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, complemented by a variety of other techniques. An important component of Haystack’s mission is the education of students through research opportunities using the Observatory’s facilities.

Over the past year, the radio astronomy program at Haystack has continued to focus on the advancement of the astronomical VLBI technique to observe our galaxy and other galaxies, particularly at short millimeter wavelengths as a means of probing the immediate environment of supermassive black holes. Haystack scientists also use the national radio astronomy facilities to conduct research on a variety of astrophysical targets. The primary objective of the geodetic VLBI research program is to improve the accuracy of measurements of the Earth’s shape and orientation in space for better geophysical understanding. Key progress has been made toward the forthcoming rollout of operational next-generation measurement systems. The goal of the atmospheric and geospace science programs is to understand the effects of solar disturbances on the Earth’s upper atmosphere and near-earth plasma environment using the Observatory’s radars, extensive use of Global Positioning System (GPS) measurements, and a variety of measurements from both ground- and space-based platforms. A focus of the group is deciphering the complex interrelationships between different components of the geospace environment. Development of advanced low-frequency aperture array systems has been conducted, with simultaneous applications for both astronomical and geospace research topics. The Observatory research portfolio is expanding in scope, with the recent addition of astro- and geo-informatics programs, initiatives for space-based radio frequency measurement systems, and research into the Earth’s cryosphere enabled by radio measurement techniques. 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 also enjoys a close relationship with Lincoln Laboratory, and provides extensive engineering and facilities support for a range of Lincoln Lab projects and installations at the field site. Significant new technical collaborations with Lincoln Lab have been initiated, particularly involving innovative CubeSat projects.

The research program is carried out under the auspices of the Northeast Radio Observatory Corporation (NEROC), a consortium of nine educational and research institutions that includes MIT, Boston University, Brandeis University, Dartmouth College, Harvard University, Harvard-Smithsonian Center for Astrophysics, University of Massachusetts, University of New Hampshire, and Wellesley College. Haystack Observatory also supports Lincoln Laboratory’s space surveillance program, with which it shares some of the facilities at the Westford site. The Observatory receives financial support for its research programs from federal agencies, including the National Science
Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Department of Defense. During the past year, a strong record of proposal successes has been sustained, and the Observatory is showing significant growth in both funding and staffing. The projected research volume in FY2016 is near $13 million, and the Observatory staff has grown from approximately 75 to almost 85 during the past year.

In September 2014, the Observatory celebrated the 50th anniversary of the iconic 37-meter Haystack telescope, an event that drew more than 300 attendees from MIT and many other places across the country. The chief engineer for the original Haystack telescope, Herbert Weiss ’40, made a generous financial donation to the Observatory for projects and activities of high value that would otherwise be difficult to fund through conventional channels.

**Senior Staffing Changes**

During the past year, John Foster stepped down as associate director, and Philip Erickson, the principal investigator of the NSF-funded geospace facility at Haystack, was promoted to assistant director with responsibility for the atmospheric sciences group. Anthea Coster was also promoted to assistant director, with responsibility for various aspects of Observatory communications, including interactions with researchers at NEROC institutions and on the MIT campus, education and public outreach, and international outreach. Michael Hecht was promoted to associate director in recognition of the key role he plays in research management across the full range of Observatory programs. Pedro Elosegui was hired in September 2014 as a senior member of the science staff, and as the new lead for the geodetic VLBI program. Elosegui also brings the field of cryosphere research into the Haystack portfolio.

**External Staff Activities**

Haystack staff members have been engaged in a wide variety of activities in service to the broader scientific and engineering communities. Alan Whitney served on the board of trustees for Internet2. He has held multiple positions within the International VLBI Service (IVS) organization, including membership on the directing board. Arthur Niell served on multiple IVS committees and is a member of the directing board. He is also a member of the technical and scientific advisory committee for the Spain-Azores RAEGE project for geodesy. Colin Lonsdale serves on the Murchison Widefield Array (MWA) board and on the Event Horizon Telescope (EHT) Consortium interim board. Sheperd Doeleman is a member of the National Radio Astronomy Observatory (NRAO) user’s committee and of the Atacama Large Millimeter Array (ALMA) North America science advisory committee. Frank Lind recently completed a term as chair of the US URSI (International Union of Radio Science) Commission. Larisa Goncharenko’s activities include NSF review panels, serving as International Space Science Institute team lead for whole atmosphere studies, chairing multiple conference sessions, and serving as lead for a NASA Living With A Star Focused Science Topic team in whole atmosphere coupling. Shun-Rong Zhang has convened major Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) and American Geophysical Union (AGU) science sessions, is a member of the international scientist committee for the upcoming Chinese electromagnetic satellite mission, and continues as a key member of the International Reference Ionosphere science board. Both Phil Erickson and John Foster are on the
mission science team for the NASA Van Allen Probes twin spacecraft mission launched in late August 2012. Anthea Coster served as a co-chair for the Institute of Navigation’s Satellite Division and served on multiple committees, including a NASA heliophysics graduate fellowship board. Phil Erickson co-convened major CEDAR and AGU sessions on mid-latitude dynamics and was a 2014 panel reviewer for the Canadian Space Agency. He chairs the MWA Solar, Heliospheric, and Ionospheric working group, and serves on the NASA Measurement Techniques in Solar and Space Physics science and program committee, along with the organizing committee for the International Symposium on Equatorial Aeronomy 2015, Bahir Dar, Ethiopia.

**Research Instrumentation**

Major facilities used in Haystack’s research programs include:

- A 37-meter-diameter radio telescope used for astronomical observations and radar measurements. This telescope has undergone a successful major upgrade through a Lincoln Laboratory program. The upgraded dish represents a world-class combination of aperture size and surface accuracy, and a modest NSF grant has been awarded to restart astronomy operations on the dish.

- An 18-meter-diameter radio telescope known as the Westford antenna, involved in VLBI measurements of the Earth’s rotation parameters and orientation in space.

- A high-performance computing cluster and associated hardware, software, and operational infrastructure to support VLBI software correlation.

- A 2.5 megawatt UHF (ultra high frequency) radar that utilizes two large antennas, 46 meters and 67 meters in diameter, to study the Earth’s upper atmosphere using incoherent backscatter techniques.

