A 585 GHZ COMPACT RANGE FOR SCALE MODEL RCS MEASUREMENTS

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Abstract

A 585 GHz compact range has been developed for obtaining full-scale RCS measurements on scale model targets. The transceiver consists of two CW submillimeter-wave gas lasers along with two cooled-InSb heterodyne mixers. Coherent detection has been implemented to maximize sensitivity and allow for a vector measurement capability. In addition, the target can be rapidly translated in range to generate a doppler modulation which is used to reject background signals during low-RCS measurements.

Although most scaling is accomplished with metal targets, a materials program has evolved to develop non-metallic materials with scaled dielectric properties as well as submillimeter-wave anechoics. As part of an on-going validation and test program, RCS measurements are made on scaled simple and complex shapes and compared with full-scale measurements and computer predictions.

A description of this 585 GHz compact range along with measurement examples are presented in this paper.

Keywords: Compact Range, Scale modeling, RCS, Submillimeter-Wave

1. Introduction

As radar technology continues to evolve, demand is increasing for target RCS data used for both radar system development and target RCS reduction. Alternatives to full-scale field measurements such as computer codes and compact ranges are often used where full-scale measurements are not practical or when cost must be reduced. The technique of using scale models and scaled frequencies to study electromagnetic scattering on targets at full-scale frequencies dates back to the 1940s [1] and continues to grow in popularity [2,3].

The use of submillimeter-wave lasers for scale model measurements was first reported in the late 1970s and early 1980s [4,5]. The University of Massachusetts Lowell (UML) has improved on these early near-field ranges and incorporated the submillimeter laser into a true compact range through the addition of a 45" dia. diamond-turned, spherical reflector. In addition, sensitivity has been enhanced significantly by development of a coherent, heterodyne receiver system. Scale factors used in the submillimeter compact range typically extend from 10:1 through 60:1, although ~200:1 has been successfully demonstrated using a 3 THz laser.

The 585 GHz compact range described herein is based on CO_2-pumped, CW, submillimeter-wave lasers which are capable of producing power levels from 1-100 mW at hundreds of different frequencies throughout the submillimeter-wave region. The 585 GHz laser line has become popular at UML because of its ease of operation, and because it scales several of the popular microwave and millimeter-wave bands with reasonable scale factors. With the use of good anechoics in the measurement chamber combined with signal processing to eliminate stray radiation, measurement sensitivity is typically limited only by the available transmit power.

Since the lasers currently are narrow band, they are used primarily for full-illumination, low-RCS measurements or high resolution scanning-spot imagery. For wide-band measurements, UML has developed two other type of systems: 1.) a completely solid-state, fully-polarimetric, wide-band transceiver and 2.) a wide-band laser/solid-state hybrid using submillimeter-wave Schottky mixers. These systems operate at lower power levels and are designed primarily for obtaining high-range-resolution (HRR) data and ISAR images. The solid-state system is currently limited to frequencies below 600 GHz while the laser hybrid is capable of operating well into the THz regime. Details of these systems will not be presented in this paper.

To handle a broad variety of RCS measurements, several target handling systems have been developed. For small ($l \leq 20\lambda$), low-RCS objects such as flat plates, cylinders, cones, etc., a free-space sling-suspension system has been developed. For larger targets where sling mounting is not practical, a variety of low-RCS pylons have been fabricated which allow for the automated positioning of targets in aspect and depression. For studying scattering from objects on a ground plane, a 24' long ground plane has been developed incorporating a removable surface sheet to allow different metal or dielectric surfaces to be substituted onto the support structure.

A very important part of the submillimeter compact range development program has been testing and validation. Since many issues such as the frequency limits of scaling and the fidelity of models are a concern to users new to submillimeter modeling, an extensive validation program was developed and is on-going. The premise of the validation program is to make full-scale and modeled measurements on identical targets starting from simple canonical shapes, and progressing towards complex targets to verify system integrity.

