Haystack Observatory

Introduction

MIT Haystack Observatory is a multidisciplinary research center located in Westford, Massachusetts, 27 miles northwest of the MIT campus. The Observatory conducts a broad range of astronomy, geodesy, and geospace science studies, using the Very Long Baseline Interferometry (VLBI) technique, high-power incoherent scatter radar, and many other techniques and instruments. An important component of Haystack's mission is the education of students through research opportunities using the Observatory's facilities.

Haystack REU poster and presentation session

The Observatory research portfolio is broad in scope, with an overarching theme of radio science. Haystack has a number of established programs, as described later in this report, that together provide stable funding comprising a large fraction of the total budget. Recent emphases have involved 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 these disciplines.

Strategic Planning Summary

The Observatory has an established policy of conducting in-depth strategic review. The current plan was developed in 2019 and covers the time period from 2020 to 2030, with emphasis on the first 5 years. The plan is conceived as a general roadmap for Haystack Observatory, with specific recommended actions as appropriate. The annual budget of the Observatory was on the order of $13M at the time of the strategic review, with a staff that had varied from about 75–85 people in recent years. Since then, the budget has increased to around $20M, and staffing has grown to approximately 100.

With the unforeseen impact of the COVID pandemic, followed by the lifting of all COVID restrictions in early 2023, and combined with major growth in both funding and staffing at the Observatory, another strategic planning effort is necessary in the relatively near future. The timing and intensity of this exercise will be determined by circumstances and staff commitment levels, but would optimally occur no more than 18–24 months from the date of this report.

Publications

Haystack's long track record of scientific publications continues. From January 2019 through May 2023, Haystack authors generated 477 scientific and engineering publications, or an average of approximately 108 publications per year. The full list of publications includes mainly peer-reviewed, refereed journal articles, along with conference proceedings, white papers, and other professional contributions

Funding and Staffing

Haystack researchers continue to generate a high volume of funding proposals and awards. During the period covered by this report, new funding proposals were submitted on average every 9 days, and success rates hover around 50%. At any given time, of order 60 funding awards are typically active across the Observatory. This performance has allowed the Observatory to grow significantly in both total research volume and staffing levels. Total research volume grew through this period by about 50%, to around $20M per year, and staffing grew by 25–30%. Additional robust growth is foreseen.

Growth in projects, funding, and staffing has proven to be a welcome yet challenging situation to manage, with consequences for overcommitment of existing staff and pressure to accelerate learning curves for new staff. These challenges have been compounded by pandemic-related inefficiencies.

The federal funding outcomes for both FY2022 and FY2023 at both NASA and NSF were disappointing relative to early hopes. Nevertheless, both agencies still saw modest increases, and risks to Haystack budgets appear limited for now. 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.

Astronomy

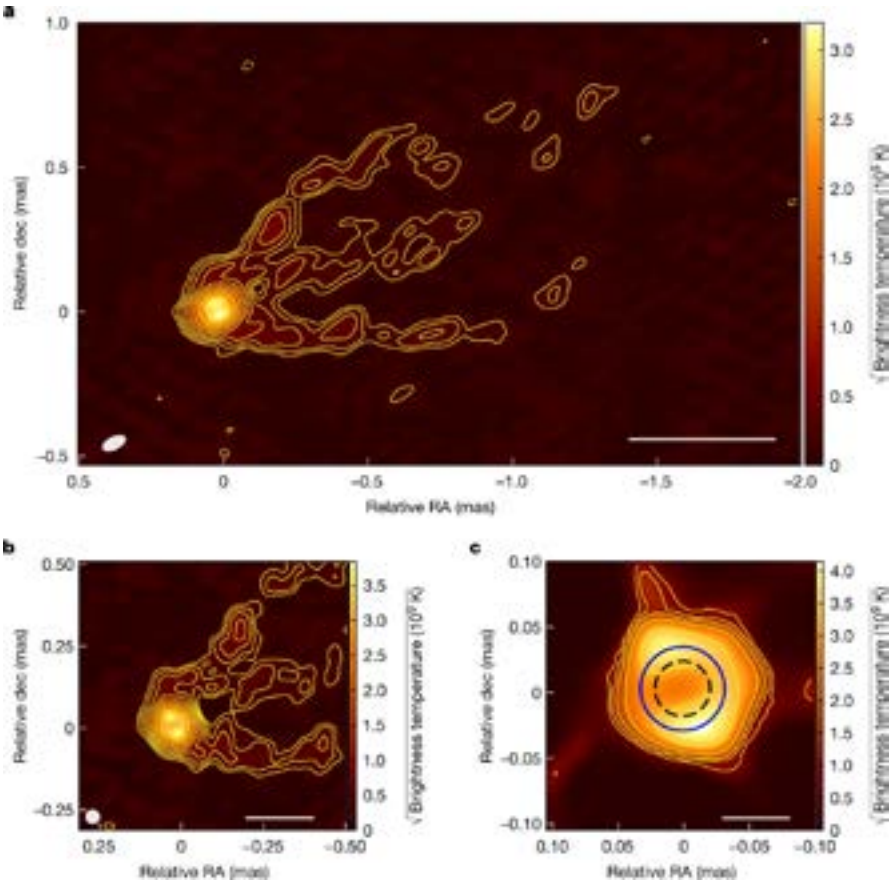
The project portfolio in astronomy is very broad. Excluding space-based projects, 41 funding proposals were submitted during the reporting period, of which 20 were awarded and 6 were still pending at the time of writing. The work can be generally split into instrumentation-related activities with science objectives, and pure astrophysical research activities. Most of the awarded funding is generated in projects involving some form of instrumentation or technique work. Astrophysical research projects using data from major external facility instruments (ALMA, SOFIA, JWST, etc.) also play an essential role in the work of the observatory, as they connect the observatory's researchers to the wider community and provide the environment needed for the gestation of ideas that can lead to next-generation research instrumentation.

