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 upper atmospheric observations using high-power incoherent scatter radar and 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 used 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, and key milestones have been met in the development and demonstration of next-generation measurement systems. The goal of the atmospheric science program is to understand the effects of solar disturbances on the Earth's upper atmosphere using measurements from the Observatory's radars and observations from Global Positioning Satellites, as well as deciphering the complex inter-relationships 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. 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 LL projects and installations at the field site.

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, 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, the National Aeronautical and Space Administration, and the Department of Defense.

Senior Staffing Changes

Important evolution in the composition of the Haystack Director's Office and senior staff has occurred in the past year. Alan Whitney, Associate Director, formally retired but retains a close connection to the Observatory, coming in two days per week. John Foster, Associate Director, now works half time. Shep Doeleman, Assistant Director, assumed a split appointment between Haystack and the Smithsonian Astrophysical Observatory in Cambridge, in recognition of the close collaboration on the Event Horizon Telescope (EHT) project, and the need for unified leadership across the two institutions. Michael H. Hecht, formerly of JPL, joined Haystack in 2012 as Assistant Director for Research Management, and adds extensive formal project management experience to the leadership team. Anthea Coster was promoted to Principal Research Scientist. Victor Pankratius joined the Haystack staff in January 2013, and brings strong expertise in applied computer science to the Observatory, significantly broadening our research horizons.

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 also has held multiple positions within the International VLBI Service (IVS) organization, including membership on the Directing Board. Arthur Niell serves 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 an NSF facility management review panel. Shep Doeleman is a member of the NRAO User's Committee, and is a member of the ALMA North America Science Advisory Committee. Michael Hecht served on the Mars 2020 Independent Assessment Team. Frank Lind is chair of US URSI Commission G, and also serves as chair of the technical advisory committee for the EISCAT 3D phased array radar project in Europe. Larisa Goncharenko's activities include NSF review panels, multiple CEDAR and AGU special session organization and chairing efforts. Shunrong Zhang is a member of the URSI/COSPAR working groups, and convened a CEDAR science session. 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. Phil Erickson co-convened several CEDAR sessions on mid-latitude dynamics, and serves on the NASA Measurement Techniques in Solar and Space Physics science and program committee. Anthea Coster is the 2012-2013 secretary of the Institute of Navigation's Satellite Division. She served on the 2013 National Research Council panel on HAARP and ITM physics.

Research Instrumentation

Major facilities used in Haystack's research program include:
A 37-m-diameter radio telescope used for astronomical observations and radar measurements. This telescope has undergone a successful major upgrade through a Lincoln Laboratory program, and commissioning work is nearing completion. The upgraded dish represents a world-class combination of aperture size and surface accuracy. It has been unavailable for Haystack research use during the past year.

- An 18-m-diameter radio telescope, known as the “Westford antenna”, involved in VLBI measurements of the Earth’s rotation parameters and orientation in space
- A 10-station wideband VLBI correlator used to process global geodetic and astronomical observations, and a new, high-performance computing cluster to support software correlation
- A 2.5 MW UHF radar that utilizes two large antennas, 46 m and 67 m in diameter, to study the Earth’s upper atmosphere using incoherent backscatter techniques
- A 12-m-diameter radio telescope located at Goddard Space Flight Center, used for geodetic and astronomical observations.

Radio Astronomy

Low Frequency Arrays

Haystack Observatory continued to support the Murchison Widefield Array (MWA) project during the buildout and commissioning of a 128-antenna system in outback western Australia. The array is designed for studies of the early universe during the formation of the first stars and galaxies, can provide unprecedented diagnostics of solar wind plasma conditions that will aid in space weather prediction, and is a powerful research tool for a wide variety of radio astronomy investigations in a poorly explored spectral window. Scientific operation of the MWA facility formally commenced in 2013, and Haystack continues to be a lead member of the MWA consortium. The primary scientific use of the array by Haystack scientists will be in the field of solar, heliospheric and ionospheric research. In particular, a proposal is pending with the Air Force Office of Scientific Research (AFOSR) to us the MWA for remote sensing of magnetic field orientations in coronal mass ejections. Such studies have the potential for greatly improving the prediction reliability for major geomagnetic storms, and allowing at least 24 hours of advance warning of potentially hazardous conditions.

Haystack is also leading the development of next-generation low frequency array technology through the RAPID project (Radio Array of Portable Interferometric Detectors) in collaboration with Cambridge University in the UK, and JPL. Through the links to Cambridge University, Haystack is now an associate member of the international Square Kilometer Array (SKA) aperture array development consortium. The RAPID work is supported by a MRI grant from the NSF. The array architecture is general in terms of its ability to sample the radiation across an arbitrary aperture, and in the nature of the data capture which does not limit subsequent data processing flexibility 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, creating synergies and strengthening the technical foundations at the Observatory. More details on the RAPID program are presented in the atmospheric science section of this report.

High Frequency VLBI

Haystack leads a major program focused on extending the VLBI technique to the shortest possible wavelengths to study supermassive black holes on Event Horizon scales. Earth-diameter VLBI baselines observing at 1.3mm and 0.8mm wavelengths achieve angular resolutions comparable to strong-field gravity effects that should become evident at the boundary of a black hole. A coordinated program with many international collaborators, led from Haystack and supported by a series of NSF awards, is targeted at the creation and steady growth of a network of mm and submm wavelength antennas and supporting VLBI infrastructure, collectively entitled the Event Horizon Telescope (EHT). With most technical developments needed for completion of this array already underway, the prospects for transformative observations that will impact a broad range of black hole physics are excellent.

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, SgrA*, marks the position of a 4 million solar mass black hole. Initial EHT observations resolved structure on the scale of a few Schwarzschild radii within SgrA*, which is most logically interpreted as asymmetric emission from the accretion disk surrounding the hole, as reported in the journal Nature. Later observations showed SgrA* to exhibit time-variable structures near the black hole event horizon. Theoretical work published by Haystack scientists and collaborators use the SgrA* data to considerably tighten constraints on the black hole spin, disk inclination, and orientation of SgrA*. A schematic of the environment these observations seek to probe is shown in figure 1.

