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, with an overarching theme of radio science. Recently, there has been an increasing emphasis on space-based projects and research into the Earth's cryosphere. A robust 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 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 notable 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. Work to incorporate the 37-meter Haystack telescope into the astronomy program, both for VLBI and for single-dish molecular line studies, continues to progress.

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. That grant also generates a heavily used global ionospheric data product derived from global navigation satellite systems (GNSSs) and the largest worldwide ground-based geospace observational database. The program is supplemented and complemented by a wide range of smaller science grants, mainly from NASA and NSF. Geospace activities also support a range of internal science investigations, provide extensive geospace science community support for users across the country and the world, and include a significant advanced engineering and technical development component.

The growing Haystack space program includes the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) on board the Perseverance Mars Rover. This toaster-sized device continues to successfully demonstrate the production of oxygen from the Martian atmosphere. Haystack is also leading the NASA Heliophysics CubeSat Auroral Emission Radio Observer (AERO) Vector Interferometry Space Technology using AERO (VISTA), or AERO-VISTA, project in close collaboration with Lincoln Laboratory; the project involves two satellites designed to measure auroral radio emissions and perform demonstrations of interferometry between the satellites.

Strategic Summary

Strategic planning is an essential activity at the observatory and is key to efficient coordination of Haystack's diverse yet interconnected and related research activities. Over the past year, an organized, in-depth series of planning meetings was conducted covering long-range issues and opportunities for future Haystack activities. Existing strategic priorities were reconfirmed and elaborated upon, and new strategic initiatives were identified and recommended. The anticipated, lasting effects of the pandemic, including the future role and importance of remote work, were extensively debated and found to be distinct in character for different categories of employees.

Selected priorities for the observatory include the following:

- A continuing emphasis on joint projects with Lincoln Laboratory and with campus researchers. Alignment of strategic priorities, notably in the arena of space-based radio science, has recently been reinforced through close coordination with Lincoln Laboratory leadership. Several research collaborations with campus faculty are being actively pursued.
- Robust support of the long-standing Northeast Radio Observatory Corporation (NEROC), comprising regional universities with interests in Haystack-facilitated radio science. The popular annual NEROC scientific symposia represent an example of the lasting benefits and collaborative opportunities provided by continued close engagement.
- Maintenance of leading roles in the EHT project with respect to governance, technical, and scientific matters. This includes a major role in defining and participating in the long-term evolution of the project, including the possibility of extension of the array into space.
- Broadening of the astronomical research program to become less dominated by the EHT project. This involves expanded effort on non–event horizon scale VLBI studies, growth of a subgroup studying galactic astronomy including stellar processes, study of the early universe using highly redshifted neutral hydrogen 21-centimeter line measurements, and hiring of postdoctoral researchers in astronomy with distinct but complementary science interests.
- Reestablishment of the 37-meter telescope as a globally competitive astronomy research tool, including provision of essential supporting infrastructure such as a maser frequency standard, lab facilities for advanced receiver and backend development, and a flexible, highly integrated modern software system for telescope control and data handling.
- Maintenance and refinement of the existing megawatt-class ISR facility at Haystack. A $4.5 million NSF award was secured to support and accelerate this work.
- Design, development, and construction of advanced low-frequency arrays for a broad range of radio science applications spanning and supporting multiple Haystack research fields. Such arrays should leverage rapidly advancing digital technologies to deliver new levels of flexibility and versatility. Deployment of such arrays in space is a compelling long-term goal.

- Maintenance and expansion of global technical leadership in VLBI, including recording and correlation systems to support greatly increased bandwidths. These technical efforts should be simultaneously responsive to the long-term research needs of both the astronomy and geodesy communities.
- Establishment of a self-sustaining 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. Effective management of characteristically episodic funding streams for such work, with protection of a core engineering team, is a key focus area.
- Growth of Haystack's education and public outreach program, including ongoing updates to research descriptions on the overhauled and expanded website and revitalized social media platforms.
- Implementation of a diversity, equity, and inclusion policy, currently in draft state and under review by management.

