MIT Haystack Observatory

Haystack Observatory is a multidisciplinary research center located in Westford, MA, 27 miles northwest of the MIT campus. The Observatory conducts astronomical studies using radio techniques, geodetic measurements using very-long-baseline interferometry (VLBI), and observations of the geospace environment using high-power incoherent scatter radar (ISR), 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 is broad in scope with an overarching theme of radio science. Recently there has been an increasing emphasis on space-based projects, research into the Earth's cryosphere, and technologically advanced radio arrays. 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 representing the bulk of the Observatory's 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 Observatory's astronomical VLBI effort. These programs share technical developments in data recording and correlation. The geodesy program includes a major focus on implementation of next-generation broadband receiver and back-end systems as part of the US investment in the Global Geodetic Observing System (GGOS), while the astronomical VLBI program is primarily driven by the Event Horizon Telescope (EHT) project, which relies on Haystack for a range of correlation, technical, and data analysis functions. To lead a new push for research topic diversity and growth in the astronomy program, an experienced radio astronomer was hired in late 2017.

Another major program, conducted by the geospace science group and partially supported by a large facilities grant from the National Science Foundation (NSF), involves operation of the powerful incoherent scatter radar instruments on site. Efforts are under way to diversify funding and expand research into the development of novel arrays, such as the versatile RAPID (Radio Array of Portable Interferometric Detectors) portable array platform (described below) and a next-generation radar concept. 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 advanced engineering and technical development component.

The growing Haystack Observatory space program now includes not only the MOXIE (Mars Oxygen In-Situ Resource Utilization Experiment) Mars rover component but also AERO (Auroral Emissions Radio Observer), an auroral NASA CubeSat project. Several new Haystack initiatives are intended to lead to participation in potential future missions.

Haystack continues to enjoy a close relationship with Lincoln Laboratory and provides extensive engineering and facilities support for a range of Lincoln Lab projects and installations at the field site. The Observatory has significant technical collaborations with Lincoln Lab, with multiple recent joint submissions to NASA for innovative CubeSat concepts being of particular note.

Haystack research programs also involve future-oriented efforts that will seed the major programs of the next decade and beyond. Haystack is pursuing a rich portfolio of initiatives, which in the past year has led to the submission of a strikingly large number of funding proposals to different agencies. 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 and is key to efficient coordination of Haystack's diverse yet interconnected and related research activities. A number of clear research priorities for the Observatory are being pursued:

- Continued expansion of collaborative efforts with Lincoln Laboratory and with campus researchers.
- Continuing development of the recently expanded and rescoped 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. As part of its renewed participation in the regional radio science research community, NEROC has launched a highly successful series of science symposia that draw participants from many member and non-member institutions.
- Establishment of a stronger, more diverse astronomical research program under a new group leader; 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 technologies. This effort, 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.
- Establishment of a viable program of space-based radio science investigations, with a long-term goal of expanding the range of mission aspects that the Observatory is equipped to execute. A key foothold in this area is provided by the award of a NASA grant for AERO, a novel CubeSat that will study auroral emissions from space.
- Overhaul and expansion of Haystack's presence on the web and in the media in terms of both professional and public communications. A completely new website is being developed and designed.

Personnel

Last year's report outlined a number of new hires at the Observatory designed to address growth in the size and complexity of the research portfolio. These hires have been highly effective, with broad positive impacts on the operation of the organization. There will, however, be a pause in the steady staffing growth of the Observatory pending the maturation of a number of initiatives driven by the strategic priorities noted above.

Finances and Funding

Haystack staff continue to generate a high volume of proposals to funding agencies, with 37 funding proposals submitted by 12 different principal investigators (PIs) during the 12-month period covered by this report. Eighteen of these proposals are still pending, and 14 of the 19 for which decisions have been made have been awarded, a success rate of 74%. With such a large number of pending proposals, some of them for significant amounts, budgetary projections necessarily carry substantial uncertainty.

While Haystack financing and staffing remain healthy, the federal funding landscape has become significantly more challenging, with extreme volatility in projected agency budgets and continuing resolutions leading to long delays in finalization of budgetary levels. This has led to agency caution in committing to awards and, in some cases, even to bypassing key proposal solicitations; an example is the Advanced Technologies and Instrumentation program in the NSF Division of Astronomical Sciences, to which Haystack routinely makes proposals. The impact on Observatory budgets has been noticeable. Simultaneously, the elevated risk levels resulting from the federal landscape mandate caution in hiring at Haystack, necessarily limiting opportunities for expanding and optimizing skill sets across the organization, which in turn impacts the range of future funding proposal opportunities that can be exploited. These negative effects have been mitigated to the extent possible by preferentially maintaining efforts in targeted growth areas, minimizing delays or challenges in resuming an aggressive Observatory growth stance if and when conditions allow.

Haystack has for some time been implementing strategies to reduce risk and promote growth in the face of chronically tight federal budgets. These strategies include diversification of both projects and sponsors, identification and promotion of synergies in the technological underpinnings of projects to improve agility in response to opportunities, and an energetic, 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 exploring opportunities with a variety of potential non-federal sponsors while recognizing the substantial lead time involved.

Of concern is a trend, most notably at NSF in divisions relevant to Haystack research, toward smaller science grants, increasing the effective cost of proposal writing activity while tending to fragment the time of individual staff members across a larger number of more tightly constrained research programs with narrower deliverables. The Observatory's responses to this trend are to triage proposal opportunities more stringently than has previously been deemed necessary or desirable and to identify development paths in areas likely to be associated with robust agency budgets in the near and medium term.

Research Areas

Geodesy

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

VLBI Geodetic Observing System

Under NASA sponsorship, the Haystack geodetic VLBI group continues to develop the VLBI Geodetic Observing System (VGOS) for the next-generation broadband geodetic VLBI network. VLBI is one of the fundamental space geodesy techniques essential to realizing an accurate and stable Terrestrial Reference Frame (TRF). The TRF is crucial for 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.

The VGOS is the VLBI component of the Global Geodetic Observing System. Under its Space Geodesy Program, NASA is leading the development of a global network of about 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 span the Earth's surface.