In this paper, the 585 GHz transceiver will be described along with the design of the compact range into which it has been incorporated. In addition, the target-handling stages and the ground plane will be described. Finally, data from selected simple and complex shapes will be presented along with comparisons with full-scale measurements or computer predictions.

2. Transceiver Description

The 585 GHz transceiver, shown in figure 1, is based on a pair of CW, optically pumped, molecular gas lasers [6]. One is used as the transmitter while the other serves as the receiver local oscillator (LO). A 50 Watt CO_2 laser operating at a wavelength of 9.28µm is used as the optical pump. The desired 585 GHz line is obtained from the lasing of a molecular transition in formic acid vapor. The laser's gain-bandwidth of a few MHz allows them to be set to a difference frequency of ~500 KHz, thus defining the IF frequency. The submillimeter laser output is a clean gaussian beam with a 12mm FWHM. Although solid-state sources are now available at this frequency range, the laser is capable of delivering significantly more power, albeit at discrete frequencies and with limited tunability.

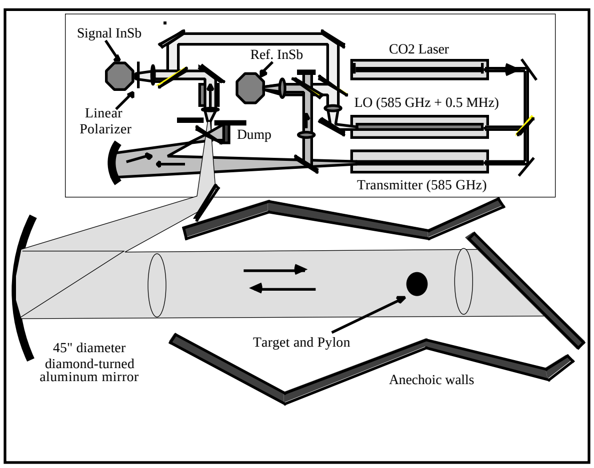

Figure 1. Diagram of 585 GHz transceiver and compact range.

The receiver consists of a pair of liquid-helium-cooled InSb detectors used as the low-noise input mixers (NEP ~1.0 x 10^{-19} W/Hz). The two mixers are utilized in a coherent heterodyne receiver system which is capable of providing vector measurements with a selectable pre-detection BW nominally set to 100 Hz.

The InSb mixer is the same type often used in submillimeter radio astronomy [7]. The detector consists of an InSb element which has been cut and etched into a needle and mounted across a TE_{11} circular waveguide in the mixer block. The circular waveguide is terminated on one end by a tunable backshort and on the other by a simple conical feed horn. The mixer block is mounted onto a liquid-helium-cooled cold finger inside the dewar.

The feed horn is oriented in a down-looking configuration looking through a submillimeter filter and vacuum window. The down-looking orientation facilitates the optimization of the mixer for polarization by simply rotating the entire dewar in which the feed horn is centered. The mixer's electrical signals are routed via an electrical feed-through to a shielded RF enclosure mounted directly to the dewar. The mixer bias circuitry, a low-noise pre-amplifier, and the battery supply are located in this enclosure.

Quasi-optical, free-space techniques are used to transport the beams to the various couplers and mixers throughout the transceiver. Optical techniques offer lower losses and are simpler to implement than waveguide at these frequencies. Mylar beam splitters, TPX lenses, aluminum mirrors, and wire-grids are some of the optical elements used for beam handling and polarization control.

The transmit signal originates at the output of the transmit laser and is directed to an optical splitter. Here, about 1% is coupled off, attenuated, and combined with the LO laser in the reference InSb detector to create the 500 KHz reference beat frequency. The balance of the radiation continues past the splitter and is focused by a spherical mirror at a point coincident with the antenna mirror focal point. The beam continues through a 50% beam splitter where half the beam expands towards the 45" diamond-turned antenna mirror and half is used for an in-scene power monitoring system. The beam splitter also serves to combine the transmit and receive paths needed to realize a monostatic system.