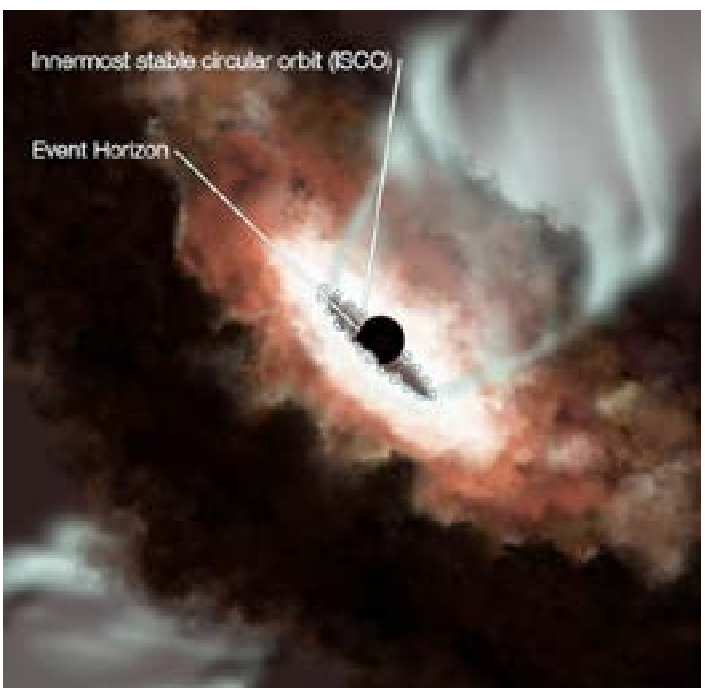

Figure 1: Artist's impression of the immediate surroundings of an accreting supermassive black hole, such as those found in the center of our galaxy and in the nearby active galaxy M87. Material spirals inward within a disk-shaped structure, and high-velocity oppositely-directed polar outflows (jets) may be present. Radio emission is expected from material outside the innermost stable circular orbit (ISCO), and will be strongly distorted in appearance by gravitational lensing. The Event Horizon Telescope (EHT) will achieve imaging resolution on scales similar to the ISCO the galactic center and M87.

The second major target of this work is the nearby giant elliptical galaxy M87, which also houses a supermassive black hole, and for which Schwarzchild radius scales are also accessible via this powerful technique. In this case, the emission is thought to arise in a jet of material accelerating away from the black hole, rather than from the accretion disk itself. Recent work on data from M87, published in the journal Science, indicate that the jet diameter is only a few Schwarzchild radii across. This finding strongly suggests that the black hole is spinning, since otherwise general relativistic effects would cause the jet launching region to be larger than the observed size.

The observing campaigns are steadily improving in both sophistication and sensitivity as the instrumentation is developed and as new telescopes are added to the EHT. Recording data rates are increasing, with the spring 2013 observations capturing 8 Gbit/sec. Telescope arrays in California and Hawaii are now being tied together to act as single, more sensitive dishes, pilot experiments are being conducted with antennas in Chile, and measurements have recently been made that are sensitive to the polarization properties of the sources. These stepwise improvements form part of a carefully risk-managed and balanced progression aimed at achieving the capability to directly image the immediate surroundings of these black holes. Funds have been successfully acquired to tie together the 60 dishes of the new ALMA array in Chile, and work is progressing toward a 2014 first light for that transformative capability for the EHT. Funds are also in hand to equip a telescope at the South Pole, further expanding the array and improving both imaging quality and angular resolution. A joint US-Mexican team also staged the first VLBI experiment incorporating the Large Millimeter Telescope (LMT) in Mexico. This successful test has paved the way for a continued collaboration with Mexican colleagues that will cover all developments needed to add the LMT to the EHT array. The array is illustrated in figure 2.

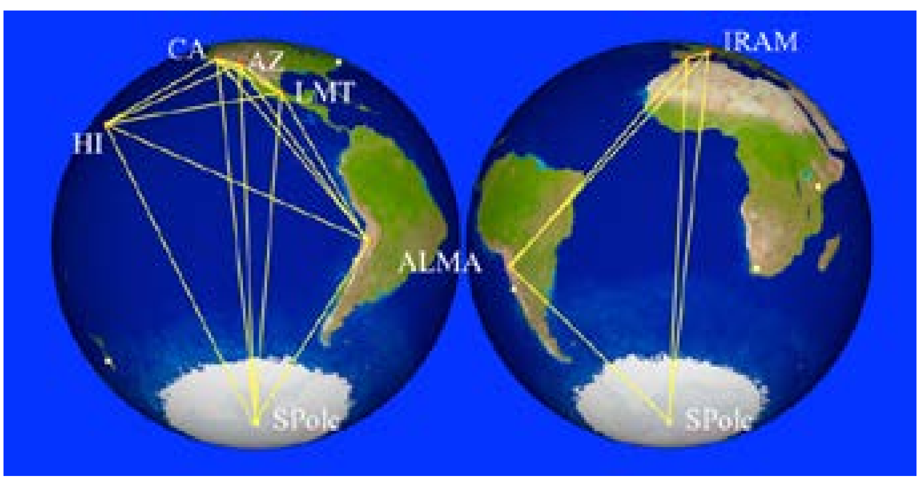

Figure 2: The telescopes of the EHT, as they are planned to exist in ~2015, as seen from one of the primary science targets, the galactic center. Most science experiments to date have used the three US sites in Arizona, California and Hawaii. Funded work is proceeding across an international team to bring all the other sites to operational status for this project, yielding a wide range of baseline lengths and orientations (yellow lines), suitable for imaging studies. The yellow dots show sites of potential future EHT telescopes, including the Haystack 37-meter dish which has a surface precision sufficient to support observations at 1.3mm wavelength.