Funding

Haystack researchers continue to generate a high volume of funding proposals and awards. As a consequence of a highly successful long-term strategy of encouraging and developing a deep bench of experienced principal investigators (PIs) and investing in an excellent administrative support team for grant writing, 28 proposals were submitted from 13 different PIs to many different sponsors. An ongoing high acceptance rate has allowed the observatory to grow significantly in both total research volume and staffing levels, with further robust growth foreseen in FY2023. Some of this anticipated expansion is facilitated by increasing levels of collaborative activities with Lincoln Laboratory researchers.

Growth in both projects and staffing has proven to be a welcome yet challenging situation to manage, with consequences for overcommitment of existing staff and pressure on new staff to accelerate learning curves. These challenges have been compounded by pandemic-related inefficiencies and a highly competitive market for hiring skilled engineers but also somewhat ameliorated by Covid supplementary funding from sponsors on various grants.

Fiscal year 2022 federal funding outcomes at both NASA and NSF—which are the agencies of greatest financial importance to the observatory—were disappointing relative to early hopes. The final appropriations fell well below the figures requested by the president, as well as those initially favored by both the House and Senate. Nevertheless, both agencies still saw modest increases, and risks to Haystack budgets appear limited. As reported last year, Haystack places emphasis on agility with which to respond to changing funding circumstances facilitated by a culture involving the nurturing of staff versatility and broad skill sets. This approach, combined with a large number of proposals and projects addressing different yet technically synergistic aspects of radio science, creates long-term resilience against unpredictable gyrations in sponsor circumstances and associated proposal opportunities.

Staffing growth is leading to significant office space issues; hiring is occurring at a faster rate than people are retiring or leaving. This situation is being managed by increasing the efficiency of space utilization, including time sharing of some offices, especially for individuals who have been approved to work part time from home. Further optimization of space is occurring with interior construction activities conducted by the Haystack facilities team. The need for a more substantial renovation of existing interior space, or possibly the rental of portable space, is clearly foreseen.

Personnel

A consequence of recent observatory growth, in both research volume and diversity, is added administrative complexity, with increasing burdens on members of the director's office. Along with this growth, lasting repercussions from the Covid-19 pandemic and the resultant remote workforce requirements have dramatically increased demands on our information technology team and the general administrative support team. To address these challenges, Haystack has recently added several positions in both areas and expanded the responsibilities of the recently hired assistant director for administration. Hiring has continued among the research staff, with a mix of new postdoctoral researchers, research scientists, and engineers. Some of the expanded workload is being managed via temporary appointments and external contracts, along with engagement of students in suitable selected subprojects and well-defined tasks of modest scope.

Astronomy

Event Horizon Telescope

The Event Horizon Telescope is a groundbreaking project with a mission to study the radio structure and properties of emission close to supermassive black holes in the centers of galaxies, on scales comparable to the event horizons of those black holes. The project is based on the technique of VLBI, which employs dishes scattered across the globe to achieve extraordinarily high angular resolutions as small as 20 microarcseconds (or roughly the size of a golf ball as seen from the Moon).

Building on decades of VLBI experience and innovation, Haystack has continued to support the development, deployment, and maintenance of high-capacity digitization and recording systems that allow the EHT to operate, and the observatory performs interferometric data combination (correlation) using a specialized on-site supercomputing cluster. Transforming the resulting correlated data into images, particularly polarized images, has required the development of new and rigorous calibration strategies and image reconstruction algorithms. Haystack staff are involved in operations, data reduction, and analysis aspects related to the EHT, making foundational contributions on many fronts.

The two primary targets are the supermassive black holes in the nearby elliptical galaxy M87 (also known as Virgo A) and at the center of our own Milky Way galaxy (Sagittarius A*). The EHT also observes the powerful radio jets emanating from more distant active galactic nuclei (AGNs) and may in the future use the unique capabilities of the EHT array to explore a range of other environments and phenomena such as astrophysical masers and molecular material seen in absorption against AGN sources.

In May 2022, the collaboration published images of the black hole in the Milky Way galaxy showing a similar ringlike structure and breaking additional new ground in radio interferometer imaging techniques.

Vincent Fish served as PI on $2 million EHT-related awards to Haystack covering US EHT operations and key aspects of future-oriented development for the EHT community, with the former supporting many functions of the current EHT science program. An example is an extensive observing run in spring 2022 that included preparation of the Haystack 37-meter telescope for participation in EHT observations at the 1.3-millimeter wavelength (230 GHz) with strong synergies for a broad range of other future astronomy work using the telescope.

