
A New Compact Range Facility for Antenna and Radar Target Measurements

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■ A new antenna and radar-cross-section measurements facility consisting of four anechoic chambers has recently been constructed at Lincoln Laboratory on Hanscom Air Force Base. One of the chambers is a large compact range facility that operates over the 400 MHz to 100 GHz band, and consists, in part, of a large temperature-controlled rectangular chamber lined with radar-absorbing material that is arranged to reduce scattering; a composite rolled-edge offset-fed parabolic reflector; a robotic multi-feed antenna system; and a radar instrumentation system. Additionally, the compact range facility includes a gantry/crane system that is used to move large antennas and radar targets onto a positioning system that provides the desired aspect angles for measurements of antenna patterns and radar cross section. This compact range system provides unique test capabilities to support rapid prototyping of antennas and radar targets.

LINCOLN LABORATORY has maintained several antenna and radar cross section (RCS) measurement facilities in its history. The largest was an outdoor facility on leased land located in Bedford, Massachusetts, near the north side of Hanscom Air Force Base [1]. This facility had a 2000 ft outdoor range, a 700 ft range, two small (20 ft) measurement chambers, and a small compact range (to test up to 4 ft diameter antennas). This self-contained facility, which included a small machine shop, technician work areas, and a staging area, was principally used for measurements of antennas for satellite communications and radar applications. Measurements could be made from VHF to 50 GHz on the outdoor ranges, from 1 to 60 GHz in the two small chambers, and from 2 to 90 GHz in the compact range.

In another building on Hanscom Air Force Base, there were also two small anechoic chambers and a large compact range (for testing up to 6 ft antennas) that was primarily used to support the development of coun-

termesures. Antenna development and RCS measurements were performed in these chambers at frequencies from 2 to 10 GHz in the small chambers and from 2 to 95 GHz in the compact range.

Finally, a moderate sized (up to 30 ft antennas), near-field range was built near the original Lincoln Laboratory Flight Facility. This chamber could be used either for near-field measurements or, for smaller antennas, as a far-field range at frequencies from VHF to approximately 10 GHz.

In 1997, a small group was commissioned to assess Laboratory facilities, specifically focusing on antenna ranges. This group was charged with identifying current and future users and their needs, surveying facilities' capabilities, considering consolidation and closing of the Bedford facility, and estimating the impact of the various options. This group considered options for closing and relocating both the Bedford antenna test facility and the countermeasures test facility (in an Air Force hangar not contiguous with Laboratory buildings) to have a con-

solidated test facility. The group concluded that antenna and RCS measurement needs would continue, and the existing facilities and their personnel provided excellent service and covered the measurement requirements.

The study of electromagnetic measurement needs and upgrades/relocations continued for the next few years. During this time, measurement needs evolved to include more complex phased-array antennas, including verification of system-level performance such as space-time adaptive processing, adaptive nulling, and electromagnetic compatibility of systems. In 2000, the user community was canvassed again by the study group for Laboratory needs. As a result of the study, it was decided to close the Bedford facility and build an indoor collection of chambers to replace and significantly enhance testing capabilities at the Laboratory [2]. The flagship of this new facility would be a large, compact range that covered 0.4 to 100 GHz and be capable of accurately measuring targets up to 12 ft diameter.

Among the institutions surveyed for candidate designs for this facility was the Ohio State University ElectroScience Laboratory (ESL), which is well known for its designs of compact ranges and instrumentation systems.

Professor Walter Burnside of ESL consulted with Laboratory staff and eventually provided the design of the chamber size, absorber type and location, and most importantly the reflector [3]. A blended, *rolled-edge* reflector design was selected for the Lincoln Laboratory compact range, as has been used in other facilities [4, 5]. The rolled-edge reflector is used to reduce edge diffraction and is particularly effective in reducing the quiet-zone ripple and achieving large quiet zones at low frequencies. The compact-range design parameters developed by ESL were provided to Lehman Chambers and MI Technologies, who were contracted to build the facility. Lehman Chambers was responsible for the chamber construction and microwave-absorber installation, while MI Technologies provided the rolled-edge reflector and target/antenna positioners and their controllers.

Compact Range Facility Description

A diagram of the overall compact range facility is shown in Figure 1. The antenna/target handling room (antechamber), which is 30 ft long by 44 ft wide by 38 ft high, is electromagnetically shielded. A large gantry/crane, shown in Figure 2, is used to move personnel,