The primary antenna collimates the expanding transmit beam which then propagates to the target area. The beam has a gaussian amplitude profile (typically 20" FWHM) and has a phase-front flat to better than $\lambda/16$. Minor changes in the optics allow the beam size at the target to be varied anywhere from about 0.5" to almost 30" while maintaining a flat phase-front.

The radiation returned from the target proceeds back to the antenna mirror and is focused through the 50% beam splitter into the receiver aperture. In the receiver section, the desired receive polarization is selected by a wire-grid. The radiation is then combined with the LO via a beam splitter and focused into the signal InSb detector feed horn. The resulting 500 KHz beat signal is then amplified and pre-filtered in a 400 KHz wide bandpass filter. The filtered signals from the two InSb mixers are then routed to vector lock-in amplifier (synchronous detector) which measures the amplitude of the scattered signal and its phase relative to the reference mixer signal. Data-acquisition and processing is accomplished with *LabView*® software from National Instruments Corp. running on an Apple Macintosh® computer.

3. Target Modulation

One of the major concerns with any RCS measurement system is to isolate the target return from other unwanted signals. In a pulsed or wideband system, signals can be accepted or rejected according to range. The submillimeter lasers currently in use operate in a continuous wave (CW) mode. Therefore, discriminating scattering via range is not an option, although pulsed lasers are under development. The stray signals include diffracted signals from the mirrors, beam splitters, and back wall of the anechoic chamber. For very large flat plates or targets containing them, interactions of the target with the chamber can be a problem. For example, as a flat plate with an RCS 100 dB above the system noise floor is rotated away from normal incidence, the chamber must attenuate this specular reflection by close to 100 dB to avoid spurious signals.

Good anechoic materials and clever chamber design can provide a minimum of 40 dB of rejection and usually at least 80 dB from these target-chamber interactions. Software or hardware range-gating in wide-band systems is often used to provide the balance of the needed rejection. To discriminate against these unwanted signals in this narrow-band system, a target modulation scheme has been implemented which utilizes the vector nature of the coherent heterodyne receiver to provide rejection of the unwanted signals.

Under normal operation, a target is rotated through a range of aspect angles where the phase and amplitude of the scattered return is recorded as a function of angle. For any fixed measurement angle, the electric-field incident on the receiver is the vector sum of all the individual scatterers within its field-of-view, including all unwanted stray signals. Also summed into the vector return are transceiver leakage signals and demodulator offsets. Under normal conditions, the phase and amplitude of the unwanted signals remain constant. Since the phase of the target scattering is related to the range of the target, if the target is precisely translated in range, the phase of the target scattering vector will rotate 360° for each half wavelength of motion along the measurement axis.

In the current implementation of the target modulation software, the target is moved to the desired angle and then translated several wavelengths in range either towards or away from the antenna. The scattered signal vector is digitized at precise increments during this translation. This short measurement burst is frequency filtered to isolate only the signal with the correct phase rotation rate (frequency). Signals at zero frequency are stationary stray signals from the range. Signals at other frequencies can originate from interactions between the target and the anechoic chamber (target-chamber-target-receiver). Interactions between the target and the front of the anechoic chamber appear at or near twice the target-modulation frequency. Interactions between the target and the rear of the anechoic chamber appear at or near zero frequency. Interactions with other parts of the chamber appear at frequencies between zero and 2F, proportional to the angle between the measurement beam and direction of the interaction. This implies that interactions with the side walls of the chamber will appear at or near the desired target modulation frequency requiring extra care in anechoic materials in this area.

A waterfall plot showing a sequence of these modulation burst spectra is illustrated in fig. 2. Each horizontal trace in the waterfall plot represents a different aspect angle from 0° to 360°. Notice that the zero-frequency peak (center) which is due to the background is nearly constant throughout the run. The signal at F is the target signal as a function of aspect and is used to obtain the RCS.