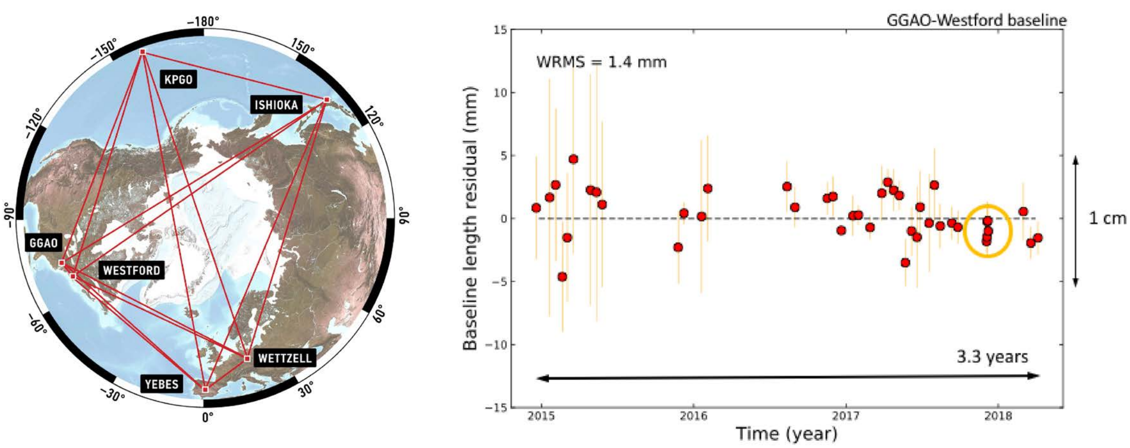
Development is well under way on the second VGOS station, which is being built at the McDonald Observatory by the University of Texas following the design of the Kōke'e Park Geophysical Observatory (KPGO) in Hawaii. Haystack is making rapid progress on the signal chain build for McDonald, including design and construction of its front end and back end and development of engineering test units for vibration and performance assessments of the main dish.

Progress on building the front end of the signal chain for the VGOS telescope at McDonald Observatory in Texas. Shown is the front-end positioner in the Westford technical laboratory in March 2018.

Haystack continues to provide support for the first VGOS antenna deployed at KPGO, as well as the VGOS prototype baseline telescopes at Westford and at the Goddard Geophysical and Astronomical Observatory (GGAO) in Maryland. Haystack also continues to provide routine support for geodetic VLBI through means such as data quality evaluations, assessments of geodetic estimate precision and accuracy, and network support.

Haystack frequently releases forward-looking software and technologies with the aim of advancing VLBI systems and bringing new levels of flexibility and measurement accuracy to the geodetic VLBI community. These efforts help shape the GGOS vision even for systems that will succeed the VGOS network, which is currently in a rollout phase. Also, they leverage and overlap with an installed base of networked broadband 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 information content.

Over the past year, Haystack has made major contributions toward the validation of the VGOS concept, as well as improving and maintaining the physical network of NASA telescopes. A milestone in this ongoing process was achieved in December 2017, as the original three VGOS stations—Westford, GGAO, and Kōke‘e—were joined by three additional stations—Yebes (Spain), Wettzell (Germany), and Ishioka (Japan)—for five days of continuous observations. This observation run, called CONT2017, took place simultaneously with observations made by the so-called S- and X-band legacy VLBI network to verify VGOS readiness, advance toward a smooth transition from legacy to VGOS observations, and verify the precision and accuracy of VGOS science products.



Left: Map of the six VGOS stations participating in five-day continuous observations during CONT2017, a milestone in the VGOS broadband network rollout. Right: Demonstration of the millimeter-level precision of the Westford-GGAO VGOS baseline length estimate from observations spanning three years, including (yellow circle) CONT2017 data.

The first VGOS results were presented by the Haystack geodetic group at the 2018 International VLBI Service for Geodesy and Astrometry (IVS) general meeting in Norway: Pedro Elosegui discussed VGOS performance, precision, and geodetic accuracy; Arthur Niell examined the transition from legacy to VGOS observations; Chester Ruszczyk described improvements in signal chain digitization capabilities; and John Barrett outlined new VGOS correlation algorithms and methods. These are all important milestones as they demonstrate the advancement of the VGOS from a promising design concept to first data and science results.

Under a separate NASA sponsorship, a new postdoctoral researcher in the geodesy group, Dhiman Mondal, is exploring innovative methods to improve the accuracy of the TRF by incorporating information from small-scale atmospheric structures at core geodetic sites.

Polar Geodesy

Polar geodesy research is relevant to the high-profile topics of global climate change and sea level change. Initial collaborative polar geodesy efforts are focusing on the cryosphere, including precision measurements of the flow, drift, and deformation of various forms of ice (sea ice, glaciers, icebergs, ice shelves) via deployable GPS-based systems. In summer 2017, four continuous GPS receivers were successfully deployed for a week on an iceberg in Sermilik Fjord, near Helheim Glacier in East Greenland, resulting in the first direct detection and quantification of iceberg melt using GPS systems. In summer 2018, eight receivers have been deployed in Sermilik Fjord to study the temporal variability of iceberg melt and meltwater fluxes via high temporal resolution. Some of the results of this polar geodesy work were presented at last year's American Geophysical Union (AGU) fall meeting, with an update to be presented at this year's AGU fall meeting.

MIT GPS receivers are placed on an iceberg in Sermilik Fjord, East Greenland, to study iceberg melt, meltwater input, and mesoscale ocean circulation.

Another 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; the goal is to monitor the response of the shelves to ocean forcings using satellite communications for near-real-time data downloads 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" land glaciers and triggering major ice sheet collapses and associated sea level rise, are critical cryosphere-ocean research topics. Currently, MIT graduate student Alice Cooper is performing computer simulations to design and test aerodynamic and ice-penetrating models. A Haystack summer undergraduate intern, Samuel Mekonnen, is completing a project on the development of a power budget for the avionics system of the ice penetrator.

Geospace

Geospace research is a major component of the Haystack portfolio, encompassing investigations from the sun to the lower atmosphere and everything in between. The geospace community has rapidly evolved to study the full range of physics across these domains, and Haystack's research in this area has followed suit, providing foundational studies with international impact from a set of PI-led science programs supported by multiple agencies. This geospace science is matched by a heavy concentration on observational techniques and development using Haystack radio science depth and expertise, including a decades-long program of precise and highly flexible ionospheric measurements gathered from the large, powerful on-site incoherent scatter radar facility. In recent years the group's research footprint has broadened significantly to both lead and follow emerging technologies and trends, and it now includes a wide variety of system-scale science, measurement systems, and innovative analysis techniques across geospace remote sensing areas. Science studies on frontier topics—for example, whole atmosphere coupling, long-term ionosphere trends, geospace storm response, traveling ionospheric and atmospheric disturbances, eclipse perturbations, and magnetosphere-ionosphere coupling—highlight the expansion of the Haystack geospace group's leadership role in investigating complex feedback processes between atmospheric regions.

