MIT Haystack Observatory

Introduction

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

The Observatory research portfolio is broad in scope, with an overarching theme of radio science. There has been an increasing recent 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 several major, established programs that together provide stable funding comprising the bulk of the total budget. Supported primarily by NASA, Geodetic VLBI continues to be a mainstay, and enjoys strong technical overlap and synergy with the astronomical VLBI effort at the Observatory. These programs share technical developments in data recording and correlation. The geodesy program includes a 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. Efforts are progressing to incorporate the 37-meter Haystack telescope into the astronomy program, both for VLBI and for single-dish molecular line studies.

Another major program is conducted by the geospace science group, which is partially supported by a large-facilities grant from the National Science Foundation (NSF) and operates the powerful incoherent scatter radar (ISR) instruments on site. This program is supplemented and complemented by a wide range of smaller science grants, mainly from NASA and the NSF. This program also supports a range of internal science investigations, provides extensive geospace science community support for users across the country and the world, and includes a significant component of advanced engineering and technical development.

The growing Haystack Observatory space program includes the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) on board the Perseverance Mars Rover, which landed during the reporting period. This toaster-sized device has successfully demonstrated the production of oxygen from the Martian atmosphere. Haystack is also leading a project, Vector Interferometry Space Technology using AERO—Auroral Emission Radio Observer (AERO-VISTA) in close collaboration with Lincoln Laboratory (LL), involving two CubeSats designed to measure auroral radio emissions and perform demonstrations of interferometry between the satellites.

Haystack continues to enjoy a close relationship with Lincoln Laboratory and provides extensive engineering and facilities support for a range of LL projects and installations at the field site. The Observatory has significant technical collaborations with LL on a growing list of projects.

Strategic Summary

Strategic planning is an essential, continuous activity at the Observatory and is key to efficient coordination of the diverse yet interconnected and related research activities. A number of clear strategic initiatives for the Observatory are being pursued. Among them and in no particular order are the following:

- An expanded portfolio of joint projects with LL and with campus researchers, which continues to progress well and with significant recent exploration of potential new collaborations.
- Increased engagement with the Northeast Radio Observatory Corporation (NEROC), which comprises twelve regional education and research institutions with interests in radio science, collectively offering many collaborative opportunities. Periodic NEROC scientific symposia have been well attended and highly successful in forging research linkages. The NEROC Board of Trustees helps to guide Haystack's radio science programs and appoints the Visiting Committee. The pandemic circumstances have temporarily impeded progress on some NEROC initiatives, though a conference was successfully held online in November 2020.
- Continued diversification of the astronomical research program, including re-establishment of the 37-meter telescope as a competitive research tool.
- Maintenance and incremental refinement of the existing megawatt-class ISR facility at Haystack and, in parallel, the development and eventual construction of a replacement instrument using advanced low-frequency array technology. Well underway, this effort 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.
- Continued global technical leadership in VLBI, exploiting hardware and software synergies between the astronomy and geodesy programs.
- 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. Key milestones in pursuit of this overarching goal have recently been achieved.
- Overhaul and expansion of Haystack's presence on the web and in the media, for both professional and public communications. A new website has been implemented and has been designed to serve as a catalyst for these goals.

Funding

Supported by an extraordinarily efficient financial and proposal preparation team, Haystack researchers continued a long-standing pattern of generating a high volume of funding proposals. A total of 37 proposals were submitted during the reporting period, primarily to NASA and NSF, involving 11 different principal investigators (PIs). A high success rate, sustained for many years and continued during the reporting period, has placed the Observatory in a strong financial position with significant growth in total research volume accompanied by extensive hiring activity. Additional strong growth is projected for fiscal year 2022, based on awarded and pending proposals.

This growth, while welcome and generating ample opportunities for future broadening of the Observatory research portfolio into new and fertile arenas, also brings challenges that have demanded prompt actions and have increased workloads on many staff members. Many projects have been impacted by the pandemic and the inherent inefficiencies of the work-from-home environment. The pace of hiring has inevitably fallen somewhat behind increasing demands for project deliverables; despite some allowances for circumstances on the part of sponsors, the workload on individual staff members has risen in some instances to levels that are not sustainable in the long term. The response has been to redouble efforts to fill key positions and to bring new employees up to speed as quickly as possible. These too have been subject to now-easing challenges that were created by the pandemic.

The federal funding outlook both at NASA and NSF appears to be favorable for research of the type that Haystack does, with healthy increases foreshadowed in the relevant segments of agency budgets in the near term. Haystack maintains a highly agile posture in part by promoting versatility of the research staff and encouraging individuals to work on two or more projects simultaneously, often in diverse roles. This facilitates flexible, short-term reassignments of responsibilities and rapid adaptation to new, often unanticipated project opportunities. This strategy has proven to be successful and contributes to a dynamic and ever-changing research environment that most staff members embrace and thrive in.

Although sustained Observatory growth is obviously highly desirable, it eventually generates challenges that must be met. One is the issue of physical space; another is the maintenance of a relatively flat management structure, which is associated both with highly efficient internal communications and a tight-knit culture and community. Physical space is expected to be the more important constraint over the next few years.

Personnel

One of the consequences of recent Observatory growth, in both research volume and diversity, is added administrative complexity and increased burdens on members of the director's office. Along with this growth, the ongoing Covid-19 pandemic and resultant remote workforce requirements have dramatically increased demands on our information technology team. To address these challenges, Haystack has recently added several positions (including two IT staff members) and expanded the responsibilities of the recently hired assistant director for administration.

Other new hires—including software developers, postdoctoral researchers, a lead space technology engineer, and a mechanical engineer—complement the existing technical expertise within the Haystack staff, further strengthen all research groups, and expand the range of challenges that can be met with confidence.

Astronomy

Event Horizon Telescope

The EHT 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. Current technologies pioneered by Haystack Observatory, including instrumentation to downconvert, digitize, and record large bandwidths of radio spectrum, allow for imaging and analyzing supermassive black holes on event horizon scales. 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.

In April 2019, the EHT Collaboration (EHTC)—comprising more than 300 scientists, engineers and technicians around the globe—published revolutionary images of the black hole in M87 and showed a striking ring morphology with a dark center, as predicted by modeling of general relativistic effects close to the event horizon. The dark center is referred to as the shadow of the black hole. The released image fueled a remarkable, worldwide media event, with six simultaneous press conferences around the globe. This work garnered numerous prestigious professional accolades, notably including the 2020 Breakthrough Prize in Fundamental Physics.