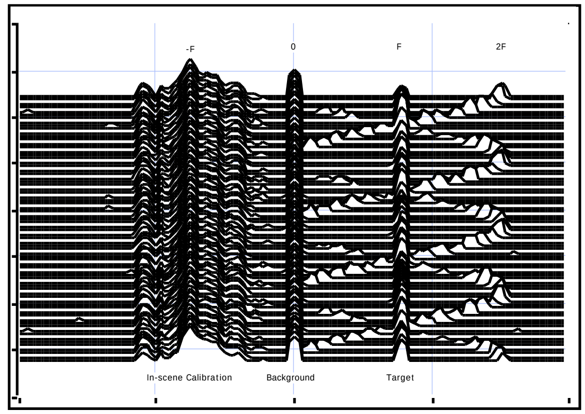

Figure 2. Waterfall plot showing a sequence of spectra processed from the target modulation. Each trace represents a different aspect angle.

The dual "S" pattern weaving in and out of the target peak is from the interaction of the target with the room. In this example, the target was a truncated pyramid (fig. 5). The interaction with the chamber is due to the four large vertical flat plates of which two are visible at any given angle. One of them scatters radiation towards the front of the chamber producing frequencies > F while the other, scattering towards the back producing frequencies < F. The wide peak to the left side of the waterfall plot is an in-scene calibration object which was modulated at negative F (same velocity but in the opposite direction). The wide irregular shape of this calibration peak is due to the lack of synchronization between the target and in-scene calibration stages. Better stages with linear encoders could remedy this situation.

Anechoic materials have been developed to satisfy the unique requirements for absorber in the submillimeter. A wedge anechoic [8] is the primary material used at 585 GHz. This material offers a minimum of ~45 dB attenuation at normal incidence and is much better at other angles. For less critical areas of the chamber, certain pure wool carpets have been shown to exhibit good anechoic properties. In addition to chamber absorber, dielectrics have been fabricated to model a number of other materials such as RAM, RAS and other dielectric objects which need to be scaled to submillimeter wavelengths.

4. Free-Space Positioners

Two types of free-space target positioners have been used for measurements in the submillimeter compact range: the sling mount and the low-RCS pylon. The sling stage, shown in figure 3, has been used for small, low-RCS objects which could be supported by the tiny dielectric support fibers. Examples of shapes that were measured include small flat plates, cylinders, cones, frustums, dihedrals, trihedrals, boxes, wedges etc. The sling stage has two motorized box beams in which numerous attachment hooks are located. From these hooks, the smallest, sufficiently strong, synthetic fibers are strung diagonally from top to bottom. Targets such as cylinders and cones are simply slung at the intersection of several pair of fibers to provide the mount. Targets such as flat plates were attached to the intersection of the fibers with thin layers of adhesive applied to the back of the plates. The primary disadvantage of the sling stage is its inability to be tilted to various depression angles. However the target can be tilted to specific angles and rotated about that orientation.

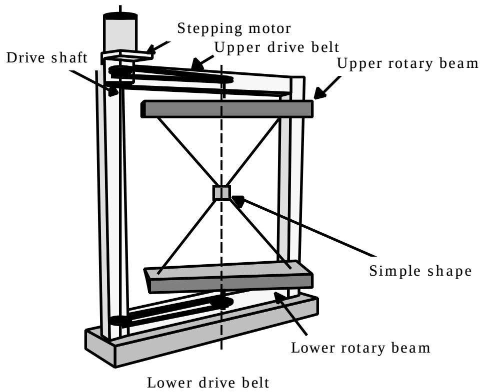

Figure 3. Free-space 360° sling mount used for small. low-RCS targets.

