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 atmospheric observations using high-power incoherent scatter radar. 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 priorities of the radio astronomy program at Haystack have involved the development of radio arrays operating at low frequencies to study a range of phenomena from the solar corona to the early universe, and 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. 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. 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 (GPS) satellites, as well as deciphering the complex inter-relationships between different components of the geospace environment. 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 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 whom it shares some of the facilities at the Westford site. The observatory receives financial support for its research programs from federal agencies including the National Science Foundation (NSF), the National Aeronautical and Space Administration (NASA), and the Department of Defense.

External Staff Activities

Haystack staff members engage in a wide variety of activities in service to the broader scientific and engineering communities. Associate director Alan Whitney serves on the board of trustees for Internet2. He also holds multiple positions within the International VLBI Service (IVS) organization, including membership on the Directing Board. Principal research scientist Arthur Niell participates extensively in planning and coordination activities of the IVS. Director Colin Lonsdale serves as vice-chair of the Murchison Widefield Array (MWA) Board. Associate director John Foster is chair of the NSF Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) program. Research engineer Frank Lind is chair of US International Union for Radio Science (URSI) Commission G, and also serves as chair of the technical advisory committee for the European Incoherent Scatter Scientific Association (EISCAT) 3D phased array radar project in Europe. Research scientist Larisa Goncharenko is American Geophysical Union Secretary for the Space Physics and Aeronomy section, and has served on the CEDAR science steering committee. She has also served as guest editor for a special issue of the Journal of Geophysical Research. Research scientist Shun-Rong Zhang is a member of the URSI/Committee on Space Research working group for the International Reference Ionosphere ionospheric model. Principal research scientist Anthea Coster is guest editor for a special issue of Radio Science, has served in coordinating roles for two conferences, and has delivered multiple invited lectures including one of the plenary lectures for the 2012 National Radio Science Meeting. She was chair of the MWA solar/heliospheric/ionospheric science collaboration of the MWA project for 2011. Principal research scientist Phil Erickson is a member of the NASA Measurement Techniques in Solar and Space Physics steering committee, lecturer at the Erasmus Mundus Space Master's degree course at the Swedish Institute for Space Physics in Kiruna, and lecturer and course organizer for the 2012 Incoherent Scatter Radar summer school held in Banff, Alberta, Canada.

Research Instrumentation

Haystack 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 major upgrade through a Lincoln Laboratory program, and is currently undergoing commissioning work. It has been unavailable for 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 ultra high frequency (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, and to serve as a remote station for the next generation geodetic observing system.

Radio Astronomy

Low Frequency Arrays

Work continued on the Murchison Widefield Array (MWA) project at a reduced level, to support 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. It can provide unprecedented diagnostics of solar wind plasma conditions that will aid in space weather prediction and will be a powerful research tool for a wide variety of radio astronomy investigations in a poorly explored spectral window. Haystack is not currently funded for this project, but proposals to the NSF have and will continue to be submitted for the scientific use of the finished facility. Scientific operation of the MWA facility is expected to commence in 2013. Haystack Observatory continued to be a lead member of the MWA consortium, and in 2012 Professor Lonsdale served as vice-chair of the MWA board. The Haystack team remains committed to the advanced instrumentation concepts and the associated scientific opportunities underlying the MWA project.

The technology upon which the MWA is based is now 5 to10 years old, and the march of digital technologies has since created new opportunities for innovation in radio array design. To exploit this, Haystack has embarked on a new multidisciplinary project based on highly portable systems, using a very broadband antenna, with fully autonomous sampling, signal processing, and data recording, all powered by small solar panels and backup batteries. The recorded data can subsequently be processed offline at the home institution. In this way, a fully functional imaging interferometer array can be assembled with no physical connections between antennas, and no permanent infrastructure of any kind. By dramatically reducing deployment and/or reconfiguration costs, such an array can be readily tailored to a variety of science applications, and can be independently optimized for each to great effect. The project, known as RAPID (Radio Array of Portable Interferometric Detectors) is a collaboration with Cambridge University in the UK, and NASA's Jet Propulsion Laboratory. The initial science goals will involve strong signal strength applications, such as bistatic ionospheric radar imaging via deployment close to existing transmitters. The design is also a potent one for multiple strong-signal astronomical investigations, as well as for studying ultrahigh energy cosmic rays via the radio pulses generated by the resulting cascade of relativistically moving subatomic particles known as airshowers.