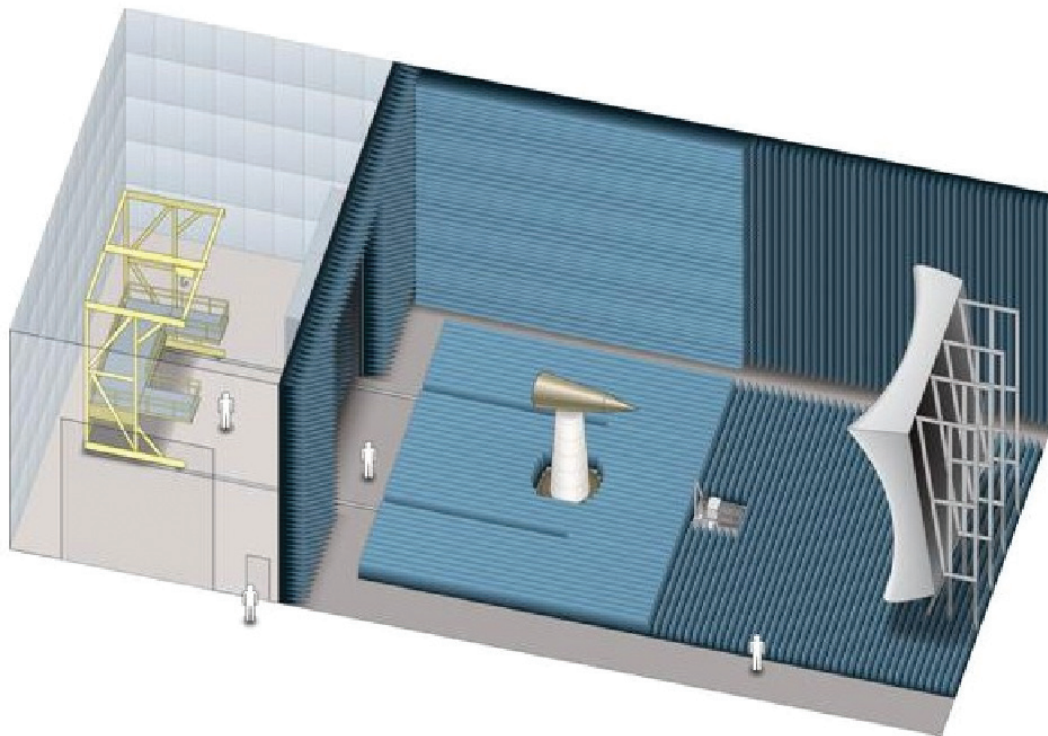


FIGURE 1. Compact range facility at Lincoln Laboratory. On the left is a gantry/crane system used to bring large test objects into the anechoic chamber. On the right is a large rolled-edge parabolic reflector with a set of feed antennas that are located at the focal point of the reflector.

equipment, antennas, and radar targets to and from the test positioner. Its overhead bridge crane has a lifting capacity of 2500 lb, and the scissors lift has a lifting capacity of 1000 lb for personnel and equipment. The gantry/crane is electrically powered and rides on two rails, which are recessed in the concrete floor and spaced approximately thirteen and a half feet apart. Large automated double doors provide a target access opening 30 ft high by 15 ft 4 in wide. Two independent air conditioning systems provide temperature and humidity control to the anechoic chamber, the target handling room (antechamber), and the control room. The temperature of the anechoic chamber is maintained in the range of 68°F to 72°F to ensure a stable environment for maintaining the reflector surface shape and for RCS background subtraction. The background subtraction procedure is described in the following sidebar. The reflector, feed, and target support structures are located on a single concrete slab isolated from the hangar floor to mitigate vibration effects that could degrade the RCS measurements.

The compact range anechoic chamber is large, 66 ft long by 44 ft wide by 38 ft high, and employs both wedge- and pyramidal-shaped absorber on the walls, floor, ceiling, and support structure for the reflector and feed. The pyramid absorber is used closest to the reflector, because it works best with near-normal incident microwave energy. Away from the reflector, near the target/antenna area, the wedge absorber is used because it is most effective at low-incidence angles. The absorber in this region has thicknesses varying in height from 36 to 44 in, as determined by a Chebyshev polynomial [6, 7]. This microwave-absorber shaping feature, developed by the group at ESL, reduces the constructive addition of reflections from the tips of the wedges. The chamber back wall is covered with pyramidal absorber, also in a Chebyshev pattern, with absorber height varying from 36 to 44 in. An early-warning fire-detection system with telescopic sprinkler heads comprises the fire-protection system, along with the fire-retardant microwave absorber.

The main feature of the compact range is the 24 ft square reflector depicted schematically in Figure 3. This was a rolled-edge design from ESL in which the center 12 ft approximately square section is a perfect offset parabola (approximately <0.0015 in root-mean-square [RMS] designed surface error, 0.002 in RMS surface error achieved). As the distance from this center section



FIGURE 2. Gantry/crane system used in moving large test objects and support crew into the compact range chamber. The suspended object is a towed target frequently used for aircraft interceptor tests.

increases, the surface slowly deviates from a parabola so that, at the edge, the surface rolls around until its normal points almost toward the wall behind the reflector. The first four derivatives of the surface contour are controlled to ensure that this transition from pure paraboloid to the rolled edge is sufficiently smooth that it reduces the ripple in the resulting reflected plane wave. The energy reflected from this reflector would produce the desired plane wave in the quiet zone, but also would have significant radiation toward the walls, floor, and ceiling from the rolled edges. Therefore, the absorber quality and treatment are crucial with this reflector design.