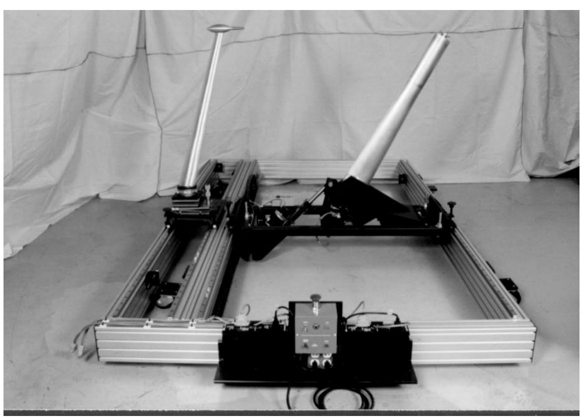

Figure 4. Side view of the free-space calibration (left) and target (right) pylons on translation base.

Several types of free-space pylons have been fabricated, each with a particular characteristic necessary to hold a class of target object. A stage on which both a target and calibration pylon are mounted is shown in fig. 4. The target pylon has full 360° aspect capability and can swing 20° in depression. Different heads are available in 20° bias increments to allow the stage to reach 0° - 90° in depression. The entire pylon can be translated in range to allow the doppler modulation technique to be used. The linear rails on which the pylons are mounted allow either pylon to be quickly translated into or out of the beam.

In addition to target pylons, a two-axis field probe has been designed for the purpose or characterizing the beam profile. This system has the capability of scanning a 5'x5' scan zone with either a mirror (for two-way profiles), or a receiver (for one-way profiles).

5. Ground Plane

Measurements on ground planes (GP) are useful where multi-path scattering with the GP are of interest. A truncated pyramid which has been recently measured [9] is shown in fig. 5. This photo shows a view looking from behind the pyramid down the ground plane towards the 45" antenna mirror. The ground plane flat section is 24' long with a 30' long, 4' wide sheet of aluminum adhered to the center to form the actual GP surface. The surface layer is allowed to curve off the leading and trailing edges of the basic structure to allow the edges to be well away from the beam. This layer can be removed and replaced with other metal or dielectric planes with various surface characteristics. The ground-plane can be positioned to nearly any depression angle, the minimum being limited by the height of the target and the diameter of the beam.

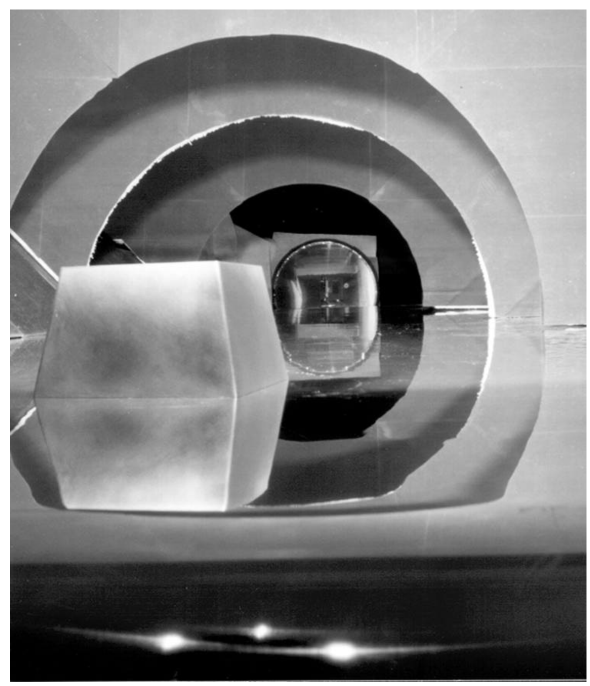

Figure 5. Truncated pyramid and its image on the submillimeter range ground plane looking towards the 45" antenna mirror.

The target positioner is located on the back side near the trailing edge of the GP. The positioner consists of a two axis translation stage on which a rotary stage is mounted. The X-axis stage allows for doppler modulation along the direction of the GP. The Y axis allows the targets height above the GP to be adjusted. The rotary stage provides the aspect positioning. The entire GP structure is flipped up on its side during the measurements so the GP coordinate system is rotated 90° with respect to the free-space system. This rotated orientation allows the depression angle of the GP to be easily set. Polarization of the transceiver is rotated 90° to compensate for the GP rotation.

