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 have also use the national radio astronomy facilities to conduct research on a variety of astrophysical targets. The Haystack 37-meter telescope is being equipped with new instrumentation to support future astronomy research. 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, and a major milestone has been achieved toward the implementation of operational next-generation measurement systems. The goal of the atmospheric and geospace science programs is to understand the effects of disturbances in the coupled Earth-Sun system on the Earth's near-space plasma environment, including the neutral and ionized upper atmosphere, through observational studies employing the Observatory's radars, extensive use of global positioning system (GPS) measurements, and a variety of globally distributed 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 technologies has continued, serving both astronomical and geospace research areas.

The Observatory's research portfolio continues to broaden in scope with the addition and maturation of the astro- and geo-informatics programs, the initiation of space-based projects, and research into the Earth's cryosphere. 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. The Observatory has significant technical collaborations with Lincoln Lab, 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, in addition to MIT, Boston University, Brandeis University, Dartmouth College, Harvard University, the Harvard-Smithsonian Center for Astrophysics, the University of Massachusetts, the University of New Hampshire, and Wellesley College. Efforts to restructure and enhance the research potential of NEROC are ongoing, with the endorsement of the consortium's board of trustees. The Observatory receives the bulk of its financial support for research programs from federal agencies including the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Department of Defense. Haystack enjoys a very high proposal success rate, fueling steady growth in funding and leading to an increase in Observatory staffing from approximately 75 to nearly 90 over the past two years.

Senior Staffing Changes

In June 2016, after 24 years of service to and leadership within Haystack Observatory, Shep Doeleman accepted a full-time position at the Smithsonian Astrophysical Observatory (SAO) and became a senior member of the newly formed Black Hole Initiative at Harvard. Doeleman had held a joint Haystack/SAO appointment for the previous three years in order to facilitate collaborations between the two institutions on the Event Horizon Telescope (EHT) project. That collaboration will continue, and Dr. Vincent Fish has assumed leadership of the EHT program at Haystack.

A number of senior Haystack staff members have reduced their hours or formally retired, and the process of renewal and restructuring for the future has continued with a steady pace of hiring. The emphasis during the reporting period has been on strengthening the engineering staff.

External Staff Activities

Haystack staff members have been engaged in a wide variety of activities in service to the broader scientific and engineering communities. Arthur Niell served on multiple International VLBI Service (IVS) committees and is a member of the directing board. He is also a member of the technical and scientific advisory committee of the Spain-Azores RAEGE project for geodesy. Pedro Elosegui served on the steering committee for the European Union–sponsored ICE-ARC (Ice, Climate, Economics–Arctic Research on Change) program. Lynn Matthews chaired a review of global VLBI proposals for the Event Horizon Telescope Consortium. She also served as a proposal reviewer for the Giant Metre Wave Telescope and refereed manuscripts for several major journals. Victor Pankratius participated in an advisory role in the March 2015 NSF "Intelligent and Information Systems for Geosciences" workshop in Washington, DC. Pankratius also served on the scientific organizing committee for the 2016 International Astronomical Union Astroinformatics Symposium and gave a keynote speech on computer-aided discovery in astronomy at the 2015 "Multicore World" conference.

Colin Lonsdale served on the Murchison Widefield Array (MWA) board and on the EHT Consortium interim board. Shep Doeleman served as a member of the National Radio Astronomy Observatory user's committee and the Atacama Large Millimeter/submillimeter Array (ALMA) North American Science Advisory Committee. Larisa Goncharenko's activities include participating in NSF review panels, serving as an International Space Science Institute (ISSI) team lead for whole-atmosphere studies, chairing conference sessions, and leading a NASA Living With A Star Focused Science Topic team working in whole-atmosphere coupling. Shunrong Zhang is a lead for ISSI Beijing studies of the upper atmosphere and a key member of a NASA Living With A

Star Focused Science Topic team examining the topside ionosphere. 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 continue on the mission science team for the NASA Van Allen Probes twin spacecraft mission launched in late August 2012, and they are co-authoring multiple chapters in a major ISSI text focused on the scientific foundations of space weather. Anthea Coster served on multiple committees in 2016, including a NASA heliophysics graduate fellowship board and the AGU Africa Space Science Award Committee, and was elected a fellow of the Institute of Navigation in January 2016. She also served as a program organizer for the Beacon Satellite Symposium. Phil Erickson co-convened major CEDAR/Geospace Environment Modeling program and AGU sessions on mid-latitude dynamics, served on the NASA ICON/GOLD Geospace Observations and Analysis Opportunities science and program committee, and was a guest editor for AGU's Journal of Geophysical Research: Space Physics (and the European Geosciences Union's Annales Geophysicae.

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 underwent a successful major upgrade through a Lincoln Laboratory program and now represents a world-class combination of aperture size and surface accuracy. Astronomy instrumentation on the telescope has been upgraded and modernized, 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 uses two large antennas, 46 meters and 67 meters in diameter, to study the Earth's upper atmosphere via incoherent backscatter techniques.
- A 12-meter-diameter radio telescope located at the 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. Based on design principles developed at Haystack and brought into operation primarily by Australian funding and institutes, this innovative instrument has proven remarkably scientifically productive, with many refereed journal articles each year reflecting an extraordinary return on a modest financial investment.

The array has particular value and relevance to Haystack scientists in the arena of solar, heliospheric, and ionospheric research. Through a grant from the Air Force Office of Scientific Research (AFOSR), efforts continue to use the MWA for remote sensing of magnetic field orientations in coronal mass ejections. This is done via polarimetric imaging techniques, for which the MWA is uniquely well suited. Progress on this project is strong, with the establishment of data reduction pipelines capable of generating millions of high-fidelity solar images. The MWA has collected over 2 petabytes of solar data to date, of which only a tiny fraction has been processed. The aim of the AFOSR-funded effort is to help develop a capability for reliably predicting major geomagnetic storms and allowing at least 24 hours of advance warning for potentially hazardous conditions.

Building upon the demonstrated success of the MWA concept pioneered by Haystack, the Observatory continues to develop next-generation low-frequency array technologies through the RAPID (Radio Array of Portable Interferometric Detectors) project in collaboration with Cambridge University and NASA's Jet Propulsion Laboratory. The RAPID work is supported by NSF and is closely synergistic with other Haystack projects. The project is creating a technical foundation for a range of applications such as next-generation incoherent scatter radar designs and adaptations for different antennas covering a broad range of frequencies.

The RAPID system consists of a large number of individual broadband antenna elements configured as an interferometric array. The antennas operate from 48 to 615 MHz and are a variant of the low-frequency SKA antenna developed at Cambridge. Individual RAPID antennas are equipped with a solar-powered high-performance digital data capture system, allowing each antenna to autonomously capture raw voltage data to local storage for subsequent downloading and processing. Deployments can be made to arbitrary locations with no site infrastructure requirements, supporting a wide variety of scientific applications. The initial build of the RAPID system will comprise approximately 60 antenna units, and the system is highly scalable. Additional funding is being sought to expand the size of the build and help drive down unit costs. There has been major progress in the development and prototyping of the system, and the design has been brought close to its final form. Full system prototyping and array buildout are scheduled for 2017.