A particularly important recent milestone is the demonstration that the EHT can reliably measure closure phase – this is a quantity that depends on asymmetric source structure, and is virtually immune to instrumental or atmospheric effects. Measurements of closure phase open the door to a variety of non-imaging source structure investigations, including periodicities in the structure due to orbital motions of persistent emission structures (should they exist) around the black hole. Polarization measurements offer similar opportunities, and in this way the scientific productivity of the EHT is expected to progress even while a true imaging capability is under development. A new postdoctoral fellow at Haystack, Rusen Lu, has published two papers within the last year that report the first 1.3mm VLBI phase measurements and use these new data to derive complex models of several quasar sources.

To date the EHT has been coordinated through Haystack via a series of NSF awards. The promise and steady success of the project have also attracted private funding. In February 2013, the EHT program received a $1.8M grant from the Gordon and Betty Moore Foundation (GBMF), part of which will underwrite high-speed recorder development at Haystack. As the scale of the effort grows, a more formal structure is required to maintain the cohesion of the increasingly diverse and engaged national and international groups. To this end, Haystack is leading the organization of technical and scientific roadmaps, and pursuing a Memorandum of Understanding between all partners. As of late 2012, a Letter of Intent (LoI) was signed by all international EHT participants, and it is anticipated that progress towards signed MOU's will result in a clear EHT organizational structure by the end of 2013. Haystack's leadership position in the EHT is due in part to a strong program of visiting scientists and students from collaborators. In the past year, the EHT group welcomed 5 visitors from Taiwan, 2 from Japan, and 3 from Mexico, all of whom worked on EHT data and algorithms during extended (>3 week) stays.

EDGES

Under a NSF award and in collaboration with the Arizona State University, work is progressing on 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). The Experiment to Detect the Global EoR Signal (EDGES) employs a single broadband dipole antenna to search for a subtle and exceedingly faint change in the overall sky brightness as a function of frequency, at wavelengths of a few meters. This challenging measurement relies on extremely precise characterization and calibration of the frequency response of the antenna and receiving system, and can only be done in a remote and radio quiet location. Techniques for precision calibration at hitherto unattainable levels have been devised, and preparations continue for an observing campaign in the Australian outback. Major improvements in current limits on the character and duration of the EoR process are anticipated from this system. The work at Haystack is led by Alan Rogers.

Astrophysics Research

Haystack staff continue to conduct a variety of independent research programs using open-access facilities maintained by the National Radio Astronomy Observatory (NRAO). Through a funded NSF award, Lynn Matthews is studying evolved stars via

21cm HI line emission, using the Very Large Array (VLA), as a unique and powerful tracer of mass loss over time from these stars. Haystack hosted an international meeting on radio stars with 50 attendees in October 2012, organized and led by Lynn Matthews. 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 (VLBA) to explore the interaction and evolutionary connection between intense star formation activity and the initiation of accretion onto a supermassive black hole.

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 these were overcome and the new dish has met a target rms surface accuracy of 100 microns, enabling high efficiency operation at millimeter wavelengths. The primary Air Force mission is long range, high resolution imaging radar at 90 GHz, a capability that was demonstrated in 2013. Haystack personnel have worked with Lincoln colleagues to install radio astronomy systems on the telescope, which have been used by Lincoln and Haystack staff to establish an accurate pointing model for the telescope via sensitive observations of celestial radio sources with precisely known positions. The radio astronomy receivers and other instrumentation are now available to help re-establish 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.

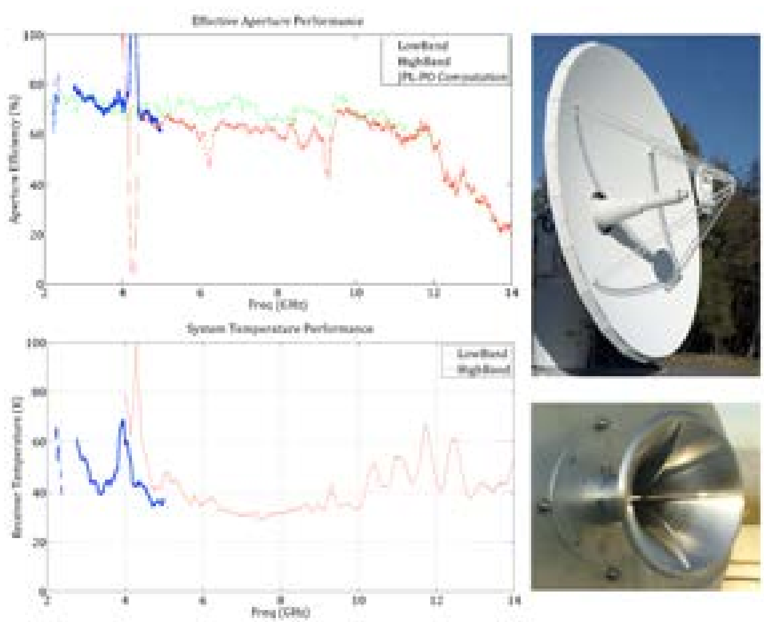

Figure 3: The GGOS antenna and receiving system, installed in Greenbelt, MD. The antenna is 12 meters in diameter (top right), and the broadband feed horn allows operation from 2-12 GHz (bottom right). The analog radio performance of the system is illustrated in the two graphs. At top left is the aperture efficiency as a function of frequency, showing that the system achieves better than 60% across almost the full range, while the bottom left plot shows that the noise temperature performance is better than 50K. The combination indicates that key system sensitivity goals have been met and exceeded.

VLBI Geodesy

Progress continues on the development and implementation of the next generation VGOS (VLBI2010 Geodetic Observing System) antennas for NASA. Both the 12m antenna owned by MIT but installed at the Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt, Maryland (figure 3), and the 18m Westford antenna at Haystack Observatory, which were described in last year's report, continue to perform well. Several sessions have been conducted in the past year to demonstrate advances in the capabilities of the new broadband systems and to evaluate the functionality of both the data acquisition systems and post-acquisition correlation and data analysis.