RAPID

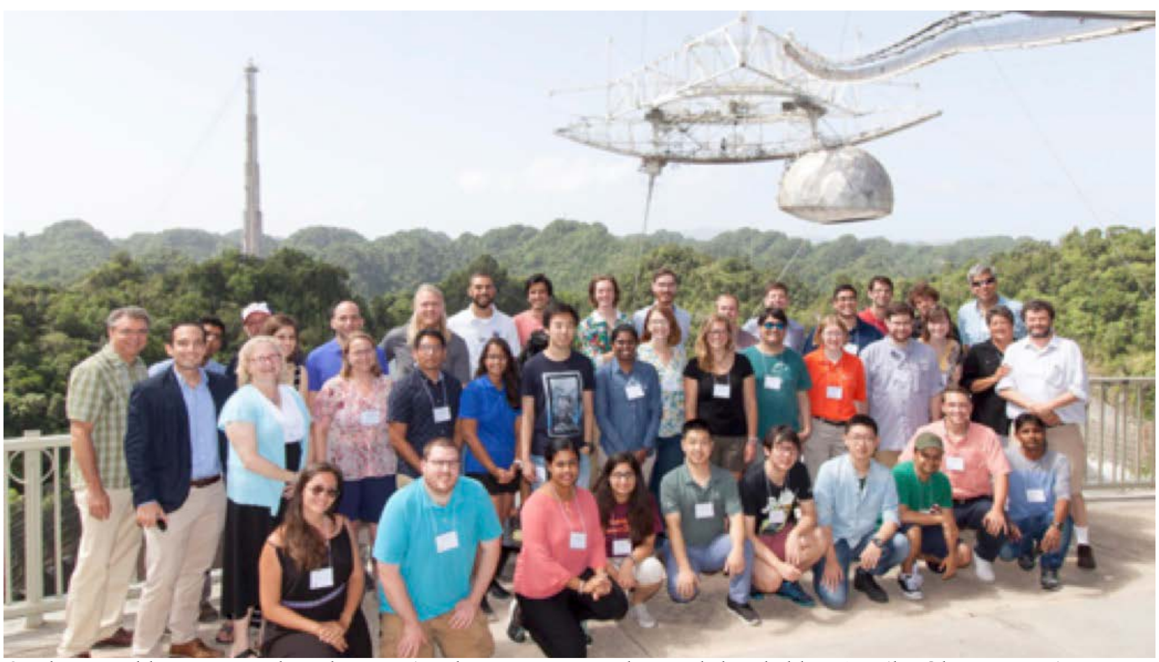
The Radio Array of Portable Interferometric Detectors is an NSF-sponsored innovative, portable, and flexible low-frequency radio array developed in collaboration with Cambridge University and the Jet Propulsion Laboratory (JPL). The individual antennas in the array use per-element software-defined radios and a flexible software signal processing architecture to study a wide range of natural phenomena via 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, which will initially consist of approximately 50 small, low-gain antennas operating over a frequency range of 48 to 615 MHz, will be completed in the near future and made available for community use. Major array hardware components are now being procured.

RAPID has already resulted in several generations of increasingly integrated prototype hardware using commercial software radios for a wide range of data acquisition needs. Over the past year, the RAPID team has successfully deployed remote capture systems in a number of locations for diverse uses, including irregularity research involving passive and active illumination. Prototype lightning research (with NEROC partners at the University of New Hampshire) and pilot studies focusing on Jovian decametric emission imaging have also been conducted as the program emerges from its development cycle.

A RAPID self-contained interferometric sensor. Solar and battery power support the capture of raw voltages from the broadband antenna for fully flexible offline processing following the field experiments.

Madrigal

The atmospheric and geospace sciences group continues to actively develop the Madrigal distributed database, a standard in the upper atmospheric community that originated at Haystack in the early 1980s. Madrigal has become the community standard interaction portal for all CEDAR (Coupling, Energetics and Dynamics of Atmospheric Regions) data, representing a large fraction of the historical and current US ground-based geospace observational repository (and some of the international repository). During the past year, 463 unique users from 192 separate institutions across the space science community obtained data from the CEDAR Madrigal site and the Millstone Madrigal site (the community-based archives hosted at the Observatory). Community interactions continue to be a main focus of Madrigal efforts, allowing data providers to easily upload information and maintain high data availability in Madrigal with minimal human interaction. The latest software release of Madrigal, 3.0, is now in use at the main CEDAR Madrigal site. In this new release, the system's web interface has been substantially overhauled using modern open source software tools.



Students and lecturers at the July 2017 incoherent scatter radar workshop held at Arecibo Observatory in Arecibo, Puerto Rico.

UHF Radar

During the past year the Millstone Hill UHF radar system, which has been operated for decades by Haystack under a cooperative agreement with NSF, was used frequently for extensive observations. The space science community continues its significant use of Millstone Hill in its capacity as an NSF geospace facility. Routine maintenance of the transmitter system to ensure continuing operations is ongoing. Updates to core incoherent scatter radar and derived data product software are in current development and will add new features for improved operations and measurement fidelity. Several derived data sets from community- and Haystack-requested experimental campaigns have significant scientific potential and have attracted multiple in-progress scientific studies.

Significant radio frequency (RF) development has also taken place through the creation of various UHF frequency solid-state transmit and receive modules. These modules will lead the way toward future array-based architectures using low-cost radar components that are easily scalable and can be integrated into ionospheric radar class apertures.

GNSS Global Observations

As part of the NSF Millstone Hill Geospace Facility, the enhanced MIT Automated Processing of GPS (MAPGPS) software suite continues to be applied to routine calculations of global total electron content (TEC) maps deposited directly into the Madrigal database for community use. TEC maps based on global navigation satellite systems (GNSSs) are generally made available in Madrigal three to four days behind real time. These products are heavily used in international geospace research and provide prominent collaborative potentials for Haystack science. A significant new GNSS TEC product has recently been made available to the community through Madrigal, providing an amount of information increased by an order of magnitude that is ideally suited for frontier research on ionospheric variability and space weather studies.