Event Horizon Telescope

The Event Horizon Telescope (EHT) is a ground-breaking project with a mission to study the radio structure and properties of emission close to supermassive black holes in the centers of galaxies, on event horizon scales. It is based on the technique of Very Long Baseline Interferometry (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 viewed on the Moon from the Earth).

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 performs the interferometric data combination (correlation) using a specialized onsite supercomputing cluster. Turning the resulting correlated data into images, and particularly into polarized images, required the development of new and rigorous calibration strategies and image reconstruction algorithms. Haystack staff are involved in operations, data reduction, and analysis aspects of the EHT, making foundational contributions on numerous fronts.

The EHT Collaboration (EHTC), comprising more than 300 scientists, engineers, and technicians around the globe, in April 2019 published the world's first image of a black hole, in the M87 galaxy, showing a striking ring morphology. This work garnered numerous prestigious professional accolades, notably including the 2020 Breakthrough Prize in Fundamental Physics. It was followed by an image with linear polarization, which offered clues to the role that magnetic fields play in the black hole accretion process.



High-resolution images of M87 at 3.5 mm obtained on 14–15 April 2018 (Lu et al., 2023)

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

Vincent Fish served on two multimillion-dollar EHT-related awards, as Principal Investigator on a Haystack MSIP award and institutional Principal Investigator on a subaward to Haystack, covering US EHT operations and key aspects of future-oriented

development for the EHT. The former supported many functions of the current EHT science program, including observing runs in Spring 2022 and Spring 2023; the latter includes preparation of the Haystack 37-meter telescope for participation in EHT observations at the 1.3-mm wavelength (230 GHz), with strong synergies for a broad range of future astronomy work using the telescope, and modernization of the Haystack Observatory Postprocessing System (HOPS) software used to reduce correlated VLBI data.

Haystack staff members fulfill many of critical roles in the international EHT collaboration (EHTC) organization, including chairmanship of the governing Board of Stakeholders and other leading roles.

Haystack 37-meter Telescope

The instrument was rebuilt in 2010–2014 to deliver a much-improved dish surface accuracy of <0.1 mm, a capable radar imaging system at frequencies of 92–100 GHz, and a variety of other improvements. The Haystack 37-meter telescope is available for astronomical research on a time-share basis: Lincoln Laboratory operates the radar systems for government agencies for about two-thirds of the time, while Haystack Observatory typically has access to the dish at 23:00–07:00 on weekdays and around-the-clock access on weekends. This instrument offers a combination of surface precision, pointing accuracy, and wintertime atmospheric transparency that enables the telescope to deliver sensitive observations at frequencies up to about 230 GHz. This fast-slewing dish has the potential to be among the world's largest and most sensitive at these challenging high radio frequencies. The radio astronomy instrumentation on the telescope is being updated to make use of these capabilities.

Current work on the telescope focuses on (1) characterization of the instrument and the site, and (2) "demonstration science" that showcases the scientific capabilities of the telescope. This work is done specifically in support of an NSF-funded study which includes investigation of inclusion of the telescope in the EHT array, and more generally to support preparation of funding proposals to agencies.

Phasing ALMA for VLBI and other work

Lynn Matthews continued leadership of the ALMA Phasing Project (APP) Phases 2 and 3, which are developing and commissioning new and expanded VLBI capabilities at the Atacama Large Millimeter/submillimeter Array (ALMA) in northern Chile. Haystack Observatory's role has been focused on allowing the collection of ALMA dishes to operate as a "phased" array. In this special mode of operation, the telescopes are synchronized to function together like a single, giant antenna. Using VLBI, such a phased array can join networks of telescopes around the world which are operating together as an earth-sized telescope, like the EHT. The inclusion of ALMA in global VLBI networks enabled by this work played a critical role in the EHT's first-ever imaging of two black holes. Recently introduced VLBI capabilities at ALMA as part of APP2/APP3 include flexible tuning, spectral line VLBI, and a phased array (pulsar) observing mode.