- A 12-meter-diameter radio telescope located at Goddard Space Flight Center, used for geodetic and astronomical observations.

**Radio Astronomy**

**Low-Frequency Arrays**

Haystack Observatory remains strongly engaged with the Murchison Widefield Array 128-antenna system in outback western Australia, a system that became fully operational in July 2013. Designed for studies of the early universe during the formation of the first stars and galaxies, the array can provide unprecedented diagnostics of solar wind plasma conditions that will aid in space weather prediction, and it is a powerful research tool for a wide variety of radio astronomy investigations in a poorly explored spectral window. The primary scientific use of the array by Haystack scientists is in the field of solar, heliospheric, and ionospheric research. This work is funded by a grant from the Air Force Office of Scientific Research to use the MWA for remote sensing of magnetic field orientations in coronal mass ejections. Such studies have the potential to greatly improve the prediction reliability for major geomagnetic storms, allowing at least 24 hours of advance warning for potentially hazardous conditions.
Haystack is also leading the development of next-generation low-frequency array technology through a project called RAPID (Radio Array of Portable Interferometric Detectors), in collaboration with the Jet Propulsion Laboratory (JPL) and Cambridge University, UK. Through its links to Cambridge University, Haystack is an associate member of the international Square Kilometer Array (SKA) aperture array development consortium. The RAPID work is supported by a Major Research Instrumentation grant from the NSF, with cost sharing from Cambridge.

The RAPID system consists of a large number of individual broadband antenna elements configured as an interferometric array. The antennas operate from 48 MHz to 615 MHz and are a variant of the low-frequency SKA antenna developed at Cambridge. RAPID differs from conventional interferometric arrays in that the individual antennas are each equipped with a high-performance digital data capture system and a battery-backed integrated solar power system. This makes each antenna autonomous in the field, capable of capturing raw voltage data to local storage. The interferometry is performed offline in a cloud-computing environment after the data is downloaded from each antenna unit. The system will operate in campaign mode, with deployments to arbitrary locations and zero site infrastructure requirements. The deployments can be readily tailored to any of a wide variety of scientific applications. The initial build of the RAPID system will comprise 50 to 75 antenna units, and the system is highly scalable.

Figure 1. CAD drawing of a RAPID deployment, showing 12 antenna systems. The initial RAPID system will consist of 50–75 such units that can be deployed in an arbitrary layout that can be compact, as shown here, or extended over tens or even hundreds of kilometers. Each antenna system has its own data acquisition unit on the left and energy unit on the right. Solar panels are integrated into the antenna bases. The antenna design is a log-periodic dual polarization wireframe with receiving electronics at the apex. The frequency range is 48–615 MHz.

The array architecture is fully flexible in terms of its ability to sample the radiation across an arbitrary aperture, and in the nature of the data capture, which does not constrain subsequent data processing options in any way. Consequently, the scientific applications are broad and diverse, spanning both astronomy and atmospheric science. The project thereby broadens and deepens links between different parts of Haystack, creates synergies, and strengthens the technical foundations at the Observatory.
High Frequency VLBI

Haystack maintains a leadership role in a major program focused on extending the VLBI technique to the shortest possible wavelengths to study supermassive black holes. Earth-diameter VLBI baselines observing at technically challenging 1.3 mm and 0.8 mm wavelengths achieve angular resolutions of a few tens of microarcseconds, corresponding to event horizon scales for the 4 million solar mass black hole at the center of our galaxy, and also for the 6.6 billion solar mass black hole in the nearby active galaxy M87. A coordinated program with many international collaborators, and supported by a series of NSF awards, is creating and growing a network of millimeter- and submillimeter-wavelength antennas and supporting VLBI infrastructure, collectively entitled the Event Horizon Telescope.

In recent years, several key observations using a preliminary EHT array have targeted the nearest and largest supermassive black holes. At the center of the Milky Way, a compact radio source, Sgr A*, marks the position of a 4 million solar mass black hole. Initial EHT observations detected structure on the scale of a few Schwarzschild radii within Sgr A*, leading to publication in the journal Nature. Later observations showed Sgr A* to exhibit time-variable structures near the black hole event horizon. Theoretical work published by Haystack scientists and collaborators uses the Sgr A* data to considerably tighten constraints on the black hole spin, disk inclination, and orientation of Sgr A*. Recent polarimetric observations, submitted to Science, indicate that the magnetic field is ordered in the innermost part of the accretion disk around Sgr A*. Detections of the closure phase of Sgr A* observed with a triangle of stations in Arizona, California, and Hawaii demonstrate conclusively that Sgr A* is asymmetric on Schwarzschild-radius scales, demonstrating that the EHT is resolving structures likely associated with the Doppler-enhanced approaching side of the accretion disk just outside of the photon ring predicted by general relativity.

The second major target of this work is the nearby giant elliptical galaxy M87, which also hosts a supermassive black hole, and for which Schwarzschild radius scales are also accessible via this powerful technique. In this case, much of the emission is thought to arise in a jet of material accelerating away from the black hole, rather than from the accretion disk itself. Results from observations of M87, published in the journal Science, indicate that the jet diameter is only a few Schwarzschild radii across, placing constraints on the spin rate of the black hole as well as on the alignment of the spin axes of the black hole and inferred accretion disk. EHT observations of M87 during an enhancement in very-high-energy gamma rays have been used to place limits on the size of the TeV-emitting region, with implications for the composition of the jet.

The observing campaigns are steadily improving in both sophistication and sensitivity as the instrumentation is developed, wider bandwidths are utilized and new telescopes are added to the EHT. Recording data rates are increasing, with the spring 2015 observations capturing 16 gigabits per second. Telescope arrays in California and Hawaii have been tied together to act as single, more sensitive dishes; experiments are being conducted with antennas in Chile and at the South Pole; and measurements are being made that are sensitive to the polarization properties of the sources. New additions to the array include the highly sensitive Large Millimeter Telescope (LMT) in Mexico,
which sits atop the 15,000-foot Volcán Sierra Negra, and a telescope at the South Pole that participated in observations in 2015. These diverse efforts have expanded the array and are improving both imaging quality and angular resolution.