The flexibility of RAPID and its ability to sample radiation across an arbitrary aperture allow a broad range of novel and important scientific investigations provided that the signals are sufficiently strong to be studied using the relatively modest effective collecting area offered by tens of small antennas. Among the initial science targets are irregularities in the ionosphere illuminated by radio and TV station transmitters or dedicated ionospheric radar transmitters, the synchrotron radiation from relativistic plasma permeating the interstellar medium of our galaxy, intense pulses of radiation associated with subatomic particle showers triggered by high-energy cosmic rays, and high-resolution imaging of a rich set of radio emitting phenomena in the solar corona. The project broadens and deepens links between different parts of Haystack, creates synergies, and strengthens the Observatory's technical foundations.

High-Frequency VLBI

The Event Horizon Telescope is a millimeter-wavelength VLBI array used to observe and image the supermassive black hole in the center of our galaxy (Sagittarius A*, or Sgr A* for short) as well as the one in the center of the nearby giant elliptical galaxy M87. The EHT has successfully observed these sources nearly every year since 2007 and has shown that there are compact emissions in the sources within several Schwarzschild radii of the central black hole. Technical enhancements through the years have led to progressively better data along with a concomitant increase in scientific impact.

One of the EHT group's goals is to obtain observations in April 2017 suitable for producing images with enough resolution to detect the black hole shadow predicted by general relativity. Activities at Haystack have been focused on the improvements necessary to image these black holes.

The most significant addition to the collection of EHT observatories is the Atacama Large Millimeter/submillimeter Array in Chile. The ALMA array consists of more than 50 dishes, each 12 meters in size, located at one of the driest sites on the planet. Haystack leads the ALMA phasing project, which has built a system to combine the signals from each of the ALMA telescopes to create the most sensitive millimeter VLBI site on the planet. The hardware and software for the project are complete, and initial commissioning observations demonstrate that the system is ready for shared-risk observations. As a result, ALMA has agreed to offer the ALMA phasing system for use in 1.3-mm and 3.5-mm VLBI networks in its next observing cycle, with VLBI observations scheduled for April 2017.

Another important improvement to the EHT is the widening of observing bandwidths at existing EHT sites, resulting in data with a higher signal-to-noise ratio. Bandwidths have been increased in part due to the development and deployment of digital backends and very fast data recorders capable of scattering data across large banks of hard drives. In 2015 we quadrupled the data rate of the EHT to 16 Gb/s, and in 2016 we doubled it again to 32 Gb/s. The data volume from an experiment can be large, easily exceeding a petabyte. To handle this large amount of information, we have also expanded the Haystack correlator, which processes the data recorded at all of the sites to produce a much smaller and more manageable data product for further analysis. We are currently analyzing these data sets for the dual purpose of science utilization and setting up the data reduction pipeline for 2017 and beyond.

The Haystack EHT group has been busy interpreting data and publishing science papers. Polarization data indicate that the magnetic field threading the plasma in the inner accretion flow of Sgr A* is partially ordered and exhibits variability on intra-hour time scales. Nevertheless, the 1.3-mm emission from the accretion flow is persistently asymmetric over time scales of years, perhaps due to the viewing geometry of the accretion disk. The rapid variability associated with Sgr A* poses challenges to imaging the source with Earth-rotation aperture synthesis, but this variability can be mitigated to produce an average image, which is important for testing general relativity by measuring the size of the black hole shadow. To produce a high-fidelity image, Haystack researchers are exploring modern imaging techniques that offer the promise of finer angular resolution than traditional imaging methods for radio interferometry. The

Haystack group also studies Sgr A* at longer wavelengths in order to provide a context for high-resolution EHT data.

Haystack participation in the EHT project is funded by NSF through a Midscale Innovations Program award, augmented by a Major Research Instrumentation Program grant for ALMA phasing, and multiple ALMA development awards. Another recent award from NSF will support research on radio jet physics in the sources used for EHT calibration, employing both data from the EHT itself and VLBI arrays at lower frequencies.

Consistent with guidance outlined in the February 2016 report of the Visiting Committee, the Haystack director has remained deeply involved in the development of a formal collaborative structure governing the far-flung and complex EHT international project. The resulting collaboration document is undergoing a final legal review before a formal signature.

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 (EoR). EDGES is a collaboration between Haystack and Arizona State University, with the work at Haystack led by Alan Rogers. Instrumentation consisting of wideband dipoles and spectrometers covering 50–100 MHz and 100–200 MHz has been deployed at the Murchison Radio Observatory in western Australia, and this equipment has undergone multiple cycles of refinement in order to improve measurement accuracy.

Progress on these systems has been steady, with recent data approaching levels necessary for detection of the sought-after signals. Early efforts focused on high-precision post facto fitting of the spectral response of the system, while more recent work has pivoted to developing a deeper understanding of the instrumental effects, ameliorating them through a variety of physical modifications, and thereby reducing the number of free parameters needed to fit the data. A new proposal was submitted to NSF to continue this cutting-edge work.

Astrophysics Research

Lynn Matthews has been leading two programs studying radio emissions from nearby stars. The first employs spectroscopic imaging observations of the 21-cm line of neutral hydrogen to trace the extended mass-loss histories of dying, Sun-like stars known as asymptotic giant branch (AGB) stars. Data obtained from the Very Large Array (VLA) have revealed highly extended (parsec-scale) hydrogen emissions around a number of AGB stars, as well as clear signatures of the interaction between these stars and their interstellar environments. Evidence of gaseous ejecta has also been discovered in association with two Cepheid variables, consistent with significant mass occurring during the Cepheid evolutionary phase.

The second program (in collaboration with Mark Reid of the Harvard-Smithsonian Center for Astrophysics and Karl Menten of the Max Planck Institut) uses high-resolution imaging of radio continuum emissions obtained with the VLA to study the "radio photospheres" of nearby AGB stars. The observations resolve the stellar disk, showing not only that AGB stars have non-spherical shapes but that their shapes appear to evolve on time scales of several months. The data also reveal evidence of brightness non-uniformities on the stellar surface, consistent with the presence of giant convective cells.

Colin Lonsdale continued his research as part of a team investigating a highly selected sample of cosmologically distant, powerful active galaxies. He conducted high-resolution radio observations using the Very Long Baseline Array, the VLA, and the MERLIN array in the United Kingdom to look for signatures of strong interactions between powerful radio jets and a dense, turbulent interstellar medium in the host galaxy. Such interactions are poorly understood yet are central to the evolution of galaxies and the role of black hole accretion in the energetics of the universe.