For the next five years, Lynn Matthews and Geoff Crew will be working with the National Research Council of Canada (NRC) and the National Science Foundation's National Radio Astronomy Observatory (NRAO) on VLBI aspects of a newly funded project to upgrade ALMA's correlator for further expansion of ALMA's scientific

capabilities. This next-generation correlator upgrade will provide a major boost in ALMA's efficiency, sensitivity, and bandwidth, and will allow it to contribute fully to an evolving and ever-more capable EHT array

EDGES

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, deployments in only 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 (Bowman et al., 2018), with surprising properties that have generated intense interest from the cosmology community. Independent confirmation of this unexpected and profoundly important result has proven elusive to date, as the technical demands on such experiments are extreme. Meanwhile, the EDGES team has sought to refine the original measurement, and to add to the variety of measurement circumstances across which a real cosmological signal would be invariant. This effort has led to the development of the next-generation EDGES-3 system. In addition to instrumental improvements, it is also valuable to make measurements from more than one geographic location, as a true signal would be invariant to different sky brightness distributions as seen from different latitudes. Two recent deployments have been conducted or are underway, one to the original EDGES-2 site in western Australia, and one to Devon Island in the high Canadian Arctic. Both sites are extremely remote and sufficiently radio quiet for this challenging experiment.

Astrophysical Research Projects

Lynn Matthews used 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 for 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. Analysis of follow-up observations of Betelgeuse from the VLA and ALMA is ongoing. Matthews also recently led the publication of the first discovery of radio emission associated with a classical Cepheid based on measurements from the VLA.

Thushara Pillai is leading a NASA/SOFIA Legacy project (SIMPLIFI) on characterizing the magnetic polarization in molecular clouds across its evolutionary cycle. SIMPLIFI seeks to systematically combine the gas dynamics and density structure of molecular clouds discerned via wide-field line mapping observations of well-studied molecular clouds in the Milky Way with magnetic fields. Thanks to the team of international experts, these data are contextualized via synthetic observations of state-of-the-art magnetohydrodynamic simulations. The exquisite resolution and sensitivity of SIMPLIFI multi-wavelength and multi-scale dust polarization data will allow us to quantify the role of magnetic fields in cloud evolution and forming low- and high-mass stars.

Research scientist Thushara Pillai and the SOFIA airborne observatory

Pillai is also leading NSF-funded ALMA projects (such as CoCoA) to constrain the earliest phase of high-mass star formation. CoCoA is a systematic search for high-mass starless cores complete to within 5 kiloparsecs. It uses thermal dust continuum and spectral line diagnostics of physical and chemical conditions towards the coldest most massive cores in the Milky Way.

Jens Kauffmann's Line Emission as a Tool for Galaxy Observations (LEGO) project 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.

Geodesy

Geodesy research at MIT Haystack follows a two-pronged approach in which technology innovations go hand-in-hand with scientific applications for geodetic studies that focus on the solid Earth, the neutral atmosphere, and the cryosphere (the frozen water part of the Earth's climate). Our main research activities include the development of the next-generation VLBI systems and an expanding polar geodesy program. Our efforts are supported by NASA, NSF, and a few other institutions and agencies such as the Office of Naval Research (ONR) and the National Geospatial Intelligence Agency (NGA). Our projects provide opportunities for significant hands-on research experience

to students of various departments (including AeroAstro and Earth, Atmospheric, and Planetary Studies [EAPS]) on MIT's main campus.

Next-generation VLBI Geodesy

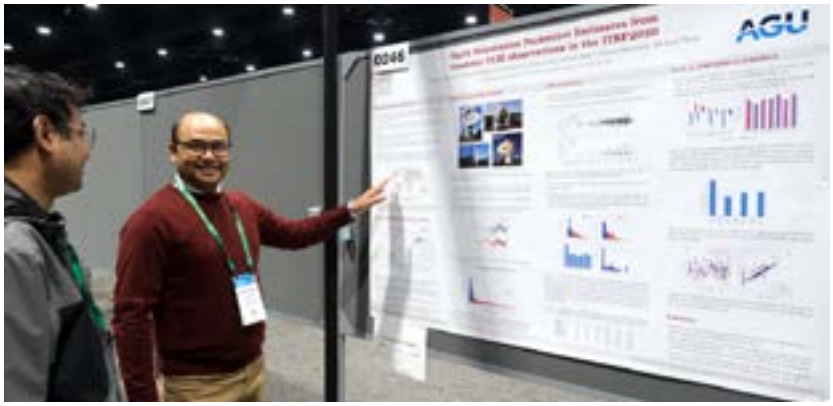
Under NASA sponsorship, the Haystack geodetic VLBI group continues development of the advanced system known as VLBI Geodetic Observing System (VGOS) for the next-generation broadband geodetic VLBI network. VLBI is one of the fundamental space geodesy techniques essential to realize an accurate and stable 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 (GGOS). Under its Space Geodesy Program (SGP), NASA is leading the development of a network of about ten GGOS stations. The NASA VLBI network is being globally expanded with additional stations funded and built by partners of the International VLBI Service (IVS) in Germany, Japan, Spain, Sweden, and elsewhere, with the goal of eventually forming a global array of GGOS stations.