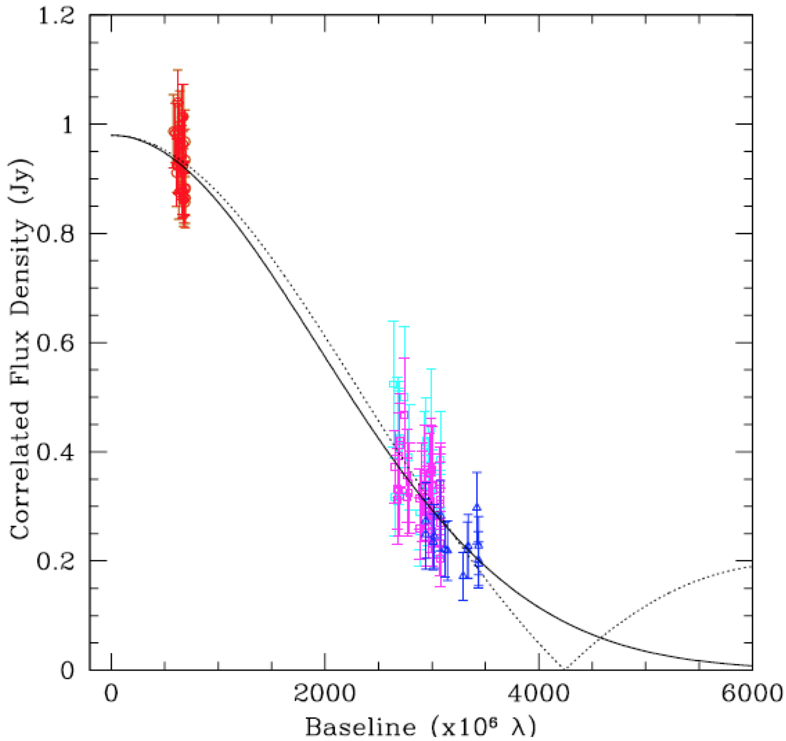
This work is expected to generate opportunities for collaboration with international colleagues as the global radio astronomy community pushes aggressively toward implementation of the low frequency component of the Square Kilometer Array (SKA) in western Australia. Despite the lack of explicit US astronomy funding for SKA development, projects like RAPID and its successors offer strong multidisciplinary science appeal, and allow mutually beneficial collaborative development with SKA-funded groups in Europe, Australia, and elsewhere.

Astronomical VLBI

Activities within the astronomical VLBI group at Haystack primarily focus on extending the VLBI technique to the shortest possible wavelengths to study supermassive black holes on event horizon scales. 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 antennas and supporting VLBI infrastructure, collectively called the Event Horizon Telescope (EHT).

At the center of the Milky Way, a compact radio source, SgrA*, marks the position of a 4-million-solar-mass black hole, which has been the focus of several 1.3mm VLBI observing campaigns. Initial 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 at Harvard and CITA (Canadian Institute for Theoretical Astrophysics) use the SgrA* data to considerably tighten constraints on the black hole spin, disk inclination, and orientation of SgrA*.

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 indicates that the jet diameter is only a few Schwarzchild radii across, which in turn 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.



Measuring the size of the M87 core with 1.3-mm VLBI. Correlated flux density data from three consecutive days of observing are plotted as a function of baseline length. The different baselines are shown in different colors, and calibration errors of 5% have been added in quadrature to the random errors associated with the incoherent fringe search performed on each baseline. The weighted least squares best-fit circular Gaussian model is shown as a solid line, and has a total flux density of 0.98 Jy and a FWHM size of 40.0 micro arcseconds. A hybrid model (dotted line) combines a circular Gaussian of the same size with a thin ring of diameter 40.0 micro arcseconds, which represents the expected shadow feature due to illumination of the central supermassive black hole from behind by a counter-jet in M87. In the hybrid model, the Gaussian and ring components each contribute one-half the flux density.

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 2012 observations employing 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 Atacama Large Millimeter/submillimeter **Array** (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 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.

To date the EHT has been coordinated through Haystack via a series of NSF awards, but 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 played a lead role in organizing an international EHT workshop in January 2012 in Tucson, AZ, during which plans were laid for development of technical and scientific roadmaps, and a memorandum of understanding (MOU) between all partners. Progress continues to be made toward these goals, with signing of a MOU targeted for the end of 2012.

37-Meter Telescope

The iconic Haystack radome-enclosed 37-meter radio telescope was upgraded in 2010 and 2011 via a project funded by the United States Air Force and managed by Lincoln Laboratory. The new dish has a target root mean squared (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. Haystack personnel have worked with Lincoln colleagues to install radio astronomy systems on the telescope, which are to be used by Lincoln Lab to establish and maintain an accurate pointing model for the telescope via sensitive observations of celestial radio sources with precisely known positions. Upon completion, the radio astronomy receivers and other instrumentation will be used to help re-establish Haystack astronomy and education programs that have been rendered dormant by the upgrade project (up to 35% of the telescope time) will be available for this purpose, if operating funds can be secured.

The system was originally scheduled to be operational by the second half of 2012, but significant problems were encountered with the azimuth bearing, necessitating extensive analysis, engineering, and modification by the Lincoln Laboratory team, supported by Haystack personnel. These activities have caused substantial delay, and initial operational capability is now projected for the spring of 2013.

Geodetic VLBI Program

Within the NASA contract for Engineering and Research for Geodetic VLBI, Haystack Observatory is developing the instrumentation and assembling the prototype of the next-generation geodetic VLBI system. The high-sensitivity system has now been utilized for the first geodetic session with the broadband signal chain. The broadband equipment was implemented on both the new MIT 12-m antenna installed at the Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt, MD, and on the 18-m Westford antenna at Haystack Observatory. The objective of this first session was to demonstrate the operability of the broadband delay capability from data acquisition through session analysis.