Work on the EHT has continued to be a major activity for Haystack Observatory during the reporting period. Vincent Fish is the PI for a large operations-focused NSF award with subcontracts to nine other US institutions. Fish is also PI for a subaward from the Smithsonian Astrophysical Observatory on another major NSF grant aimed at developing the technologies to support a transformational enhancement of EHT observational capabilities in the second half of the 2020s. This work includes preparation of the Haystack 37-meter telescope for participation in EHT observations at the 1.3 mm wavelength (230 GHz).

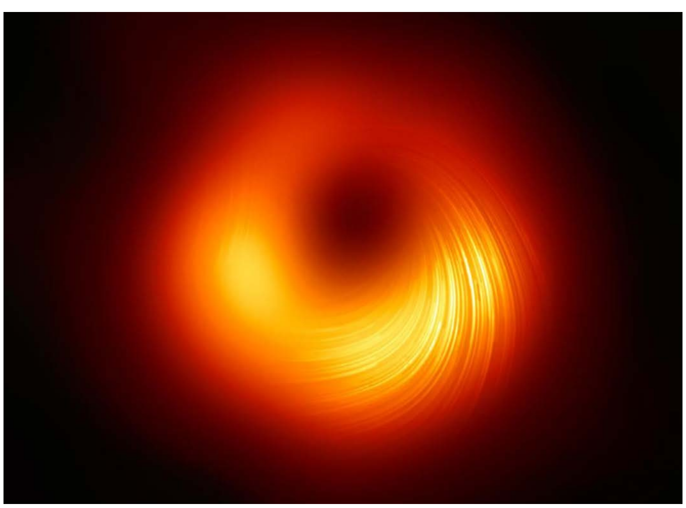

Figure 1. Artist's conception of the polarized view of the black hole in M87; lines mark the orientation of polarization, which is related to the magnetic field around the shadow of the black hole.

A significant recent EHT milestone was the publication of an image of the M87 ring in linear polarization (figure 1). The morphology of the polarized emission indicates that the magnetic field plays a dynamically important role in regulating the accretion flow surrounding the black hole. The EHT also published images of the jet in Centaurus A (figure 2) that show a high degree of collimation and edge brightening.

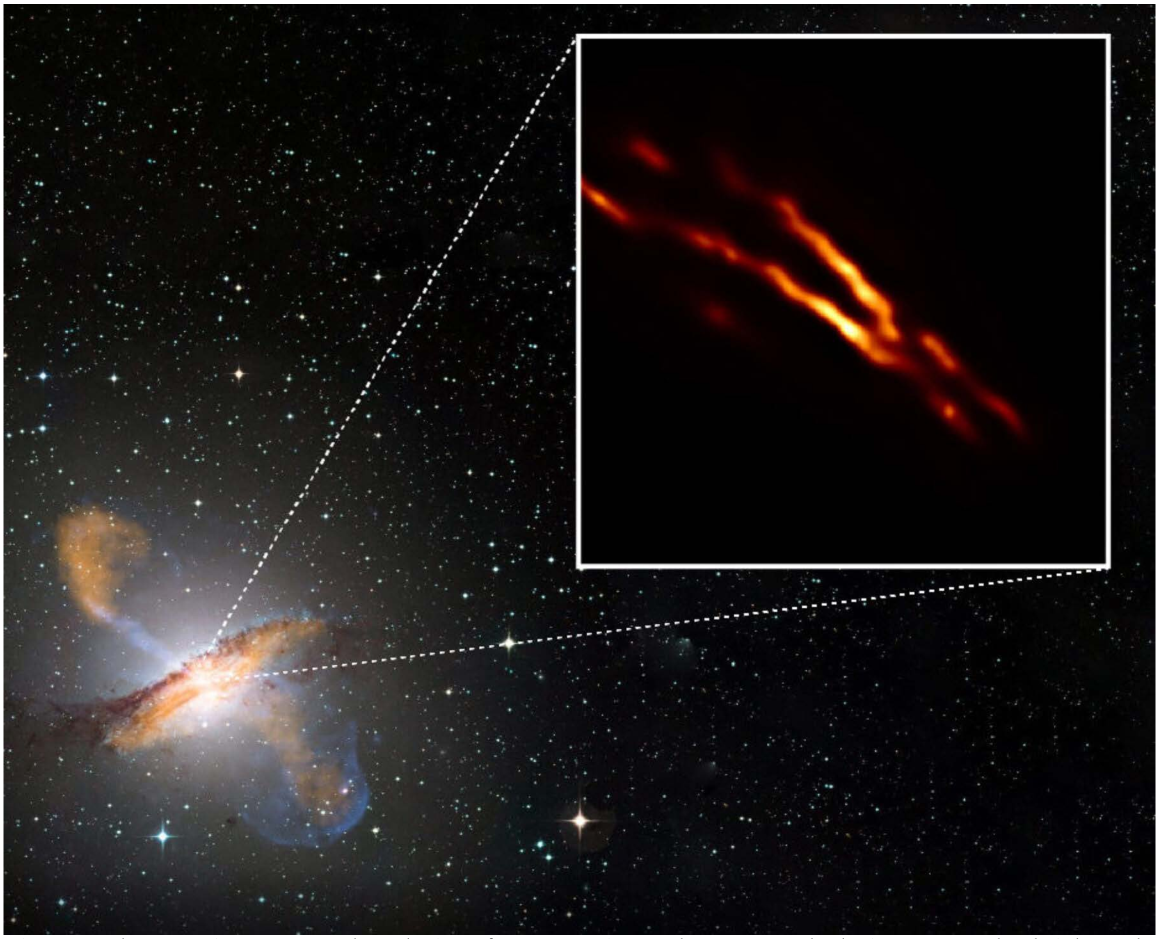

Figure 2. The ~20 micro-arcsecond resolution of Event Horizon Telescope reveals the innermost edge-brightened structure of the jet in the nearby radio galaxy Centaurus A.

The EHT is composed of 11 individual millimeter-wave radio astronomy observatories scattered across the globe in a variety of remote and high-elevation sites from the South Pole to Greenland and from Hawaii to the Alps in Europe. These sites have been selected for favorable atmospheric transparency, and data recorded at these dishes are combined in a VLBI to yield an angular resolution on the scale of 20 microarcseconds. These data are combined—correlated—at Haystack Observatory and at the Max-Planck-Institut für Radioastromie (MPIfR) in Bonn, Germany, using highly specialized, massively parallel computing systems. Turning the resulting correlated data into images, particularly polarized images, required the development of new and rigorous calibration strategies and image reconstruction algorithms. Haystack staff have been and continue to be deeply involved in operations, data reduction, and analysis aspects of the EHT, making foundational contributions on many fronts.