37-Meter Telescope

Work continued to reestablish a research-grade suite of astronomy instrumentation on the iconic 37-meter telescope. Since the upgrade of this instrument a few years ago by Lincoln Laboratory with Air Force funding, the formidable potential of the telescope for high-quality astronomical studies at millimeter wavelengths has been widely noted. With a root-mean-square surface accuracy of 75 microns, combined with fast slewing, highly accurate tracking, and excellent angular resolution provided by the large aperture, it is clear that the Haystack 37-meter telescope can once again be competitive in terms of astronomical science on the world stage.

Discretionary funds have been used to bring the K-, Q-, and W-band receiver systems up to a level sufficient for convincing capability demonstrations. A dual polarization signal path has been established, delivering roughly 14 GHz of bandwidth to intermediate-frequency conversion and digitization systems on the ground. A forward-looking architecture for a powerful spectroscopic capability has been implemented and successfully tested. This involves digitization on a commercial card, with the digital data ingested by a computing system equipped with a graphics processing unit (GPU). Since the spectrometer then consists of software running on the GPU, it can be made arbitrarily fast and arbitrarily high spectral resolution with a minimum of development effort simply by adding more capable computing infrastructure (e.g., more and faster GPU engines).

The initial system is limited to 200 MHz of radio frequency (RF) bandwidth but can be expanded to 1 GHz or more with extremely modest hardware investments. Demonstration results from this system can then be used as justification in a funding proposal, with the aim of replicating the hardware and covering much or all of the available 14 GHz of RF bandwidth. This would be a scientifically powerful system with bandwidths comparable to or greater than any competing instrument around the world.

In the longer term, the telescope could be equipped with a multi-pixel camera, greatly multiplying its survey speed. With such a system, combined with high angular resolution, a high-quality primary beam, and an abundance of available overnight observing time, the Haystack 37-meter telescope would occupy a valuable niche in observing capabilities for a broad range of single-dish astronomy projects.

The 37-meter telescope will also be a valuable asset for high-frequency VLBI arrays. In preparation for participation in observing sessions with such arrays, a hydrogen maser was integrated into the receiving system, and phase stability measurements were conducted to validate system performance.

VLBI Geodesy

The Haystack geodetic VLBI group continues to develop 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 (NSGN). NSGN is an integrated, multi-technique network of stations each comprising a VGOS and next-generation satellite laser ranging systems that are co-located with a global navigation satellite system and a DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) system. The NASA Space Geodetic Network is the centerpiece of the NASA Space Geodesy Project, and 10 space geodetic stations are expected to be deployed over approximately the next 10 years.

The Haystack-developed VGOS system involves a fast-slewing 12-meter antenna coupled with a cryogenic broadband feed and receiver system, intermediate-frequency conversion electronics, a field-programmable gate array–based digital backend system, and a high-capacity, high-speed disk-based Mk6 recording system. Also central to the project goals are advanced software correlation capabilities and post-processing, diagnostic, and quality control software systems.

Over the past year, Haystack met a number of critical milestones in preparing for the operation of a VGOS system at the Koke'e Park Geophysical Observatory (KPGO) on the island of Kauai, including a critical design review, a system integration review, and a pre-shipping review. These activities culminated with the successful installation of KPGO in January 2016. Haystack has also successfully passed and met more recent reviews and milestones such as a signal chain acceptance review and the commissioning phase of the KPGO system. This clears the way for the upcoming operations readiness review in September 2016 and the transfer of scheduling and operations to IVS later in the year, making KPGO the world's first operational VGOS system.

Haystack is already preparing for the next two NASA VGOS systems, in Texas and Tahiti. Components of the Haystack-developed system are attracting strong interest from international partners including the Norwegian Mapping Authority, which is installing a twin VGOS-compatible system on the island of Svalbard in the high Arctic, and the Onsala radio observatory in Sweden, which is installing a similar twin-antenna system.

The first fully operational VGOS system installed at Koke'e Park on the island of Kauai. The new VGOS antenna is on the right.

As an essential part of the development effort, prototype VGOS systems were installed at the Goddard Geophysical and Astronomical Observatory in Maryland and on the Westford 18-meter telescope at Haystack, providing a VGOS testbed baseline. There were 18 VGOS test sessions conducted in 2015–2016 on this baseline and another three demonstrations involving mixed-mode observations between VGOS at one end and traditional S/X systems at the other end. In addition, Haystack is coordinating a series of observing sessions with Germany, Spain, and Japan to ensure broadband compatibility across the various VGOS systems.

In addition to the above-noted Westford telescope operations, Haystack continued its routine support of geodetic VLBI through data quality monitoring, various types of network support, and support of UT1 monitoring.

VLBI Technology Development

Haystack has led the way in VLBI technology for decades, with state-of-the-art analog and digital backend systems, high speed instrumentation-grade tape recorders, custom hardware correlator systems, and highly tuned post-processing software. With the advent of high-speed digitizers, high-capacity and high-speed spinning disk drives soon to be superseded by solid state drives, and the development of software correlators running on commodity hardware, the VLBI technology development frontier has shifted to new areas. Performance areas that once were key bottlenecks for scientific productivity and required highly customized and costly solutions now can be addressed more economically as industry invests in technologies to record and process ever-increasing volumes of complex information.

The falling cost of high-speed data handling systems has been aggressively and successfully exploited to drive VLBI bandwidths to unprecedented levels, soon to reach 64 Gbits per second in support of high-frequency astronomical VLBI. This has been achieved long before the availability of suitable off-the-shelf commercial systems. However, looking beyond the next few years, the need to develop custom systems to support such improvements will decline.

Accordingly, Haystack has embarked on a forward-looking series of internal workshops aimed at identifying technologies and techniques with the potential to revolutionize VLBI systems and bring new levels of flexibility and measurement accuracy to the geodetic VLBI community. This effort is intended to help shape the vision for systems that will succeed the VGOS network in a manner that leverages and overlaps with an installed base of VGOS systems around the world. Among the topics being explored are lower-cost antennas, improved cryogenic systems, novel observing strategies, better methods for estimating water vapor in the troposphere, correlation systems that are easier to port and maintain in the face of evolving computing platform architectures, and more sophisticated data reduction and analysis approaches.

Haystack regularly participates in the annual International VLBI Technology Workshop, and the 2016 meeting in October will be hosted at the Observatory. Haystack seeks to establish a leading role in coordinated international efforts to pursue a joint vision for advanced future systems in the service of geodetic science.