Our geodetic group at Haystack has recently started the design phase of a new VGOS antenna, which will be deployed at the VLBI site in Fortaleza, Brazil, by 2025. Expanding the network to the southern hemisphere will contribute to improved accuracy of the International Terrestrial Reference Frame (ITRF). Also in the southern hemisphere, Haystack is providing technology support to the upcoming VGOS station at Hobart, Australia, which will further strengthen the global geometry of the VGOS network.

VGOS and Latest ITRF Realization

For the first time, VGOS observations were included in ITRF2020, its latest realization. The ITRF is crucial to monitoring key phenomena such as global sea-level rise. There has been a series of successively better ITRF constructions every five years or so, starting in the mid-1980s, and the ITRF2020 will be the most accurate yet. As with prior realizations, this ITRF includes geodetic station positions from the four space geodetic techniques: VLBI, GNSS, satellite laser ranging (SLR), and Doppler satellite tracking system (DORIS). The VGOS sessions contributing to the ITRF2020 were primarily scheduled, observed, correlated, and reduced at Haystack, which has spearheaded the VGOS development effort.



Research scientist Dhiman Mondal at the AGU 2022 Fall Meeting

The VGOS Intensive Program for Rapid UT1 Estimation

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 (EOP). VLBI is the premier technique for measuring the phase of Earth's rotation, UT1–UTC, and nutation (the wobble of the Earth's rotation), from which we gain a deeper understanding of the interior of the Earth.

Since the inception of VLBI, Haystack has been helping the USNO fulfill its responsibility for determining and predicting the UT1– UTC measurement using standard 24-hour VLBI sessions as well as the Intensive series, one-hour observing sessions between a VLBI station in Hawaii and in Germany that are run daily to obtain a UT1–UTC estimate in near real time. Haystack coordinated the launch of an Intensives program in 2020 using the VGOS stations at those two locations. The program has now matured and recently expanded to include several baselines, for improved accuracy and robustness.

Broadening VGOS to Also Observe GNSS Signals

One of the limiting sources of error in establishing a robust and stable ITRF that is suitable for modern accuracy goals is the local geodetic ties. These are the differential vectors between station reference points at co-located sites necessary to effectively tie into a unified ITRF the otherwise disconnected reference frames of the individual space geodetic techniques, such as VLBI and GNSS. Unfortunately, the disagreement between local ties and space geodesy solutions is generally significantly larger (i.e., several millimeters) than the formal uncertainties of the local surveys used to obtain them.

A possible approach to improve the accuracy of the TRF and of the ties between techniques is the fusing of the various geodetic techniques into unified instruments. Various satellite-based methods that follow this approach have been pursued energetically, but rather unsuccessfully. Instead, under NGA support, we are exploring the concept of fusing the (microwave) space techniques, particularly VLBI and GNSS, at the observation level by developing a single instrument capable of observing both VLBI and GNSS signals.

Atmospheric Remote Sensing

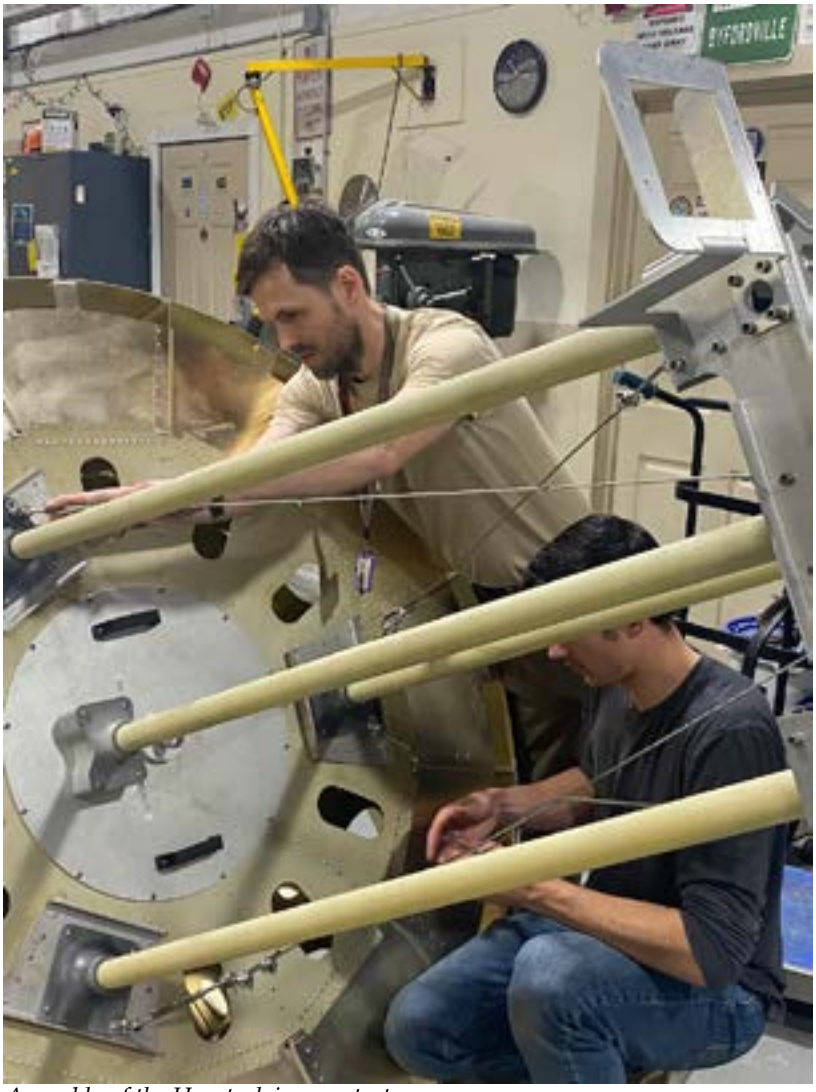
The Haystack geodesy group has been turning atmospheric knowledge into research ideas that have the potential to expand the project portfolio into atmospheric science opportunities. Recent awards proposed include the investigation of teleconnections between the Indian Monsoon and Indian Ocean Dipole fusing GNSS and MODIS precipitable water data products, and the probing extreme weather events in a warming climate with GNSS and atmospheric reanalysis in the Azores Islands.