The installation of the compact range reflector, as shown in Figure 4, was completed in August 2004. The reflector consists of seven panels, a center 12 ft square panel, four corner panels, and two side panels [8]. Each

BACKGROUND SUBTRACTION

ONE OF THE PROBLEMS in measuring the radar cross section (RCS) of targets is isolating them from the measurement equipment and physical supports. For example, to measure RCS in the compact range, we could place a foam tower on the positioner and put the target on the top of the tower. Even though the polystyrene foam has low reflection, it still may be large enough to mask small features of the target. In addition, small reflections from the chamber itself may corrupt the measurement. The mitigation technique is to coherently subtract a measurement of the chamber and tower without the target from the measurement that includes the target. This process is similar to the cancellation of clutter in a moving-target indicator (MTI) radar. The residual scattering contains chamber and tower features that may have changed between measurements because of vibration or temperature variations and parts of the tower or chamber that are shadowed when the target

is in place. However, these changes are generally very small. It is typical of good RCS measurement systems to achieve a reduction of 30 to 40 dB in stray scattering from the tower and chamber. The background measurement of the chamber and tower is acquired over all the angles and frequencies that constitute the target measurement.

Figure A shows the reduction in the background intensity resulting from subtraction. In this plot, a wide-frequency bandwidth is translated to range in the chamber. The polystyrene foam tower is clearly visible near the center of the original data. Its appearance in the data is reduced by approximately 40 dB in the subtracted data.

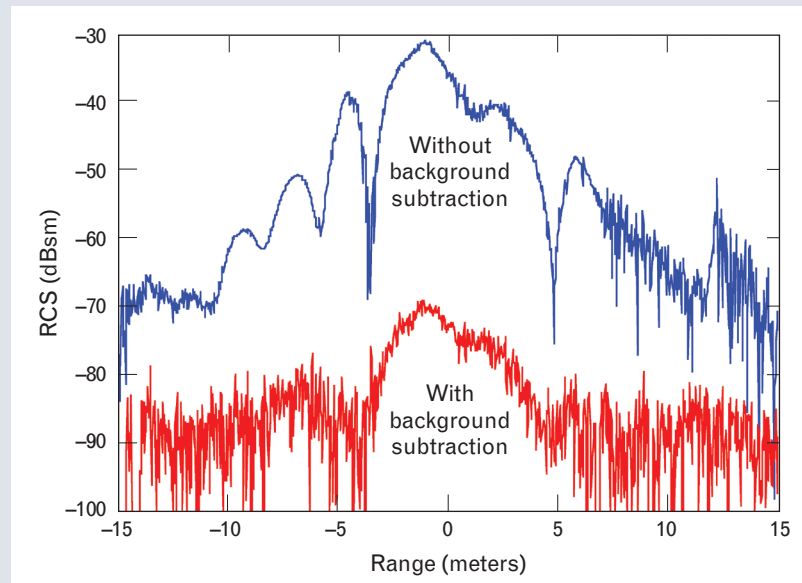


FIGURE A. Background subtraction methodology. The data are from the compact range with no sample in place at frequencies from 8 to 18 GHz.

reflector panel was constructed on a frame of aluminum honeycomb panels forming an egg-crate structure whose initial surface was the approximate desired shape. A thin layer of fiberglass was bonded to this frame and a layer of epoxy was applied to this surface as well. The epoxy was then machined to the desired surface shape. Thermocouples were embedded under the surface of the epoxy for temperature monitoring, and each panel was temperature cycled three times in a large oven to relieve manufacture stresses.

Lincoln Laboratory contributed a crucial design change to the reflector assembly to address a concern that the reflector would not return to its original shape if it experienced a large ($\pm 10^\circ\text{F}$) temperature excursion from the normal operating temperature (70°F). A major factor in this concern was the difference in the coefficient of thermal expansion between the steel back-up structure and the aluminum-fiberglass reflector. The original design by the manufacturer mounted each of the seven panels individually to the steel structure, aligned them

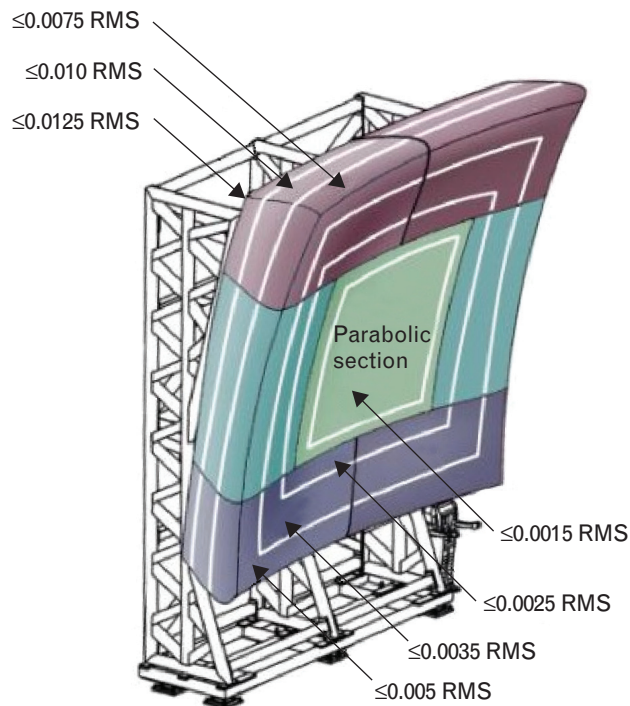


FIGURE 3. Compact-range-reflector surface-accuracy specifications to achieve operation up to 100 GHz. All root-mean-square (RMS) tolerances are in inches.