Progress has continued in the effort to tie together the 60-plus dishes of the new ALMA array in Chile, under a Major Research Instrumentation award from the NSF. In December 2014, the ALMA Phasing Project (APP) passed a full acceptance review and was granted formal approval from ALMA to proceed with commissioning. Part of the APP effort involved installation of a hydrogen maser frequency standard, which became the primary standard for the ALMA array itself in November 2014. Commissioning efforts led to the demonstration of array phasing and intercontinental VLBI fringe in March 2015 (Figure 2). The fully operational APP system is targeted for availability in ALMA cycle 4 observing, which would allow ALMA participation in a spring 2017 EHT observing campaign.

![Figure 2. First intercontinental VLBI fringes at 1.3 mm wavelength between phased ALMA and the IRAM 30 m telescope at Pico Veleta, in Spain. The source 3C 273 was detected with signal-to-noise ratio 60 in one minute of observing.](image)

To date the EHT has been coordinated through Haystack via a series of NSF awards, as well as a grant from the Gordon and Betty Moore Foundation. Most recently, the EHT team was successful in winning a significant five-year, $6.5 million “midscale instrumentation” award from NSF against formidable competition. Substantial additional funds have been secured by groups in Europe. As the scale of the global effort grows and funding lines proliferate, the development of a formal governance structure and policies has become urgent, and an interim board has been convened to formalize the collaborative arrangements.

The EHT project has attracted considerable attention in the mainstream media. *Scientific American* magazine hosts a blog, “Dark Star Diaries,” that chronicles the development and progress of the EHT. The project was the subject of an article in the September 2013 issue of *Discover* and was featured in an episode of the documentary TV series *Through the Wormhole*, hosted by Morgan Freeman (season 5, episode 8). A feature-length article on the EHT, co-written by Shep Doeleman, appears in the September 2015 special issue of *Scientific American* commemorating 100 years of Einstein’s general theory of relativity. A PBS NewsHour segment on the APP and EHT aired in November 2014, and a feature-length *New York Times* science article entitled “Black Hole Hunters” covered Doeleman and other scientists at the LMT during the March 2015 EHT observing session.
EDGES

The Experiment to Detect the Global EoR Signature (EDGES) is a project to constrain the nature and duration of a fundamental change in the state of the early universe from mostly neutral to mostly ionized, known as the Epoch of Reionization. EDGES is a collaboration between Haystack and Arizona State University, with the work at Haystack led by Alan Rogers. In 2014, accurately calibrated data from the deployment of a wideband dipole and spectrometer covering 100 to 200 MHz at the Murchison Radio Observatory were obtained. These data and the associated laboratory tests have led to a method of accurate antenna reflection coefficient at the level of about 0.02 dB, and the team has published an evaluation of the effects of the ionosphere on the detectability of the extremely weak spectral features in the all-sky spectrum predicted to be present during the Epoch of Reionization.

A more permanent deployment of the EDGES 100–200 MHz instrument has been made at the Murchison Radio Observatory. This new installation includes a calibration unit for automated antenna reflection measurements, improvements to the antenna to achieve a more constant beam shape, and better thermal control of the electronics. There is now a trench for the cables located underground and a cavity under the ground plane for the low-noise amplifier and associated electronics, leading to more uniform antenna characteristics, including beamshape, as a function of frequency. A study of potential sites for an EDGES “low-band” system covering 50–100 MHz, where the 21cm line from the early universe is expected to be present in absorption, is under way, and a deployment is expected in 2015.

Astrophysics Research

Haystack staff members continue to conduct a variety of independent research programs using open-access facilities, including both those maintained by the National Radio Astronomy Observatory and others run by international entities (e.g., the MERLIN [Multi-Element Radio-Linked Interferometer Network] array in the United Kingdom, and ALMA in Chile). Lynn Matthews continues to study evolved stars via 21cm hydrogen line emission, using the Very Large Array, as a unique and powerful tracer of mass loss over time from these stars. This work is supported by a grant from the NSF. Both Lynn Matthews and Vincent Fish study astrophysical maser sources of various kinds. Colin Lonsdale conducts high-resolution imaging observations of cosmologically distant, powerful active galaxies using the Very Long Baseline Array,
the Very Large Array, ALMA, and MERLIN to explore the interaction and evolutionary connection between intense star formation activity and the initiation of accretion onto a supermassive black hole which results in a quasar. All these studies involve student participants in the NSF-funded Research Experiences for Undergraduates (REU) program at Haystack, now in its 28th consecutive year.

37-Meter Telescope

The iconic Haystack radome-enclosed 37-meter radio telescope was upgraded in 2010 and 2011 via a project funded by the Air Force and managed by Lincoln Laboratory. Significant problems were encountered, resulting in delays, but the problems were overcome, and a root-mean-square (RMS) surface accuracy of approximately 75 microns has been achieved, enabling high-efficiency operation at millimeter wavelengths. The primary Air Force mission is long-range, high-resolution imaging radar in the 90–98 GHz band, a capability that has been fully commissioned, leading to a formal ribbon-cutting ceremony in February 2014.

The radio astronomy receivers and other instrumentation have also been installed and tested to help reestablish Haystack astronomy and education programs that were rendered dormant by the upgrade project, and up to 35% of the telescope time will be available for this purpose if operating funds can be secured. Professor Gordon McIntosh from the University of Minnesota spent a sabbatical at Haystack during 2013 and 2014 to assist in the reestablishment of astronomy capabilities on the telescope, resulting in high-quality spectra of multiple astronomical targets, to serve as material for proposals to the NSF. This has resulted in funding to provide teaching and research opportunities on a major instrument for undergraduates at a range of remote locations. Development of the necessary interfaces for remote observations is under way.

The possible development of an advanced phased array feed system for the telescope is under study, with the aim of achieving a highly competitive millimeter-wave astronomical research capability on the telescope, despite its vulnerability to poor weather due to low geographic elevation, and despite the signal losses inherent in the radome material and support structure. By exploiting Observatory expertise in relevant technologies, a state-of-the-art phased array feed system is possible, enhancing aperture efficiency and, more important, creating a much wider field of view for mapping and survey projects. Such a system is rendered feasible by continued rapid gains in digital signal processing capabilities for a given cost.