6. Calibration

Calibration is accomplished with a set of objects which are measured sequentially before each aspect angle scan. Generally, the calibration objects consist of several different size spheres chosen to sample a range of RCS values expected in the data. In addition to spheres, flat plates, dihedrals, and trihedrals are sometimes used as calibration objects. Once the data is calibrated, the calculated values of the different objects are compared with the measured values to verify correct system operation.

To correct the data for any power fluctuations during the measurements, an in-scene calibration is used. Using the target modulation described in section 3, a sphere is translated at a different rate than the target allowing its signal to be isolated. The target data is then ratioed to this continually monitored calibration.

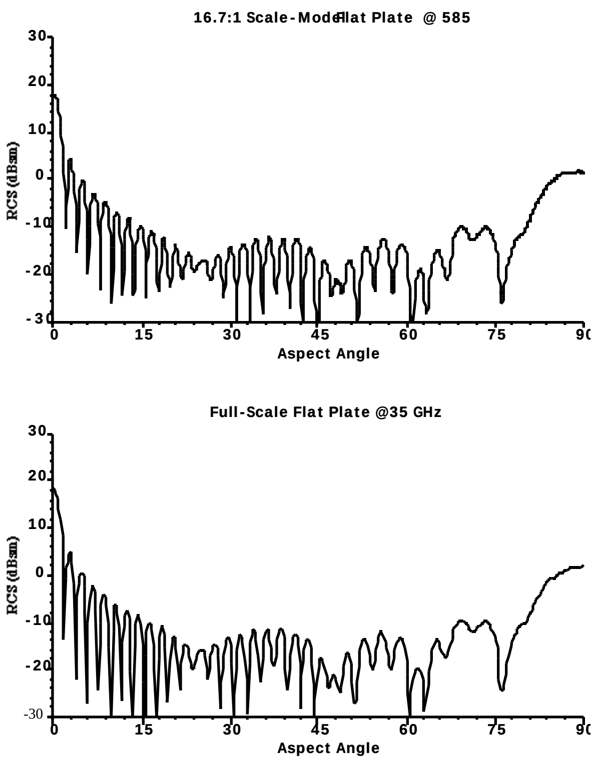

Figure 6. Comparison between full-scale and model measurements of a flat plate.

7. Validation Program

The objects used for test measurements are, whenever possible, based on data which has already been measured on full-scale ranges and requires only the fabrication of a model. Where particular scattering phenomena need to be examined, full-scale and modeled shapes are built and measured on both systems, and compared. More recently, submillimeter modeling has been used as a method to check computer prediction codes, with very encouraging results. Several shapes have been designed which include a wide variety of scattering features. Generally, these shapes were intended to be challenging targets to fabricate and measure, yet simple enough to study and understand.

One of the first shapes to be tested was a thick, flat plate (14.7λ x 17.7λ x 2.2λ) measured at 35 GHz by Ross [10]. Figure 6 shows both the full-scale and model measurements. Fig. 7 shows a measurements of a more complex shape consisting of a rectangular box with cavities in the opposing end faces. Both of these shapes were positioned using the free-space sling stage.