A major challenge to realizing the broadband concept has been the design of an antenna feed that will accept the full frequency range of the radio signal but whose characteristics are largely independent of frequency. While two candidates were considered, the Quadridge Feed Horn (QRFH) feed is clearly superior for the application. An important development in the past year that allowed implementation of the full signal chain for testing was the design modification and construction of a second QRFH feed for the Westford antenna by Caltech, also validated in a cryogenic environment at Haystack.

The other principal components of the signal chain consist of the frequency downconverters, Roach Digital Back End (RDBE) digital back ends, and Mark5C recorders. The frequency converters were designed and built entirely by Haystack, while the RDBE has been a joint development with the National Radio Astronomy Observatory, and the Mark5C a joint development with Conduant Corporation in Longmont, CO. The RDBE and Mark5C are both commercially available.

The geodetic session spanned six hours and provided validation of several important new features of the broadband system.

> The signal chain instrumentation operated as expected, producing a formal delay precision of less than a picosecond, although the scatter in the data was larger than this for well understood reasons.
>
> The signal-to-noise ratios for each observation agreed well with the expected values calculated from the measured sensitivity of the two antennas and the strength of the radio sources.
>
> The data were correlated on the Distributed FX (DiFX) software correlator at Haystack. Several modifications to DiFX by Haystack were required to optimally process the observations.
>
> The new phase calibration system designed at Haystack performed well and allowed alignment of the phases across the 7 GHz of radio frequency spanned by the data acquisition system.
>
> For the first time the data from four bands spanning 3 to 10 GHz and in two polarizations were coherently fit for delay, amplitude, and rate as well as the differential atmosphere between the sites.
>
> The ionosphere-corrected delays were successfully used to provide a preliminary estimate of the position of the 12-m antenna relative to the Westford antenna with an uncertainty of approximately 8 mm in the vertical and 2 mm in the horizontal. These uncertainties are dominated by the modeling of the atmosphere and are expected to decrease with further analysis, particularly in future observation sessions.

A significant challenge to achieving the maximum geodetic capability for operation of the broadband system has been uncovered at the GGAO site. The VLBI system is one of four techniques to be collocated at the fundamental integrated stations being implemented by NASA for the Global Geodetic Observing System. Unfortunately, the satellite laser ranging system uses an aircraft radar to ensure that the laser beam does not pose a hazard to aviation, and that radar operates within the passband of the VLBI broadband system producing severe radio interference. Mitigation of this interference has been a major study over the past year at Haystack, in collaboration with NASA personnel at the Goddard Space Flight Center (GSFC). These studies have led to detailed measurements of the radiation pattern of both the 12-m antenna and the radar antenna. From these results, limits on the co-operability have been defined, but these significantly restrict the sky visibility of the VLBI system, and reduce the accuracy of the station position estimates. Alternative strategies are being investigated, such as blocking the radar signal in the direction of the 12-m antenna, or intercommunication of times when the radar would point toward the VLBI antenna, in conjunction with adaptability of the VLBI observing schedule.

Considerable work remains to be done to make the system fully operational, but current results represent a significant milestone.

VLBI Instrumentation Development

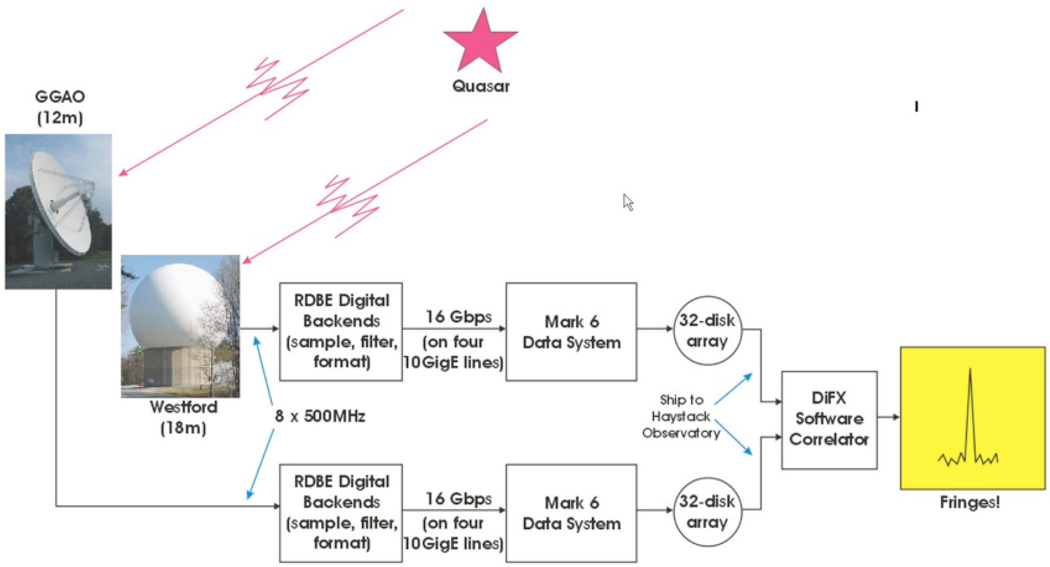
Haystack Observatory has long been known for its expertise in VLBI data acquisition technology. That tradition has continued with the creation of a new digital back end and high data rate recorder. These are being used in two applications: with existing antennas for very high frequency VLBI to study the radio emission from black holes, and with a new relatively small antenna to push the accuracy of geodetic VLBI. Haystack is also involved in cutting-edge VLBI correlator technology. Over the past year the most significant progress has been in data recording and correlation.