Geospace Research and Applications

The geospace group has moved largely 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 a growing number of central processing unit cores and petabyte-class storage. The system is also accessible via a virtual private network, allowing secure remote access. Many of these advanced features are unique to NSF-supported geospace facilities such as Millstone Hill.

Digital RF, an open source data format developed at Haystack for community disk storage and retrieval of radio signals, achieved a significant milestone: Digital RF 2.0 is built upon native HDF5 standards, making use of existing libraries and tool sets. Ease of use is a primary Digital RF design feature. This format was developed jointly for the Millstone Hill Geospace Facility and RAPID applications. It provides many advantages to 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. 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 summer 2017.

MACAWS

The Monitors for Alaskan and Canadian Auroral Weather in Space (MACAWS) project was launched this year under NSF funding. Its goal is to install an additional 35 GNSS scintillation receivers in northern Alaska and northwestern Canada (northern Alberta, Saskatchewan, and Manitoba). Five units have been sent to Alaska, one is on loan to the Arecibo Observatory, and another is installed and being tested at Merrimack College. An additional five units will be sent to Canada in August 2018. New science products created from the data sets obtained through the MACAWS project will enable a better understanding of the physical mechanisms behind space weather disturbances.

Eryl Derome (Haystack Observatory) and Christine Alcalde (Merrimack College) worked on the MACAWS GPS receivers sent to Alaska.

Astronomy

Current astronomical research and instrumentation development at Haystack falls broadly into four categories: (1) VLBI at high frequencies (i.e., above approximately 100 GHz), (2) astronomy at low frequencies (i.e., below approximately 300 MHz), (3) single-dish spectroscopy with the Observatory's Haystack and Westford telescopes, and (4) work with facility telescopes worldwide. Activities in these domains have resulted in numerous research publications, some with a high impact both professionally and on the public.

Haystack's astronomy group has been augmented by the addition of an experienced observational radio astronomer, Jens Kauffmann, who will take primary responsibility for organizing and planning the group's activities. Kauffmann brings expertise that strengthens efforts to make the Haystack 37-meter telescope available for astronomical research.

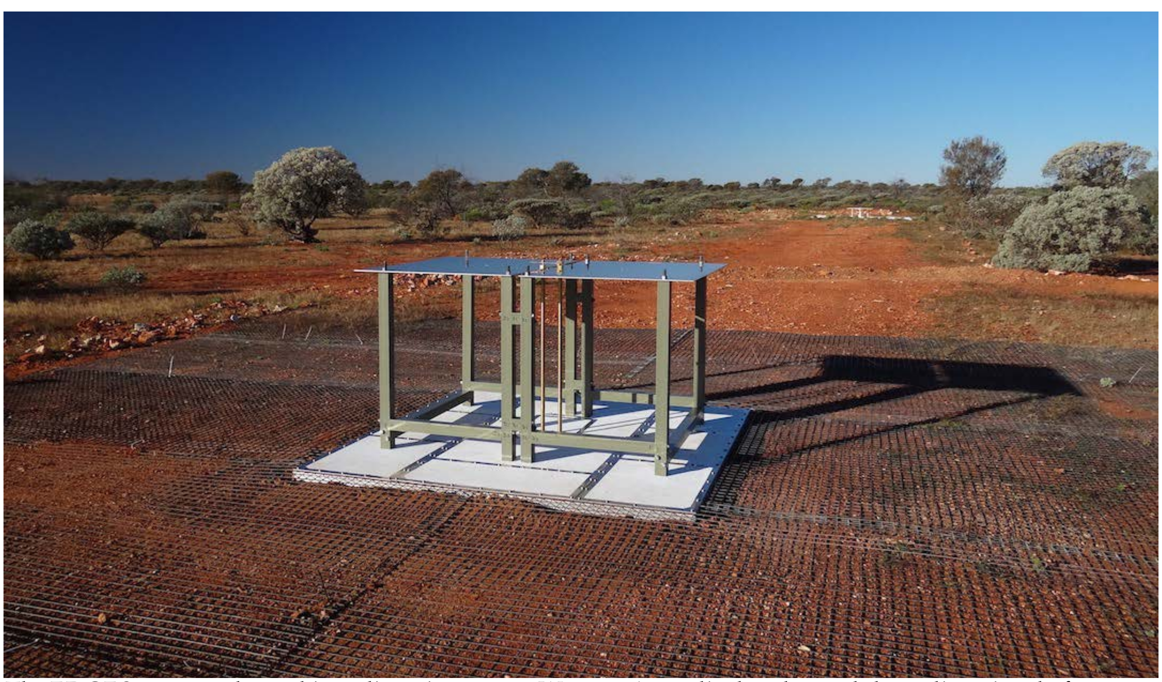
Lynn Matthews organized the Radio Stars II conference at Haystack in November 2017, an event that attracted numerous researchers from around the world.

Sensing the First Stars of the Cosmos at Low Frequencies

The epoch of reionization (EoR), during which the first stars in the universe ionized the neutral gas filling the early cosmos, remains one of the most exciting frontiers in astronomy. The onset of this phase lies at redshifts of order $z = 15$, or approximately 200 myr after the Big Bang, when ultraviolet light from the first stars started to influence the energy state of primordial neutral hydrogen. This is well beyond the domain that is currently accessible to optical and infrared telescopes, which generally explore redshifts below 10. However, at least in principle, this realm can be explored through radio observations that search for the signature of the 21-centimeter emission of neutral hydrogen in the early universe, redshifted into the 50 to 150 MHz frequency range. This is an extremely challenging endeavor that requires separation of the weak signal of interest from a range of much stronger emissions of both natural and manmade origin and the complex interactions of those stronger signals with the imperfect instrument response.

The Experiment to Detect the Global EoR Signature (EDGES) team, which includes Haystack scientist and engineer Alan Rogers, delivered the first solid observational evidence for this signal in early 2018. The resulting publication in the journal Nature has had a substantial impact on the professional community and the general public. In addition to the detection of a redshifted 21-cm absorption signal, the EDGES result appears to have yielded a major surprise regarding the strength and characteristics of the signal, presenting challenges to theoretical interpretations and possibly shedding unexpected new light on physical conditions and processes in the early universe. Efforts are under way by the EDGES team and others to generate the essential rigorous and independent confirmation that a result of this potential significance demands.