individually, and secured them to one another. The final design, as suggested by a Laboratory staff member in the Mechanical Engineering group, secured the center panel in three axes (after all the panels were aligned and secured to one another) to the steel structure, and the remaining panels were allowed to move with respect to the back-up structure in the two axes transverse to the reflector normal. This alteration allowed the steel structure to expand and contract with temperature independently of the reflector.

The steel structure was assembled in the chamber and aligned to the chamber's main axes before being secured to the floor. Next, the panels were individually mounted and aligned to the room. The panels were then secured together and another verification measurement was made. Hand-finishing the surface resulted in the reflector meeting the surface tolerance and room alignment requirements. The reflector was then painted with a silver paint. After installation, reflector surface accuracy measurements were performed by using a tracking laser interferometer [8].

The measured RMS surface accuracy of the reflector conductive surface was 0.0012 in over the 10 ft by



FIGURE 4. Photograph of the new 24 × 24 ft compact range reflector installed at Lincoln Laboratory. The reflector is a composite surface of several large machined panels that were hand-finished to the required tolerances before being coated with multiple layers of silver conducting paint and a final layer of white latex paint. The combined weight of the reflector and steel backup structure is approximately forty-four thousand pounds.

10 ft parabolic section, 0.002 in over the first transition section (0 to 28 in outboard of the parabolic section), 0.0021 in over the second transition section (28 to 56 in outboard of the parabolic section), and 0.0031 in over the third transition section (56 to 84 in outboard of the parabolic section to the shadow boundary). The measured surface resistivity of the reflector was 0.11 ohms/square maximum over the surface of the reflector. Once the reflector surface accuracy was verified and surface resistivity measurements were completed, the reflector was coated with a white latex paint.

Instrumentation Radar

Once the chamber construction was complete, a system capable of making measurements for antennas and RCS targets was developed. This instrumentation system has frequency coverage commensurate with the design of the compact range reflector, 400 MHz to 100 GHz, and takes full advantage of the 12 ft diameter quiet zone of the chamber. A custom radar system design was preferred because it could be maintained and upgraded as needed by Lincoln Laboratory personnel. ESL was selected as the source for this instrumentation system because of their experience in providing such range instrumentation radars for numerous organizations over a period of decades [9, 10]. An important consideration in the selection of ESL to provide the instrumentation was their participation in the design of the chamber and reflector. Problems encountered during initial checkout were the responsibility of a single supplier, avoiding the confusion when determining that the measurements or the chamber was in error.

The proposed ESL radar system was based on a system used in their chamber in Columbus, Ohio, which can scan 2000 frequencies per second. On the basis of an RF network analyzer, the proposed system substantially shortens the measurement time over the existing Lincoln Laboratory compact range radar system. In addition, this ESL system had high dynamic range, an internal test and diagnostic capability, and a graphic user interface (GUI)-based operations software.

Requirements discussed with ESL included an RCS sensitivity of -60 dBsm at frequencies up to 18 GHz, -40 dBsm at frequencies between 18 and 65 GHz, and -35 dBsm from 90 to 100 GHz. The system would also be required to have sufficient long-term stability to maintain 30 dB background subtraction over a 24 hr period. The control software was to have an easy-to-use GUI and run on a standard personal computer (PC) with a Windows operating system. A built-in test capability, allowing failure identification to the subsystem level, was to be included. Finally, the system would be evaluated first in the ESL compact range with targets supplied by Lincoln Laboratory before shipment. The system would have to control the MI Technology positioners that were installed in the compact range. An important feature of the effort was a level of documentation sufficient to allow the system to be maintained and upgraded by Laboratory personnel. This documen-

tation was to include schematics, a full parts list, and adequate notation of the component voltages, currents, power levels, and frequencies.

The effort started with a system-definition meeting in Columbus, Ohio, in August 2003. The proposed system would improve on an existing design by replacing the analog baseband filtering with a new dual-channel digital receiver to provide synthesized in-phase/quadrature data after digital downconversion of the 11.6 MHz intermediate frequency (IF). The existing system employed a frequency synthesizer designed and built by ESL to achieve rapid frequency scan; however, commercial units were now available at acceptable costs that could meet the frequency switching times and spectral purity requirements. A joint decision to purchase a commercial synthesizer from Communications Techniques, Inc., was made after a visit to the company by ESL and Lincoln Laboratory representatives. Figure 5 shows a block diagram of the ESL instrumentation radar system design.

