History of Haystack

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In the 1950s, Lincoln Laboratory built the Millstone Hill radar in response to the national need for a tracking radar with a specific sensitivity requirement. The Haystack radar, constructed in the following decade, marked the next technological step in the evolution of high-performance microwave systems. Over the years, Haystack has undergone several modifications and upgrades that have enhanced its utility in a variety of applications and developed its reputation as a premier microwave facility.

» **By 1953, the United States and the Soviet** Union were fully engaged in a nuclear arms race. Having successfully tested thermonuclear devices, both nations were competing to develop long-range missiles capable of delivering these devices to enemy targets. While Allies in Europe permitted the U.S. to deploy within their territories intermediate-range missiles capable of reaching Moscow in 10 to 20 minutes, the Soviets had no such territorial advantage. Because of this disparity, the Soviets began to develop a long-range intercontinental ballistic missile (ICBM). Accordingly, the U.S. intelligence community needed to closely monitor Soviet progress in missile development. Soviet missile tests, however, were conducted deep inside their territory and were not at all easily monitored from the available borders. This inability to track Soviet missile activity meant the United States would need sensors capable of tracking small, warhead-sized targets at distances of 3000 miles or more.

Up until this time, radars had been used to detect aircraft at ranges up to only a few hundred miles. The new combination of longer ranges and smaller targets meant that a tracking radar with a sensitivity improvement factor of about 1,000,000 times that of traditional radars was needed. The Department of Defense, the principal supplier of technology hardware to the intelligence community, recognized that there was too much risk in the commercial development of such a system because of its novelty and the possibility of its improper application. To mitigate this risk, the Office of the Secretary of Defense (OSD), aware of Lincoln Laboratory's recent successful development of the Semi-Automatic Ground Environ-

FIGURE 1. The original 1957 Millstone Hill radar that detected *Sputnik I* was upgraded in 1962 from an ultrahigh-frequency radar operating at about 450 MHz to an L-band radar operating at 1.295 GHz; the new antenna installed during this upgrade is pictured above. Millstone provides 18,000 deep-space satellite observations a year, making it a key contributor to the national deep-space surveillance program.

ment (SAGE) air defense system, asked the Laboratory to develop a preprototype (i.e., a model that lacks firm performance specifications, in this case because the technology was not yet well enough understood) radar system.

In response, Lincoln Laboratory designed the Millstone Hill radar, meeting the sensitivity requirement needed to detect Soviet ICBMs and satellites (Figure 1). In fact, Millstone, almost ready for initial operation, was quickly brought online in 1957, in time to detect *Sputnik I*, the first man-made satellite to orbit the Earth; soon thereafter, it skin tracked (i.e., tracked a target without the assistance of a transmitted beacon signal) the satellite [1]. Millstone was the first high-power radar to use gas transmit-receive tubes to protect the receiver input—a low-noise parametric amplifier—from damage caused by transmitter signals. Millstone was also the first radar to utilize an all-solid-state computer, the CG-24, which was designed and built at Lincoln Laboratory for real-time data processing and antenna pointing control. Based on these breakthrough technologies demonstrated in the Millstone radar, the FPS-79 tracking radar was successfully developed and built by commercial industry in Pirinçlik, Turkey, as the first operational system to employ the Millstone radar technology.

A Technological Step

Unlike the Millstone radar project in which Lincoln Laboratory was asked by OSD to help solve a critical national need, development of the Haystack radar was internally motivated. The world-class team of radar developers who had come together for Millstone began to look at the state of radar technology and concluded that there was yet another potential major advance that could impact future missions critical to both national security and scientific progress. This approach of developing technology in the national interest persisted over the years as the Laboratory, faced with new challenges, moved on to support other missions.

Lincoln Laboratory proposed the development of the Haystack radar as the next significant technological step in the evolution of high-performance microwave systems. A team led by staff member Herbert Weiss designed Haystack as an experimental facility for research on space communications and radar (Figure 2). The advantages of high-frequency operation (e.g., increased bandwidth and higher antenna gain) and the availability of high-power transmitter tubes led to the selection of an 8 GHz operating frequency. A surplus 150-foot radome was modified to allow the use of a 120-foot fully steerable parabolic Cassegrain antenna. Construction of a microwave antenna of this size was a significant challenge because of thermal gradients and gravitational loading, both of which could

FIGURE 2. Haystack project lead Herbert Weiss spoke at the Haystack dedication on 8 October 1964 in Tyngsboro, Massachusetts, half a mile up the road from Millstone.