VLBI Geodesy

For many years, the Haystack geodetic VLBI group has been developing advanced systems for the next-generation geodetic VLBI network, under NASA sponsorship. This is known as the VLBI Geodetic Observing System (VGOS), and it is a key component of the NASA Space Geodetic Network, an integrated, multi-technique network of stations each comprising a VGOS and Next Generation Satellite Laser Ranging system co-located with a Global Navigation Satellite System and a Doppler Orbitography and Radiopositioning Integrated by Satellite system. The NASA Space Geodetic Network is the centerpiece of the NASA Space Geodesy Project, and the deployment of 10 space geodetic stations is envisaged over the next 10 years.
VGOS is characterized by a series of technical innovations and advancements over current geodetic VLBI systems. The essence of the new capability is greatly expanded data bandwidth, permitting the use of much smaller and more agile antennas, producing a more versatile system capable of better atmospheric calibration at lower total procurement and operational cost. The fundamental observable is also being changed from group delay across a relatively modest radio frequency (RF) bandwidth at X-band to phase delay using a much broader band spanning approximately 12 GHz of RF. Uniformity across the array of stations will further enhance the data quality and precision relative to the current heterogeneous network. The effort is global in character, and the international geodetic community is coordinating the technology efforts in order to maximize the compatibility of next-generation VLBI systems around the world. Ultimately, on the order of 40 VGOS or VGOS-compatible stations are expected to be built.

A VGOS system has many critical components, the majority of which have been developed or heavily contributed to by Haystack. These include the 12-meter antenna itself, delivered by a commercial entity in close collaboration with the project; the cryogenic broadband feed and receiver system; intermediate frequency (IF) conversion electronics; the field programmable gate array or FPGA-based digital backend system; and the high-capacity, high-speed disk-based Mk6 recording system. Also critical to the project goals are advanced software correlation capabilities, as well as post-processing, diagnostic, and quality control software systems.

From mid-2014 to mid-2015, major progress was achieved in pulling together all these disparate components of VGOS, involving a continued major engineering development effort, guided and validated through tests and observations between the prototype VGOS installation near Goddard Space Flight Center in Maryland and the 18-meter antenna at Westford, retrofitted with VGOS signal path hardware. The successful completion of these tasks has led to ongoing implementation of the first production VGOS station at Kok‘ee Park, Kauai, and plans are being laid for the second VGOS
station at McDonald Observatory, Texas. Subsequent stations are expected at the rate of about one per year. Haystack is taking primary responsibility for the design, fabrication, installation, and validation of the signal chain of the first two or three of these systems, before transferring the bulk of the tasks to industry partners for subsequent builds. As of mid-2015, roughly 75% of the work for the Kok’ee VGOS was complete. The Kok’ee system has recently undergone a successful critical design review, and the Texas system has passed a preliminary design review.

The recent five-year contract from NASA ended on December 21, 2014, and a new contract has been successfully negotiated and implemented under the direction of Pedro Elosegui. The new contract has a different flavor from those Haystack has been executing for many years, due to the fact that VGOS is part of a project, the Space Geodesy Project, with clearly defined phases of design, construction, and operation. This contrasts with the environment of continual refinement and development of existing capabilities that has characterized all prior geodetic VLBI contracts with NASA. The long-term future prosperity of the Haystack geodesy program is likely to require diversification of funding lines to fully exploit and maintain the deep technical capabilities of the group and to ensure a strong advanced research and development component of the VLBI effort.

An established Haystack strategic priority is to have strong engagement in the science applications of geodetic techniques and to leverage that engagement to operate at the intersection of science and technology in true Haystack tradition. Concrete steps in this direction have taken the form of collaborations and funding proposals for science projects with members of the MIT faculty, led by Victor Pankratius and Pedro Elosegui. Through such projects, Haystack seeks to expand the footprint of the geodesy group by attracting funding and geodetic scientists independent of the NASA-funded Space Geodesy Project effort, while maintaining the health of the NASA VLBI program both to participate in VLBI-based science and to support and maintain core Observatory technical capabilities.

**VLBI Recording and Correlation Systems**

The Haystack-developed Mk6 recording system is now in use for a rapidly increasing set of VLBI experiments and networks. This system is based on commercial off-the-shelf hardware components, supported by high-performance software developed by Haystack staff. This system is inexpensive, yet capable of continuous recording at a rate of 16 gigabits per second. In the recent March 2015 EHT campaign, eight disk media packs were employed, each with 48 terabytes of storage. A single Mk6 unit can record to four disk packs, a total of 192 terabytes, allowing for 24 hours of uninterrupted recording at the 16 gigabits per second rate.

This system is scalable, and as media cost and device input/output speeds improve, the software can be ported to new platforms, ensuring compatibility and interoperability of different generations of hardware. In this way, the bandwidth capability of modern VLBI systems can closely track industry gains in performance, with attendant improvements in VLBI array sensitivities. The assembly, testing, sale, and support of complete Mk6 recording systems have been transferred to industry.
In recent years, the era of custom-built, hardware VLBI correlators has passed, and general-purpose computing cluster platforms can provide the necessary levels of number-crunching power. This has led to the dominance of the DiFX correlation software package, originally developed in Australia but now a de facto community standard. Haystack Observatory operates a capable cluster running DiFX, has contributed significantly to the DiFX code base, and has implemented significant functional upgrades to support both the VGOS program and the EHT. This has proven to be a major endeavor requiring significant investment of highly skilled software effort.

Haystack has recognized a need for improved code maintainability—one that is better than what is currently afforded by DiFX, which contains a great deal of legacy code dating back decades, in some cases, plus the more general need for a flexible correlation and digital signal processing ecosystem. Accordingly the Observatory is designing a powerful new software infrastructure based on a highly modular approach. This will feature software plugin modules, facilitating contributions to the ecosystem from external groups, while permitting a centrally controlled and regulated code base for the core system, a feature of value to current and potential sponsors.