The instrumentation system progressed through design to a critical design review in June 2005. During this time, one of the problem areas of the overall system was the design of an automatic feed-antenna positioning system that would remotely change the reflector feeds in the chamber, placing any one of seven feed horns at the focal point of the reflector. An initial concept was a rotating unit that would house the instrumentation radar; when the desired feed rotated into position, the feed would be raised to the focus on a moving post. However, this concept did not adequately address cable management and access to the electronics. The final design employs a translation motion to move the desired feed (and entire radar electronics) to a stationary post, where the feed is then raised to the height corresponding to the focus, as shown in Figure 6. Three linear slides are used, two for the horizontal motion of the radar electronics and one for the near-vertical motion of the feed. Stepper motors provide repeatability and enable the control software to independently position each feed to its proper location. This effort required mechanical design expertise not available at ESL. Precision Fabrication of Columbus, Ohio, was contracted to design and fabricate the feed positioning unit.

It was also decided during this period to locate the control computer with the radar system inside the chamber rather than in the control room. This position eased potential problems associated with system tim-

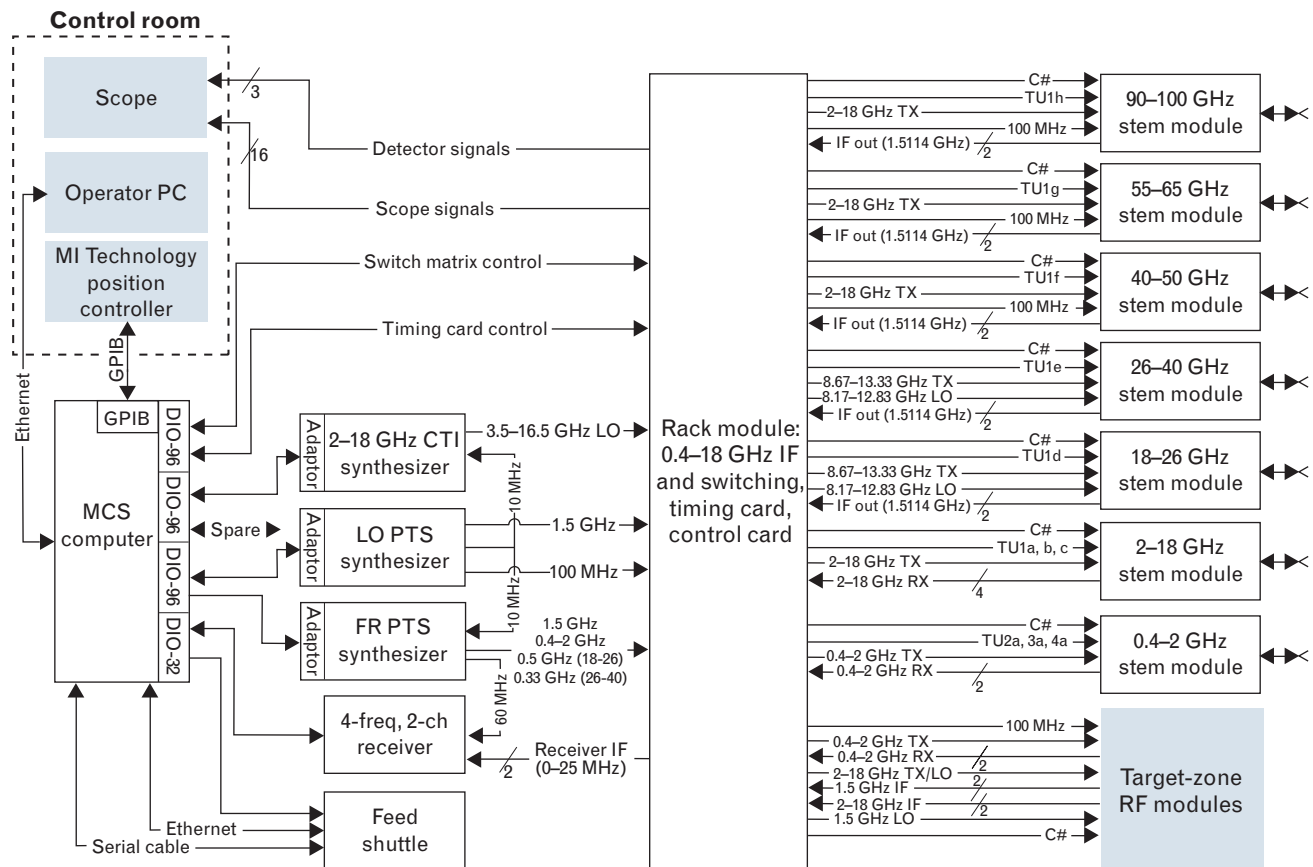


FIGURE 5. Block diagram of the instrumentation radar system for the new Lincoln Laboratory compact range. GPIB stands for general-purpose interface bus; MCS is a measurement control system computer; LO PTS and FR PTS are a local oscillator and frequency response units from Program Test Sources; and CTI stands for Communications Techniques, Inc.

ing and long universal serial bus cable runs. However, it did require long general-purpose interface bus cables to connect to the controllers for the antenna positioners. A computer in the control room would run Virtual Network Computing's remote connection program to operate the radar's control computer.