Multiple generations of hardware, software, and analysis techniques were needed to improve the sensitivity of EDGES over time to eventually enable detection of the cosmological signal. EDGES was conceived and in part built at Haystack, while the actual observations were carried out in a radio-quiet region of Australia. Haystack is pursuing further hardware and software system refinements to improve measurement precision and accuracy.



The EDGES antenna, located in radio-quiet, remote Western Australia, has detected the earliest signal of hydrogen from the first stars in the universe. (Photo courtesy of Judd Bowman)

MWA and RAPID Arrays

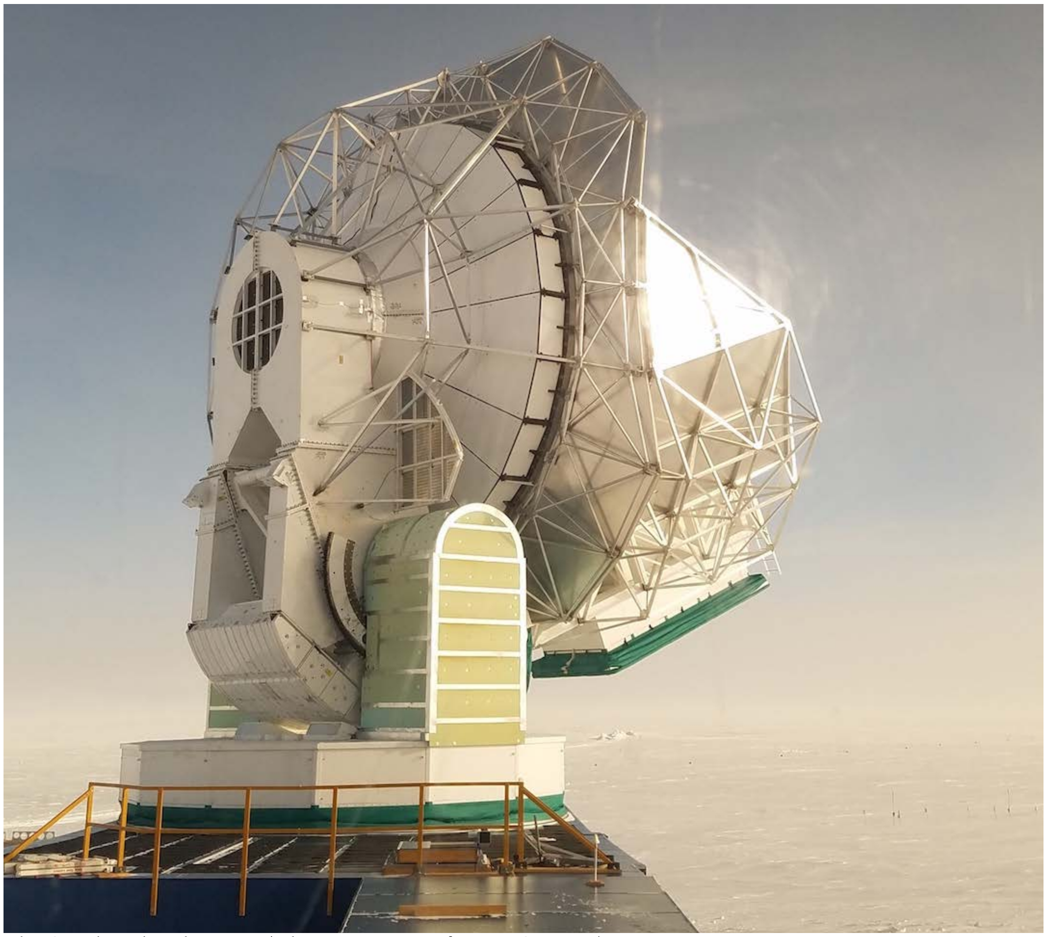
Research using the Murchison Widefield Array (MWA) in Western Australia continued under the sponsorship of the Air Force Office of Scientific Research. This instrument, which was conceived and extensively designed by Haystack, is unique in its ability to produce high-fidelity images with very small amounts of observing time and at very low frequency ranges. 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, featuring rich temporal and spectral structures. Recent tests demonstrate the ability to achieve imaging dynamic ranges approaching 105:1, which is three orders of magnitude better than competing arrays. This opens a rich landscape of scientific investigations of both the sun itself and the interplanetary medium, with relevance to space weather prediction. Development and refinement of a data reduction pipeline in collaboration with international partners for the several petabytes of raw data that have been collected to date is ongoing.

Plans are being made to use RAPID, developed under the geospace program, to perform groundbreaking observations of the powerful Jovian decametric emission, and a funding proposal for this work has been submitted to NASA. These observations will reveal, for the first time, the highly complex time, frequency, and polarimetric behaviors of this phenomenon in a spatially resolved manner. More generally, the unique capabilities of RAPID are being assessed to prioritize the deployment of the array in a variety of astronomical and heliospheric research projects.

High-Frequency VLBI: Black Holes Near and Far

The Event Horizon Telescope is an array of observatories operating in campaign mode at a wavelength of 1.3 mm. 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, since 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.

EHT observations of Sgr A* and M87 were held in April 2018 (following similar observations in April 2017) using VLBI telescopes in the United States, Mexico, Spain, and Chile; a VLBI telescope at the South Pole; and a new telescope in Greenland. The 2018 observations were recorded at a data rate of 64 Gbit per second, twice the rate in 2017. Jason SooHoo traveled to the South Pole to install the recording equipment needed for the observations. The additional station in Greenland is important because it extends an already wide range of baseline lengths and orientations, an essential prerequisite to reconstructing model-independent images of M87. Imaging is performed in a blind fashion involving painstaking cross-checks and quality control and multiple independent teams. Scientifically impactful results are expected in the near future based on the 2017 data.



The South Pole telescope. (Photo courtesy of Jason SooHoo)

A major and scientifically essential sensitivity boost to the EHT array was provided by the inclusion of the Atacama Large Millimeter Array (ALMA) in EHT observations. Over the course of the last several years, Haystack led an international team that designed and implemented a system to phase up the approximately 60 ALMA dishes to operate as a single large aperture. Geoffrey Crew traveled to Chile during the observations in 2017 and 2018 to assist local staff in operating the ALMA phasing system. When all antennas are accurately phased up, the sensitivity of ALMA is equivalent to a dish of more than 80 meters in diameter, making the phased ALMA the most sensitive millimeter-wavelength aperture on the planet. Lynn Matthews now leads a team that will further expand ALMA's VLBI capabilities, including the addition of submillimeter and spectral line VLBI. Much of the practical implementation of the system is handled by Geoffrey Crew.