Mark 6 VLBI Data System

The demand for ever-higher VLBI data rates is particularly acute in two areas of research supported by the Observatory: geodetic-VLBI, for which as much data as possible must be gathered over a multi-GHz bandwidth in a period of 5 to 15 seconds, and mm-VLBI observations of black holes, where there is typically a need for greater sensitivity, as well as the need to gather as much data as possible during the atmospheric coherence period of 30–60 seconds. For both of these applications, capturing data at 16–64Gbps and recording it to disk are pressing technology development challenges. The current generation of Mark 5 recorders is limited to 4Gbps recording rate, too low for the current and near-future demands of either geodetic-VLBI or mm-VLBI.

The Mark 6 VLBI data system is being developed at Haystack Observatory, in collaboration with Conduant Corporation and the High-Performance Networking Performance Group at NASA/GSFC, to support sustained 16Gbps rate to an array of 32 disks. Designed to be constructed almost entirely of commercial-off-the-shelf parts, the Mark 6 has now been used in several demonstration experiments at 16Gbps; one such demonstration conducted in early 2012 is shown in Figure 2. VLBI data were collected on 18 May 2012 from the NASA/GGAO station in Greenbelt, MD, and the Westford antenna in Westford, MA, using the ultra-wideband receiver and digital-backend systems being specifically developed at Haystack for geodetic VLBI. The Mark 6 disk data from both sites were returned to Haystack for correlation processing, and analysis indicated that all systems performed nominally; these results establish a new milestone for captured and processed VLBI bandwidths and allow Haystack to move forward to exploit this capability to pursue expanded science opportunities.

The cost of the Mark 6 system is significantly lower than the earlier Mark 5 systems even though the capabilities are several times greater.



Block diagram of 16Gbps VLBI demonstration experiment between Westford, MA, and GGAO, Greenbelt, MD antennas.

VLBI Correlator Systems

As VLBI-recorded bandwidths increase, correlation capabilities must keep pace. The era of custom hardware-based VLBI correlators is now mostly in the past, and future progress will be in the use of software-based systems on commodity computing hardware. The current *de facto* standard package for VLBI correlation is the DiFX program developed in Australia, and already in wide use around the world. Haystack has been an active member of the DiFX development community and is contributing on two separate fronts. First, efforts are ongoing to increase the throughput of cluster-based DiFX platforms for the support of ever-wider recorded bandwidths through use of high-performance infiniband interconnects. Significant technical issues have been identified that are being actively debugged. Second, the DiFX core package must be interfaced to complex and highly capable Haystack-developed pre- and post-correlation software suites for both millimeter VLBI and geodetic VLBI applications. Roger Cappallo has been heavily engaged in making the necessary modifications and enhancements to facilitate this interfacing. In December 2011, Haystack hosted the annual DiFX workshop for users and developers, organized by Roger Cappallo, and involving about 20 participants from around the world.

VLBI correlation can also be done in a distributed fashion, using a cloud computing model, when global data transport bandwidths and logistics mature sufficiently. Haystack is investigating a series of incremental developments along the path to such a cloud-based model, which holds the promise of significantly more cost-effective and scalable VLBI operations in the long term.

Atmospheric Science

Radar Operations

The Millstone Hill UHF radar system executed approximately 1,000 hours of observations, the nominal amount supported by the NSF Cooperative Agreement with the Atmospheric and Geospace Sciences division's Geospace Facilities. 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 mid-latitude 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; meteoroid-head echo experiments exploring fundamental plasma processes associated with ablating micrometeors; and mid-latitude stormtime response to geomagnetic disturbances and coronal mass ejections in the increasing activity phase of Solar Cycle 24. In 2011 –2012, many of these studies have directly involved graduate students and faculty members from Boston University, Dartmouth College, Stanford University, and Virginia Polytechnic Institute and State University.

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 atmospheric coupling, and fine scale and mesoscale ionospheric perturbations.