FIGURE 3. The construction of Haystack, seen from its exterior in the photograph above, was completed in 1964.

significantly distort the antenna's surface. The solution, verified by extensive mechanical analysis, was a rigid, all-aluminum structure of circular rings attached by spokes with lightweight honeycomb panels as a surface.

The radome protected the antenna from snow, ice, and wind loading and from direct solar radiation. Consequently, it was possible for the antenna to be constructed with more lightweight material than that required for an antenna exposed to weather, yet still be unperturbed by the wind during precision pointing. After panel alignment, a root-mean-square (rms) error of 885 μm averaged over the entire quarter-acre surface was achieved. The Cassegrain design supported the use of interchangeable radio-frequency boxes that enable the system to operate as a radar, communications receiver, or radio telescope. The versatile design of the Haystack system has sustained its long-term utility in a variety of applications.

Through the Decades

Construction of the Haystack radar began in Westford, Massachusetts, in 1960 and was completed in 1964 (Figure 3). After operations began, the system was used for experiments in space communications and radar measurements. Throughout the following decade, Haystack served as a planetary radar, making many important contributions to space science, including mapping of the lunar surface in preparation for the 1969 Apollo landing led by the National Aeronautics and Space Administration (NASA). In 1970, Haystack ownership was transferred to MIT and the Northeast Radio Observatory Corporation (NEROC), and the site was named MIT Haystack Observatory. Haystack Observatory operated the system as a remotely accessible radio telescope at millimeter wavelengths for astronomical research and education. (At the time, the antenna efficiency at millimeter wavelengths was too low to support the use of Haystack's radar function; the Haystack radar has the capability to operate at millimeter wavelengths today thanks to an upgrade of the system in 2013.)

Under Advanced Research Projects Agency (ARPA) sponsorship, the Haystack radar was upgraded in 1978 to a high-power, broadband, long-range imaging radar (LRIR) that operates at a frequency of 10 GHz (X band) with 1 GHz of bandwidth, allowing for the generation of radar images with 25 cm in-range and cross-range resolution [2]. With sufficient cross-range motion, LRIR is capable of providing 25 cm resolution images of satellites at geosynchronous ranges. Satellite images are generated in near real time on workstations using Laboratory-developed software. These high-resolution images support the U.S. Air Force in assessing satellite structure, mission, and status.

Beginning in 1990, Haystack participated in a measurement program to characterize man-made orbital debris [3]. This program has supported the manned spaceflight activities of NASA. Radar measurements have helped calibrate a statistical model of the number of space debris objects of various sizes and the distribution of these objects in altitude and inclination.

In 1992, several modifications were made to improve the quality of the antenna's reflector surface [4]. A deformable subreflector with active actuator control was installed to correct for gravity distortion of the truss structure and surface panel deflections. Active thermal control was used to compensate for thermal-lag effects in large truss members. These surface improvements reduced the rms error to 210 μm and allowed operation of the antenna at 115 GHz for radio-astronomy applications.

In This Issue

Haystack's heritage as a vanguard microwave facility continues with the recent completion of a major upgrade of the Haystack radar—the focus of this issue. Jointly sponsored by the Defense Advanced Research Projects Agency (DARPA) and the U.S. Air Force, this upgrade to the system, now called the Haystack Ultrawideband Satellite Imaging Radar (HUSIR), added a millimeter-wave radar capability that operates in the 92 GHz to 100 GHz frequency band. The new radar uses innovative sig-