**Atmospheric and Geospace Science**

**Geospace Facility Ionospheric Radar Operations**

The Millstone Hill UHF radar system committed over 1,000 hours of observations from September 1, 2014 to September 1, 2015, in accordance with the nominal yearly support level provided by its NSF Geospace Facilities operations grant. Approximately 43% of these hours were internationally coordinated through the World Day program, with the remainder of observations used for ionospheric studies particular to the mid-latitude location of Haystack. The facility was used extensively by scientists from across the space science community.

Among the major programs supported were coordinated magnetosphere-ionosphere multi-instrument studies in conjunction with the NASA Van Allen Probes dual spacecraft mission and the newly launched NASA Magnetospheric Multiscale mission, which are whole atmosphere coupling studies focusing in particular on stratospheric warming effects reflected in the ionosphere, mid-latitude traveling ionospheric disturbance studies, neutral-ion coupling studies using simultaneous on-site radar and optical observations, local/regional ionospheric synoptic measurements, and prompt response observations of geomagnetic disturbance effects.

**Geospace Research Activities**

The atmospheric science group at Haystack conducts scientific research into many aspects of the geospace environment. As in recent years, the primary focus has been in four main areas: radiation belt physics, including system-scale phenomena in the magnetosphere, plasmasphere, and ionosphere; coupling effects between the upper and lower atmosphere; climatology of sub-auroral electromagnetics in the ionosphere; and long-term trends and climate change in the upper atmosphere.
**Radiation Belt Physics**

John Foster and Phil Erickson, with collaborators across the observational and modeling community, continue to be very active users of data from the dual NASA Van Allen Probes spacecraft, carrying a comprehensive suite of sensors for high-energy particles along orbits that swing through the radiation belts many times per day. The combination of these data with a range of other space and ground-based assets has unlocked a series of multiscale investigations of near-Earth space and its response to energy inputs. Investigations being actively pursued include elucidation of processes responsible for unexpectedly dynamic electron acceleration across a broad range of energies, and system-scale magnetosphere-ionosphere coupling studies using the Millstone Hill radar as well as riometers, GPS total electron content (TEC) measurements, and data from multiple spacecraft in the NASA Great Observatory.

Also under way are studies of transport and acceleration pathways and impacts of ionospheric oxygen ions and wave processes on magnetospheric and terrestrial electrodynamics, and the effects of low-altitude, cold plasma redistribution of ionospheric origin on dayside magnetic reconnection, a fundamental regulator of solar wind energy input to the magnetosphere. Results from these investigations have been published this year in several high-profile manuscripts, including *Nature*. More publications are in progress, including an invited *Geophysical Research Letters* Frontier Article reviewing recent cutting-edge advances “in a leading scientific field at the forefront of one or several AGU disciplines.”

![Figure 5. The Van Allen radiation belt probes. To the left is a schematic of a typical orbit for the mission. The ~9 hour repeating orbit provides data approximately three times per day on the inner and outer radiation belts to approximately 5–6 Earth radii at a range of local times. Note that the radiation belt positions are highly variable in space and time.](image)

**Lower-upper Atmosphere Coupling Studies**

Larisa Goncharenko and collaborators have continued their pioneering and fruitful research into the global ionospheric effects of sudden stratospheric warming events. These apparently localized lower-atmosphere phenomena in the polar regions have profound global effects on the ionosphere that are directly associated with previously unexplained variability in electron density, plasma velocity, and plasma temperature. Despite identification of their effects, the root causes and prime energy pathways of whole atmosphere coupling remain poorly understood. Detected signatures that have yet to be fully explained include low-latitude changes in total electron content of up to
100%–150% during sudden stratospheric warming periods, and sharp, deep electron density drops before sunrise extending to mid-latitudes in both the northern and southern hemispheres, likely driven by anomalous neutral atmosphere dynamics. The observational series fueling this line of investigations is heavily supported by NSF long-term measurements by the Millstone Hill ionospheric radar and the entire NSF incoherent scatter radar chain. An extensive set of publications continues along these lines.

**Sub-Auroral Climatology**

Long-term Millstone Hill incoherent scatter radar observations, combined with an easy means of access through the MIT Haystack–authored Madrigal distributed database system, offer the opportunity for comprehensive studies of plasma drift variations as a function of a number of variables—season, local time, magnetic index, solar wind drivers—during low- to medium- magnetic-activity conditions. A better understanding of these climatologies in the crucial region of overlap between the cold, dense, inner plasmasphere and the hot, tenuous, outer plasmasphere is driving improvements to, for example, the community International Reference Ionosphere model, used by a wide basic- and applied-science and applications community. These studies are led by Atmospheric Sciences Group (ASG) personnel, including Shun-Rong Zhang, with a series of modeling codes and publications.

**Upper Atmospheric Climate Change**

This work, in collaboration with Boston University, complements the ongoing Haystack effort to characterize ionospheric trends over a multi-decade time baseline, by investigating long-term changes in the neutral and ionized atmosphere. The observational data set used, focusing on ionospheric radar measurements by Millstone Hill and other NSF radar facilities, provides a direct monitor of the thermal status of the upper atmosphere. Recent results show an unexpected and substantial ionospheric cooling trend with large altitude and time dependence. This has led to new proposed mechanisms for secular changes, involving gravity wave modulations in atmospheric cooling that propagate from lower atmosphere, orographic sources. Observational collaborative community studies led by Shun-Rong Zhang and John Holt at Haystack are thus providing a considerable challenge to state-of-the-art atmospheric dynamics models. Several publications have been completed, and more are in preparation.

**Geospace Technical Initiatives**

The atmospheric sciences group remains very active in the development and implementation of a range of innovative hardware and software systems for geospace science. These include the RAPID array, ubiquitous space weather sensor networks through the Mahali project, cloud software infrastructure and database development, technical development of low-cost distributed remote beacon and ionosonde sensors for ionospheric characterization, geo-informatics work for computer-aided analysis and discovery, and ongoing technical development of next-generation incoherent scatter radar technology. All these initiatives are guided by an overarching Haystack vision of the current trends in the field of radio remote sensing and how they can be optimally applied to the geospace environment.
The RAPID array is a centerpiece of the Haystack technical program. The first two major planned deployments of RAPID in Alaska and Peru will target imaging of coherent scattering structures in the auroral and equatorial ionosphere respectively. On a longer timescale, RAPID-based technology is intended to provide a foundation of a next-generation incoherent scatter radar system with significantly lower cost and far greater capability than current systems. Technical solutions developed for RAPID are readily transferable to other Observatory projects.