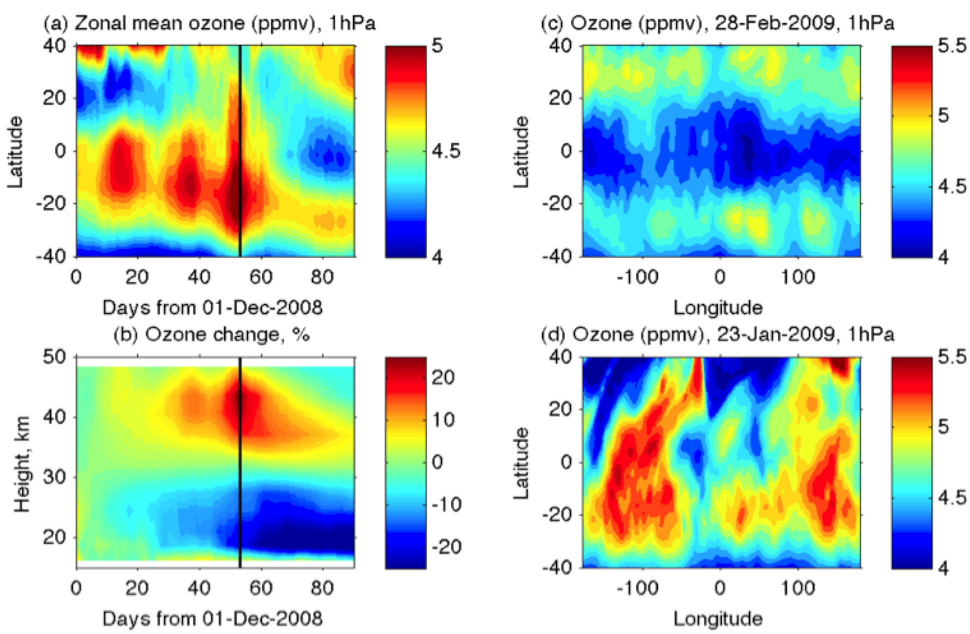
Geospace System Science

In keeping with an increased emphasis and new system science strategic direction in our NSF 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. One specific example is involvement in the NASA Radiation Belt Storm Probes (RBSP) mission, scheduled for launch in late 2012 with primary mission activities through 2016 and beyond. Haystack contributions to RBSP will help to advance the main project science focus on the direct coupling of the Earth's ring current and the ionosphere-thermosphere-magnetosphere system, along with the impacts of this coupling on radiation belt particles, human spaceflight activities, and space weather in the

Sun-Earth system. In the CEDAR community, Haystack project activities focus on the long-term Millstone Hill observational and science record dynamics within the subauroral plasmasphere boundary layer. The overlap of hot, tenuous plasma with cold, dense plasma in this region creates a number of mesoscale, system-level phenomena whose study, led by Haystack staff, directly addresses central questions in the NSF CEDAR Strategic Plan released earlier this year.

Dynamics of lower-upper atmospheric coupling

The recent discovery of large ionospheric disturbances associated with sudden stratospheric warmings (Chau *et al*., 2009, Goncharenko *et al*., 2010) has challenged the current understanding of mechanisms coupling the stratosphere and ionosphere. Non-linear interaction of planetary waves and tides has been invoked as a primary mechanism for such coupling. Analysis of stratospheric and ionospheric data collected during incoherent scatter radar campaigns shows that planetary waves may play a more complex role than previously thought. Planetary wave forcing induces a global circulation that leads to a strong and long-lasting buildup of ozone density in the tropics at 30- to 50-km altitude. A persistent increase in the variability of ionospheric total electron content (TEC) coincides with the increase in stratospheric ozone, as demonstrated in Figure 3 [Goncharenko *et al*., 2012], suggesting that the ozone fluctuations affect the ionosphere through the modified tidal forcing.



(a) Variations in zonal mean ozone mixing ratio at 1 hPa show distinct increases in ozone mixing ratio coinciding with enhancements in the planetary wave activity. Vertical lines indicate January 23, 2009, the peak of stratospheric temperature at 90oN and 10hPa during the major sudden stratospheric warming. (b) Change in ozone as function of time and altitude, calculated as departure from December 1-10 mean. (c) Longitudinal distribution of ozone at 1hPa in the absence of planetary waves on February 28, 2009 and (d) during the peak of the warming, on January 23, 2009.

These findings suggest that short-term perturbations in stratospheric ozone are important mechanisms connecting terrestrial and space weather at both low and middle latitudes. These initial results became the basis for the proposal to the NASA Living with a Star (LWS) Focused Research Topic competition and a collaborative proposal to NASA from the MIT Earth, Atmospheric and Planetary Sciences (EAPS) department and MIT Haystack Observatory.

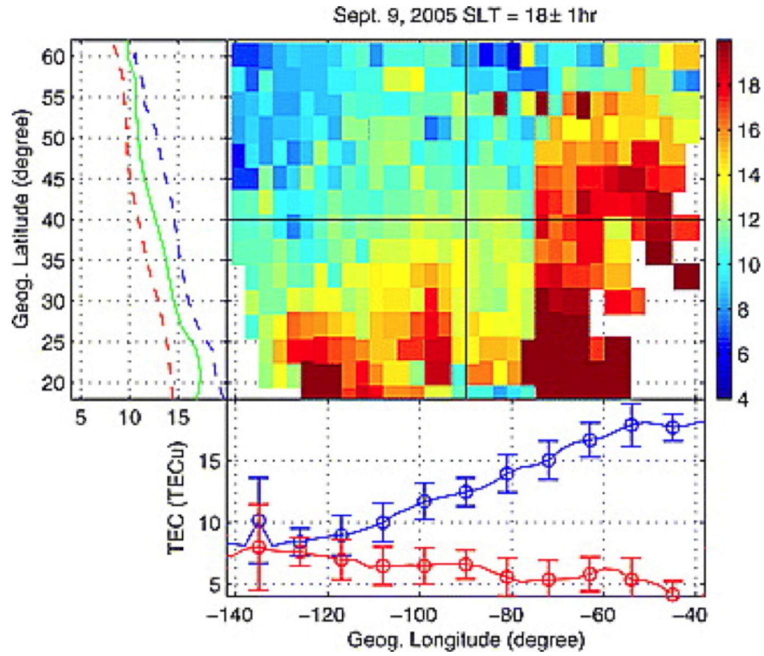
Ionospheric Storm Studies During the Current Solar Maximum