Haystack staff fulfilled a number of critical roles in the international EHT collaboration. Colin Lonsdale served as chair of the board of stakeholders, the collaboration's top-level governing body, and Mike Hecht was board secretary, with administrative support from Dianne Tonelli. Other Haystack staff members served on a range of EHT collaboration committees and working groups, often in prominent leadership positions.

Haystack 37-Meter Telescope

The Haystack 37-meter telescope is available for astronomical research on a time-share basis and is currently equipped for measurements at 13-, 7-, and 3-millimeter wavelengths. This dish has a combination of surface precision, pointing accuracy, and common occurrence of winter nighttime conditions that together are sufficient for high-sensitivity observations at wavelengths as short as 1.3 millimeters. This fast-slewing telescope has the potential to be among the world's largest and most sensitive at these challenging high radio frequencies.

Significant progress has been made in establishing accurate pointing, high sensitivity, operational convenience, and other milestones toward scientific capabilities of various kinds. Observations were conducted in conjunction with other telescopes around the world, and high-quality VLBI results were demonstrated. Sufficient results were obtained to support new funding proposals, which are to be prepared for NSF opportunities in November 2022 and January 2023 focused on high-resolution, wide-bandwidth spectroscopy.

Much work must still be done before the telescope can be routinely used for science research. This includes improvements and extensions to the signal chains in all three frequency bands, polarimetry support, implementation of beam switching using a versatile database and a high-time-resolution metadata approach, and a number of other components. Most of this work is needed to demonstrate feasibility of participation in future EHT observations at 230 GHz and is supported under the EHT-related development award mentioned above. Jens Kauffmann is leading and coordinating the telescope upgrade program.

The telescope, once fully operational, will likely be in significant demand for educational uses, as a rare opportunity for students at various levels to obtain firsthand experience with a major research instrument. Long-standing interest in such educational uses exists among several regional universities.

Experiment to Detect the Global EoR Signature

In a collaboration with Arizona State University, retired senior engineer and radio scientist Alan Rogers, recipient of multiple prestigious awards over a long and distinguished career and currently a Haystack research affiliate, is leading the technical development of the Experiment to Detect the Global EoR Signature (EDGES) with a small Haystack team. This is a single, exquisitely well-calibrated antenna system that "sees" most of the sky at once, with the goal of detecting absorption of the cosmic background radiation by neutral hydrogen in the early universe. Due to widespread strong interference from artificial sources, only deployments in the most remote of sites are suitable for this work.

An initial detection of the predicted weak spectral feature was published by the EDGES team in the journal *Nature* in 2018, with surprising properties that have generated intense interest from the cosmology community. The current challenge is to make the result more robust (or identify any potential issues with the initial detection) and further refine the measurement and the properties of the absorption feature. Technical developments led by Rogers have led to important refinements of the hardware, culminating in the current EDGES-3 system.

Other Research Activities

Jens Kauffmann's Line Emission as a Tool for Galaxy Observations (LEGO) seeks to establish how the physical properties of molecular gas in galaxies can be inferred from observations of millimeter-wave molecular emission lines via wide-field line mapping observations of well-studied molecular clouds in the Milky Way. A key aim is to improve the astrophysical understanding of the "Gao & Solomon relation," an essential tool in the study of star formation in nearby galaxies that posits that hydrogen cyanide (HCN) emission is a probe of the presence of dense molecular gas. LEGO now delivers the most comprehensive data available to show that HCN is not, in fact, a reliable probe of dense gas, with important consequences for our view of how galaxies form stars.

Lynn Matthews continued leadership of Atacama Large Millimeter/submillimeter Array (ALMA) phasing projects phases 2 and 3, which are developing and commissioning new and expanded VLBI capabilities at ALMA in northern Chile. Matthews also continued using the Karl G. Jansky Very Large Array (VLA) and ALMA to carry out spatially resolved radio observations of mass-losing evolved stars. Her VLA study of the red supergiant star Betelgeuse uncovered evidence of a recent temperature decrease in the stellar atmosphere that appears to be linked to the passage of a shock wave following a recent large-scale mass ejection. Haystack is also providing technical expertise in support of a balloon-borne VLBI experiment led by Laura Fissel at Queens University in Kingston, Ontario.