Geodetic Science

The geodesy group leader, Pedro Elosegui, is seeking to build a strong geodetic science research program at Haystack. Initially, the group's efforts are focusing on the cryosphere, including precision measurements of ice movements via deployable GPS-based systems. Such work is relevant to the high-profile topics of global climate and sea level change. A specific initiative is the NSF-funded development of an air-droppable penetrator system intended to allow dense instrumentation of Antarctic ice shelves with geophysics-grade broadband seismometers and geodetic-quality GPS receivers (to monitor the spectral response of the shelves to ocean forcings) as well as satellite communications for near-real-time data downloading to a central repository. Such a system would eliminate the challenging logistics currently faced in obtaining such measurements, replacing those logistics with efficient helicopter-based deployment. The manner in which the ice shelves behave and the mechanisms by which they collapse, "uncorking" land glaciers and triggering major ice sheet collapses and associated sea level rise, is a critical cryosphere-ocean research topic. Elosegui and Michael Hecht taught a two-semester capstone course in the Department of Aeronautics and Astronautics (AeroAstro), in collaboration with the AeroAstro faculty, in which the deliverable was a penetrator system design developed with student assistance. Such penetrator technology has broad potential applicability, well beyond the initial application to Antarctic ice shelves.

Elosegui has also participated in a study based on GPS data in the Sumatran subduction zone, investigating the phenomenon of slow slip earthquakes in collaboration with researchers from the Nanyang Technical University in Singapore.

In collaboration with Professor Tom Herring of the Department of Earth, Atmospheric and Planetary Sciences (EAPS), Victor Pankratius is leading a NASA-funded project to study land deformation phenomena using a range of complementary data sources and advanced data fusion and informatics techniques. A software infrastructure has been developed to provide meaningful machine assistance in the interpretation of a wealth of diverse data sets that would otherwise be much more challenging to interpret.

Atmospheric and Geospace Science

Millstone Hill Geospace Facility Ionospheric Radar Operations

The Millstone Hill UHF megawatt-class radar system, part of the Geospace Facilities program of the NSF Atmospheric and Geospace Sciences (AGS) division, completed approximately 700 hours of observations between September 2015 and August 2016 in accordance with the nominal yearly support level provided by its operations grant. Approximately 40% of these hours were internationally coordinated through the World Day program, with the remainder of the observations used for ionospheric studies particular to the mid-latitude location of Haystack. The facility, with its unique observational field of view spanning the full range of mid-latitude and sub-auroral geospace physical features and processes, is 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, whole-atmosphere coupling studies focusing on stratospheric warming effects reflected in the ionosphere, internationally coordinated topside ionospheric studies, 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 Sciences Group (ASG) at Haystack conducts scientific research into many aspects of the geospace environment. Similar to prior years, the primary focus in 2015–2016 centered on four main areas: radiation belt physics (outer radiation belt loss and acceleration), upper-atmosphere long-term trends and climate change (ionospheric secular trends), whole-atmosphere coupling effects (neutral and ionized atmosphere interdependency, including triggered wave activity), and sub-auroral electrodynamic features and associated ionospheric climatology.

Radiation Belt Physics

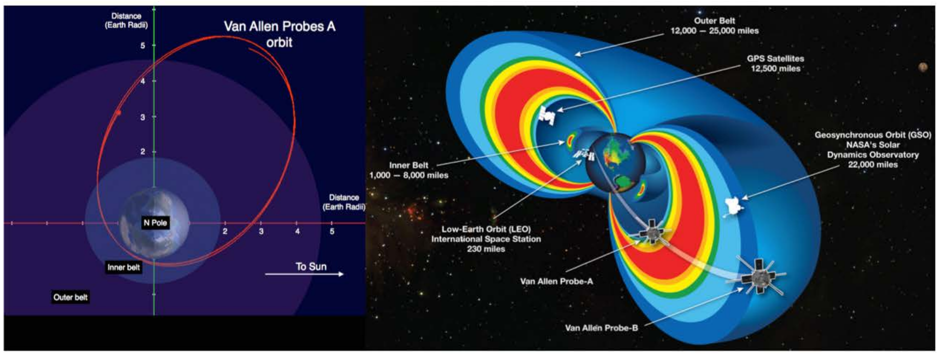
John Foster and Phil Erickson, with collaborators across the observational and modeling community, continue to be very active users of data from the dual NASA Van Allen Probes spacecraft, carrying a comprehensive suite of sensors for high-energy particles along orbits that swing through the radiation 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 multi-scale investigations of near-Earth space and its response to energy inputs. These studies, involving leading international theoretical magnetospheric physicists, are showing that the time scale for outer radiation belt dynamics, thought for decades to be a span of days to months, is much more rapid and that nonlinear processes are at times primary agents of change. In particular, the high coherence of nonlinear wave-particle interactions can result in medium-energy “seed” electrons being accelerated to energies beyond relativistic levels (approximately 500 keV) in fractions of a second.

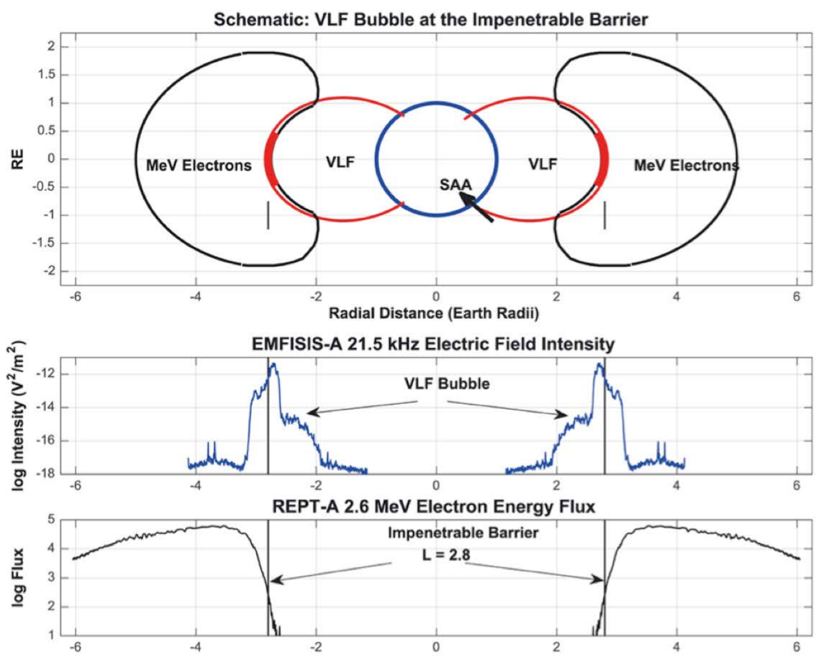
Along with these super-rapid acceleration pathways, a fascinating “barrier” to the inward penetration of newly created relativistic outer belt electrons during strong geomagnetic storms has also been discovered just inside a distance of three Earth radii from the planet’s center, even though conventional wisdom held that the edge should occur at a much closer distance. Outer belt particles are of intense interest to the space weather community, as they represent “killer electrons” that can seriously damage or destroy spacecraft assets. Recent studies are also unexpectedly implicating the existence of human-generated powerful transmitter signals at very low frequencies (intended for naval submarine communications) as a factor in multi-step storm-time pathways that maintain the inward “barrier” location.