RAPID flexibility has already borne fruit in an Air Force Office of Scientific Research award supporting design and demonstration activities for a next-generation incoherent scatter radar based ionospheric parameter profiler. The design has the potential to produce a full incoherent scatter radar instrument at a fraction of the cost of current systems, enabling a network of profilers and providing significant improvements in space weather monitoring and datasets for science discovery.

The Mahali project, an NSF INSPIRE–funded grant led by Victor Pankratius, is another example of synergy in technical approach, and continues with vigorous activity. This program is targeting low-cost expansion of GPS–based TEC sensing by using mobile devices (phones, tablets) to gather and pre-process dual-frequency GPS data and transmit the results to a central repository for further analysis. Ultimately, the introduction of dual-frequency capability to the mobile devices themselves, driven by market pressure for greater navigational accuracies, will create an extraordinarily dense sensor grid and take ionospheric remote sensing to a new level. The software and networking infrastructure to support this crowdsourcing vision is a primary target of Mahali, supported by new postdoctoral personnel in the expanding Haystack astro- and geo-informatics effort. Mahali efforts have produced a set of robust solar-powered deployment boxes that will be deployed in Alaska in fall 2015 as a reconfigurable network for multi-scale GPS total electron content studies of the high-latitude ionosphere. Some of the Mahali equipment is closely related to, and derived from, RAPID subsystem development.

Efforts in cloud infrastructure and database development continue, centered on remote sensing instrument data capture and the Madrigal distributed database system. Madrigal is the upper atmospheric observational community standard repository centered at Haystack under NSF facility support, and provides the field’s long-term data repository as well as uniform software interfaces easing data discovery activities. Madrigal development is moving to standard HDF5 platforms in preparation for future cloud-based architectures. The number of instruments supported by the Madrigal database grew once again by 25%–30% in 2014. Such growth is made possible by automation, combined with comprehensive staff support from Haystack, sharply reducing the investment of time and effort required of the custodians of the instruments and their data archives.

Remote sensing platforms using software radar and other information extraction patterns implemented as a network of cloud-based processing engines are a highlight of technical development activities. In this vein, Juha Vierinen and Frank Lind continue to develop low-cost distributed remote sensors with a wide variety of applications.
Inexpensive high frequency radar-based ionospheric sounders have been demonstrated using loop-based compact antennas at power levels a factor of 100 or more below conventional systems, representing a potentially disruptive technology for widespread ionospheric remote sensing with many applications. The same RAPID spinoff platform has also been used with large facility incoherent scatter radars such as Arecibo, Sondrestrom and Millstone Hill, and also with space-borne coherent Doppler beacons for tomography-based widefield ionospheric characterizations. The flexible software nature of these instruments allows a large diversity of applications without requiring a total instrument redesign, maximizing reuse.

Significant progress has been achieved in the area of software radar and cloud-based processing. This includes advanced radar control architectures, cloud data storage and processing frameworks, and modular signal processing infrastructure. Routine use of advanced radar waveforms and analysis techniques continues, thanks to a system design providing minimal overhead needed to implement new schemes. Once again, the RAPID development has directly led to benefits and synergies for other areas of research, and an advanced RF data format and application programming interface (API) are available with wide applicability to community radio science instrumentation. Most of the software being developed in Haystack geospace areas is designed at a core level for a cloud environment, which makes it easier to migrate to new platforms and take advantage of scalable, expanding computing hardware resources.

**Geospace Collaborations**

The Haystack group continues to collaborate with a large variety of community technical and science personnel and projects. Extensive collaborations with groups in China are occurring under the Meridian Circle International Observation (MERINO) project, implementing coordinated space weather monitoring along meridian 120 east / 60 west longitudes. The observations are designed to study important magnetosphere-ionosphere-thermosphere system-scale processes that affect vertical coupling across atmospheric layers under the influence of solar-terrestrial processes. The meridian circle spans America and Asia longitude sectors of particular geophysical interest due to differing geodetic/geomagnetic pole offsets. MERINO campaigns have been conducted with a range of radio and optical instruments at facilities from the Chinese Meridian Project, the World Incoherent Scatter Radar network, and the Global Ionosphere Radio Observatory, as well as from individual research institutions and regional networks in Asia and America. ASG scientists have also collaborated with emerging new Chinese ionospheric radars with unique geophysical fields of view across low and equatorial latitudes. These span both technical radar and scientific investigations, and a series of visits by John Foster and Shun-Rong Zhang in fall 2015 to various locations will continue this work with the Chinese Academy of Sciences.

Collaboration continues with Boston University with Professor Joshua Semeter and a student, supported by the Millstone Hill Geospace Facility award, to work on comprehensive 3D/4D ionospheric radar analysis during geophysically dynamic periods at high latitudes. A *Journal of Geophysical Research* publication has already occurred on the student’s initial research line, with future publications planned. Frank Lind continues to work closely with graduate students in Professor John Sahr’s program.
in the Electrical Engineering Department at the University of Washington. This is part of a community coordinated effort to develop advanced techniques for passive radar imaging of ionospheric electric fields and irregularities using transmissions of opportunity such as FM radio and digital television broadcasts. Frank Lind and Anthea Coster are collaborating with Professor Jim Labelle at Dartmouth College in connection with distributed remote sensing systems and networks.

A new link to undergraduate student involvement in Haystack geospace research is emerging from the recent appointment of Professor Allan Weatherwax as the dean of science at Merrimack College in North Andover, MA. Professor Weatherwax has an extensive existing research line in Arctic and Antarctic radio remote sensing of natural auroral and magnetospheric phenomena, and the proximity of Haystack to the Merrimack campus provides an ideal connection to ongoing geospace radio remote sensing projects and a crucial student research exposure boosting the emerging science programs there.