Investigations of the ionospheric perturbations and storm-time space weather effects over the US and Canada have resumed as the new solar maximum approaches. Coordinated radar, radio, GPS TEC, and in situ satellite experiments are addressing the occurrence, characteristics, variability, and causative mechanisms associated with storm-enhanced density (SED) plumes which form southward of high and polar latitudes, and the deep ionospheric depletions (troughs) observed along their poleward border. Figure 3 shows GPS Total Electron Content maps of a continent-spanning SED plume (Sep 26, 2011) and a plume/trough event (Oct 25, 2011). A NASA proposal has been submitted to the LWS Supporting Research and Technology program to support investigations of geospace coupling and related ionospheric effects in the plasmasphere boundary layer region associated with these features.

An important new dimension to these studies is provided by the wide field of view of the mid-latitude Super Dual Auroral **Radar** Network (SuperDARN) high-frequency radar systems arrayed across the US and Canada, providing a multi-hour snapshot of strong velocity channels known as the subauroral polarization stream. Collaborations with the mid-latitude SuperDARN investigators at Virginia Tech and the Johns Hopkins University Applied Physics Laboratory are under way to take advantage of this unique multi-instrument view of subauroral processes.

Longitude Variations in the Upper Atmosphere

Haystack scientists have recently uncovered a new type of ionospheric longitudinal variation at mid-latitudes. Zhang and collaborators found that substantial US east-west coast ionospheric differences exist in GPS TEC as observed by the dense International GNSS Service network of ground based receivers (see Figure 4). These differences exhibit a clear local time variation, with the evening TEC higher on the east coast than on the west, and vice versa for the morning TEC. Further analysis reveals that morning-evening variability in this east-west TEC difference minimizes at -90◦E longitudes, along the line of zero geomagnetic declination in the central US.



Longitudinal variations of total electron content (TEC) over the continental US at 1800 LT, September 9, 2005. The top-right panel shows TEC as a function of longitude and latitude, the bottom panel shows TEC variations for 40N latitude as longitude (blue line for 1800 LT; red line for 0600LT), and the top-left panel shows TEC latitudinal variations for the US west-coast (red line), the US east-coast (blue line) and the central US (green line).

A follow-up study using eastern US data from long-term Millstone Hill incoherent scatter radar observations and climatologies has provided further evidence of this type of ionospheric longitudinal variation. An extensive set of experiments has used Millstone Hill's wide coverage to measure electron density (Ne) with east-west separations up to 40◦ in longitude. The study concludes that east-west electron density difference over the eastern US is persistent, reaches magnitudes up to 60%, and varies with local time in a similar fashion as in the GPS TEC results over the continental US. These marked longitudinal differences in ionospheric TEC over the continental US are likely driven by a combined effect of varying magnetic declination and thermospheric zonal winds.

Ionospheric Disturbance Investigations using Signals of Opportunity

Collaborations between MIT Haystack science staff and Dartmouth College resulted in a senior honors thesis "Numerical and Experimental Investigations of Ionospheric Sounding using AM Radio" by Michael Chilcote in the Dartmouth Physics Department under the supervision of professor Jim Labelle. The project was based on observations collected by the Intercepted Signals for Ionospheric Science (ISIS) Array software radio instrumentation network, augmented by GPS data.

During March and April 2012, nighttime medium-scale traveling ionosphere disturbances (MSTIDs) propagating in the lower F region of the ionosphere were detected by means of Doppler shifts in AM radio signals. Federal Communications Commission Class A designated commercial AM radio oscillators broadcasting on 810 kHz and 1030 kHz were used as transmitters. AM receivers were located at Dartmouth College, Haystack, and Siena College, and 11 nights' data were collected. Correlated Doppler shifts in the signals produced by movement in the F layer of the ionosphere were detected, and analysis showed a maximum in MSTID detection towards midnight local time. GPS vertical total electron content data from a receiver located at Haystack Observatory taken from the same time periods shows similar variations in the ionosphere at comparable times as those observed in this study.

Technical Initiatives

Millstone Ionospheric Steerable Antenna Upgrade

Upgrade activities have focused on motion control and safety system replacement for the 46-m-diameter Millstone Ionospheric Steerable Antenna (MISA), a centerpiece of the Group's UHF radar system. 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, mid-latitude, 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.

As of summer 2012, motion control of the 46-m antenna has been fully restored. This was delayed from the planned fall 2011 completion date due to funding limits and project complexity. Final tuning of the motion control systems is under way and safety checkout, pointing calibration, and radiofrequency testing (leading to radar operations) are planned for August 2012. This will result in a return to operations in September 2012. 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 funding.