Polar Geodesy

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

Under ONR sponsorship, the Sea Ice Dynamic Experiment (SIDEx) project is helping improve predictions of how the sea ice deforms and fractures as it is subject to stresses from atmospheric winds and ocean currents. In the Arctic Ocean off northern Alaska, Haystack teams designed, built, and deployed 12 autonomous geodetic-quality GNSS buoys forming a small-scale strain network, in 2021. The resulting data allow better understanding of the effects of climate change on sea ice and an improvement in short-term ice prediction and navigation maps for ships in the Arctic circle.

Antarctic ice-shelf behavior, and the mechanisms by which they collapse—thus "uncorking" the land glaciers and triggering major ice sheet collapse and associated sea level rise—is a critical cryosphere-ocean research topic. A specific Haystack initiative in this area is the NSF-funded development of an air-droppable Antarctic Seismo-Geodetic Ice Penetrator (SGIP), designed to allow dense instrumentation of Antarctic ice shelves with broadband seismometers and GPS receivers to monitor the response of the shelves to ocean forcings, with satellite communication for near-real-time data download to a central repository. The system will eliminate the challenging logistics currently faced in obtaining such measurements, replacing those logistics with efficient aircraft-based deployment.



Assembly of the Haystack ice penetrator

Geospace

Geospace research at MIT Haystack focuses on science, underpinned by observations, for studies of dynamics of the near-Earth space environment in both ionized and neutral species. Main research lines include the major NSF-supported Millstone Hill Geospace Facility (MHGF) operated by MIT Haystack, along with a number of technical and science initiatives at both the national and international level under various agency funding lines.

A central focus of the program is the MHGF facility, which 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 and backed by a productive scientific team. A long-term (five-year) NSF award provides facilities and operations support. The core instruments of the facility are the Millstone Hill incoherent scatter radar (ISR) for ionospheric observations, GNSS total electron content data products with global coverage, and the Madrigal database system.

Geospace Facility Operations

The MHGF facility operates three program elements: the Millstone Hill incoherent scatter radar (ISR) has operated onsite since 1960 and uses a UHF megawatt-class transmitter combined with the 46-meter steerable Millstone Ionospheric Steerable Antenna (MISA) and 68-meter Zenith antenna systems. The ISR technique dates to the 1960s and is the most powerful, flexible ground-based technique for probing the dynamics of thermal plasma in Earth's ionosphere in a unique, altitude-resolved manner. Millstone Hill is the only ISR operating in the continental United States with a key midlatitude field of view spanning the eastern United States and the Atlantic Ocean.

A major $4.5 million refurbishment of the Millstone Hill 46-meter steerable UHF antenna is underway in 2023, funded by the NSF. This construction project will stabilize the antenna foundation for long-term use as well as improve radar receiver sensitivity for enhanced mid-latitude ionospheric observation capabilities.

Haystack's GNSS-based total electron content measurements, calculated from separately operated scientific quality sensors across the globe, are also used constantly by the community with worldwide coverage of ionospheric variations and features. The NSF Geospace Facility also developed and now oversees the Madrigal Distributed Database, comprising the community standard interaction portal for all NSF ground-based upper-atmospheric data. Madrigal and GNSS services are in heavy use by the geospace research community: over the most recent 12-month period, 360 unique users from 151 institutions used GNSS data products and downloaded daily data more than 140,000 times.