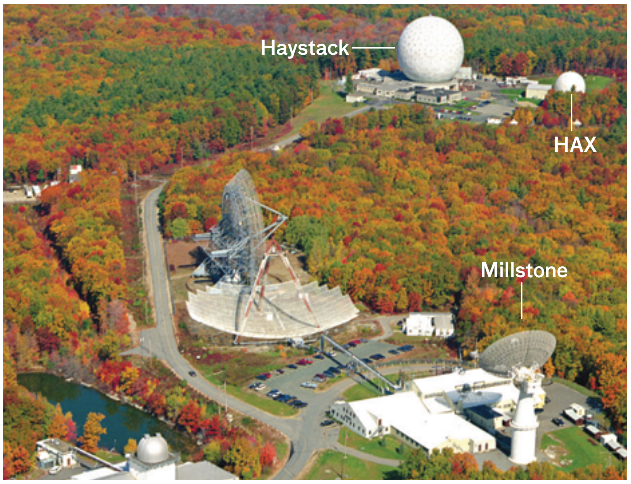

FIGURE 4. The Lincoln Space Surveillance Complex, located in Westford, Massachusetts, comprises three major radars—the Millstone Deep-Space Tracking Radar (L band), the Haystack Ultrawideband Satellite Imaging Radar (X and W band), and the Haystack Auxiliary (HAX) Radar (Ku band). The complex provides key data for space situational awareness and valuable information for radio astronomy.

nal processing to compensate for atmospheric effects and to take advantage of the wide 8 GHz bandwidth, which is critical to achieving image resolution that is about 10 times better than that achieved with Haystack's previously available capabilities. The existing 120-foot antenna has been replaced by a new dish with an rms tolerance of 100 μm averaged over its entire surface. The new antenna surface also permits the Haystack radio telescope, operating in the 150 GHz range or higher, to attain high-resolution imaging, making it a premier radio-astronomy instrument. HUSIR is the first new Lincoln Space Surveillance Complex sensor since the addition of the Haystack Auxiliary radar in the early 1990s (Figure 4). ■

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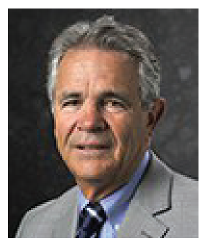
ABOUT THE AUTHORS

William M. Brown is a technical staff member in the Advanced Electro-optical Systems Group and former head of both the Aerospace and Engineering Divisions at Lincoln Laboratory. His current work focuses on project management and on the development and performance assessment of advanced radio-frequency and optical sensors. Prior to his appointments as division head, he founded and led the Sensor Technology and Systems Group, where he initiated a new mission area in environmental monitoring. After joining the Laboratory in 1969, he went on to develop electronic countermeasure concepts for strategic missile systems, design prototype hardware, demonstrate these countermeasures in experimental flight tests, and invent the Electronic Replica Decoy. He has participated in studies led by the National Oceanic and Atmospheric Administration (NOAA) and NASA to define new instruments, spacecraft, and technology for geostationary and polar environmental satellites. From 2003 to 2005, he was a member of NASA's Earth System Science and Application Advisory Committee. He received bachelor's and master's degrees in electrical engineering from the Georgia Institute of Technology.



Antonio F. Pensa is an assistant director emeritus of Lincoln Laboratory. He began his career at the Laboratory in 1969, initially working on reentry systems and air traffic control programs. Subsequently, he was responsible for the development and implementation of the coherent integration tracking that led to the realization of a U.S. operational deep-space radar capability. He was instrumental in establishing the space surveillance program at Lincoln Laboratory. An internationally recognized expert in space systems and information intelligence, he has served on the Air Force Scientific Advisory Board, Defense Science Board (DSB) Task Force on Space Superiority, DSB/Science Advisory Board Task Force on National Security Space, Intelligence Science Board, and in the U.S. Strategic Command Advisory Group. Currently, he is a member of the Air Force Space Command Independent Strategic Assessment Group and the Space and Missile Center Space Program Assessment Group. Throughout his career, he has received numerous awards, including the National Reconnaissance Office Director's Award for Distinguished Service, the Air Force Award for Distinguished Service, and the NASA Group Achievement Award. In 2007, he was recognized with an Outstanding Engineering Alumnus Award by his alma mater, Pennsylvania State University, where he received master's and doctoral degrees in electrical engineering and where he currently serves as an advisory board member of the College of Information Sciences and Technology. He received his bachelor's degree in electrical engineering from the University of Rhode Island.