The instrumentation system employed a common module to generate the desired signal and two identical but independent receive paths at each of the two lowest bands (0.4 to 2 GHz and 2 to 18 GHz). The downconverted signal in each path was then routed to the digital section (A/D and digital filtering), where the resulting data are collected in the control computer. In each section, switches allowed signal routing to a few receiver subsections for test and diagnosis. Located near the feed antenna, a high-frequency *stem module* would contain the final transmit amplifier, a transmit/receive (T/R) switch, and a power divider for directing the re-

ceive signal to the two-channel receiver and appropriate receive amplifiers. The 2 to 18 GHz band employs two 2 W amplifiers, one for 2 to 6 GHz and the second for 6 to 18 GHz. The T/R switch is used to select the proper path for transmit and the receive path for the reflected pulse. The low frequency (0.4 to 2 GHz) and the main frequency (2 to 18 GHz) stem modules also contained switches, allowing the transmit signal to be directly routed to the receive module for test purposes. Finally, detectors attached to directional couplers are positioned at various locations in the transmit and receive paths so that pulse timing can be adjusted by using the oscilloscope in the control room, which displays the actual pulsed RF.

For the higher frequencies, custom converter modules were commercially procured. One set of these modules, called the *stem module*, would be located at their respective feed antennas and a second set, called the *re-*

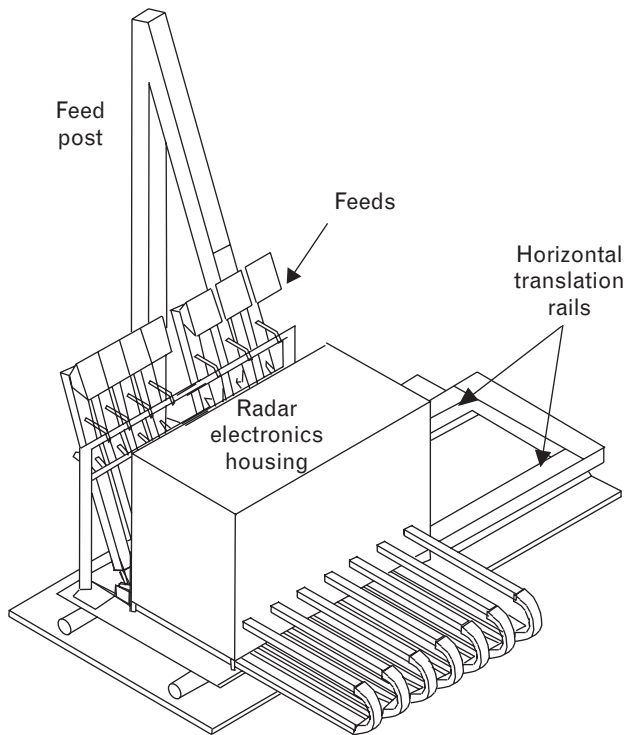


FIGURE 6. Translating-feed-shuttle concept for compact range. The desired feed horn is placed at the focal point of the reflector by using a horizontal rail system, which also moves the radar electronics, and vertical feeds along the feed post.

mote module, would be positioned with an antenna to be measured. The conversion from a 2 to 18 GHz signal to the desired band is performed by using either a mixer or a combination of a mixer and a frequency multiplier.

The feeds used in this system consisted of commercial horns except for the 2 to 18 GHz band. This 2 to 18 GHz feed—an ESL-designed transverse-electromagnetically fed dielectric-rod antenna—is in development to achieve the desired beamwidth over the frequency band to maintain the desired 12 ft quiet zone. ESL staff also designed the ortho-mode couplers for the 18 to 26 GHz and 26 to 40 GHz bands, since the required performance could not be achieved with commercially available hardware.

The radar system was delivered and installed at Lincoln Laboratory in November 2005. A base plate was leveled and secured to the floor with a clearance hole over a mark directly beneath the reflector focus. A second plate was mounted to the base plate to permit the radar to be correctly positioned and aligned to the room. The horizontal translation rails and feed post were mounted to the second plate and the instrumentation housing

was secured to the rails. Then the feeds and stem modules were installed and the equipment was located in the housing. A photograph of the completed radar system with the feed antennas is shown in Figure 7.

