the educational background of the students, as well as in the sources of support. The aim is to further broaden and enrich the program going forward.

Colin John Lonsdale
Director