Geospace

MIT Haystack's NSF-supported Millstone Hill Geospace Facility (MHGF) runs, coordinates, and develops numerous instruments for a program of investigations of upper atmospheric morphology and dynamics and the near-Earth space environment coordinated with community requests and initiatives. A long-term five-year NSF award provides facilities and operations support. The core instruments of the facility are the Millstone Hill ionospheric scatter radar, GNSS total electron content (TEC) data products, and the Madrigal database system.

The Millstone Hill ISR uses an ultra-high-frequency (UHF) megawatt-class transmitter combined with the Millstone Hill Ionospheric Steerable Antenna (MISA) and Zenith antenna systems. ISR is the most powerful and flexible ground-based technique for probing the dynamics of thermal plasma in Earth's ionosphere. Millstone Hill is the only ISR operating in the continental United States with a key mid-latitude field of view spanning the eastern United States and the Atlantic Ocean.

Haystack's GNSS-based total electron content measurements, calculated from sensors across the globe, are also used constantly by the community and provide worldwide coverage of ionospheric variations and features. The NSF Geospace Facility also developed and now oversees the Madrigal Distributed Database, the community standard interaction portal for all NSF ground-based upper atmospheric data. Madrigal as a system contains data from 172 instruments in the Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) Madrigal database, totaling over 62 TB of data. During the past year, 360 unique users from 151 institutions used MIT Automated Processing of GPS data products and downloaded daily data more than 140,000 times.

The Millstone Hill UHF radar system executed a number of community-focused observations, producing science-quality data experiments using the Madrigal database. Investigations concentrated on whole-atmosphere coupling, especially during large neutral atmosphere perturbations related to sudden stratospheric warming, along with high-time-resolution regional ionospheric variability.

Geospace Facility Operations

NSF funding for the core MHGF grant supports 1,250 hours per year of radar operations. Over the past year, operations were curtailed due to several factors: (1) the global Covid-19 pandemic, (2) a shortage of qualified radar technicians following a departure in 2019, and (3) technical resource burdens caused by a major and unanticipated repair of the MISA system. These issues, which forced a delay of a month-long continuous experiment originally planned for this year, are being addressed and new technicians have since been hired. We anticipate that resolution of these issues will allow a significant increase in operational duty cycles, including an initial long-duration ionospheric radar observation.

Geospace Science Highlights

In early 2022, Haystack scientists and colleagues published research in the journal *Frontiers in Astronomy and Space Sciences* confirming that the January 15, 2022, eruption of Tonga's Hunga Tonga–Hunga Ha'apai volcano launched far-reaching, massive global disturbances in the Earth's atmosphere.

In addition, in a study published in March 2022 in the journal *Space Weather*, Ercha Aa and colleagues from both the Haystack Observatory and the NCAR High Altitude Observatory developed a new TEC-based ionospheric data assimilation system, TIDAS, to provide high-fidelity regional three-dimensional ionospheric information. TIDAS incorporates multiple types of ground- and space-based ionospheric observations, such as GNSS TEC measurements, satellite radio data, and measurements by the Millstone Hill ionospheric radar facility at Haystack.

John Swoboda was awarded a grant from the Office of Naval Research Young Investigator Program. His project, Enabling Volumetric Ionospheric Imaging Using Vector Sensor Ionosondes, launched in April 2022.

As part of a NASA Living with a Star Targeted Research and Technology research team focusing on ionospheric superstorms, Anthea Coster, Larisa Goncharenko, and Shunrong Zhang provided observational data support and interpretation expertise for improving understanding of ionosphere-thermosphere coupling during such storms.

Geospace Community Activities

The Haystack geospace research program was represented at a wide range of scientific meetings, focused workshops, and community service activities, including national and international leadership roles. Participation at regional, national, and international levels maintains a high degree of collaborative research essential to advancing current mesoscale geospace community science. Phil Erickson is a member of the National Academies Committee on Radio Frequencies, which protects scientific use of the radio spectrum. He also served on the science steering committee for an NSF workshop on Strong Thermal Emission Velocity Enhancement subauroral emission structures in fall 2021. Larisa Goncharenko is actively involved in community service as a member of the NASA Heliophysics Advisory Committee and the American Meteorological Society Science and Technology Committee on Space Weather, and she is chair of the CEDAR Science Steering Committee. Anthea Coster is co-chair of the NASA Heliophysics Living with a Star Program Analysis Group.