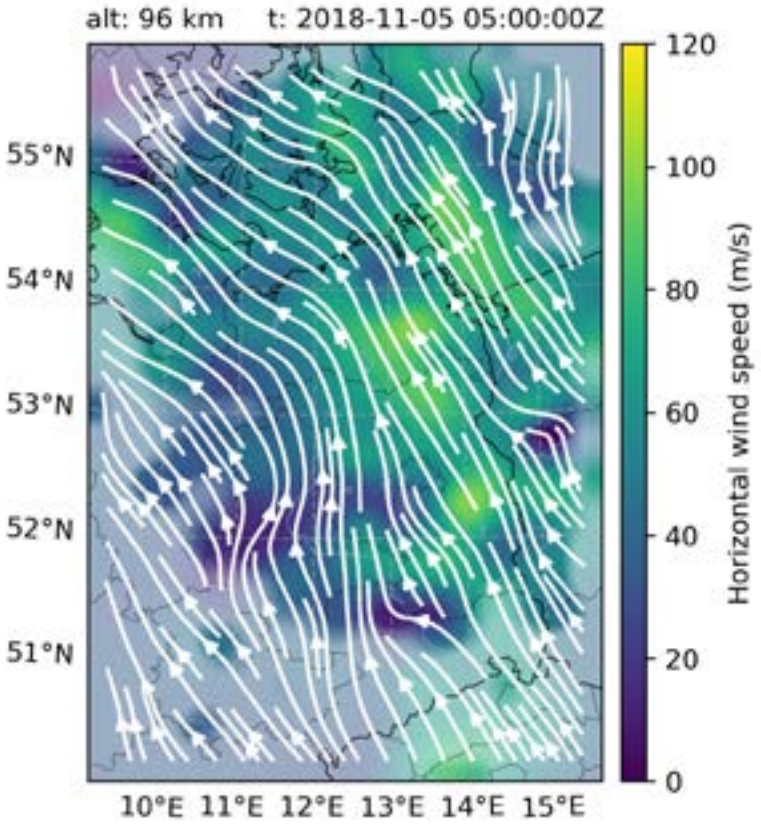
Geospace Science Analysis

Outside of the MHGF program, MIT Haystack maintains a diverse geospace portfolio of individual technical and science grants, both as lead Principal Investigators and as part of team awards such as NASA's Living with a Star Focused Science Teams. As of March 2023, 33 of these awards exist under 7 individual Principal Investigators.

As part of a NASA Living with a Star (LWS) Targeted Research and Technology research team focusing on ionospheric super-storms, Anthea Coster, Larisa Goncharenko, and Shunrong Zhang provided observational data support and interpretation expertise for improving understanding of ionosphere-thermosphere coupling during super-storms. Other studies, both in LWS and elsewhere, focus on connections between the topside ionosphere, plasmasphere, and inner magnetosphere, radiation belt physics, hemispheric asymmetries, electrodynamics of traveling ionospheric disturbances, and upper atmosphere climatologies.

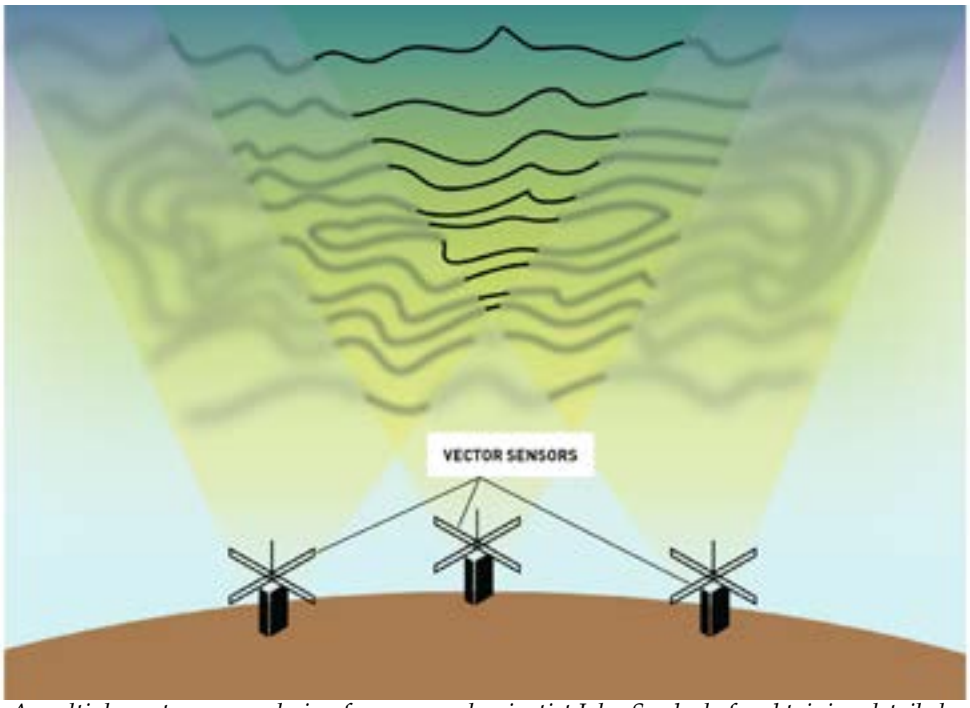
Other Instruments and Arrays

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 MIT Lincoln Laboratory. Millstone Zephyr meteor radar work initially targets observations of fine-scale altitude-resolved neutral wind dynamics during the April 2024 US East Coast eclipse.