The EHT data collected around the world are eventually correlated on machines located in Bonn (Germany) and at Haystack. This correlation process reduces the observed data to interferometric observables that, with suitable coverage of baseline lengths and orientations, can then be turned into images. EHT experiments collect petabytes of data in typical observing runs, and as recording rates have grown and telescopes have been added to the array, data processing burdens have risen dramatically. The Haystack correlator was therefore significantly upgraded in 2017 to readily handle this increase in processing load.

In the case of Sgr A*, the effective resolution of the longest baselines in the EHT array is about half the angular diameter of the "shadow" predicted by general relativity. Making an image of the shadow with higher resolution thus in principle enables a test of general relativity: is the shadow nearly circular and of the predicted size? Kazunori Akiyama, a Jansky Fellow at Haystack with sponsorship by the US National Radio Astronomy Observatory (NRAO), is leading the way in developing new image reconstruction software that makes use of compressed sensing techniques and robust VLBI observables to optimally and reliably extract structural information on the smallest possible scales. The new techniques significantly outperform conventional radio array synthesis imaging algorithms and have applications beyond the EHT.

Science and Education with the Haystack and Westford Telescopes

A variety of activities are under way with the objective of making the Haystack 37-meter telescope available for astronomical research and education, a capability of strategic importance to the Observatory. The astronomical receivers are connected to the equipment in the control room via recently upgraded optical fibers. Optimization of receiver parameters in late 2017 brought the W-band receiver (approximately 90 GHz) back into operation. A new shutter system now protects this receiver from radiation emitted when the telescope is used as a space radar. This system greatly simplifies switching between operational modes and sharply reduces operational inefficiencies. Generally, work has sometimes been hampered by equipment reliability issues, since there is still substantial 1990s-era legacy hardware present in the signal chain and support systems. Funding at a level to support full replacement with more modern systems requires an initial demonstration of the high performance of the new dish with science-quality data, and this is the focus of current activities.

Work on the Q-band receiver (approximately 40 GHz) focused on design improvements to increase receiver performance. An ALMA band 1 amplifier was identified and then ordered from NRAO to implement these design changes, and it will be installed in early fall 2018. The K-band system (approximately 20 GHz) continues to serve as Haystack's workhorse receiver. The workforce available for the Haystack telescope has increased substantially. Receiver engineer Ganesh Rajagopalan has received required training and is now formally cleared for work in the receiver cabin. Jens Kauffmann joined Haystack with specialist skills in single-dish observing. Operator Philip Shute was trained as an additional person qualified to control the astronomy systems on the telescope. These improvements in hardware and personnel availability are expected to facilitate progress toward science-quality observations, with testing and science demonstration campaigns planned for winter 2018–2019.

The Haystack telescope was targeted for a program that seeks to make a US radio telescope easily available for educational purposes. This project is led by Lynn Matthews and funded by the NSF Department of Undergraduate Education. The program is similar to one that existed on the Haystack telescope before it was upgraded during 2010 to 2013, and many of the universities and astronomy departments that participated in the earlier program have signed up for the new one. This project is employing a new graphics processing unit–based spectrometer as a critical part of the educational hardware, and the effort involves John Barrett and consultant Stephen Levine. Initially the new system is being deployed and debugged on the Westford 18-meter telescope instead of the Haystack telescope, since this reduces operational inefficiencies in the development phase related to Haystack's frequent use as a space radar by Lincoln Laboratory. Test data have been acquired, and key elements of an education-ready system are expected in the fall.

Jens Kauffmann currently leads efforts that will (1) establish the key parameters of the upgraded Haystack telescope relevant to real-world astronomical performance; (2) identify high-impact science cases, in conjunction with regional astronomy groups (e.g., NEROC institutions), where this telescope can make groundbreaking contributions; and (3) connect Haystack telescope development activities to activities at other telescopes around the globe. In the long term, this work seeks to place Haystack in a unique, important, and financially supportable location in the parameter space populated by other millimeter-wave telescopes worldwide.

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. The second program uses the VLA in its highest resolution configuration to obtain resolved images of the surfaces of AGB stars. The resulting data are being imaged using a novel algorithm known as sparse model imaging, developed by Kazunori Akiyama.

Colin Lonsdale and collaborators are pursuing a multifaceted research effort into bolometrically luminous, highly obscured 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 MERLIN (Multi-Element Radio Linked Interferometer Network) telescope in the United Kingdom, with additional studies in other wavebands. Lonsdale, Akiyama, and Vincent Fish are using the VLBA and the Global Millimeter VLBI Array, as well as EHT capabilities, to study radio jet launching and collimation processes in bright radio galaxies and quasars.

Jens Kauffmann has launched the Line Emission in Galaxy Observations (LEGO) project at the IRAM (Institute for Radio Astronomy in the Millimeter Range) 30-meter telescope near Granada, Spain. Including data from pilot studies, LEGO has been awarded 600 hours of telescope time. LEGO is generating the first comprehensive overview of molecular line emissions from parsec-scale sections of molecular clouds in the Milky Way in molecular species other than carbon monoxide. The project, which is being pursued by an international collaboration of about 20 researchers, provides key knowledge supporting efforts to understand how galaxies transform diffuse gas into the stars and planets that populate the sky.

Radio Stars Conference

Lynn Matthews organized the Radio Stars: From kHz to THz conference at Haystack Observatory, held November 1–3, 2017. The event attracted 51 registered participants from 10 countries. A primary motivation was to bring stellar astrophysicists (including observers, theorists, and modelers) from a variety of subdisciplines to explore common themes in the study of stars across the Hertzsprung-Russel diagram, particularly those that exploit the unique potential of the latest generation of radio instruments.
This conference was the second such meeting to be held at Haystack (the first was held in 2012). The program included 12 invited reviews and 24 contributed talks. This lively and successful meeting enhanced the reputation of Haystack Observatory as an attractive venue for conferences, workshops, and other collaborative events.

Participants in the 2017 Radio Stars conference, organized by Lynn Matthews at the Haystack Observatory.