Other Instruments and Arrays

Developments under the NASA-funded AERO-VISTA CubeSat program led by MIT Haystack (see below) have resulted in the implementation of an advanced low-power software radio named Aurora. This is a compact radio suitable for use with RAPID hardware or advanced electromagnetic vector sensors. The Millstone Zephyr meteor radar network will be implemented under the leadership of Ryan Volz using these radios and vector sensor antennas with the support of Lincoln Laboratory. Millstone Zephyr meteor radar work targets observations of fine-scale altitude-resolved neutral wind dynamics during the April 2024 US east coast eclipse.

A number of ongoing technical efforts will enable future distributed and deployable geospace instruments, radio arrays, and facility assets.

Geodesy

Haystack Observatory’s significant legacy of VLBI technology innovations for geodetic application continues under group leader Pedro Elosegui, who has also continued to expand the Haystack polar geodesy program and has strengthened ties to departments on the MIT main campus.

VLBI Geodetic Observing System

Under NASA sponsorship, the Haystack geodetic VLBI group continues development of the advanced system known as 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, natural hazard warning and prevention, disaster mitigation, sustainable development, and society at large.

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 is being expanded with additional stations funded and built by partners of the International VLBI Service in Germany, Japan, Sweden, Spain, and elsewhere, with the goal of eventually forming a global array of GGOS stations.

The Haystack group continues to make major contributions toward the validation of the VGOS concept and improvement and maintenance of the physical network of NASA telescopes at Kōke`e Park Geophysical Observatory (KPGO) in Hawaii and the McDonald Observatory in Texas, as well as the prototype and developmental testbed VGOS telescopes at Westford and the Goddard Geophysical and Astronomical Observatory in Maryland. Haystack also continues to provide routine support of geodetic VLBI through extensive correlation development, multiple forms of network support, data quality evaluation, assessment of precision and accuracy of geodetic estimates, and support of Universal Time (UT1) monitoring through a US Naval Observatory contract.

Haystack has recently started the design phase for the deployment of a new VGOS antenna at the VLBI site in Fortaleza, Brazil. Expanding the network to the southern hemisphere will contribute to improving the accuracy of global reference frames such as the International Terrestrial Reference Frame (ITRF). Haystack is also providing technological support to the upcoming VGOS station in Hobart, Australia, which will further strengthen the global geometry of the VGOS network.

VLBI Geodetic Observing System and the International Terrestrial Reference Frame

VGOS observations were included in ITRF2020, its latest realization. The ITRF is crucial to monitoring key phenomena such as global sea-level rise. There have been a series of successively better ITRF constructions every five years or so, starting in the mid-1980s. ITRF2020 has recently been released for public perusal, and it promises to be the most accurate ever. As with prior realizations, this ITRF includes geodetic station positions from the four space geodetic techniques: VLBI, GNSS, satellite laser ranging, and the Doppler satellite tracking system. VGOS sessions have largely been scheduled, observed, correlated, and partially analyzed at Haystack, which has spearheaded the VGOS development effort. ITRF2020 marks an inflection point whereby the VGOS networks will become ever more important going forward. Since 2021, the observing rate of VGOS sessions has been increased to weekly, advancing toward the ultimate goal of making VGOS a continuously observing technique.

VLBI Geodetic Observing System Intensive Program

The VGOS program for estimation of the Earth's rotation is now a reality. Geodetic VLBI observations are organized to a large extent for the determination of Earth orientation parameters. VLBI is the premier technique for measuring the phase of the Earth's rotation, UT1–Coordinated Universal Time, and nutation, from which we gain a deeper understanding of the interior of the Earth.

Polar Geodesy

Polar geodesy research is relevant to the high-profile topics of global climate and sea-level change. Initial collaborative polar geodesy efforts are focused on the cryosphere, including precision measurement of various forms of ice—sea ice, glaciers, icebergs, ice shelves—in terms of flow, drift, and deformation via deployable GPS-based systems.