Although EHT observations in 2020 were canceled due to the pandemic, the array resumed operations in 2021. Science observations in April were the first to include the new 12-meter telescope on Kitt Peak and the phased Northern Extended Millimeter Array in France. These telescopes provide critical shorter baselines (to the Submillimeter Telescope in Arizona and the Institute for Radio Astronomy in Millimeter Range 30-meter telescope on Pico Veleta, Spain, respectively) that will be sensitive to the larger-scale emission connecting the M87 ring seen on horizon scales to the prominent jet seen on arcsecond scales and beyond. The April campaign also included commissioning observations at 345 GHz, in anticipation of offering proposal-driven science observing at this higher frequency starting in 2023. Recorded data from most sites have been returned to Haystack Observatory and MPIfR for correlation and initial quality checks.

Haystack staff fulfilled many critical roles in the EHTC during this reporting period; Colin Lonsdale serves as chair of the EHTC board of stakeholders, the top-level governing body of the collaboration; Mike Hecht is board secretary; Dianne Tonelli provides administrative support; Vincent Fish serves on the Science Council; Lynn Matthews is data manager; Kazunori Akiyama co-leads the imaging working group; and Nancy Kotary is a member of the EHTC communications team.

Haystack 37-meter Telescope

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

The telescope is currently undergoing astronomy-specific upgrades, in part driven and funded by plans to join the EHT array in the 2023 to 2025 timeframe. It will be a key addition to the EHT by virtue of both high sensitivity and an advantageous geographic location, helping to fill an important gap in longitude coverage. The upgrade work is also aimed at facilitating single-dish spectral-line observations across wide bandwidths, observing many molecular spectral lines simultaneously with high angular resolution. Such observations can deliver new insights to cosmic star formation history by studying molecular emission lines in the Milky Way and nearby galaxies. Once upgraded, the telescope will also be better able to support a range of educational programs.

During the reporting period, work continued on improving a receiver covering 70–115 GHz to deliver state-of-the-art noise performance. New observing modes were implemented on the digital backend, which processes the analog signals from the receivers, and a high-quality optical link between receivers and backend was designed. A complete replacement of the hardware and software systems for telescope control was initiated and prototyped. Collectively, these efforts simplify telescope maintenance, create modern interfaces for adding new subsystems, and are foundational to establishment of a robust facility operation. The work is led by Jens Kauffmann, with hardware, software, and commissioning support from several staff members. The work is largely funded by the NSF as part of the push to incorporate the telescope into the EHT array.

Experiment to Detect the Global EoR Signature (EDGES)

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 EDGES—Experiment to Detect the Global EoR (epoch of reionization) Signature—in a collaboration with Arizona State University. This is a single, well-calibrated antenna system specifically designed to measure tiny departures from a smooth spectral shape across the low-frequency radio sky in all directions. The antenna "sees" most of the sky at once, and the goal is to detect and characterize a predicted slight dimming of the background sky brightness caused by absorption of the cosmic background radiation by neutral hydrogen in the early universe. The spectral precision required is on the order of one part in 10^5, demanding novel approaches to instrument design and deployment in locations free of artificially generated radio noise. The cosmological signal of interest is redshifted from the 1.4 GHz frequency of the spin-flip transition of neutral hydrogen down to about 70 MHz, close to the extraordinarily noisy FM band so only the most remote of sites are suitable for this work.

A dramatic and somewhat unexpectedly high-confidence initial detection of this feature was published by the EDGES team in the journal *Nature* in 2018, with properties that pose fascinating theoretical challenges for our understanding of the state of the universe during the epoch when the very first stars were forming (figure 3). 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. To date, competing teams have been unable to achieve the level of measurement and calibration precision that would permit a fully independent confirmation of the result, though progress is being made. Meanwhile, technical developments led by Rogers aimed at significant improvements in the EDGES instrumentation have continued.

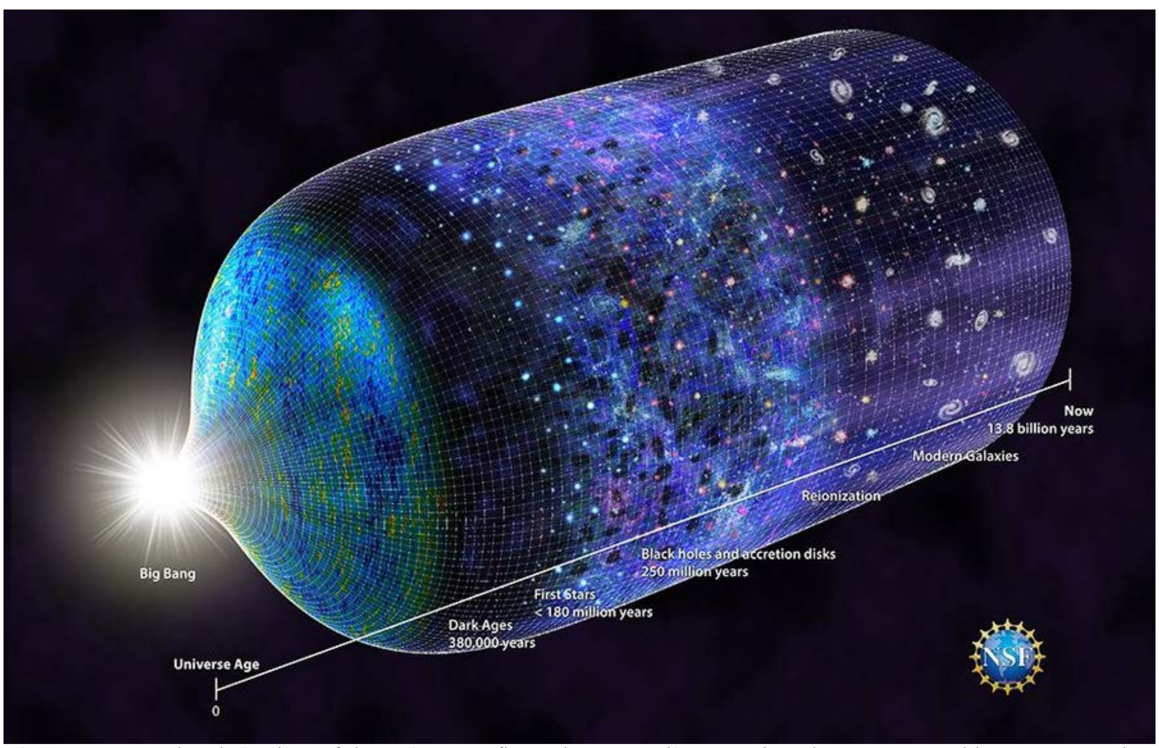

Figure 3. An updated timeline of the universe reflects the recent discovery by Alan Rogers, Judd Bowman, and colleagues that the first stars emerged by 180 million years after the Big Bang.