Actively involved in all of these studies are wave and particle observations across a broad range of energies (eV to MeV), along with system-scale magnetosphere-ionosphere coupling studies using the Millstone Hill radar as well as riometers, GPS total electron content measurements, and data from multiple spacecraft in the NASA

Great Observatory. The Haystack multi-view system-level scientific perspective on these topics, which at the core involve both ground-based and in situ observations, is unique within the Van Allen Probes science community and is fundamental to these new insights. The emerging results have the potential to reframe the field's paradigms for terrestrial radiation belt dynamics. Also continuing separately are studies on the effects of low-altitude, cold plasma redistributions of ionospheric origin on dayside magnetic reconnection, a fundamental regulator of solar wind energy input to the magnetosphere.

Results from these investigations have already been published this year in several high-profile articles in journals such as Nature, and four to six more publications are under way.





The Van Allen radiation belt probes form part of NASA's Great Observatory. At top left is a schematic of a typical orbit for the mission. The approximately nine-hour repeating orbit provides data around three times per day on the inner and outer radiation belts to about five to six Earth radii at a range of local times. Note that the radiation belt positions are highly variable in space and time. The "barrier" to inward motion of the electrons in the outer radiation belt (bottom panel) coincides with the outward propagation boundary of ground-based naval very-low-frequency transmitters (middle panel).

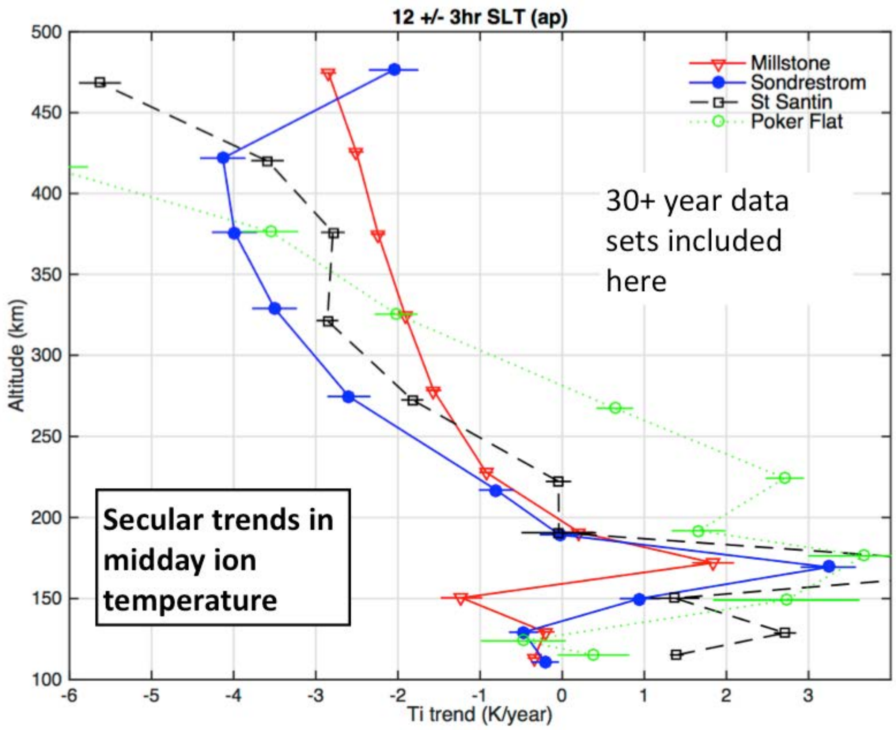
Lower- and Upper-Atmosphere Coupling Studies

Larisa Goncharenko and her 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 its effects, the root causes and prime energy pathways of whole-atmosphere coupling remain poorly understood. Recent research has focused on interhemispheric coupling signatures that globally couple the neutral and ionized atmosphere from pole to pole, extending from the stratosphere (40–60-km altitude) all the way to the ionosphere (more than 90–100-km altitude). In particular, emerging new theories of the nonlinear interactions of planetary waves and tides are predicting that, for example, selected signatures in velocity and energetic particle flux are tied directly to planetary wave-tide mixing processes. Progress in this field is fundamentally enabled by and aligned with Haystack approaches to observational data sets, coupled tightly to simulations (e.g., the TIMEGCM model series at the National Center for Atmospheric Research). Observations informing this line of investigation are heavily supported by NSF long-term measurements carried out via the Millstone Hill ionospheric radar and the entire NSF incoherent scatter radar chain. Sub-Auroral Climatology and Disturbance Investigations

Long-term Millstone Hill incoherent scatter radar observations, combined with an easy means of access through the Haystack-authored (and NSF community standard) Madrigal distributed database system, are a valuable resource for comprehensive community studies of plasma drift variations. This work is conducted as a function of a number of variables—season, local time, magnetic index, solar wind drivers—during conditions of low to medium magnetic activity. 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. Comparisons against this emerging climatology are now bearing fruit at Haystack and in the community in the form of unique disturbance studies that leverage the extensive background ionospheric information. For example, Haystack researchers have discovered a fundamental alteration of horizontal neutral wind patterns during storms due to unanticipated Coriolis force effects combined with fast ionospheric flows at sub-auroral latitudes, known to be driven by magnetosphere-ionosphere coupling. These efforts are led by ASG personnel, including Shunrong Zhang, using a series of modeling codes and observational studies.

Upper Atmospheric Climate Change and Long-Term Trends

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 approximately 30 years of ionospheric radar measurements at Millstone Hill and other NSF radar facilities, provides a direct monitor of the thermal status of the upper atmosphere. Recent results show unexpected and substantial ionospheric cooling trends with large altitude and time variations. Causes of these trends are still under intense study, as CO2 increases are insufficient to explain them using the best models available. Atmospheric gravity wave activity from near-ground orographic sources such as mountains appears to be a leading candidate, along with possible (and previously undiscovered) circulation patterns. Observational collaborative community studies led by Shunrong Zhang and John Holt at Haystack are thus continuing to provide a considerable challenge to state-of-the-art atmospheric dynamics models. As in previous years, several publications have been completed and more are in preparation.