Space Science

From a research perspective, space-based science offers Haystack the opportunity to observe otherwise inaccessible parts of the radio spectrum and to employ interferometer baselines larger than the diameter of the Earth. For example, work at 20 MHz and below, difficult or impossible from the ground because of the ionosphere, offers a rich variety of studies involving strong sources of coherent emissions in our solar system from the planets, the sun, and the magnetized plasma surrounding the Earth. At the highest frequencies, interferometry can yield angular resolutions far beyond those achieved even by the Event Horizon Telescope, dramatically expanding the scientific potential of the work. Space-based radio techniques and instrumentation offer diverse options for engaging in planetary science from deep space probes, such as surface-penetrating radar studies and passive radiometry to measure temperature profiles and examine subsurface heat flows. From a funding perspective, engagement in NASA-sponsored programs diversifies Haystack's grant portfolio and presents opportunities to pursue larger, more stable funding lines. From a strategic perspective, space-based science offers opportunities for collaborations with campus groups, Lincoln Laboratory, and outside organizations such as NASA laboratories.

The goal of Haystack's space science program is to establish leadership in a portfolio of small PI-led missions, particularly those involving CubeSats and SmallSats, which are growing in acceptance as university-based mission platforms. Haystack will also engage in instrument technology development activities, explore mission concepts, participate on mission science teams, and contribute to full missions. In addition, the Observatory is poised to use its facilities as elements of mission ground support and to provide coordinated ground-based observations.

Haystack's newest project, the Auroral Emission Radio Observer (AERO), is a NASA-funded CubeSat mission to study auroral radio emissions at low frequency. AERO 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 with contributions from Lincoln Laboratory, the MIT Department of Aeronautics and Astronautics, Dartmouth College, Morehead State University, and Merrimack College. A proposal to augment AERO with a second spacecraft in order to demonstrate vector sensor interferometry is under consideration at NASA.

A significant ongoing activity is MOXIE (Mars Oxygen ISRU Experiment), an *in situ* resource utilization (ISRU) prototype led by Michael Hecht for NASA's Mars 2020 mission. MOXIE will demonstrate conversion of atmospheric CO_2 to oxygen on the Martian surface. MIT is responsible for overall project leadership, scientific definition, laboratory characterization activities, and, eventually, interpretation and publication of results. Led by Haystack, MOXIE includes faculty co-investigators from MIT's Departments of Aeronautics and Astronautics and Nuclear Science and Engineering and their students. The focus of the effort to date has been to develop and validate a design for the solid oxide electrolysis component of the system, which will effectively convert dry CO_2 to oxygen, is robust against the Martian environment, and is insensitive to the frequent on/off cycling that will occur during the mission. Technical development of MOXIE hardware at JPL is nearly complete. Flight models will soon be delivered to the Mars 2020 project, and engineering hardware will be delivered to MIT to continue characterization and preparation for mission operations.

Other proposals pending decisions include a mission study for the Cosmic Dawn Explorer (CoDEx), a sensitive low-frequency radio observatory operating in a radio-quiet zone in the shadow of the moon, and a proposal (with Lincoln Laboratory) to develop a planetary radar based on the vector sensor. The CoDEx project would follow up on the recent EDGES observation of a signature from the earliest stars.

Teaching and Outside Activities

During the past year, Haystack and its staff engaged in a wide variety of activities in service to the broader scientific and engineering communities:

- Pedro Elosegui served on the steering committee for the European Union–sponsored Ice, Climate, and Economics—Arctic Research on Change project. Also, he is currently mentoring an MIT graduate student, Alice Cooper; a Haystack postdoctoral researcher, Dhiman Mondal; and a Haystack summer undergraduate intern, Samuel Mekonnen.

- Arthur Niell served on multiple IVS committees and is a member of the group's directing board. He is also a member of the technical and scientific advisory committee for the Spain-Azores RAEGE geodesy project.
- In April 2018, Arthur Niell (presenting on multimode VGOS observations) and Chester Ruszczyk (presenting on interoperability guidelines for VGOS observing sessions) attended the 23rd Working Meeting of the European VLBI Group for Geodesy and Astrometry in Sweden on behalf of the Haystack geodesy group.
- In June 2018, Pedro Elosegui, Chester Ruszczyk, and Arthur Niell attended the IVS annual meeting in Norway on behalf of the Haystack geodesy group; also, John Barrett and Dhiman Mondal presented posters at the meeting.
- Haystack organized a very successful open radar workshop attended by approximately 30 students from various institutions.
- In July 2017, a large NSF-sponsored one-week incoherent scatter radar workshop was conducted in Arecibo, Puerto Rico, for graduate and advanced undergraduate students.
- Phil Erickson gave a weeklong series of lectures as part of a joint European Erasmus Mundus master's degree program concentrating on space science and technology.
- Anthea Coster was an invited speaker at the University Corporation for Atmospheric Research (UCAR) in Boulder, CO, in September 2017 and presented a seminar at Harvard University in November 2017. She was also a session chair and speaker at the International Union of Radio Science (URSI) general assembly in Montreal. In addition, she was an invited attendee at the United Nations Space for Women meeting in New York City in October 2017. She won a best presentation award at the ION (Institute of Navigation) GNSS conference in Portland, OR, in September 2017.
- John Foster gave a keynote lecture on the dayside ionosphere at an AGU Chapman Conference in Chengdu, China, in July 2017 and then participated as a lecturer at the Space Physics Summer School at Peking University in Beijing, China. In addition, he presented talks at the URSI general assembly in August 2017. Foster is a member of the science advisory committee for the International Meridional Circle Project.
- Shunrong Zhang was a member of the program committee for the 10th International Long-term Trend Workshop (May 2018) and the advisory board for the International Reference Ionosphere 2017 workshop. He gave invited talks at the International VarSITI Assembly (Russia) and the International Association of Geomagnetism and Aeronomy/International Union of Geodesy and Geophysics Joint Assembly (South Africa). Also, he is a member of the international scientist committee for the upcoming Chinese Seismo-Electromagnetic Satellite mission and the science advisory committee for the International Meridional Circle Project.
- Phil Erickson is a member of the organizing committee for the 15th International Symposium on Equatorial Aeronomy.
- Larisa Goncharenko's community activities include serving as a member of the NASA Heliophysics Advisory Committee, the Space Weather Committee of the American Meteorological Society, the AGU F. L. Scarf Award Committee, and the UCAR Jack Eddy Postdoctoral Fellowship Committee. She is also a member of the international team at the International Space Science Institute (Bern, Switzerland.