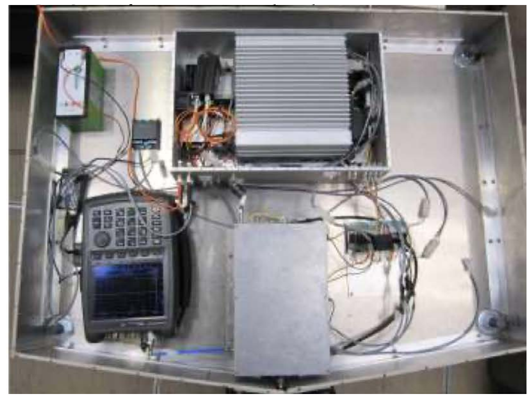

Figure 4. Experiment to Detect the Global EoR Signature (EDGES) is a single, exquisitely well-calibrated antenna system, specifically designed by Alan Rogers and colleagues to measure tiny departures from a smooth spectral shape across the low-frequency radio sky in all directions.

Other Research Activities

Haystack astronomy staff are also engaged in a variety of other scientific and technical investigations and projects. Vincent Fish and Kazu Akiyama continued studies of jet collimation in active galactic nuclei, Jens Kauffmann pursued research on the physical conditions in molecular clouds, and Lynn Matthews pursues investigations of stellar atmospheres. Lynn Matthews and Geoff Crew continued to refine and expand the capabilities of the phasing system for the ALMA array in Chile, and Matthews and Akiyama pursued the development of advanced new imaging algorithms for ALMA and other imaging arrays.

Geospace

MIT Haystack's NSF-supported Millstone Hill Geospace Facility (MHGF; figure 5) 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 five-year NSF award provides facilities and operations support. The core instruments of the facility are the Millstone Hill ionospheric radar, Global Navigation Satellite Systems (GNSS) total electron content (TEC), and the Madrigal database system.

Figure 5. MIT Haystack's National Science Foundation (NSF)-supported Millstone Hill Geospace Facility.

The Millstone Hill ISR, operated since 1960, uses an ultra-high frequency (UHF) megawatt-class transmitter combined with the Millstone Hill Steerable Antenna (MISA) and Zenith antenna systems. ISR has proved to be the most powerful and flexible ground-based instrument for probing the dynamics of thermal plasma in Earth's ionosphere.

GNSS-based TEC data, another facility product, is also very popular in the community and provides worldwide coverage of ionospheric variations and features. Finally, 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 165 instruments in the Couplings, Energetics, and Dynamics of Atmospheric Regions (CEDAR) Madrigal database, totaling over 46 TB of data. Over the last 12 months, 308 unique users from 155 unique institutions have used MIT Automated Processing of GPS (MAPGPS) data products over the past year. Those users downloaded daily data more than 240,000 times.

During this report period, the Millstone Hill UHF radar system executed a number of community-focused observations using the production workstation-based Millstone Hill Incoherent Scatter Data Acquisition System (MIDAS-W) software radar system, producing science-quality experiments in the Madrigal database. Science 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. Also included were focused observations yielding intercomparisons with NASA's low Earth polar orbit Ionospheric Connection Explorer (ICON) satellite instruments, which observe electron density and motions in the upper atmosphere. Dedicated Millstone Hill observations of the partial solar eclipse were executed on June 10, 2021, which traversed mid- to high-latitude regions in the northern polar cap just after local sunrise.

Geospace Facility Operations

NSF funding for the core MHGF grant nominally supports 1,250 radar operations hours. However, operations were curtailed primarily due to two factors: the global Covid-19 pandemic, and a severe weather event in May 2020 that shifted the MISA antenna off its elevation axis, disabling its motion and also locking out the UHF transmitter.

Regarding the latter event, an intense weather front and associated storm passed through eastern Massachusetts on May 15, 2020, causing extensive damage to Haystack infrastructure due to the effects of a localized severe microburst with wind speeds 95 mph and higher. During this event, impulsive force from wind loading pushed the 46-meter MISA antenna sideways off its elevation bearings, destroying the antenna system's left elevation encoder in the process and completely disabling any possibility of antenna motion. The azimuth drive system on the antenna also was discovered in inspections to have a mechanical issue in the form of a shattered coupling plate on one of the two driven wheels. Finally, the damage caused the transmitter to be disabled due to the interlocked safety system, so zenith operations were not possible initially even though that antenna was not damaged by the weather event.

Following the damage event, modification of the radar's antenna control and safety system settings was executed by contractors to temporarily lock out MISA sensors, enabling a resumption of UHF radar operations on a reduced Covid schedule using the zenith antenna only on October 22, 2020. Subsequent intensive work by the Haystack team, coordinated in detail with both the MIT Haystack Observatory Safety committee and with MIT Environmental Health and Safety, restored the radar to full operation on May 6, 2021, despite slowdowns imposed by Covid-19.

Geospace Science Analysis

One science study example of the research completed during the period of this report: during the last decade, numerous studies showed that Arctic sudden stratospheric warmings (SSWs) cause especially large anomalies in the low-latitude ionosphere. However, it was not clear whether similar ionospheric anomalies can be produced by Antarctic SSW, mostly because Antarctic SSW are quite rare. In September 2019, a very sudden stratospheric warming developed over Antarctica (Goncharenko et al., 2020; figure 6). Comparison of ionospheric total electron density in mid-September of 2019 against dynamically quiet mean behavior revealed prominent quasi-semidiurnal variations. These were similar to variations associated with Arctic SSW, but the semidiurnal behavior unexpectedly did not persist for an extended period of time and strongly varies with longitude, indicating that the ionosphere is likely more dynamically disturbed during this Antarctic SSW than during a typical Arctic SSW. The study also suggests new aspects that connect stratospheric weather to the state of the ionosphere.