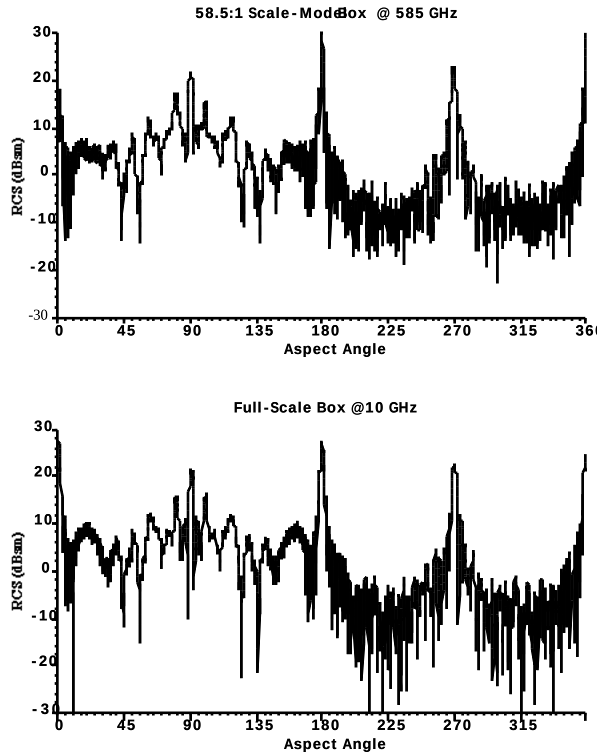

Figure 7. Comparison of full-scale and modeled rectangular box with cavities.

In an effort to create a complex shape which might have some resemblance to a real-world target, yet be simple enough to model and understand, a complex target simulator (CTS) was designed and fabricated. The CTS, shown in fig. 8, is designed to be a 16:1 scale model of a simplified military ground vehicle. It has a series of trihedrals, dihedrals, gratings, cones, cylinders, top-hats, and flat plates. It is modular so sections of it can be removed and replaced with other parts. Fig. 9 shows a comparison of this target measured by the 585 GHz range and compared with computer prediction run on the Georgia-Tech TRACK code.

8. Conclusion

A 585 GHz compact range based on submillimeter lasers and InSb mixers has been described. The incorporation of a 45" diameter diamond-turned antenna mirror allows system operation in a true compact range configuration with an adjustable beam diameter. A two-laser, two-detector scheme provides coherent, heterodyne detection. Target modulation has been demonstrated to reject background and target-chamber interactions even as the transmitter operates CW. Capabilities for both free-space and ground-plane measurements have been described.

Full-scale and scale-model measurements have been presented showing good agreement. Comparisons between computer predictions and scale-model measurements on a relatively complex shape were also shown to be in good agreement. Because small models are inexpensive to fabricate and since range space requirements are modest, submillimeter compact ranges have proven to be a viable complement to full-scale systems and computer codes.

Figure 8. The complex target simulator (CTS) shown from a rear quarter view.

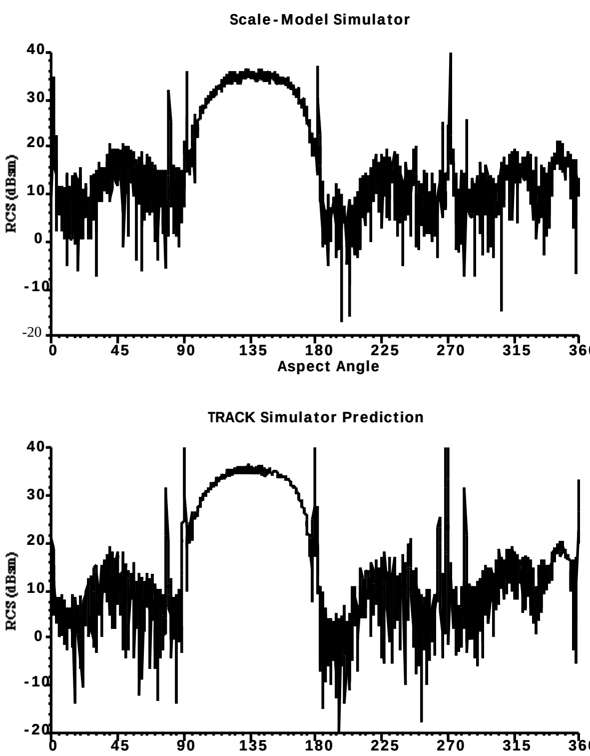

Figure 9. Comparison between computer predictions and modeled measurements of the complex target simulator.

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