Several target supports have been either made in-house or procured. The largest was furnished by MI Technologies with the chamber and consists of a large translation table mounted to the floor positioner with a fiberglass tower. This support system includes an azimuth-over-elevation positioner at the top of the tower for mounting large objects or antennas. This system is best suited for large directive antennas whose radiation pattern won't interact with either the high-dielectric tower or metal translation table. Lincoln Laboratory personnel have manufactured a 19 ft polystyrene foam tower for RCS measurements, since the interaction between the tower and target reflections is reduced. In addition, two custom foam towers were procured from System Research and Development Corporation in Florida. These towers feature a diamond-shaped cross section that provides very low reflections except at angles at which the radar views the flat sides directly. We plan to procure a low RCS target support in the near future. This support is a thin tower, angled toward the reflector with an ogive cross section. The support features very low scattering, reducing the measurement error due to the target support.

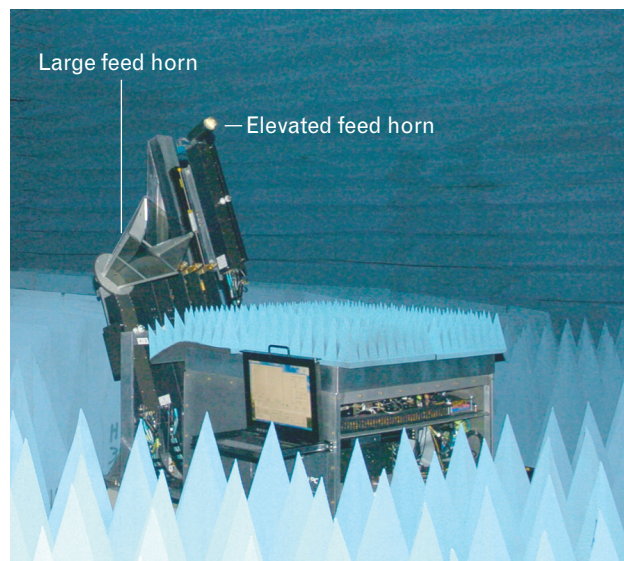


FIGURE 7. Translating-feed shuttle with integrated radar systems and feed horns. The large horn (400 MHz to 2 GHz) on the left is in stowed position while a 2 GHz to 18 GHz feed horn has been elevated to the focal point.