Haystack involvement in African sector geospace work also continues. Anthea Coster is promoting the establishment of a future incoherent scatter radar in these regions to capture space weather and ionospheric variations unique to that longitude sector, and is working with colleagues such as Dr. Baylie Damtie, the president of Bahir Dar University in Ethiopia. Phil Erickson is also making connections to the emerging African space science community through his role on the organizing committee for the 14th International Equatorial Aeronomy Symposium, to be held in Bahir Dar in October 2015.

**Astro- and Geo-Informatics**

A recent strategic addition to the Haystack staff has been Dr. Victor Pankratius, who joined the Observatory in early 2013 and currently is principal investigator for multiple important new funding awards from a range of different sponsors. He has nucleated a new informatics group at the Observatory that consists of himself, five newly hired postdoctoral researchers, and two newly hired undergraduate students. The current projects involve multiple MIT faculty members, the growth of the informatics group is rapid, and the reach of the program into diverse aspects of the Haystack research portfolio is already substantial.

Radio science as pursued by Haystack is benefitting particularly strongly from the rapid advance of digital systems and devices. Radio interferometer arrays generate very large data volumes; for example, the MWA has already accumulated on the order of 10 petabytes, while a RAPID system comprising only 75 antennas in its initial incarnation can generate hundreds of terabytes per hour when operating at full bandwidth. Even when distilled to the most information dense form possible, such datasets remain far too large for humans to meaningfully interact with. An example is MWA data from observations of the sun that has been reduced to the form of images with high time and frequency resolution; human inspection and interpretation of the resulting millions of images is wholly impractical. Somewhat smaller datasets, such as geospace radar products or global GPS TEC measurements, also contain a wealth of signatures from diverse phenomena that humans have little time or opportunity to disentangle.
The informatics approach is to merge contextual information and capacity for scientific insight, qualities associated with experienced human researchers, with the automated sifting of large volumes of data in a manner that leaves humans firmly in control of a powerful computer-assisted discovery process. This goes far beyond mere data mining and filtering, and instead employs machine intelligence and machine learning to provide the researcher with, effectively, a smart personal assistant who can intelligently identify patterns and proactively bring potentially interesting ones to the attention of the researcher. The strategic goal is for Haystack to be in the vanguard of a big data revolution in radio science and computer-aided discovery.

Informatics projects currently funded and in progress include:

- The Mahali project, an NSF-funded concept for monitoring space weather using ubiquitous handheld devices such as smartphones and tablets. This project involves MIT assistant professor Kerri Cahoy (Department of Aeronautics and Astronautics) and her students.

- An infrastructure for computer-aided discovery in geoscience, funded by NSF. This project creates a software environment engaging scientists to programmatically express hypothesized scenarios, constraints, and model variants (e.g., parameters, choice of algorithms, workflow alternatives) so as to automatically explore with machine learning the combinatorial search space of possible model applications in parallel on multiple data sets and identify the ones with better explanatory power.

- Computer-aided discovery of Earth surface deformation phenomena, funded by NASA. This project creates a novel cloud-computing environment for computer-aided discovery that supports humans in the process of searching for relevant phenomena by using data fusion of GPS, InSAR (Interferometric Synthetic Aperture Radar), MODIS (Moderate Resolution Imaging Spectroradiometer), and other data. This is a collaboration with Professor Thomas Herring (Department of Earth, Atmospheric, and Planetary Sciences).

- Mapping biochemical space to search for extraterrestrial life and for fundamental terrestrial applications. Funded by a Bose Foundation award, this project employs informatics methods to explore biochemical space in a new way based on an exhaustive survey of which small molecules are made by life, and how often they are made by life. Such molecules could be biosignature gases in atmospheres of exoplanets, and this work seeks to predict which molecules are stable, volatile, and detectable remotely by space telescopes. The project is a collaboration with Professor Sara Seager (Earth, Atmospheric, and Planetary Sciences).
Space-based Research and Development

In addition to the scientific use of data from spacecraft, such as the Van Allen Probe research, Haystack is embarking on a strategic research and development effort to access space for a range of investigations. This program encompasses the development of mission concepts; implementation in partnership with a range of entities, including MIT campus departments; and all aspects of operation, including pathfinder demonstrations, science investigations, and ground support using on-site Observatory facilities.

There is a strong strategic motivation for investment in space-based utilization of Haystack technologies. From a scientific perspective, space platforms offer the only way to access certain parts of the electromagnetic spectrum for remote sensing, to make proximity measurements of solar system objects, to pursue VLBI at a scale beyond the constraints of Earth’s radius, to view objects not visible from Earth (e.g., simultaneous views of the Sun from different perspectives), to make measurements that would be compromised by Earth’s atmosphere or ionosphere, or (in the distant future) to build structures of a size and precision that would be impossible within the bounds of Earth’s gravity. Even in geodetic VLBI, space-based measurements are increasingly seen as useful in the ongoing effort to tie GPS and other relative satellite-based measurements to the absolute terrestrial reference frame. Other opportunities may lie in areas such as in-space navigation and communication.

From a programmatic perspective, NASA is Haystack’s second-largest sponsor after NSF. Engagement in space missions is an obvious way to grow the NASA portfolio, making Haystack less dependent on the vagaries of NSF funding. Moreover, NASA has a demonstrated need for capable university-based instrument developers that are less expensive and more creative than the large aerospace companies but still can deliver the type of flightworthy product that is beyond the reach of the typical campus research laboratory. The steady growth of the CubeSat and SmallSat sector increasingly focuses attention on such small-scale hardware providers. Haystack has an opportunity to occupy that niche.

From a resource perspective, Haystack has a core of personnel with flight mission experience and strong working relationships with space-savvy institutions, including MIT Lincoln Laboratory, the Aeronautics and Astronautics and Earth, Atmospheric, and Planetary Sciences Departments, as well as outside organizations such as JPL and other NASA centers. Haystack may also conceivably benefit from an opportunity to repurpose excess in-house antenna capability as ground station support to CubeSat and SmallSat projects, an application that offers plentiful opportunities for student involvement.