In March through October 2021, in the Arctic Ocean off northern Alaska, we designed, built, and deployed 12 autonomous geodetic-quality GNSS buoys forming a small-scale strain network as part of the Sea Ice Dynamic Experiment project. The aim of this project is to improve predictions of how sea ice deforms and fractures as it is subjected to stresses from atmospheric winds and ocean currents. Preliminary results related to sea ice drift, deformation, and fracture events were presented at the 2021 fall American Geophysical Union meeting, and results in the areas of GNSS, Interferometric Synthetic Aperture Radar (InSAR), laser retroreflectors, and seismic sensors are being used to provide a combined view and improved understanding of sea ice dynamics in the Arctic Ocean. This information will allow a better understanding of the effects of climate change on sea ice and improvements in short-term ice prediction and navigation maps for ships in the Arctic Circle.

Haystack researchers transporting buoys to monitor ice behavior in the Beaufort Sea.

In Antarctica, we continue the development of a new instrument and measurement approach to monitoring the stability of the Antarctic ice shelves, a pivotal element of the Antarctic glaciology because they restrain, buttress, and modulate the flow of grounded ice to the ocean. We are developing air-droppable ice penetrators instrumented with GNSS and seismometer sensors that can measure the response of the ice shelves to atmospheric and ocean waves. Such a system would eliminate the challenging logistics currently faced in obtaining such measurements, replacing those logistics with efficient aircraft-based deployment.

Space Research and Technology

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, Lincoln Laboratory, and outside organizations such as NASA laboratories. Space-based radio science is a compelling strategic priority for Haystack.

Lenny Paritsky is leading further development of the Haystack space science and technology program. Proposals under discussion include miniature radar instruments for planetary applications, space-based nodes for VLBI networks, assessments of space weather impacts on planetary emissions, and use of space-based laser communication to link ground-based telescopes.

CubeSats

Two current major Haystack projects are the Auroral Emission Radio Observer and Vector Interferometry Space Technology using AERO, collectively referred to as AERO-VISTA: twin NASA-funded CubeSat missions to study auroral radio emission at low frequencies. Haystack continues to lead development of these twin missions to study the Earth's aurora. Lincoln Laboratory is a key partner in this effort, with additional contributions from the Department of Aeronautics and Astronautics and support from external universities (including Morehead State University and Dartmouth College) in the scientific and technical aspects of the mission.

Mars Oxygen In-Situ Resource Utilization Experiment

MOXIE is an in situ resource utilization prototype on NASA's Mars 2020 Perseverance rover mission. MOXIE produces oxygen from the carbon dioxide in the atmosphere of Mars using solid oxide electrolysis (SOE). Michael Hecht is the PI, and Jeffrey Hoffman of the Department of Aeronautics and Astronautics is the deputy PI. They lead an international science team responsible for campaign planning, data reduction, analysis, and scientific presentations and public outreach. Jason SooHoo at Haystack has led an effective operations team since the Perseverance landing in February 2021, handling all aspects of commanding, uplink, and downlink.

Haystack's MOXIE laboratory is used as a platform for operations such as calibration and characterization, testing of new software, and evaluation of next-generation hardware and controls. NASA's Jet Propulsion Laboratory led the overall development of the instrument, with OxEon Energy in Salt Lake City responsible for the SOE system itself.

MOXIE produced oxygen on Mars three times between April and June 2021. Over the past year, MOXIE operated seven more times, mapping out performance across the Martian seasons and experimenting with new techniques to improve production and increase safety of operations. It has exceeded all of its design goals, which specified a minimum number of operations, a range of environmental conditions, oxygen purity, and overall oxygen production rate. The MOXIE project has graduated two MIT PhD students and has engaged master's students as well as several Undergraduate Research Opportunities Program (UROP) students. A publication on the first year of results was submitted to *Science Advances*, and it is expected to be released simultaneously with the first round of mission papers in late August 2022.

Education and Outreach

Education and public outreach activities were hampered but not eliminated by the Covid-19 pandemic. Regularly scheduled events were successfully held online. Some major outreach events, such as the Haystack Open House events and educational in-person tours, remain on hold.