The upgrades have included:

- Safety improvements to the metal decking
- Safety improvements to wooden decking and railing
- Refurbishment of the control building on the antenna
- Power system upgrade and replacement
- Conduit and wiring upgrades
- Motion control limits, encoders, safety hardware and lights

Together, these upgrades have sharply reduced the risk of major failures and loss of operating time, implemented much more rigorous safety standards, and created new scientific capabilities along with infrastructure support for additional future enhancements in capability.

Distributed Instrument Arrays

The ASG's current primary research goal using distributed instrument systems is to experimentally investigate the plasmasphere boundary layer in order to characterize its electron density gradients, perturbations, flows, and electric fields from micro- to meso-scales (meters to 1000 km) under a range of geomagnetic conditions. These research thrusts also align with the wider Distributed Arrays of Scientific Instruments (DASI) initiative, highlighted by the 2001 Decadal Survey of Solar and Space Physics of the National Academy of Sciences. A secondary goal is to develop and investigate the capabilities of distributed arrays of small radio instruments for observations of the mid-latitude ionosphere, providing simultaneous coverage of wide spatial regions with high time and spatial resolution. Technical development has focused on assimilation of data from the global GPS network and the ISIS Array (distributed software radio sensors).

Several major geomagnetic events have been observed in 2012 and this has resulted in the first single-site passive radar detection of E-region irregularities. ISIS Array assets were also used in an undergraduate senior thesis at Dartmouth for AM radio spectral monitoring, the results of which will be published. Collaboration on ISIS and passive radar techniques with the University of Washington have also continued, involving several graduate students. Work with Burak Tuysuz, a student at Pennsylvania State, resulted in the submission of a paper to *Radio Science* detailing performance predictions for a newly developed Pennsylvania State passive radar system and its potential application for observations of the equatorial ionosphere.

Software Radar

Technical efforts continue to produce production quality components within a generic software radar platform, supporting both current and future incoherent scatter radar operations in a manner which scales to accommodate a distributed control and streaming data model. Recent collaboration with the NSF supported Ocean Observatory Initiative (OOI) has resulted in architectural prototyping of a next-generation software radar platform that has commonalities with the OOI Architecture and tool set. This platform is being developed to enable use of cloud computing resources. Developments in this area directly contribute not only to Millstone Hill and NSF community radar operations but also to future next-generation phased array radar designs where scalability is essential. Efforts to produce production-level incoherent scatter radar signal processing and analysis software have also advanced with the development of improved processing software and methodologies for calibration and validation of new data acquisition systems.

Radar Waveform Generation

Efforts to develop an arbitrary waveform capability for use with the incoherent scatter radar have reached a pre-production prototype level. New conversion software for the sequencing of such waveforms was developed along with embedded software to support the correct modes of operation expected for the device. This system has been applied to an extensive set of radar coding experiments in spring 2012 in collaboration with Sodankylä Geophysical Observatory (SGO). These tests involved a combination of advanced waveform transmission and transmitter linearization techniques to send a new class of untried radar waveforms. MIT Haystack and SGO scientists are in the process of jointly evaluating the results of these experiments within a rigorous statistical and inverse analysis framework. Efforts to finalize the waveform generation system for production level applications will continue into 2013. A highly integrated UHF radar upconverter board has been developed and fabricated as part of this integration effort.

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 2011 and 2012 with the rapidly expanding mid-latitude radar network. These collaborations have primarily been driven by experiment requests and science projects with investigators and graduate students at Dartmouth College, Johns Hopkins University Applied Physics Laboratory, and Virginia Tech.

Preparations are now underway for synchronized fall 2012 experiments to probe the plasma parameter conditions near sub-auroral polarization stream (SAPS) channels, using the continuously active SuperDARN radar network as a trigger for focused Millstone Hill incoherent scatter radar measurements. This is a step toward a North American regional DASI concept of system level science through distributed instrumentation.

Haystack-Jicamarca Collaborations

Collaborations with Jicamarca were continued in July 2012 during a month-long visit to MIT Haystack by Marcos Inoñán, a Jicamarca engineer. Inoñán worked closely with ASG personnel on the implementation of high-speed data transmission from a Field Programmable Gate Array over an Ethernet connection. This project was quite successful, and will contribute to future receiver and control efforts at Jicamarca. Marcos was also able to take advantage of MIT Haystack Research Experiences for Undergraduates staff lectures and seminars during his visit. Plans are underway to continue technical exchanges between the two facilities as an efficient means of sharing developments.

EISCAT 3D

A major effort is 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. The all-digital radar system will be located in Scandinavia and will be capable of three-dimensional volumetric imaging of the geospace environment. The system will contribute greatly to international capabilities for studies in space plasma physics, magnetosphere-ionosphere coupling, impacts of the lower atmosphere on the ionosphere, dusty plasmas, long term monitoring of upper atmospheric climate and trends, and realtime diagnostics for space weather applications. MIT Haystack Observatory has participated for the last year in the technical development of this instrument in an advisory role as part of collaborations with our European Union colleagues and the EISCAT Scientific Association. ASG members Phil Erickson and Frank Lind have made significant contributions to this effort, and Lind is the chair of the EISCAT 3D Technical Advisory Committee. Under Lind's leadership, the Technical Advisory Committee developed a major report to the EISCAT 3D Executive Board during 2012.