- Lynn Matthews served on review panels for NSF, the Giant Metre Wave Telescope, and the EHT project. She also refereed manuscripts for several major journals and served on the scientific organizing committees for two international conferences.
- Kazunori Akiyama served as a reviewer for several manuscripts submitted to major journals. Also, he chaired the Event Horizon Telescope Collaboration's first imaging workshop in October 2017.
- Jens Kauffmann was a member of the leadership council of NASA's Far-IR Science Interest Group and refereed applications for the NASA postdoctoral program. He co-chairs the Sloan Digital Sky Survey Unbiased Views of Young Stars in the Milky Way working group. Kauffmann also refereed manuscripts for several major journals.
- Colin Lonsdale served as vice chair of the board for the Event Horizon Telescope Collaboration. He also regularly reviews journal manuscripts and NSF funding proposals.

Education and Public Outreach

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 project and MOXIE, attract a high level of media attention, and staff members regularly appear in articles and interviews with media including the BBC, NPR, WGBH Radio, *National Geographic*, and the Smithsonian Channel. A particular highlight of the past year was the global press coverage of the EDGES results, also highlighted by NSF as a key discovery. The above-described EDGES discovery, first published in *Nature*, was featured in numerous top-level science publications.

MIT News now regularly includes articles featuring Haystack research from all groups, including a front-page highlight on Alan Rogers and the EDGES discovery.

Twice per year, Haystack holds an open house featuring a lecture, an extended question-and-answer session, and a tour of the 37-meter telescope. The traditional format has been augmented by hands-on demonstrations and informal interactions aimed at families with younger children, as well as by displays of a range of informational posters. These events are wildly popular, with attendance typically on the order of 150 people.

The wildly popular Haystack open house.

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 is hosted on the Haystack access road.

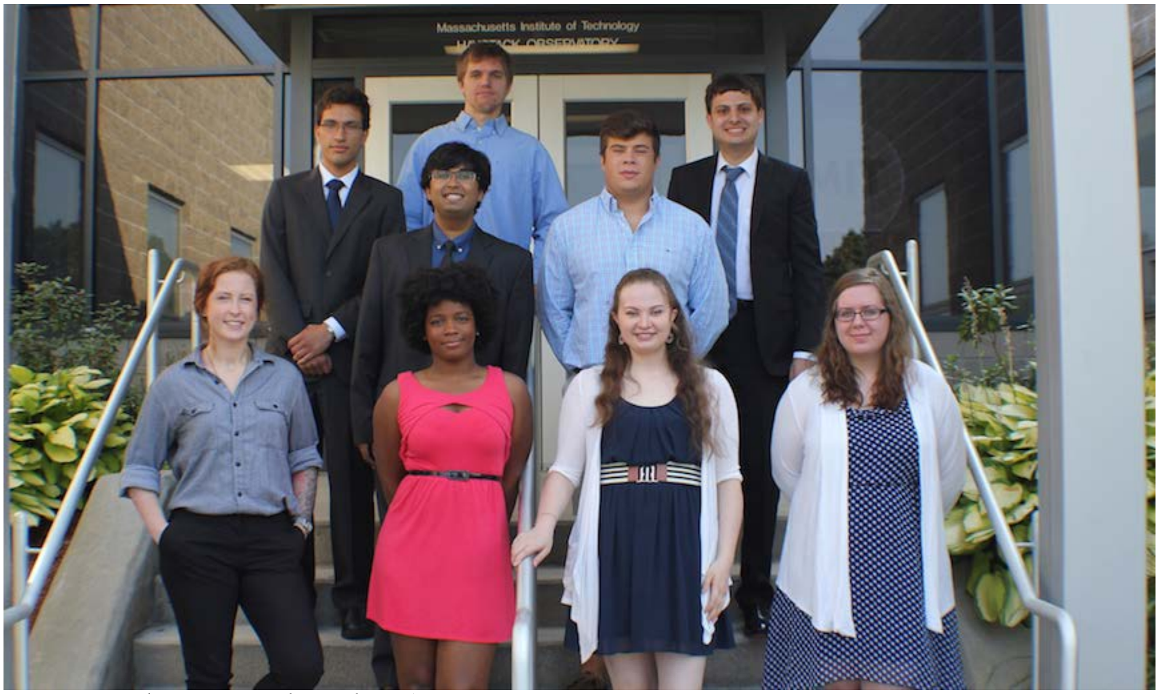
Many inquiries and questions from the public are routinely fielded by the new full-time Haystack communications officer. Maintenance of excellent relationships between Haystack and the surrounding communities is an explicit priority.

The Observatory frequently hosts tours for school groups and technical associations.

Haystack's geospace group continues an active outreach relationship with amateur radio groups, often in conjunction with HamSCI, a project that fosters collaboration between scientists and amateur radio operators. The groups participate in frequent activities and conferences, fostering technical discussions that enhance both Haystack science work and radio enthusiasts' knowledge of the latest research developments.

Haystack participates in the local high school's Job Shadow Day, in which a senior is invited to spend the day and meet with scientists and engineers from across the Observatory.

Each summer, Haystack hosts seven to 10 undergraduate students from around the country as part of the NSF Research Experiences for Undergraduates program. This long-standing and highly developed Observatory program involves supervision of student research projects by staff mentors and an extensive series of lectures spanning the full range of Haystack scientific and engineering investigations. The program has been expanded to improve diversity in terms of students' educational backgrounds as well as sources of support. The aim is to further broaden and enrich the program going forward. Also, visits to local community colleges to invite students in science and engineering programs to apply for the program have resulted in an increase in submitted applications from these institutions.



2017 Haystack summer undergraduate interns.

In November 2017 Haystack hosted the second annual NEROC science symposium, with attendees from groups working in radio science across the Northeast. Attendance increased significantly from the first symposium, and the number of institutions represented grew as well. Several collaborations have resulted from these conferences.

On April 5, Haystack and colleagues from the Onsala Space Observatory in Onsala, Sweden, celebrated the 50th anniversary of the transatlantic geodetic VLBI with a party on both sides of the Atlantic and speeches from distinguished scientists and engineers who worked on the VLBI in 1968.

In April 2018, Haystack co-hosted a very successful public Astronomy Day event with the Amateur Telescope Makers of Boston (ATMoB); guests were taught about amateur astronomy, and ATMoB members set up telescopes on the lawn for star gazing throughout the evening.

The Haystack social media feeds have been successfully revised. In addition, the Haystack website overhaul is under way, as is work on a completely new set of brochures and educational materials.

Colin J. Lonsdale
Director