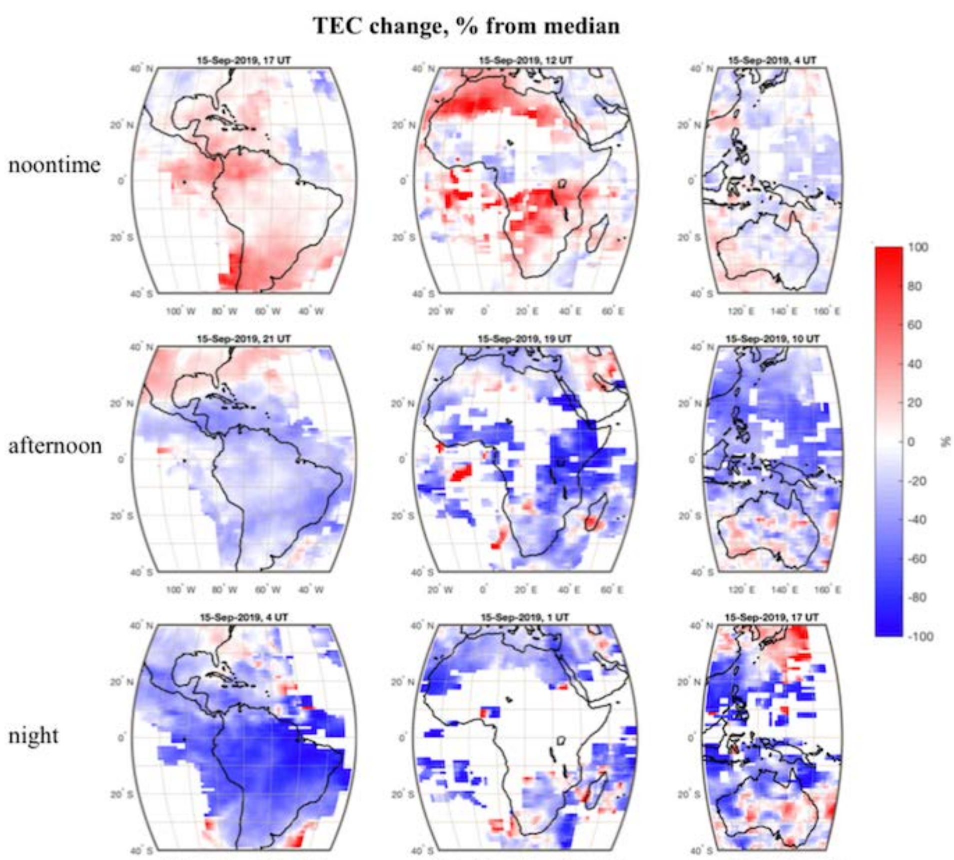

Figure 6. Change in total electron content (TEC) during Antarctic sudden stratospheric warming (SSW) on September 15, 2019, in different geographic regions and different local time sectors (Goncharenko et al., 2020).

Distributed and Deployable Instruments and Arrays

Under separate and recent funding, different distributed and deployable instruments and arrays for monitoring the atmosphere are being developed and deployed for advanced remote sensing of the neutral and ionized geospace environment. These include a new Alaskan-sector GNSS TEC system and an advanced multiple-in multiple-out distributed meteor radar system in a two-year project for monitoring Colorado-area fine-scale mid-latitude neutral winds.

For example, the Monitors for Alaskan and Canadian Auroral Weather in Space project is in the process of deploying 35 new specialized GNSS receivers in Alaska and Canada that measure phase and amplitude scintillation on GNSS signals. The motivation for this project is to increase space weather monitoring capacity in the Arctic. These receivers collect not only TEC information but also information on amplitude and phase scintillation. Scintillation is caused by plasma irregularities in the ionosphere, which are important because they can interfere with the reception of GNSS signals, thereby impacting GNSS positioning, navigation, and timing applications. Scintillation occurs more often in the high-latitude and polar regions due to the complex interactions related to magnetosphere–ionosphere coupling, of which the visible aurora is a good example. New tools have been developed to study the correlation of scintillation with aurora and changes in the total electron content. Shown in figure 7, scintillation values are overplotted onto an all-sky imager map showing the correlation of auroral activity and phase scintillation.

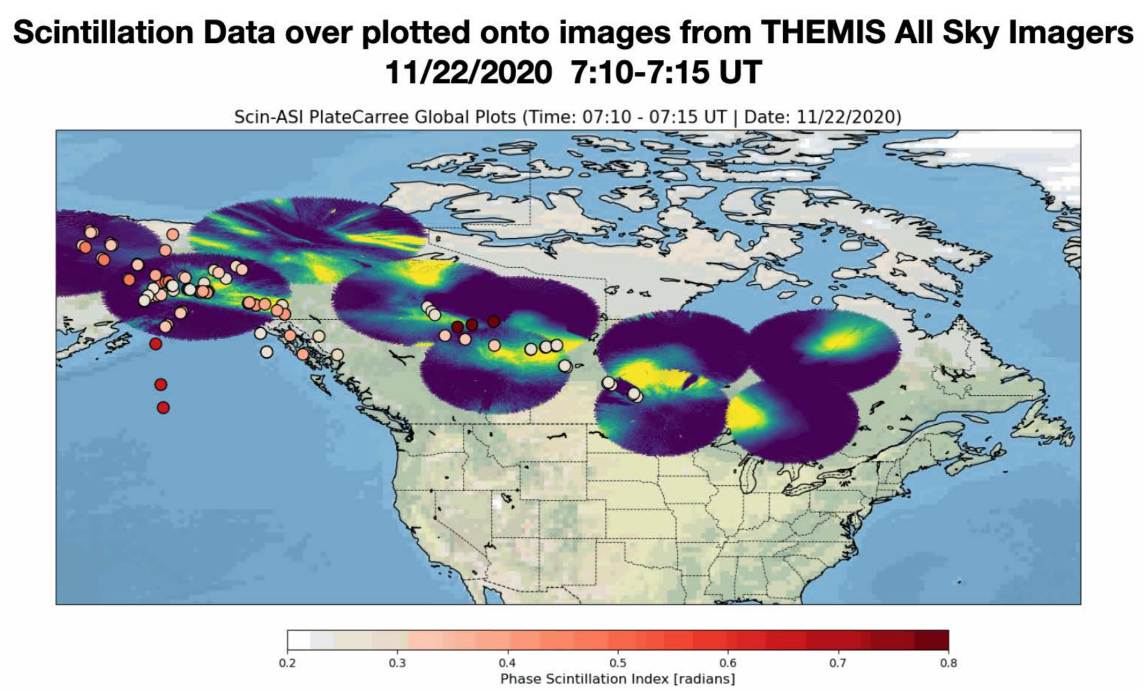

Figure 7. A new Global Navigation Satellite Systems (GNSS) ionospheric scintillation product in Haystack's Madrigal database shows locations of 10s of cm scale irregularities, overlaid onto neutral upper-atmosphere images from the Thermal Emission Imaging System (THEMIS) network of all-sky imagers.