Wind field estimate at 96km altitude over northern Germany from SIMONe (Spread-spectrum Interferometric Meteor Observation Network) 2018 campaign data (courtesy Ryan Volz, research scientist)

John Swoboda, an early/mid-career Haystack PI, was awarded a grant from the Office of Naval Research (ONR)'s Young Investigator Program (YIP). Launched in April 2022, his project "Enabling Volumetric Ionospheric Imaging Using Vector Sensor Ionosondes" seeks to produce a lower-cost, advanced capability sensor for electron density over the lower part of the ionosphere, and to enable next-generation networks for global ionospheric remote sensing.



A multiple-vector-sensor design from research scientist John Swoboda for obtaining detailed information about the ionosphere

Space Research and Technology

Space-based radio techniques and instrumentation offer diverse options for engaging in planetary science, heliophysics, and astronomy. Examples include surface-penetrating radar studies of planets and small bodies, longer baselines for VLBI initiatives like the EHT, and detection of aurorae from planets within, and outside of, our solar system. Furthermore, there is compelling science at low frequencies that can be done only from space, due to shielding by the Earth's ionosphere. 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 the NASA laboratories. In view of rapidly growing capabilities and falling costs in the field, space-based radio science is a compelling strategic priority for Haystack.

AERO-VISTA Smallsats

Two current major Haystack projects are the Auroral Emission Radio Observer (AERO) and Vector Interferometry Space Technology using AERO (VISTA), collectively referred to as AERO-VISTA: twin NASA-funded CubeSats to study auroral radio emission at low frequencies along with their connections to magnetosphere-ionosphere coupling processes. Haystack continues to lead development of this mission to study the Earth's aurora. Lincoln Laboratory is a key partner in this effort, with additional contributions from the MIT AeroAstro Department and external university support (including Morehead State University and Dartmouth College) in the scientific and technical aspects of the mission. Additional funding to continue this mission is a current focus.

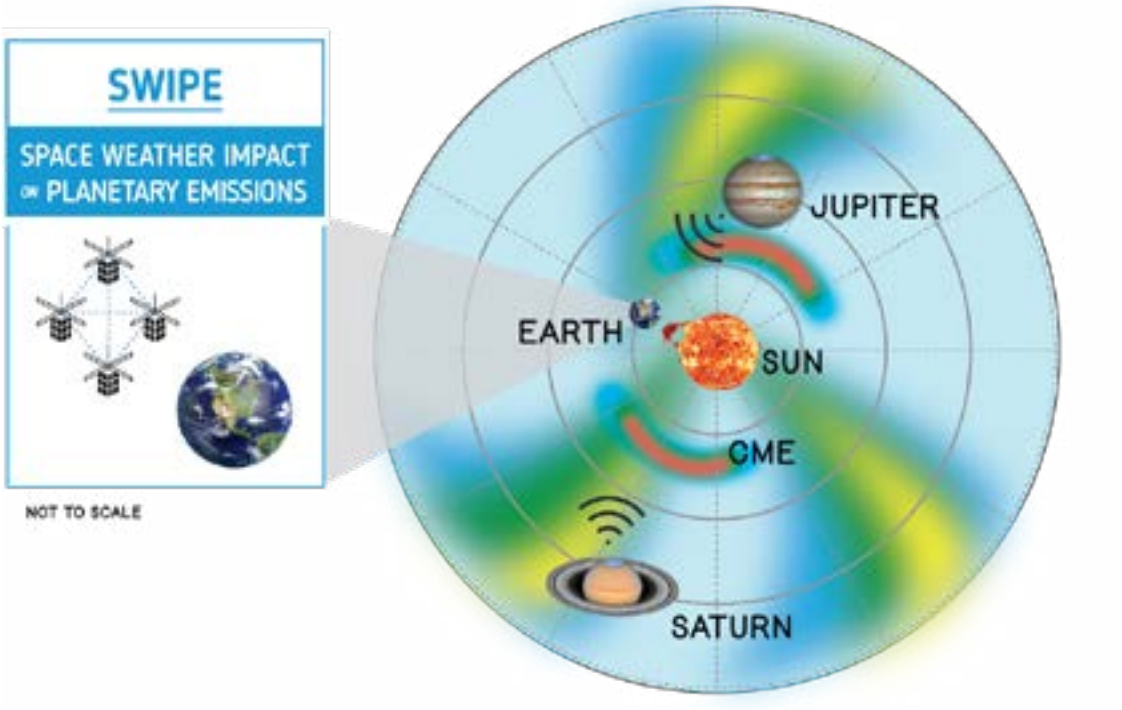
Mars Oxygen ISRU Experiment

MOXIE, the Mars Oxygen ISRU Experiment, is an in situ resource utilization (ISRU) prototype on NASA's Mars 2020 Perseverance rover mission. MOXIE produces oxygen from the carbon dioxide in Mars' atmosphere using solid oxide electrolysis (SOE). Michael Hecht is the Principal Investigator and Jeffrey Hoffman of the AeroAstro department is the Deputy PI. They lead an international science team responsible for campaign planning, data reduction, analysis, and archival, and all manner of scientific presentation 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.