In October 2012 two six-hour sessions were conducted on successive days to demonstrate the first geodesy-specific capability of the interferometer. Even with conservative observing parameters, the value of the higher slew rates of these antennas compared to the larger antennas of the existing network was demonstrated by observing approximately thirty-three scans per hour, more than a factor of two higher than a standard geodetic session. As in a previous session described in last year's report, the precision of the delay for most scans was better than one picosecond, corresponding to less than one millimeter of delay. The geodetic results were quite acceptable, having a scatter of the vector baseline components of approximately one millimeter. The two sessions differed in sky coverage: on the second day sources in about one-eighth of the sky in the south were not scheduled in order to avoid pointing the GGAO antenna too close to the direction of the Satellite Laser Ranging (SLR) system. This was done in order to minimize the possibility of damage to the VLBI receiver by the aircraft avoidance radar associated with the SLR. The significance of this action is that the two techniques, VLBI and SLR, are required to be closely co-located in order to provide the greatest accuracy for the reference frame determination, but have conflicting technological requirements, a problem that must be solved for the eventual deployment of operational systems.

Two twenty-four hour observing sessions were also completed in the past year. While the next generation systems are designed with a goal of 1-mm in baseline accuracy, it is important to relate their positions to the reference frame determined by the current geodetic network composed of the generally slower 'legacy' antennas for which the position uncertainties are a factor of five or more larger. This relationship can only be achieved by concurrent observing with antennas of both generations. One session was thus devoted to the acquisition of data by the two new systems simultaneously with seven legacy antennas. Differences between the old and new data acquisition systems have created a challenge for the correlation process, which is still being addressed. The second twenty-four hour session, using only the GGAO and Westford antennas demonstrated significant progress towards two of the goals of the new system, specifically much higher observation rate and unattended operation. For this session the observing rate was almost one scan per minute, and, significantly, after initial setup the entire session was executed under computer control. This was also the first session for which the astronomical characteristics of the observed extragalactic radio sources are being determined.

Additional improvements are in progress. The housing for the feed and receiver for the Westford antenna has been redesigned to increase the sensitivity, and a new delay calibration system will be incorporated for both antennas. Changes are being made to both systems to reduce the effects of external radio frequency interference (RFI). The new systems are more susceptible to RFI because of the broad and continuous frequency coverage, 2-14 GHz. Following the installation of these improvements, observing is expected to resume in the Fall.

With funding from the US Naval Observatory a broadband signal chain similar in design to the GGAO and Westford systems is under construction for a 20 meter antenna on Kaua'i in Hawai'i. When it becomes operational, probably in Spring 2014, the antenna will provide the first long baseline (thousands of kilometers) VGOS capability.

VLBI Recording and Correlation Systems

A key VLBI data-capture system is nearing development completion. The Mark 6 VLBI data recorder, which is capable of operating at a sustained data rate of 16 Gbps, is essential for both the new VGOS geodetic system and for the Event Horizon Telescope.

Using readily available high-end computer and data electronics, the Mark 6 captures data onto an array of standard computer disks that are packaged in shippable modules of eight disks each. Software has been developed by Haystack engineers to continuously monitor the health of all disks being used in order to work around individual 'slow' or 'bad' disks that would compromise the sustained capture rate. In the worst case, small amounts of data may be lost, but this loss is usually inconsequential for the VLBI application.

The Mark 6 system is currently in beta-testing at the Westford and GGAO antennas for use in the VGOS program, and will also be used as the primary VLBI data acquisition system for the EHT, where up to 64 Gbps must be captured. Such extreme sustained data rates can be supported by four Mk6 units operating in parallel, or by using solid state disks (SSDs) in place of spinning magnetic media. The SSD option increases media cost and reduces storage capacity, but is attractive for EHT applications.

The cost of the Mark 6 system is significantly less than the earlier Mark 5 systems, even though the capabilities are several times greater. Importantly, the system can take advantage of industry-driven improvements in performance via straightforward hardware component upgrades, with little additional development. Expected availability for operational use is late 2013.

The dramatic increase in VLBI data rates enabled by the Mark 6 system requires that correlation capabilities keep pace. As reported a year ago, the era of custom-hardware VLBI correlators is ending as off-the-shelf computer hardware has become progressively and rapidly more capable. Haystack Observatory has invested in the DiFX correlator, which is a software program running on a high performance computer cluster, and is developing and extending its capabilities to support both the VGOS and EHT programs. The legacy Haystack Mark 4 hardware correlator, which was developed in the 1990s by an international consortium including Haystack for use in a number of U.S. and European projects, was retired in late June 2013, and all correlation at Haystack has now shifted to the new DiFX correlator.

Atmospheric Science

Radar Operations

The Millstone Hill UHF radar system executed slightly over 1000 hours of observations, the nominal amount supported by the NSF Cooperative Agreement with the Geospace Facilities program of the AGS division. These experiments were divided between a regular program of internationally coordinated World Day observations, and site-specific or regionally coordinated experiments measuring characteristics of the midlatitude and subauroral ionosphere, thermosphere, and plasmasphere. As in previous years, the space science community made heavy use of Millstone Hill as a NSF Geospace Facility instrument, with external users from a number of institutions. Science investigations concentrated on mid-latitude synoptic ionospheric plasma profiling, long duration probing of planetary wave and stratospheric warming effects coupling the lower, middle, and upper atmosphere, conjunction experiments exploring magnetosphere-ionosphere coupling with NSF cubesat missions, Van Allen Probes spacecraft and Super Dual Auroral Radar Network (SuperDARN) HF ionospheric radars, neutral atmosphere – ionosphere coupling studies coordinated with community Fabry-Perot interferometer measurements campaigns, and mid-latitude stormtime response to geomagnetic disturbances and coronal mass ejections in the increasing activity phase of Solar Cycle 24. In 2012-2013, many of these studies have directly involved graduate students and faculty members from Virginia Tech, Dartmouth College, and Boston University among others.