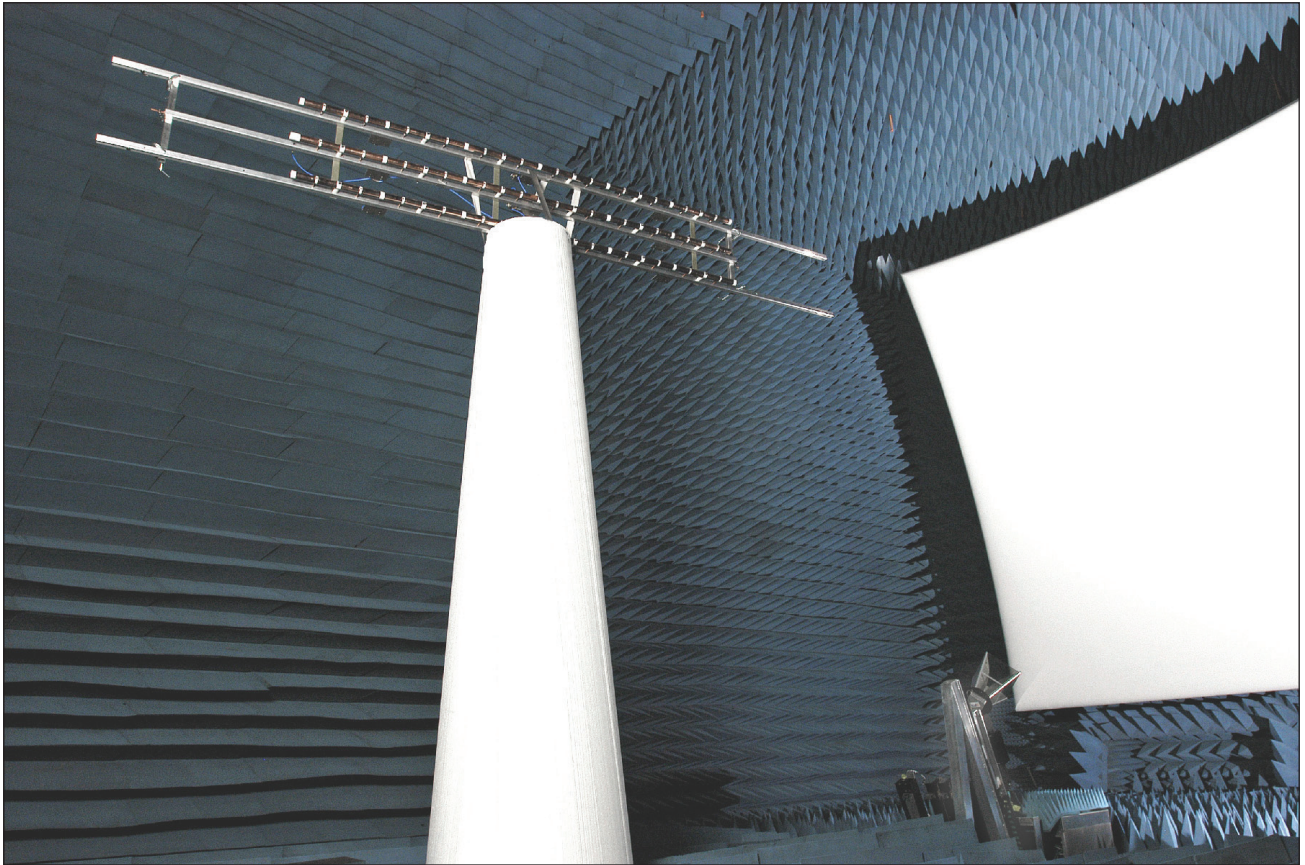


FIGURE 8. Large UHF array under test in the new compact range chamber. The array is shown mounted on a large foam tower that reduces electromagnetic scattering effects. A lower-azimuth positioner (not shown) provides the desired antenna rotation.

Example Measurements

The performance of the new compact range system was recently evaluated for antenna pattern measurements at low frequency. Figure 8 shows a photograph of a 10 ft long UHF array antenna (supported by a conical foam tower) that was fabricated to evaluate the quiet-zone accuracy of the compact range at low frequency. The 10 ft long by 2 ft high dipole array antenna was fabricated in one week with rapid prototyping techniques developed at Lincoln Laboratory. A comparison of measured and calculated radiation patterns of the array at 400 MHz is shown in Figure 9, and good agreement is indicated.

Another antenna was recently measured in the chamber. The 6 ft reflector,

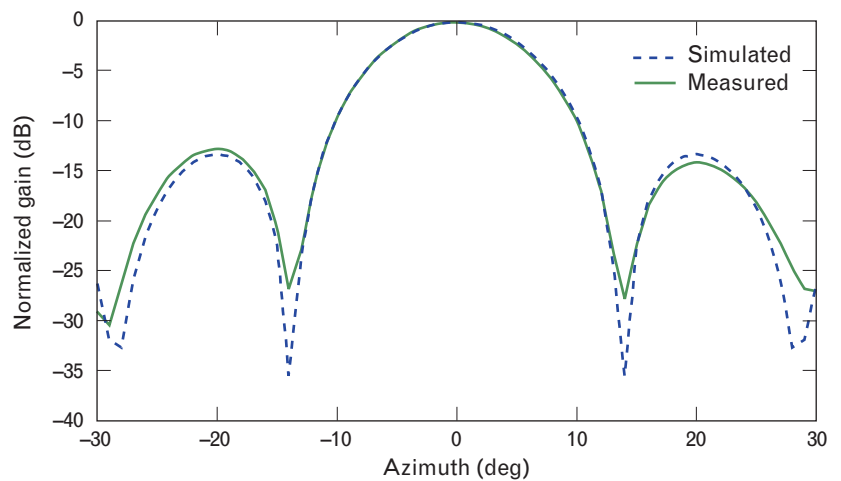


FIGURE 9. Simulated and measured azimuth gain patterns at 400 MHz. The comparison shows good agreement between a simulated radiation pattern and a measured radiation pattern for a 10 ft array antenna at in the new compact range facility.

operating at 20 and 44 GHz, was placed on the large fiberglass tower, and radiation patterns were acquired at both frequencies. These measurements proved challenging because of the narrow beamwidth and gain accuracy desired. The resulting acquired data demonstrated the stability and accuracy of the new system. During this process, the 6 ft reflector antenna under test was removed for two days and then reinstalled in the chamber. The measured peak-gain amplitude had not changed by more than 0.1 dB over the two days.

Summary

A new compact range facility at Lincoln Laboratory for antenna and radar cross section measurements will soon be in full operation. The compact range operates over the 400 MHz to 100 GHz band, and consists of a temperature-controlled large rectangular chamber lined with radar-absorbing material that is specially arranged to reduce scattering; a composite rolled-edge offset-fed parabolic reflector; a robotic multi-feed antenna system; and a radar instrumentation system. The compact range facility also includes a gantry/crane system used to move large antennas and radar targets onto a positioning system that provides the desired aspect angles for measurements of antenna patterns and radar cross section. This compact range system provides unique rapid test capabilities to support a broad range of programs that Lincoln Laboratory is pursuing.

Acknowledgements

The authors would like to express their gratitude to numerous individuals who contributed to the development of the new compact range facility. At The Ohio State University, Dr. Walter D. Burnside designed the compact range facility, including the instrumentation system, Dr. Teh-Hong Lee provided the compact range reflector electromagnetic analysis, Dr. Chi-Chih Chen contributed to the feed antenna design and development, Dr. Inder J. Gupta analyzed both the reflector surface accuracy and field probing data, Grant Hampson designed the radar digital receiver, Willie Theunissen provided the measurement control system and hardware/software integration, and Dr. Frank Paynter provided managerial and software support. At Lincoln Laboratory, Paul F. Martin provided mechanical engineering support for the compact range reflector development. Robert Meagher provided engineering support for construction of the compact range facility. Addi-

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