Education and Outreach

The Atmospheric and Geospace Sciences Group has continued its dedication to space science community service both inside and outside the Geospace Facilities program with numerous focused activities, as well as ongoing contributions to education and public outreach.

Geodesy

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

VLBI Geodetic Observing System (VGOS)

Under NASA sponsorship, the Haystack geodetic VLBI group continues to develop the advanced system known as VLBI Geodetic Observing System (VGOS) for the next-generation broadband geodetic VLBI network. Very Long Baseline Interferometry 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 Earth system such as the global hydrological cycle, which includes the cryosphere and the dynamics of the oceans and the atmosphere; natural hazard warning and prevention; disaster mitigation; sustainable development; and society at large.

VGOS is the VLBI component of the Global Geodetic Observing System (GGOS). 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 (IVS) in Germany, Japan, Sweden, Spain, and elsewhere, with the goal of eventually forming a global array of GGOS stations that spans the Earth's surface.

Haystack continues to make major contributions toward the validation of the VGOS concept along with improvement and maintenance of the physical network of NASA telescopes. These include the VGOS antennas deployed at Kōkeʻe Park Geophysical Observatory (KPGO) in Hawaii and the McDonald Observatory in Texas, as well as to the VGOS prototype baseline telescopes at Westford and at 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 (USNO) contract.

Highlights among the VGOS contributions include the hosting and organization of the biannual IVS Technical Operations Workshop in 2021 (TOW2021), which was held online for the first time due to the ongoing pandemic. Haystack also made major progress furthering development of mixed-mode (i.e., legacy S/X VLBI and next-generation VGOS) correlation and post-processing, know-how, and capabilities that are being transferred to other correlators within the broad IVS community via dedicated workshops (e.g., post-TOW2021) and meetings.

Arthur Niell and colleagues published a milestone paper in the *Journal of Geodesy* (Niell et al., 2021) measuring the components of the 31-meter vector between the two VLBI antennas at KPGO in Hawaii. These results have significant implications for the accuracy of global reference frames that require accurate local ties between geodetic instruments, such as the International Terrestrial Reference Frame (ITRF).

Contribution to International Terrestrial Reference Frame 2020 (ITRF2020) Realization

The ITRF serves as a foundation for geophysics and is crucial to monitoring such key phenomena as sea-level rise. There has been a series of successively better ITRF constructions every five years or so, starting in the mid-1980s. The upcoming ITRF2020 promises to be the most accurate ever. As with prior realizations, this ITRF will include geodetic products (basically parameter estimates including station positions and their full covariances) from the four space geodetic techniques: VLBI, GNSS, satellite laser ranging, and Doppler satellite tracking system. Each technique has its own set of strengths and weaknesses, and by combining them together an ITRF is obtained that is more accurate and robust than the individual techniques. But unlike prior realizations, this will be the very first time that observations from the fledgling VGOS network are included in the ITRF. These include approximately 40 operational VGOS sessions that have been observed following a biweekly cadence starting in 2019 and up to December 31, 2020, the closing time of ITRF2020. These VGOS sessions have largely been scheduled, observed, correlated, and partially analyzed at Haystack, which has spearheaded the VGOS development effort.

We are at the very beginning of a seamless transition from the legacy S/X to the VGOS network. The legacy/VGOS mixed-mode sessions are fundamental to successfully accomplish this transition. The upcoming ITRF2020 thus marks an inflection point whereby the VGOS networks will become ever more important going forward.

Launch of VGOS Intensive Program for Rapid UT1 Estimation

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 UT1−UTC phase—difference in time scale between Universal Time and Coordinated Universal Time—of Earth's rotation and nutation, from which we gain a deeper understanding of the interior of the Earth. There is an intimate interplay between geodynamic processes taking place in the various Earth layers and EOP variations. Beyond geodynamics and space navigation applications, UT1-UTC is essential for computation of the orbits of the GNSS such as GPS. Lacking UT1-UTC information would lead to the degradation of the GNSS navigation capabilities, thus having a significant societal impact.

Since the early VLBI days, Haystack has been helping the USNO to fulfill its responsibility for determining and predicting UT1-UTC using standard 24-hour VLBI sessions and intensives series. The latter are one-hour observing sessions between a VLBI station at KPGO in Hawaii and Wettzell Observatory in Germany; these are run daily to obtain a UT1-UTC estimate in near-real time. Starting in 2020, Haystack coordinated the launch of an Intensive program using the VGOS station at those two locations, with the occasional participation of the VGOS station at Westford in a technology supportive role. The VGOS Intensive program has now transitioned from being correlated at Haystack to USNO and from biweekly cadence to twice a week. A transition to a VGOS-based daily observing program is soon expected.

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 focusing on the cryosphere, including precision measurement of various forms of ice—including sea ice, glacier, iceberg, and ice shelves—in terms of flow, drift, and deformation via deployable GPS-based systems.

Under the Chasing Icebergs project, a total of about 15 continuously operating GPS receivers were successfully deployed in summers from 2017–2019 on a number of icebergs in Sermilik Fjord, near Helheim Glacier in East Greenland (figure 8) for up to two weeks in each season. Results from the first direct detection and quantification of iceberg melt using GPS systems were published in paper in *Geophysical Research Letters* (Schild et al., 2021). The study combined measurements of mass loss from GPS and 3D iceberg geometry constructed from aerial drone and subsurface sonar data. The results are crucial to better understand how the release of freshwater from increased iceberg calving under a warming climate will impact global ocean circulation in the future.

Figure 8. Under the Chasing Icebergs project, in summers from 2017–2019, a total of about 15 continuously operating GPS receivers were successfully deployed for up to two weeks in each season on a number of icebergs in Sermilik Fjord, near Helheim Glacier in East Greenland.

Haystack scientists and engineers designed an autonomous geodetic-quality GNSS buoy, then built and shipped twelve of these buoys (figures 9 and 10) in March 2021 to remote northern Alaska to learn more about the physics of sea ice in the Arctic Ocean. 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. Once all the data are carefully analyzed and all results synthesized, scientists will be able to learn more about the behavior of sea ice mechanics and dynamics in the Arctic. This information will 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.

Figure 9. Haystack scientists and engineers designed an autonomous geodetic-quality Global Navigation Satellite Systems (GNSS) buoy, and built and shipped twelve of the Sea Ice Dynamic Experiment (SIDEx) buoys in March 2021 to remote northern Alaska to learn more about the physics of sea ice in the Arctic Ocean.