Research Activities

The research activities of the atmospheric sciences group at Haystack Observatory concentrated on several areas of scientific investigations in topics at the forefront of the space science community's emphasis on system science, multiscale thermosphere-ionosphere-magnetosphere coupling, and fine scale and mesoscale ionospheric perturbations.

Geospace System Science

In keeping with an increased emphasis and new System Science strategic direction in our NSF CEDAR (Coupling Energetics and Dynamics of Atmospheric Research) program, the Atmospheric Sciences Group continues its leadership role in community investigations of geospace system science. Our emphasis has been on understanding the complex coupling and feedback processes interconnecting Earth's lower atmosphere with the overlying ionosphere/thermosphere, and space plasma regimes of the magnetosphere. These science foci align well with CEDAR and NASA missions and directions in the Geospace system.

A number of key studies focus on the properties of magnetosphere-ionosphere coupling and its implications for overall geospace response. These efforts are prompted by work with datasets from the twin Van Allen Probes spacecraft launched in late August 2012, and involve a large campaign of regular Millstone Hill radar measurements during conjunction periods. Magnetic footprints of the spacecraft trajectories overlap the field of view of both the Millstone Hill ionospheric radar and the wide SuperDARN HF radar monitoring network at mid-latitudes. New insights are emerging when these unprecedented multi-instrument views are combined with GPS total electron content maps and *in-situ* satellite data in the lower topside. An example involves the precise delineation of plasma structures that produce ionospheric scintillation and also alter plasma processes controlling Earth's radiation belt characteristics. Experimental, analytical, and theoretical collaborations are underway with multiple Van Allen Probe spacecraft teams, together with mid-latitude SuperDARN investigators at Virginia Tech, JHU/APL, and Dartmouth College. These efforts are well poised to further exploit this unique multi-instrument view of fundamental geospace coupling processes.

Lower-upper Atmosphere Coupling Studies/ Sudden Stratospheric Warming Events

A World Day Campaign for incoherent scatter radars (ISR) was conducted in January 2013, led by ASG scientists. This effort encompassed collection of ionospheric data at Jicamarca, Arecibo, Millstone Hill, PFISR, and Sondrestrom radar locations, and occurred in unique conditions - a major sudden stratospheric warming (SSW) during high solar activity. Analysis of this data reveals dramatic ionospheric disturbances associated with SSW events. Our results indicate that lower atmospheric drivers play a significant role in the day-to-day variability of the ionosphere, even for high solar flux conditions. These observations contrast sharply with available simulations predicting weak lower atmospheric forcing of ionospheric parameters for high solar activity conditions.

Analysis of F-region ion temperature data obtained by the Millstone Hill ISR indicated the presence of oscillations with 8-hour and 12-hour periodicity in temperature at middle latitude, as well as 16-17 hour, 3-4 day, and 10-13 day periodicities. These results reveal significant day-to-day variability in the upper thermosphere driven from below. As planetary waves (3-4 days, 10-13 days) are not expected to propagate to the F-region altitudes, these experimental results challenge current theoretical understanding of atmospheric coupling and raise questions about the potential mechanisms of connections between the lower and upper atmosphere.

Analysis is underway of lower thermospheric neutral winds collected by the Millstone Hill ISR in 2008-2013, with a focus on extracting tidal harmonics and comparing them with tidal modes observed in the lower thermosphere during non-SSW periods. This effort includes a MIT Haystack 2013 summer REU project for undergraduate student Rebecca Steeves from North Carolina State University. Several results challenge current understanding of tidal variations that are expected to occur during SSW.

Long-term Ionospheric Trend and Variability Studies

Analysis of long-term ion temperature (Ti) trends in the F-region ionosphere over different local times extends prior Haystack studies focusing on noon-time only, and provides important information for understanding differences in climatologies between incoherent scatter radar measurements and other diagnostics. In particular, a gross average of trends at 200-350 km altitudes where ion (Ti) and neutral (Tn) temperature are nearly the same shows a cooling trend of -4K/decade, close to estimates of Tn change based on satellite neutral density data. However, there exists considerable variability in the cooling - it is strong during the day and very weak during the night, and is strong at solar minimum for both daytime and nighttime. The strongest cooling for altitudes below 375 km occurs during moderate levels of solar activity. No consistent and substantial seasonal dependency across different heights was found. A fraction of the observed cooling trend may be due to a gradual shifting of the sub-auroral region away from Millstone Hill, as part of the secular change in Earth's magnetic field.

Multi-decade (39+ year long) ISR based ionospheric data series revealed two anomalous Ti drops, with possible connection to volcano eruptions in 1982 and 1991. In particular, from 1968-2006, there were 4 major volcano eruptions with a volcanic explosivity index (VEI) up to 5. Volcanic impact on the atmosphere is measured by the so-called volcanic dust veil index (DVI). DVI is a numerical index that quantifies the impact of a particular volcanic eruption's release of dust and aerosols over the years following the event, especially the impact on the Earth's energy balance. Among those 4 major eruptions, the events in 1982 (El Chichon), and 1991 (Pinatubo and Hudson) appear to have caused ionospheric effects. MIT Haystack REU 2013 student Ani Chiti (Cornell) conducted a successful project advancing these studies, with followup activity expected.

Longitude Variations in the Upper Atmosphere

A significant and characteristic ionospheric longitudinal variation at mid latitudes across zero magnetic declination has been identified recently, and represents a new climatological signature in this region. Electron densities on east and west sides of the zero declination show systematic differences that vary consistently with local time, season and solar cycle. This was first found for the continental US by Haystack scientists, and then confirmed for several other sectors by other researchers. Shunrong Zhang and collaborators proposed a declination-zonal wind mechanism to account for this class of variations. This is based on a comprehensive investigation using wide coverage Millstone Hill experiments from 1978-2011, examining climatology for both electron density longitudinal differences and the nighttime zonal winds in the eastern US. The wide coverage of observations provides spatial sampling with up to 50^{o} longitude separation. Thermospheric zonal wind is also available from on-site Millstone Hill Fabry-Perot interferometer measurements during 1989-2001. Observed zonal wind climatology is perfectly consistent with expectations based on east-west electron density differences in terms of local time, seasonal, and solar cycle dependencies. These results significantly advance knowledge of mid-latitude ionosphere-thermosphere coupling.