The Haystack News website allows for direct publication of press releases and other descriptions of Haystack research and technological developments and activities. Social media channels exhibit continued growth. Certain high-profile projects at the observatory, notably the Event Horizon Telescope work, have attracted media coverage.

Haystack scientists were selected to represent the EHT project at simultaneous press conferences on May 12, 2022, to announce the historic first imaging of the supermassive black hole Sagittarius A* at the center of the Milky Way. Vincent Fish was one of four scientists on the NSF press conference panel in Washington, DC; Colin Lonsdale and Kazunori Akiyama participated in the public Q&A forum. Geoff Crew gave the main presentation talk at the press conference at ALMA in Chile.

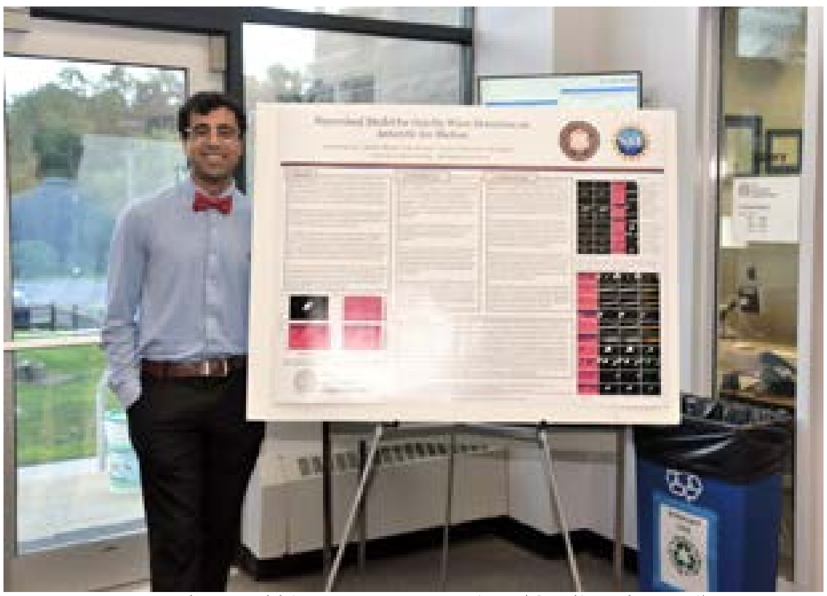
Geoff Crew delivering the announcement of the Event Horizon Telescope collaboration's imaging of Sagittarius A, the black hole at the center of the Milky Way, at ALMA in Chile. (Credit: Harriet Schwartz Crew)*

Extensive MOXIE outreach activities ranging from press conferences and media interviews to educational activities with students from preschool through graduate school have been conducted by Haystack staff.

Haystack's geospace group continues an active outreach relationship with amateur radio groups, often in conjunction with HamSCI, a citizen science and analysis project that fosters collaborations between scientists and amateur radio operators.

In March 2022, Haystack hosted the sixth annual NEROC science symposium, held virtually again this year, with attendees from groups working in radio science across the northeast. Collaborations often result from these conferences, and feedback has been positive.

Each summer, Haystack hosts 7 to 15 undergraduate students from around the country, anchored by an award from the NSF Research Experiences for Undergraduates program. Haystack also hosts UROP students in a comprehensive summer internship program. The program, once again held in person after two years of remote operation, is a long-standing Haystack Observatory tradition that involves numerous staff mentors in supervision of 10-week research projects as well as an extensive series of lectures spanning Haystack scientific and engineering investigations. The program has been expanded to improve diversity in terms of both the educational backgrounds of students and sources of support.



A 2022 REU student and his poster presentation. (Credit: John Tsai)

Haystack Job Shadow Day, an annual tradition in conjunction with local high school Westford Academy, was held again this year after being on hold due to the pandemic. The traditional format was overhauled to include additional talks, activities, and site visits. Twelve students participated this year (up from the usual one or two), and feedback was positive.

Haystack celebrated the unveiling of its museum-quality historical exhibit for visitors in the conference lobby with a talk from founder Herb Weiss, a short time before his 103rd birthday.


Herb Weiss, founder of Haystack Observatory, in front of the 37-meter radio antenna. (Credit: Boston Globe*)*

Colin J. Lonsdale
Director