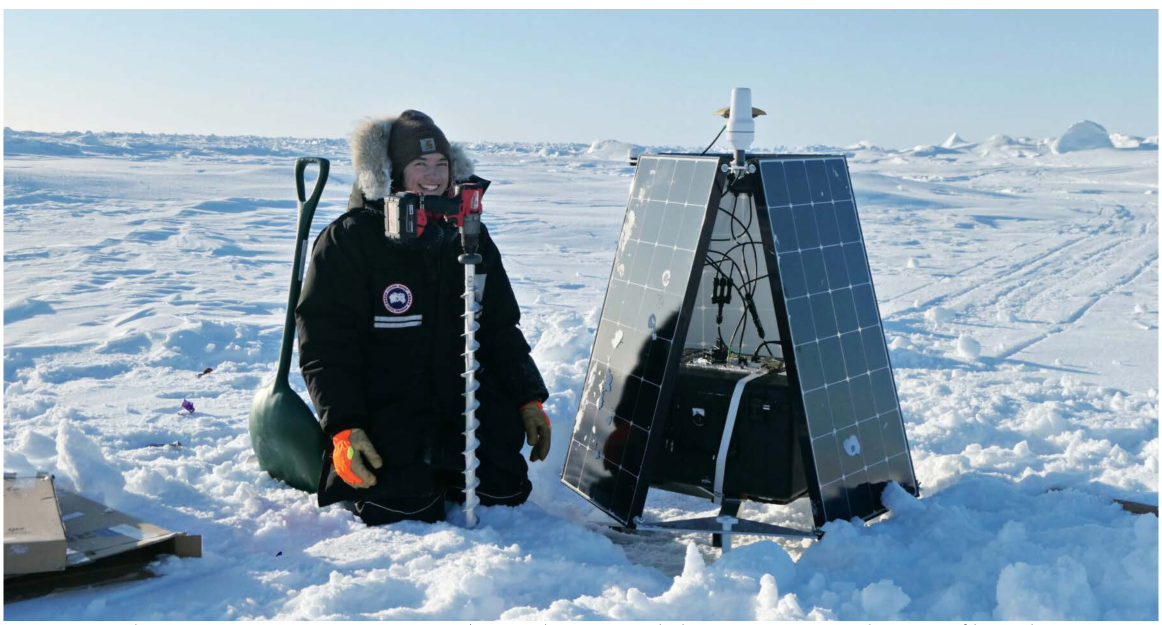

Figure 10. The Sea Ice Dynamic Experiment (SIDEx) project is helping improve predictions of how the sea ice deforms and fractures as it is subject to stresses from atmospheric winds and ocean currents.

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 to monitor the response of the shelves to ocean forcings, with satellite communication for near-real time data download to a central repository. Such a system would eliminate the challenging logistics currently faced in obtaining such measurements, replacing those logistics with efficient aircraft-based deployment. The behavior of the ice shelves and the mechanisms by which they collapse, "uncorking" the land glaciers and triggering major ice sheet collapse and associated sea level rise, is a critical cryosphere-ocean research topic. Over the last year, a group of undergraduate students have been working on various components of the project, from thermal simulations to telescoping antenna booms to machine learning for detection of infragravity waves. Furthermore, a student from MIT's Department of Aeronautics and Astronautics (AeroAstro) graduated this year with a master's thesis on the aerodynamics and ice impact simulations of an air-dropped ice penetrator.

Space Research and Technology

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 lower, difficult or impossible from the ground because of the ionosphere, offers a rich variety of studies involving strong sources of coherent emission in our solar system, from the planets, the sun, and also from the magnetized plasma surrounding the earth. At the highest frequencies, interferometry can yield angular resolutions far beyond that achieved even by the EHT, dramatically expanding the scientific potential of that 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 study 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 the opportunities for collaborations with campus, LL, and outside organizations such as NASA.

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 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. LL is a key partner in this effort, with additional contributions from MIT AeroAstro and external university support (including the University of New Hampshire and Merrimack College) in the scientific aspects of the mission.

Haystack has hired Lenny Paritsky to lead further development of the space science and technology program. Proposals under discussion include miniature radar instruments for planetary applications, space-based nodes for VLBI networks, and use of space-based laser communication to link ground-based telescopes.

Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)

A significant ongoing activity is MOXIE, the Mars Oxygen ISRU Experiment (figure 11), an in-situ resource utilization (ISRU) prototype led by Michael Hecht on NASA's Mars2020 Perseverance rover mission. An MIT-led team fully took over the project after launch with Perseverance in August 2020, leading to a successful landing on Mars in 2021.

Figure 11. MOXIE, the Mars Oxygen In-Situ Resource Utilization Experiment.

Upon landing, Haystack assembled an effective operations team led by Jason SooHoo to handle all aspects of planning, uplink, downlink, and campaign implementation planning (figure 12). The international team was largely drawn from Haystack and MIT AeroAstro.

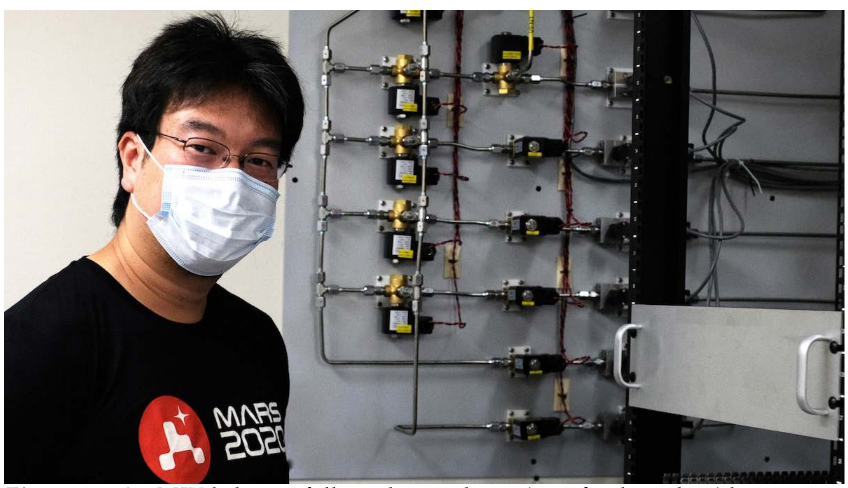

Figure 12. An MIT-led team fully took over the project after launch with Perseverance in August 2020, leading to a successful landing on Mars in 2021.

Haystack leads MOXIE participation on the Perseverance science team, contributing to all aspects of mission science. Haystack is also leading the data reduction, analysis, and archival effort as data is returned from Mars. Four complete oxygen-production runs and several diagnostic activities have been completed thus far, with data packages from the first three to be delivered to the Planetary Data System for imminent public release.