Global Total Electron Content Studies

Several initiatives this year focused on varying studies and applications of the regular total electron content (TEC) product produced at MIT Haystack and deposited in the online Madrigal distributed database system. Observations of southern mid-latitude ionospheric dynamics used deployed GPS receivers at the Murchison Widefield Array (MWA) site in western Australia. Studies of ionospheric response to lunar tides and geomagnetic storms occurred along with a characterization of TEC climatology as a function of solar flux, season, and geomagnetic activity. Antarctic continent investigations of ionospheric scintillations have also begun design phase activities in collaboration with the international scintillation research community.

Technical Initiatives

The Atmospheric Science Group is engaged in a variety of technical development projects, directly motivated by the science program.

MISA Antenna Upgrade

The 46-meter diameter Millstone Ionospheric Steerable Antenna (MISA), a centerpiece of the Group's UHF radar system, was successfully returned to operational service in October – November 2012 after a series of upgrade activities focused on motion control and safety system replacement. The MISA's field of view encompasses the entire eastern half of the US, and allows a unique measurement capability spanning the full range of tropical, midlatitude, and subauroral ionospheric and thermospheric processes. The antenna is over 50 years old, having been designed by Stanford Research Institute in the early 1960s and transferred to Haystack in 1977–1978 from Sagamore Hill Radio Observatory in Wenham, MA. After more than 40 years in the New England weather, the antenna's wiring, control, and pointing systems were in need of replacement in order to extend the system's lifetime and resiliency against failure as well as provide for new data paths and enhanced safety monitoring equipment.

Upgrades have included safety improvements to metal and wooden decking and railing, refurbishment of the antenna control building, construction of a new shed to house antenna parts, power system replacement, new motion control limits, encoders, safety hardware, and lights, and a complete antenna wiring and conduit replacement. Ongoing activities include fine-tuning of antenna response and position hold capabilities, along with absolute pointing calibration using radio stars and fixed beacons. The effort has used materials and supplies funds from the main NSF Geospace Facilities award and NSF Geospace Science Center associated American Recovery and Reinvestment Act (ARRA) funding.

Radio Interference Mitigation

New methods have also been developed (J. Vierinen) to deal with increasingly strong radio interference in the MIT Haystack environment. These methods are based on: (1) spike removal using sample estimates of noise variance as an outlier threshold, and (2) variance weighted averaging using sample estimates of range, time, and frequency localized noise variance. Implementation of these techniques was essential to allow plasma line measurements.

Software Radar

Long-term ASG efforts to develop software radar technology for remote sensing of the Geospace environment continue. Recent activities include development of software to support advanced radar control architectures, implementation of cloud data storage and processing frameworks, and production quality implementation of signal processing techniques that are modular and can be reused to meeting changing community experimental needs and requirements. Signal processing targeted at advanced radar waveforms, analysis techniques such as geophysical inverse analysis, and active and passive radar imaging are at varying stages of development. Many of these are in collaboration with the geospace radar community, including work with D. Suarez

(Jicamarca Radio Observatory) and D. Hysell (Cornell University) on full profile generic analysis code and efforts with M. Nicolls (SRI International) on an all-purpose generic community based incoherent scatter plasma spectral calculator.

Radio Array of Portable Interferometric Detectors (RAPID)

The Radio Array of Portable Interferometric Detectors (RAPID) is a new radio array with a flexible architecture. This is a cross-Observatory project jointly with the Astronomy program and in collaboration with Cambridge University and the Jet Propulsion Laboratory. The instrument being developed uses per-element software-defined radios and a software signal processing architecture to enable the flexible study of a wide range of natural phenomena using radio imaging techniques. The array will be used for investigations of ionospheric phenomena, solar radio emission, the Galactic synchrotron background, and ultra-high energy cosmic rays via air-shower emission. The array will initially consist of 100 small, low gain antennas operating over a frequency range of 48 to 450 MHz. RAPID is designed to make flexible and coherent radio observations, capturing the amplitude and phase of the electric field across a user-defined aperture with easily reconfigurable spatial sampling. Key technical elements include a novel absolute broadband antenna calibration method, elimination of a clock distribution network with a compact, low power chip-scale atomic clock in each unit, state-of-the-art high performance voltage data recording, and low power consumption, via use of the latest low-power A/D converters and digital processing chips. The system architecture is illustrated in figure 4.