In August 2014, Haystack learned of the selection of the MOXIE instrument for NASA’s Mars2020 mission (Figure 6). An in situ resource utilization prototype, MOXIE will demonstrate conversion of atmospheric CO$_2$ to oxygen on the Martian surface. Technical development of MOXIE hardware largely resides at JPL, while MIT is responsible for overall investigation leadership, scientific definition, laboratory characterization activities, and, eventually, interpretation and publication of results. From the Haystack perspective, MOXIE is a pathfinder for future instrument development projects in areas such as scientific radiometry, which we expect will establish Haystack as a valuable partner for other campus-based space instrumentation proposals.
In the area of observational science, Haystack is collaborating with a group at Lincoln Laboratory to develop a CubeSat-based vector antenna experiment with the goal of identifying and observing spatially compact structures in the low-frequency HF band that cannot be detected through the ionosphere. The effort is internally funded by Lincoln Laboratory, and optimism runs high for a flight opportunity in the next few years. Recently, extending the Haystack–Lincoln Laboratory partnership to Morehead State University and the MIT campus, Haystack prepared an ambitious proposal to place a small fleet of CubeSats in near-geosynchronous orbit to study HF emissions from the sun and other sources in the heliosphere (Figure 7). If selected, Haystack would be responsible for overall scientific leadership of the mission, key aspects of the instrumentation development, overall payload integration, and much of the mission operations.

In the area of geodesy, Haystack recently participated in a proposal led by the NASA Goddard Space Flight Center with the objective of operating a CubeSat-based geodetic reference antenna in Earth orbit.
Educational and Outreach Programs

Research Experiences for Undergraduates and RET Programs

The longstanding NSF Research Experiences for Undergraduates (REU) program at Haystack continues to provide undergraduate students with summer internships, with eight to 10 participants each year for a 10-week program. Haystack REU students have an excellent track record in their professional careers after the program ends, and in some cases they have continued to collaborate with Haystack scientists for an extended period. Haystack also hosts four high school teachers each year, who develop and test detailed lesson plans based on Haystack research areas. Haystack has been an REU site since 1987 and has hosted nearly 250 students who have conducted scientific and technical research to motivate and expand their interest in science, technology, engineering, and mathematics (STEM) careers, and to prepare them for graduate-level studies. Haystack has also been involved in the NSF Research Experience for Teachers (RET) program since its inception in 1999, hosting more than three dozen middle- and high school teachers to develop teaching units based on Haystack research disciplines. The resulting materials are made freely available to the teaching community and are in wide use.

Recently, Haystack has been able to host talented high school students from Puerto Rico and engage them in research projects similar to those typically conducted by REU students. In some instances, the REU and high school students have been able to work closely and productively together on different aspects of the same project. Arrangements are being made to formalize this high school student program through collaboration with Arecibo Observatory in Puerto Rico.
Phil Erickson has continued his annual weeklong radar series of guest lectures as part of the 2014 and 2015 Erasmus Mundus Space Masters program at the Swedish Institute of Space Physics in Kiruna, Sweden. Members of the atmospheric sciences group also gave lectures at, and co-organized, the annual incoherent scatter radar workshop, held this year at Arecibo Observatory.

**Public Outreach**

Twice per year, Haystack holds an open house, hosted by the director and featuring a lecture, an extended question-and-answer session, and a tour of the 37-meter telescope. These events have proven to be wildly popular, and to avoid problems with capacity, attendance is managed through a registration process. Typical attendance for open house events is about 100 people. In addition, the Observatory regularly hosts smaller tours for schools, hobby groups, MIT alumni groups, and many others. Each year, a “cubmobile” race is hosted on the Haystack access road. Many inquiries and questions from the public are routinely fielded by the Haystack staff. The maintenance of excellent relationships between Haystack and the surrounding communities is an explicit priority.

Periodically, members of the Haystack staff are featured in the popular media, including local television and radio stations, science websites, magazines, and newspapers. Certain high-profile projects at the Observatory attract a high level of media attention, and staff members regularly appear in articles and interviews that command a wide audience.

In July 2014, Anthea Coster was an invited presenter and teacher at the African Outreach workshop in Kigali, Rwanda, and she made a presentation at the Maranyundo Girls Middle School in Nyamata, Rwanda. She also presented an invited public science history lecture at the American Physical Society and the University of Calgary. Haystack has provided extensive educational materials generated by the RET program to a group in South Africa whose mission is to enrich educational opportunities for disadvantaged communities in that country.

**Haystack 50th Anniversary**

On September 29, 2014, more than 300 people converged on Haystack Observatory to celebrate the 50th anniversary of the landmark inauguration of the Haystack 37-meter antenna, and the de facto creation of what is now known as Haystack Observatory. Herbert Weiss ’40, the lead engineer for that antenna project, was present at the celebration to deliver a spellbinding account of postwar events, the Cold War, and the drive to develop high sensitivity radar capabilities at the Millstone Hill site. The event also included speeches from former Haystack director Joe Salah, Lincoln Laboratory director Eric Evans, MIT vice president for research Maria Zuber, and Massachusetts state representative James Arciero, who presented a formal resolution in honor of the event from the Massachusetts House of Representatives. The event included video messages from Haystack’s first director, Paul Sebring, and from longtime Haystack friend and pioneering researcher Irwin Shapiro. A congratulatory letter from US senator Elizabeth Warren was also presented.
Figure 9. Scenes from the 50th anniversary celebration on September 29, 2014. Top left: Vice President Claude Canizares and Vice President for Research Maria Zuber. Top right (left to right): Herb Weiss ’40 (architect of the telescope), Eric Evans (director of Lincoln Laboratory), Don Maclellan (former assistant director of Lincoln Laboratory), and Israel Kupiec (senior retired Lincoln Lab scientist). Lower right: audience at the formal presentation. Lower left: commemorative cake.

This event was capably and successfully organized by a joint committee of Haystack and Lincoln Laboratory employees. Financial support for the event was generously provided by the Lincoln Laboratory Director’s Office and by the Office of the Vice President for Research.

Colin J. Lonsdale
Director