Haystack is commissioning an onsite laboratory for parallel experiments with engineering model hardware to test new protocols, as well as perform operations such as calibration and characterization that require additional laboratory equipment or interactive operation. It will also be a platform for testing new software or next-generation hardware improvements.

Extensive 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. In addition to a significant conference presence, major publications are following the Perseverance team timeline, with an extension pre-mission report in *Reviews of Space Science* as a highlight.

Education and Public Outreach

Education and public outreach activities were hampered but not eliminated by the ongoing Covid-19 pandemic. Many of the regularly scheduled events and conferences were successfully held online instead of in person. However, some major outreach events—such as the Haystack Open House events, job shadow days, and educational in-person tours—were put on hold during the pandemic. Plans are underway for a virtual open house, to be held at the first possible opportunity.

MIT News now regularly includes articles featuring Haystack research from all groups, including front-page highlights on MOXIE's Mars landing, several EHT discoveries, and sudden stratospheric warmings.

The Haystack website was completely overhauled; the new website (figure 13) was launched at the end of July 2020. Haystack communications and IT staff members spent a significant amount of time working with a site developer and designing a modern, efficient, and better-organized site with ease of updates and content delivery foremost in mind. A prominent feature of the new site is a Haystack News section, which allows for direct publication of press releases and other descriptions of Haystack research and technological developments and activities.

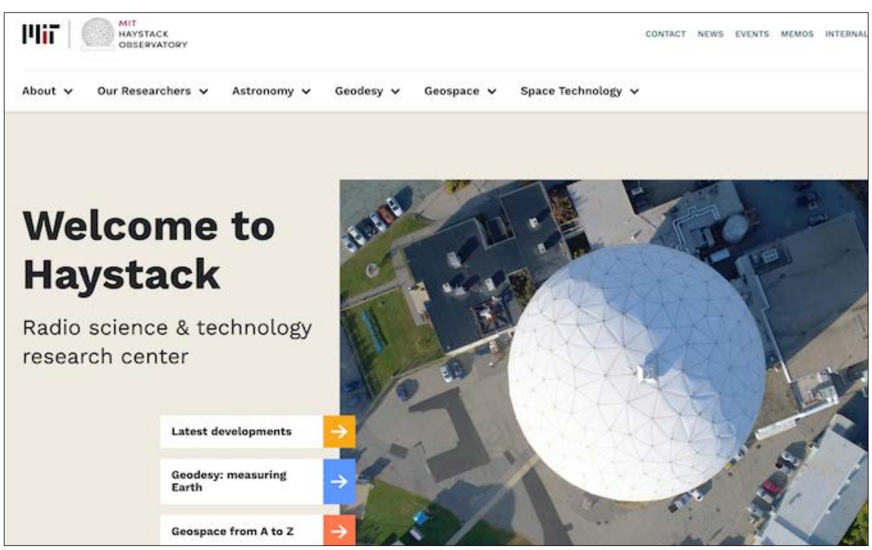

Figure 13. The newly redesigned Haystack website launched at the end of July 2020.

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

Haystack's geospace group continues an active outreach relationship with amateur radio groups. These are often in conjunction with Ham Radio Science Citizen Investigation (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.

Each summer, Haystack hosts 7–15 undergraduate students from around the country, an event that is 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.

The undergraduate internship program is a long-standing and highly developed Haystack Observatory tradition that involves numerous staff mentors in supervision of 10-week research projects for REU and UROP students (figure 14), as well as 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 the educational background of the students and in the sources of support. The aim is to further broaden and enrich the program going forward. Talks introducing the fields of research at Haystack were added, along with several career-focused seminars and science communication instruction. The introduction to the program was updated to help students get up to speed on Haystack research more quickly and easily.

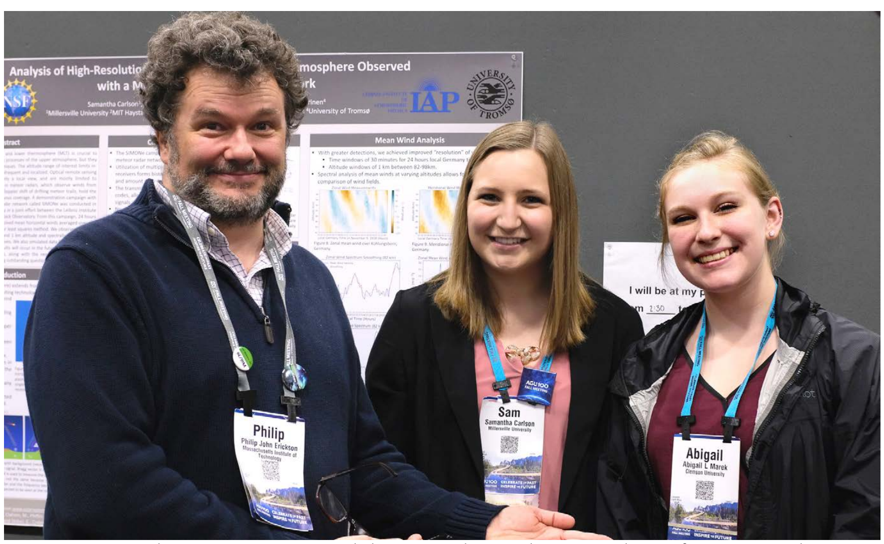

Figure 14. Each summer, Haystack hosts undergraduate students from around the country, an activity that is anchored by an award from the National Science Foundation Research Experiences for Undergraduates (REU) program.

In November 2020, Haystack hosted the fifth annual NEROC science symposium, held virtually this year, with attendees from groups working in radio science across the northeast. Attendance increases significantly with each yearly symposium, as does the number of institutions represented. Several collaborations often result from these conferences.

A set of new printed trifold brochure handouts was produced for distribution to Haystack guests and featured information on the major research programs (astronomy, geodesy, and geospace science). This proved highly popular with visitors.

The Haystack social media feeds show steady, ongoing growth in followers, impressions, and engagements.

As part of his Eagle Scout service project, local scout Carter Purple designed and installed a series of monument markers at historical sites around Westford, including one at the entrance gate to MIT Haystack Observatory and MIT Lincoln Laboratory's Millstone radar facility (figure 15).

Figure 15. As part of his Eagle Scout service project, a local Eagle Scout designed and installed a series of monument markers at historical sites around Westford, including one at the entrance gate to MIT Haystack Observatory and MIT Lincoln Laboratory's Millstone radar facility.

Colin J. Lonsdale
Director