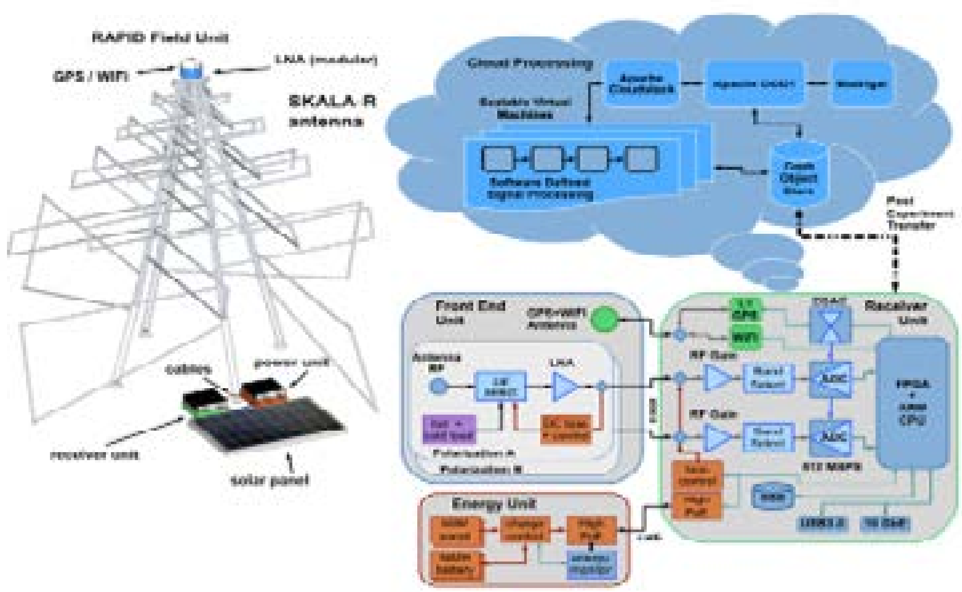

Figure 4: Schematic of the RAPID system. At left is the SKALA antenna, of which there will be ~100 in the finished array. Each antenna is designed to be easily packaged, shipped, deployed and repositioned dynamically as needed, requiring no site infrastructure of any kind. The unit is solar powered with battery backup for night-time operation, and the receiver unit performs high speed digital capture of the radio signals. After a field deployment, stored data from each unit are retrieved, uploaded to cloud-based systems, and processed with a variety of software tools. The system is highly flexible, and the science program includes a range of diverse topics.

Efforts are also underway to leverage technological developments for RAPID to increase main Millstone Hill Geospace Facility capabilities both in the near and long term. An MIT graduate student, Mary Knapp (EAPS ; Sara Seager, advisor), is currently using RAPID prototype hardware to study astronomical radio interferometry techniques as part of her graduate work. A REU student (Shayan Sohbatzadeh, University of Florida) has used prototype RAPID systems to perform interferometric studies of meteor trails via reflected commercial FM radio signals.

Advanced Data Acquisition Systems

Several advanced data acquisition systems have been implemented recently across the range of ASG programs. The first Ettus Research USRP N210 based platform allows acquisition and processing of a full 25 MHz of RF bandwidth in a sustained manner from Millstone Hill Geospace Facility radar antennas on multiple channels. Combined with advanced radio frequency interference (RFI) filtering techniques, this system has achieved successful measurement of range-resolved daytime plasma line profiles from both the 46 meter MISA steerable antenna and 68 meter zenith pointing antenna. Although the plasma line signal is very weak, the fidelity of the measurement allows highly precise absolute determination of electron density profiles along with an independent measure of electron temperature. The wide band receivers can also potentially be used to increase the dynamic range of narrow band measurements, and to perform high range resolution measurements of strong targets, such as meteors or field-aligned irregularities. Figure 5 shows an example result from of a challenging plasma line profile measurement.

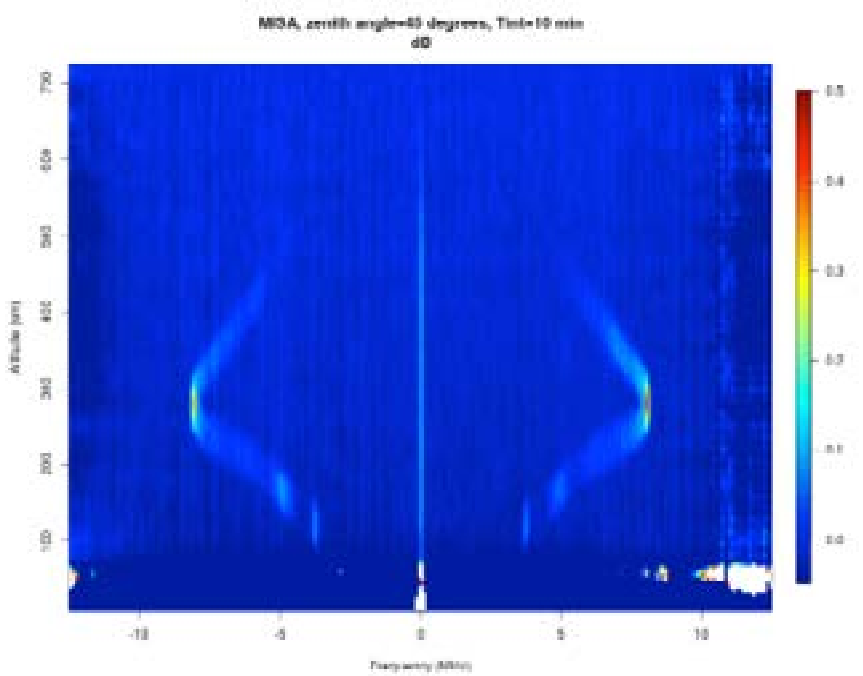

Figure 5: Plasma line profile from the Millstone Hill MISA antenna using new Ettus 25 MHz recording systems. The 10 minute integration allows a full profile derivation of < 0.1% uncertainty electron density measurements to 500+ km altitude, and precise determination of F region peak electron density (red peaks) can be attained in 10-15 seconds. This demonstrates an important new capability for the Millstone radar system, made possible by inexpensive, flexible and broad-band receiving systems, combined with improved techniques for identifying and excising radio frequency interference.

These capabilities will in the near future enable a new class of scientific data products from the facility applicable to a large range of scientific investigations, and will significantly improve radar calibration to the 0.1% level or better from the current 10% uncertainty figure. Work continues to implement realtime processing capability for these measurements and to bring the technical systems to a production, operational status. A mobile version of the platform MIDAS-MINI (Millstone Data Acquisition System - Mini) has also been developed and used for both Geospace Facilities applications and test data acquisition for RAPID. This platform is compact and fully deployable for use with scientific investigations at Geospace facilities around the world. Multiple collaborators from the global geospace community have already expressed interest in replicating or utilizing the platform.