Haystack–China Initiatives

Activities in the ASG continued to support expansion of US-China cooperation. In particular, the MIT-CAS (Chinese Academy of Sciences) collaboration centers on ground-based upper atmosphere and space weather research. One focus for collaborative activities remained expansions of the Meridian Chain Project, an array of modern space science observatories along the 120◦ E meridian line in China. In particular, the Meridian Circle Project will create a globe-circling set of geospace observatories including stations on the complementary 60◦ W meridian line along the Atlantic coasts of North and South America. In October 2011, John Foster and Shun-Rong Zhang hosted a visit to MIT Haystack by a seven-member high-level Chinese delegation including professor Hejun Yin, vice president of the CAS. Colin Lonsdale and professor Ji Wu, director of the National Space Science Center of China (NSSCC) signed a memo entitled "Areas of Mutual Interest for MIT Haystack–NSSC Collaboration" outlining areas for initial collaboration. NSSC is the leading institute for the Chinese Meridian Circle Project, and Deputy Director Chi Wang obtained a MIT PhD in physics. Shun-Rong Zhang made a three-week visit to China in October-November 2011, visiting NSSCC and five other universities and Institutes to discuss and pursue collaborative projects. This visit was fully funded by the Chinese hosts. Both Shun-Rong Zhang and John Foster will make a two-week visit to NSSCC and several of the Meridian Chain installations in October 2012.

Educational and Outreach Programs

Haystack Observatory, through the efforts of Alan Rogers, has developed the Mesospheric Ozone System for Atmospheric Investigations in the Classroom (MOSAIC), an array of single-telescope systems using small direct-broadcast satellite dishes to observe the 11 GHz line of ozone in the mesosphere. MOSAIC systems have been operating in multiple locations, and the results have yielded significant and unexpected new results leading to two scientific publications. Efforts to get this work funded for educational purposes, replicating the systems at colleges and high schools, have not been successful. However, significant interest is being generated in the atmospheric research community, and possibilities exist for replication via this route. The system is still envisaged as an excellent educational tool, and this aspect will be included if research funds are secured for the project.

In the past, Haystack also developed the Small Radio Telescope 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 2–3-m diameter C-band satellite dishes as the basis for systems capable of measuring and mapping the 21-cm line of neutral hydrogen in the galaxy. Recent work, with assistance from summer undergraduate interns, has led to an inexpensive receiving system upgrade for this installed base of systems that greatly improves their sensitivity and educational flexibility.

The long-standing NSF Research Experiences for Undergraduates (REU) program at Haystack continues to provide undergraduate students with summer internships. The NSF award was successfully renewed in 2012, based on high praise by the reviewers as a flagship program. The new award includes approval of an expansion of the scope of the program to include four high school students each year from Puerto Rico. In addition to the high school students, this year's program involved seven undergraduates from around the country, four in the atmospheric sciences program and three in astronomy. Each year's atmospheric science students attend the CEDAR workshop. Students from the 2011 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.

Science teachers from local middle and high schools participate annually in the Research Experiences for Teachers (RET) program at Haystack. In 2012, teachers from Lexington and Chelmsford, MA, worked on "Bringing Black Holes into the Classroom: Integrating Modern Physics and Astronomy into the High School Curriculum," 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. A revised school following this format took place in summer 2011 in Greenland.

Haystack staff continued to serve as lecturers in a number of capacities this past year. At the continuing request of the EISCAT director Esa Turunen, Phil Erickson gave a week-long series of lectures in April 2012 concentrating on space science and technology. The lectures on general radar theory were given in Kiruna, Sweden, to more than 40 students from over 15 countries, and we expect to repeat this on an annual basis. Phil Erickson also guest-lectured at both Stanford University and Boston University in February 2012. Anthea Coster presented lectures at MIT in 2012 to professor Kerri Cahoy's class on space weather, and is working with Professor Cahoy on the development of a graduate-level class to be taught jointly between Aeronautics and Astronomics and EAPS.

Haystack staff members are working closely with MIT undergraduate and graduate students, including two of Professor Plumb's graduate students in EAPS. In addition, Haystack continues to keep up educational ties with graduate students at other universities, such as Boston University, Rhodes University, Stanford University, Siena College, and the University of Washington. Recently, connections have also been made with students at Dartmouth College, the University of Colorado, and Virginia Tech, as well as students from institutes in Germany and Switzerland. Shun-Rong Zhang works with Chinese collaborators in mentoring their graduate students and junior researchers in projects using Millstone Hill observations. The group also plans to host a visiting Chinese PhD student for one year starting in November 2012. These relationships are generally founded on collaborative research projects between Haystack staff and faculty members of the respective institutions.

On-site public outreach programs at Haystack are now fully restored after a hiatus associated with construction activity for the upgrade of the 37-m telescope. Extremely well-attended and successful open houses were conducted in September 2011 and May 2012. A steady stream of smaller tours has also been re-established. As in past years, staff members have been 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