MOXIE produced oxygen on Mars seven times in calendar year 2021, five more times in 2022, and twice so far in 2023, mapping out performance across the martian seasons and trying out new techniques to improve production and increase safety of operations.

Great Observatory for Long Wavelengths

A Haystack proposal was recently selected for funding by the NASA Innovative Advanced Concepts (NIAC) program: the Great Observatory for Long Wavelengths (GO-LoW). Led by Haystack's Mary Knapp, the GO-LoW team of scientists and engineers includes Lenny Paritsky (Haystack), Melodie Kao (University of California, Santa Cruz), and Kat Kononov (MIT).
The GO-LoW concept consists of an array of thousands of tiny, identical satellites—each smaller than a shoebox—working in close coordination together as a group. This observatory will measure low-frequency electromagnetic radiation, which carries crucial information about exoplanetary and stellar magnetic fields (a key missing ingredient for habitability studies) and other astronomical data of high interest.



The Great Observatory for Long Wavelengths (GO-LoW) concept

Space Weather Impacts on Planetary Emissions

The Haystack space technology team was also recently awarded a NASA grant for the Space Weather Impact on Planetary Emissions (SWIPE) mission concept. SWIPE proposes four to six small spacecraft, leveraging the AERO-VISTA system design, in a near-geostationary orbit as a "weather station" to monitor the effects of solar storms on Earth, Jupiter, and Saturn.

Radio Spectrum Challenges

Haystack's research programs rely on radio science as a universal enabler for remote sensing of Earth and the universe at large. However, active, passive, commercial, and scientific use of the radio spectrum is an increasing challenge, including for onsite Haystack sensors in the crowded northeast US corridor. The faint radio science signals picked up by our exquisitely sensitive instruments have fixed center frequencies and bandwidths that are dictated not by human choices but by physics and chemistry. Multiple agencies have recognized the national need to build community discussions and efforts to proactively address these challenges at technical, use, and policy levels, and Haystack has extensive involvement in these initiatives.

Three Haystack researchers are involved in NSF's SpectrumX collective, a five-year Spectrum Innovation Initiative project conducting strategic research and workforce development projects in spectrum management, usage awareness, and mitigation strategies for science. Additionally, Haystack has a long history of involvement and is currently represented (Phil Erickson) on the National Academies of Science, Engineering, and Medicine Committee on Radio Frequencies (CORF). CORF considers the needs for radio frequency requirements and interference protection for scientific and engineering research, coordinates the views of US scientists through formal filings to the Federal Communications Commission (FCC) and other agencies, and acts as a channel for representing the interests of US scientists in the work of the International Council of Scientific Unions.

Education and Public Outreach

Education and public outreach (EPO) activities were temporarily slowed by the COVID-19 pandemic. Regularly scheduled events were successfully held online during this time period (2020–2023). Some major outreach events, such as the Haystack Open House events and educational in-person tours, were placed on a short-term hold and will be restarted in late 2023 or early 2024.

Haystack's outreach display at the 2023 Westford Climate Action Earth Day celebration

Haystack's Drew Crowley, Mary Knapp, and Jens Kauffmann at a local elementary school's science fair

Each summer, Haystack hosts 7–15 undergraduate students from around the country, an activity anchored by an award from the NSF Research Experiences for Undergraduates (REU) program. Haystack also hosts students from the MIT Undergraduate Research Opportunity Program (UROP) in a comprehensive summer internship program. In 2020 and 2021, the undergraduate programs were held entirely online, and were highly successful despite this challenging necessity. Haystack researchers have also mentored students from Westford Academy, the local high school, in the senior capstone projects. Haystack also hosts students from the MIT Undergraduate Research Opportunity Program (UROP) in a comprehensive summer internship program.

Haystack Job Shadow Day, an annual tradition in conjunction with local high school Westford Academy, was successfully overhauled to include additional talks, activities, and site visits. Job Shadow Day 2023 was held with nine students participating, and now includes Groton-Dunstable Regional High School.

An NRAO/ALMA Community Day event hosted by the MIT Haystack Observatory and organized by postdoctoral researchers Dongjin Kim and Rigel Cappallo in April 2023 was a resounding success, featuring engaging presentations and resulting in productive discussions and fruitful collaborations among local research staff, postdoctoral researchers, and graduate students from MIT, CfA, and SAO.

Vincent Fish, panel scientist at the 2022 Event Horizon Telescope Collaboration press conference

Colin J. Lonsdale
Director