Community Outreach and Collaborations

SuperDARN Mid-latitude Collaborations

The SuperDARN HF radar project is a NSF Geospace Facility network designed to continuously monitor ionospheric convection and perform radar backscatter investigations. Several SuperDARN radars have been installed in a mid-latitude configuration, observing plasmasphere boundary layer dynamics within the field of view of the Millstone Hill UHF radar system. Active Haystack-SuperDARN collaborations have continued through 2012 and 2013 with the rapidly expanding mid-latitude radar network anchored by the Wallops, Blackstone, Fort Hays, and Christmas Valley systems. These collaborations have primarily been driven by experiment requests and science projects with investigators and graduate students at Johns Hopkins University's Applied Physics Laboratory, Virginia Technical University, and Dartmouth College. The primary scientific and technical collaborators are Professors J. Michael Ruohoniemi and Joseph Baker at Virginia Tech, Professor Simon Shepherd at Dartmouth College, and Ethan Miller at Johns Hopkins University Applied Physics Laboratory, along with their students. Anthea Coster is also conducting multi-year ongoing collaborations with Virginia Tech graduate students aimed at merging SuperDARN HF radar observations with GPS TEC distributed measurements for enhanced science yields.

Haystack-Jicamarca Collaborations

Collaborations with Jicamarca were continued in July 2013 during a month long visit to MIT Haystack by Jicamarca staff members Daniel Suarez Muñoz and José Sal y Rosas. Daniel worked closely with ASG personnel (Bill Rideout, Phil Erickson) on implementation of full profile incoherent scatter analysis code originally authored by D. Hysell (Cornell) and its application to multiple radar systems, while José worked with Bill Rideout on advanced user interfaces for the Madrigal distributed database system. Both projects contribute directly to core ASG programs as well as community goals.

EISCAT 3D

A major effort is currently underway in Europe to take the next technological step in Geospace Radar systems. EISCAT 3D will be the most advanced system of its kind implemented to date and will provide the basis for significant scientific advances in our understanding of the near space environment. ASG members (Frank Lind, Phil Erickson) have made significant contributions to this effort both remotely and in person (e.g. work during an April 2013 guest lecturing visit by Phil Erickson to IRF Kiruna), and continue to be involved in technical planning and discussions as the system moves closer to implementation.

Brazilian Collaborations

Anthea Coster hosted the visit in July 2013 of three Brazilian students via the MIT-MISTI program for collaborations on geospace remote sensing programs in Latin America. An additional connection to Brazil and MIT campus programs exists through Prof. Kerri Cahoy (MIT Aero/Astro) and Anthea Coster, joint principal investigators on a MISTI grant with UNIVAP in Sao Paulo Brazil.

Educational and Outreach Programs

The long-standing NSF Research Experiences for Undergraduates (REU) program at Haystack continues to provide undergraduate students with summer internships. This program, under new NSF award starting in 2012, allows us to host four high school students each year from Puerto Rico, In addition to 7 undergraduates from around the country, with research topics generally split fairly evenly between astronomy, geospace science, and technical development. Each year's atmospheric science students attend the Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) workshop. Students from the 2012 REU program presented posters on their research at meetings of the American Astronomical Society and American Geophysical Union. Haystack REU students continue to have an excellent track record in their professional careers after the program ends, and in some cases continue to collaborate with Haystack scientists for an extended period.

Haystack staff work with, and provide guidance to, graduate and undergraduate students from many institutions including MIT, Dartmouth College, University of Washington, University of Colorado, Boston University, Siena College, U. Massachusetts Lowell, and multiple international institutions.

In the past, Haystack developed the Small Radio Telescope (SRT) that was highly replicated and placed into effective educational use at hundreds of sites in the US and around the world. This system uses small 2-3m diameter C-band satellite dishes as the basis for systems capable of measuring and mapping the 21cm line of neutral hydrogen in the galaxy. In addition, Alan Rogers has adapted small direct broadcast satellite dishes for science and educational use at low cost. Work has continued, with REU student assistance, to upgrade backend instrumentation for these systems, including the use of very low cost, commercially available software radio USB devices.

Science teachers from local middle and high schools participate annually in the Research Experiences for Teachers (RET) program at Haystack. In 2013, teachers from the local area worked on the use of radio waves for conveying information, and will develop an educational unit for use in the classroom, based on their work at Haystack.

From 2007-2010, Haystack staff served as organizers, lecturers, and leaders of a highly successful Advanced Modular Incoherent Scatter Radar (AMISR) workshop in coordination with SRI International personnel. NSF management requested an expansion of the school's scope in 2011 and beyond to include both AMISR phased array radars and conventional single antenna systems such as Millstone Hill.

In July 2013, a large and once again highly successful international one-week duration Incoherent Scatter Radar workshop was conducted at MIT Haystack for graduate and advanced undergraduate students (figure 6). Haystack personnel were instrumental in organizing activities and logistics along with curriculum development and hands-on teaching. A total of 9 instructors included four Haystack ASG staff along with lecturers from Boston University, SRI International, Boston College, and Sodankyla Geophysical Observatory (Finland). Topics centered on the theory and practice of incoherent scatter radar as a probe of the ionospheric physical state and its variations. In addition to the 9 instructors / senior staff / advisors, 34 graduate and undergraduate students attended the workshop. Attendees came from a wide range of institutions, with representation from the United States, Canada, Brazil, China, and Perú. The school has now grown to be the world's premier focused teaching opportunity aimed at introducing the powerful incoherent scatter technique to students at multiple educational levels, and in the process cultivating new users of ionospheric radar facilities such as Millstone Hill.

Figure 6: Students and lecturers at the 2013 Incoherent Scatter Radar workshop and school held at MIT Haystack Observatory.

Haystack staff continued to serve as lecturers in a number of capacities this past year. At the continuing request of the EISCAT scientific association and program staff from Luléa Technical University [Sweden], Phil Erickson gave a weeklong series of lectures in Sweden during April 2013 concentrating on space science and technology. Anthea Coster taught a GNSS short course for the Equatorial Ionosphere at the International Center for Theoretical Physics in Trieste, Italy.

On-site public outreach programs at Haystack remain active and robust, with extremely well-attended and successful open houses in October 2012 and May 2013, along with a steady stream of smaller tours. Staff members continue to be involved in other outreach activities, such as events for Cub Scouts (including "cubmobile" races) and job shadowing for high school students.

Colin J. Lonsdale
Director