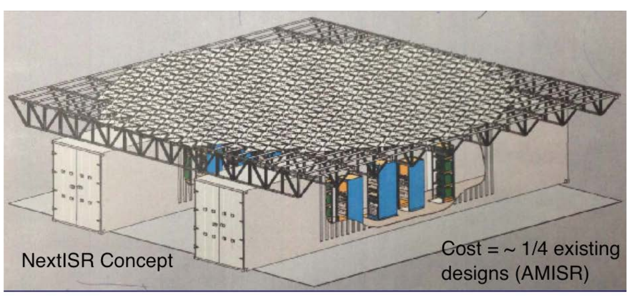
Secular trends in ion temperatures within the F region of Earth's ionosphere are similar according to data records at multiple ionospheric radar systems. The data show a change near 200-km altitude from warming over time to cooling over time driven by complex wave deposition of energy at different altitudes. (Courtesy of Shunrong Zhang)

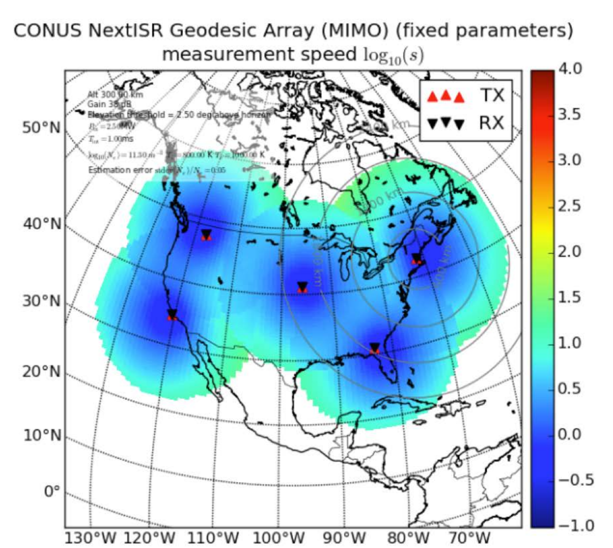
Geospace Technical Initiatives

The Atmospheric Sciences Group continued to implement a forward-leaning technical development strategy for long-term program health, with very active efforts in the development and implementation of a range of innovative hardware and software systems for geospace science. These efforts include the RAPID array described earlier, 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 of these initiatives are guided by an overarching Haystack vision of current trends in the field of radio remote sensing and how they can be optimally applied to the geospace environment in ways that align with community science investigations while simultaneously enabling discovery-class activities.

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 the equatorial ionosphere, respectively. On a longer time scale, RAPID-based technology is intended to provide a foundation for 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 is also interconnected to the Millstone Hill Geospace Facility, with 10% of facility support being redirected to RAPID technical efforts.

RAPID flexibility has already borne fruit in a US Air Force Small Business Innovation Research (SBIR) award, presented jointly to Haystack and Diversified Technologies Inc., that supports design and demonstration activities for an 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 data sets for science discovery. Phase 1 SBIR design and modeling activities were completed in early 2016, and Haystack was the only successful awardee for Phase 2 efforts. This work will take place over a period of approximately two years, and the goal is to produce a hardware and software small-scale demonstration VHF ionospheric radar array at the Haystack complex. Technical developments in this project have considerable reuse potential for future programs and proposals, such as a complete Millstone Hill replacement ionospheric radar or a potential US Air Force network of ionospheric radars for remote sensing.





Top: Concept drawing of a low-cost large aperture ionospheric radar with full electronic steering, produced as part of the Air Force SBIR project. Bottom: In a different geodesic configuration, radars of this class are more expensive but can cover the entire continental United States with only five multi-face systems. This diversity is a fundamental feature of Haystack advanced geospace radar designs and architectures.

The Mahali project, an NSF INSPIRE-funded grant led by Victor Pankratius, is another example of synergy in technical approach, and it continues with vigorous activity. This program is targeting low-cost expansion of GPS-based total electron content 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. A successful fall 2015 field campaign at the Poker Flat Rocket Range near Fairbanks, AK, used Mahali-produced solar-powered, self-contained instrument housings. The results produced detailed GPS total electron content multi-scale observations that are being jointly analyzed by Boston University and Haystack. A second extended Mahali field deployment campaign, centered at Haystack and targeting multi-scale traveling ionospheric disturbances, is under preparation for early 2017. Some of the Mahali equipment is closely related to, and derived from, RAPID subsystem development.

Efforts in cloud infrastructure and database development form the underpinnings of major Haystack technical advances in radio science for geospace, and these efforts continue to be centered on remote sensing instrument data capture and the Madrigal distributed database system. Madrigal, the upper atmospheric observational community standard repository centered at Haystack under NSF facility support, serves as the field's long-term data repository and provides uniform software interfaces easing data discovery activities. Madrigal software has moved to release 3.0 and is now using standard HDF5 platforms that will easily migrate to future cloud-based architectures. Once again, the number of instruments supported by the Madrigal database grew at a steady rate of 25% to 30% in 2015, and there were 208 unique users from over 110 separate community institutions. In 2016, data holdings increased by more than a factor of 10 in volume as a large set of historical and recent particle and wave measurements were incorporated from the Defense Meteorological Satellite Platform constellation. 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.

Technical developments in geospace at Haystack also focus on networked clusters of remote sensing platforms, wherein software radar and other information extraction patterns for analysis are implemented as a network of cloud-based processing engines in a manner designed to improve discovery within the necessarily sparse data sampling of current geospace sensors. To improve the situation further, the Haystack group continues to push forward in development of low-cost distributed remote sensors with a wide variety of applications. For example, a recent Major Research Instrumentation Program grant to Haystack in conjunction with Leibniz-Institut Für Atmosphären Physik (Germany) will support development of a redeployable spread spectrum multiple-input and multiple-output (MIMO) meteor radar with greatly increased measurement speed, multi-static capability, and a potentially disruptive technology for the long-established meteor radar field that monitors neutral winds at an altitude of approximately 100 km.

The same RAPID spinoff platform has been used with large facility incoherent scatter radars such as Arecibo, Sondrestrom, and Millstone Hill, and Sondrestrom and Arecibo have adopted the software radar platform as part of their core operational systems. Software radar innovations are also used with space-borne coherent Doppler beacons for tomography-based widefield ionospheric characterizations. The flexible software nature of these instruments maximizes reuse and allows a large diversity of applications without requiring a total instrument redesign.

To provide an information backbone for these new and existing radio sensors, large programs continue to progress in the area of software radar and cloud-based processing. Efforts such as the SBIR next-generation ionospheric radar and the MIMO meteor radar include supporting development in 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 requiring minimal overhead 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 program interface 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 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. ASG scientists have also collaborated with emerging new Chinese ionospheric radars with unique geophysical fields of view across low and equatorial latitudes. These efforts span both technical radar and scientific investigations, and a series of visits by John Foster and Shunrong Zhang in 2015 and 2016 occurred at various locations, including a collaboration with the Chinese Academy of Sciences. These visits continue a several-year series that injects Haystack forefront science and observational insights into the emerging east Asian space science sector.

In a collaboration with Boston University professor Joshua Semeter and one of his students supported by a Millstone Hill Geospace Facility award, work continues on comprehensive 3D/4D ionospheric radar analysis during geophysically dynamic periods at high latitudes. Also, Frank Lind continues to collaborate with Professor John Sahr at the University of Washington and Professor Julio Urbina at Pennsylvania State University 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. In addition, Lind and Anthea Coster are collaborating with Professor Jim Labelle at Dartmouth College in connection with distributed remote sensing systems and networks involving, for example, passive radar analysis of long-path scatter from terrestrial AM broadcast stations.

Local connections to undergraduate-focused teaching institutions have been forged with Professor Allan Weatherwax, 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 close 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. Merrimack College is keenly interested in developing initial graduate science tracks for students, and Haystack is well suited to provide immersive research experiences during student training. Initial discussions on practices and possibilities are under way.

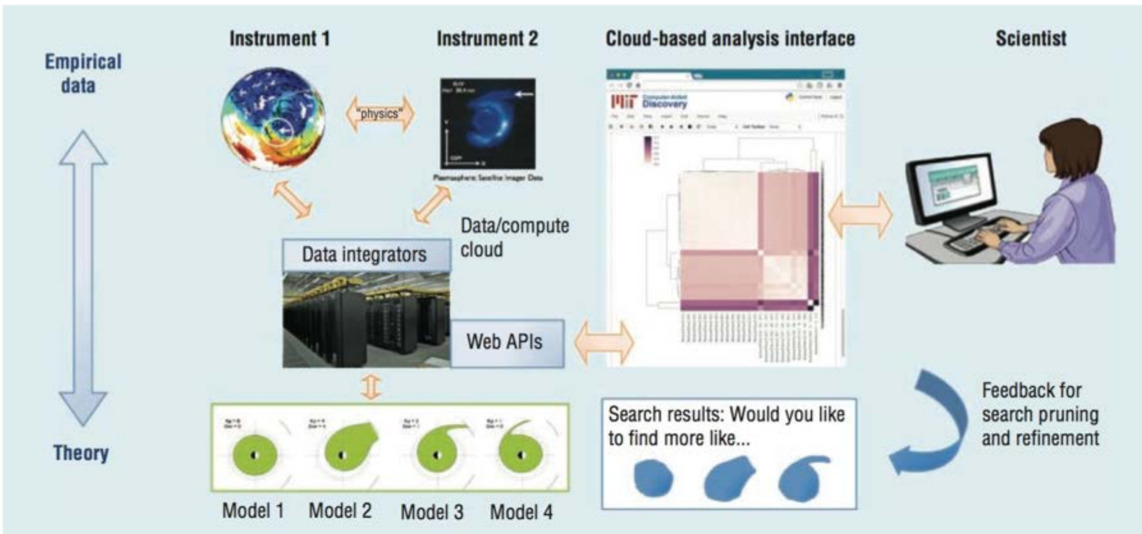
Haystack involvement in African-sector geospace work also continues. Anthea Coster is promoting the establishment of a future incoherent scatter radar to capture space weather and ionospheric variations unique to that longitude sector and is working with colleagues such as Dr. Baylie Damtie, the president of Bahir Dar University in Ethiopia. Phil Erickson's role in organizing the International Equatorial Aeronomy Symposium, held in Ethiopia in October 2015, expanded to involve multiple African scientists. Finally, several efforts are taking advantage of MIT International Science and Technology Initiatives exchange funding, including Brazilian collaborations and upcoming Peruvian collaborations in early 2017.

Portfolio Review

In 2016, the NSF Atmospheric and Geospace Sciences division completed an extensive independent review of all AGS programs, including geoscience efforts conducted by Haystack in individual science programs and the large Millstone Hill Geospace Facility award. Haystack provided extensive data input to the review and fared well in the review's conclusions. In particular, Millstone Hill was recommended as a unique facility that should continue to receive funding support for 2015–2020 (with modifications to Madrigal database support). This success was not universal across all facilities. Haystack efforts in forward-leaning technical approaches aligned well with future community directions, and a newly established "innovation and vitality" fund is an ideal target for Haystack ideas and innovations. The upcoming Millstone Hill renewal proposal in late 2017 will coordinate strategies with this AGS portfolio review, and meetings with AGS staff in fall 2016 will confirm the selected Haystack strategic directions. Of particular note, overall review strategic directions endorsed Haystack next-generation ionospheric radar development lines as a cost-effective way to upgrade legacy installations such as the current Millstone Hill UHF radar. Astro- and Geo-Informatics

A strategic addition to the Haystack staff in 2013 was Dr. Victor Pankratius, who currently is principal investigator for several funding awards from a range of different sponsors. He leads the informatics group at the Observatory, which consists of himself, five postdoctoral researchers, and two undergraduate students. 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 substantial.

The informatics approach is to merge contextual information and capacity for scientific insight, qualities associated with experienced human researchers, with 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 that can intelligently identify patterns and proactively bring potentially interesting ones to his or her attention. These techniques are particularly well suited to the type of radio science that Haystack pursues because of their large and information-rich data sets, which continue to grow rapidly in response to the plummeting costs of digitizers and digital signal processing capacity. The aim is for Haystack to play a lead role in a big data revolution for radio science and computer-aided discovery.



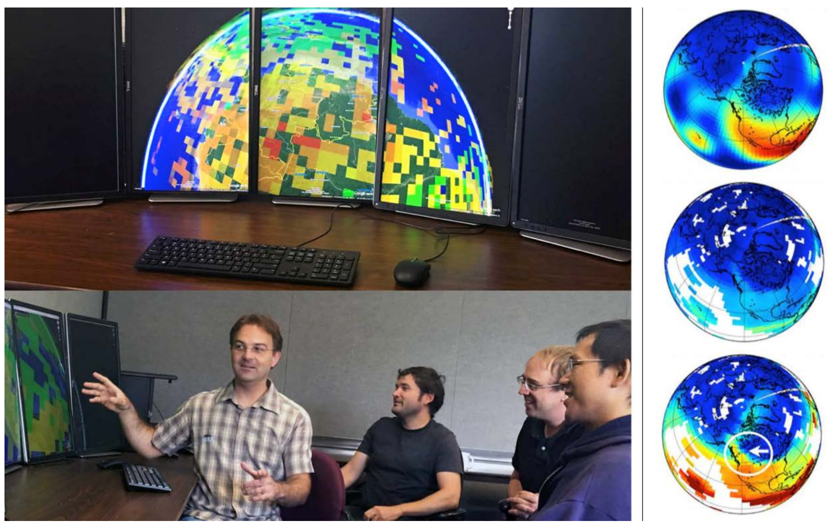
Computer-aided discovery compares empirical data sets from different sources (top row) with algorithmically defined model variants (bottom row). The matches link physical model parameters to empirically detected features and provide high-level scientific insight.

In the Mahali project (described above), the goal is to monitor space weather using ubiquitous hand-held devices such as smartphones and tablets, with GPS ionospheric observables and the built-in Internet connectivity and on-board data processing capacity of these devices.

A key effort is to create 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 on multiple data sets and identify the ones with better explanatory power. This implementation of computer-aided discovery is funded by NSF, and the approach has demonstrated successful applications in an entire spectrum of science areas, including ionospheric studies, astronomy, and planetary landing site identification for spacecraft and robotic missions.

The techniques have also been applied to the study of Earth surface deformation phenomena under a separate award from NASA and in collaboration with EAPS professor Tom Herring. This project involves fusion of GPS, InSAR (interferometric synthetic aperture radar), MODIS (moderate resolution imaging spectroradiometer), and other data. The effort has led to the discovery of novel transient inflation events in Alaskan volcanoes using 2005–2015 GPS data from the Plate Boundary Observatory. The discovered events went previously unnoticed by researchers, and computer-aided discovery algorithms helped overcome human cognitive limits in the face of growing data volumes.

The group is also working with EAPS professor Sara Seager under a Bose Foundation award, using informatics techniques to map biochemical space based on an exhaustive survey of which small molecules are made by life and how often they are made by life. This work seeks to predict which molecules are stable, volatile, and in principle detectable remotely in exoplanet atmospheres by space telescopes. Pankratius and Seager also created the first astroinformatics course at MIT and continue to involve graduate students in informatics research.



Victor Pankratius (left) and his group visualizing current conditions of the Earth's ionosphere in 3D. At right is an illustration of the same total electron content data set and how choice of workflow algorithms and parameters can affect the visibility and discovery of interesting geophysical phenomena. This is where humans can count on more efficient algorithmic support using MIT Haystack's computer-aided discovery system.

Space-Based Research and Development

While Haystack Observatory has historically provided ground-based support ranging from navigation to scientific analysis for space missions, it has not played a direct role in space technology or mission implementation since its establishment as an independent laboratory. This began to change in 2014 with assumption of leadership of the MOXIE instrument on NASA's Mars 2020 mission and subsequent forays into autonomous navigation technology (in collaboration with the NASA Innovative Advanced Concepts program) and space-based vector sensor development (in collaboration with Lincoln Laboratory).

From a strategic perspective, space science offers Haystack the opportunity to observe otherwise inaccessible parts of the electromagnetic spectrum, notably high frequency

(HF) and below; to examine ionospheric phenomena from above as a complement to measurements from below; and to extend astronomical VLBI observations to longer baselines and submillimeter frequencies. In addition, it opens up new planetary science applications to Haystack technology. Opportunities to use Haystack antennas for SmallSat and CubeSat communication are also being explored. From a programmatic perspective, space science and technology demands extensive and meaningful collaborations with both university and government laboratories. Such collaborations are expected to extend the Observatory's capability and reach across all of its research areas.

The past year has seen good progress with ongoing work. MOXIE passed its preliminary design review and is progressing well toward a critical design review. The NASA Innovative Advanced Concepts autonomous navigation study was completed, with a surprising conclusion that radio detection of millisecond pulsars is competitive with and will likely outstrip the state-of-the-art x-ray pulsar navigation methods. The vector sensor effort with Lincoln Laboratory analyzed sensitivity to multiple point sources as well as to diffuse sources and demonstrated a viable deployment scheme appropriate to a CubeSat.

Proposals for new work in the past year included development (with Lincoln Laboratory) of a miniature vector sensor for planetary radar and low-temperature spectroscopy, demonstration (with NASA's Ames Research Center and MIT AeroAstro) of a system for relative position determination in a SmallSat interferometry constellation, and development of an HF CubeSat constellation (described below). In addition, Haystack personnel were involved with the AeroAstro capstone course 16.831, which developed a prototype of a surface penetrator that has immediate applications to Haystack Antarctic geodetic science and longer-term applications as a planetary ice probe.

In 2015, in partnership with Lincoln Laboratory and campus researchers, a proposal to fly a constellation of four CubeSat spacecraft in a high-altitude orbit for HF interferometry of solar bursts was submitted to NASA. It was well reviewed in most respects, but at $6 million it proved too costly for the very modest program funds available. In 2016, a new opportunity emerged in the form of a NASA call for heliophysics explorer missions, with a cost cap of $55 million. Accordingly, a much more substantial proposal with significant science goals is being developed. Collaborators include the New Jersey Institute of Technology, Lincoln Laboratory, and campus researchers. A major Haystack responsibility for the project will be development and deployment of RAPID-based ground stations that will allow us to extend space-based measurements well into the UHF band. Haystack also proposes continuing its collaboration with Lincoln Laboratory on the vector sensor and would contribute to data processing, analysis, and scientific interpretation. In addition, the Westford radio telescope may have a key role with respect to data downlinking. The proposed array would make positional measurements of bright type II and type III solar burst emissions with far higher accuracy than past options and can be used to provide important new probes of heliospheric structures and physical processes.Research Experiences The NSF Research Experiences for Undergraduates (REU) program at Haystack has been a highly successful and rewarding activity for 30 summers, serving over 250 talented undergraduates from around the country and contributing to the training of future scientists and engineers. Since 1999, the REU program has been augmented by the

Research Experiences for Teachers (RET) program, designed to leverage professional educators to reach large numbers of high school students. The 2016 program reflected a change of emphasis for REU, which increasingly seeks the participation of more junior students, those from institutions that do not offer strong research opportunities, and those attending two-year colleges. A renewal proposal for the program submitted to NSF in 2015, targeted at students well positioned to benefit from the intense research environment at Haystack, was declined. A combination of residual NSF REU funds, NASA Space Grant funds, and other resources nevertheless enabled a vibrant 2016 summer program to proceed, with 11 highly motivated and capable students who thrived on the challenging projects to which they were assigned.

Going forward, the Observatory will continue to seek NSF funding for the REU and RET programs, but with fewer students. Haystack will maintain excellence in the summer student body by recruiting a talented mix of more senior and more junior students and establishing a guided mentoring relationship between the two groups. We will also seek to identify students from non-research-oriented institutions who are capable of fully benefiting from a Haystack research experience by working closely with trusted professional colleagues at such institutions in the New England area. At the same time Haystack will pursue financial resources for augmenting the effort, as with the 2016 program, including the possibility of hosting international students.

The 2016 class of REU program participants.

Professional and Public Outreach

Several Haystack staff members shared their knowledge in a series of guest lecture opportunities. Phil Erickson continued his annual weeklong series of lectures as part of the 2015 and 2016 Erasmus Mundus Space Masters program at the Swedish Institute of Space Physics in Kiruna, Sweden, and conducted guest lectures on plasma physics and ionospheric radar techniques at Boston University and the University of Colorado at Boulder (the latter via remote video). Also, members of the Atmospheric Sciences Group co-organized and lectured at the annual NSF incoherent scatter radar workshop, held this year at the Sodankylä Geophysical Observatory in northern Finland.

Sustained budget growth has allowed the addition of a full-time communications officer. This individual has a mandate to overhaul and modernize a wide range of now-dated outreach materials, both online and in paper form, and to coordinate and manage a variety of events at the Observatory.

Twice per year, Haystack holds an open house hosted by the director and featuring a lecture, an extended question-and-answer session, a tour of the 37-meter telescope, and hands-on demonstrations of radio science principles. These events continue to be wildly popular, with far greater demand than can be met; the May 2016 event drew 130 people despite no formal effort to advertise it. 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.

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.

Colin J. Lonsdale
Director