Submillimeter modeling of millimeter radar systems

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Abstract

A submillimeter radar modeling facility has been developed for the acquisition of data from scale models of tactical targets to determine the scattering of millimeter waves from the corresponding full-size vehicles. Advances in submillimeter optically pumped laser technology and minicomputer control and display have been utilized to achieve a versatile radar modeling system in a laboratory. High resolution imaging and radar cross section (RCS) measurements have been made and the necessary calibration techniques have been developed. Evolving submillimeter technology should permit the modeling of frequency-agile radar systems.

Introduction

During the past decade considerable progress has been made in establishing the technology base for future millimeter (30-300 GHz) radar systems. Given the inherent advantages of small size and high resolution relative to microwave frequencies, and lower attenuation through fog and smoke relative to the infrared, it is certain that such systems will be developed. The technique of utilizing model measurements for determining UHF and microwave (0.4 to 30 GHz) radar cross sections of real targets is well known and widely used. Extension of the method for the purpose of modeling the millimeter regime requires submillimeter wavelengths. Fortunately, the advances made in developing submillimeter sources and detectors during this same period, now allow such modeling measurements to be undertaken. Since millimeter systems are presently in the early stages of development, information gained from submillimeter modeling can play an important role in their proper design and implementation.

The design of the submillimeter modeling system reported in this paper departs significantly from the corresponding lower frequency systems. Instead of using conventional microwave sources, detectors and components, the system relies on optically pumped gas laser sources, liquid He cooled bolometers, photoconductors, Schottky barrier diodes in open mount corner reflectors and mirrors, lenses and beam splitters. The inherently large bandwidth of these quasi-optical components coupled with the hundreds of available submillimeter laser lines allows the exploration of virtually all millimeter wavelengths of interest using a single scale model.

Modeling theory

The linearity of Maxwell's equations implies that the distribution of radiation scattered from a full size target can be determined by measurement on a faithful scale model. The principal requirement is to maintain a fixed ratio of wavelength to target linear dimension, i.e.,

$$\frac{\lambda_0}{D_0} = \frac{\lambda_m}{D_m}$$

where $\lambda_0$ = wavelength at which scattering from actual targets is to be obtained

$D_0$ = any linear dimension on the target

$D_m$ = corresponding linear dimension on the model

and $\lambda_m$ = required wavelength for modeling.

An important application of modeling is the measurement of $\sigma_0$, the target RCS, defined as the area of an isotropic reflector which would return to the radar receiving antenna a signal equal to that from the target. Formally,

$$\sigma_0 = \frac{\lambda_m^2}{4\pi R^2} \left| \frac{F_0}{E_1} \right|^2$$

where \( R \) = distance between radar and target

\[ E_r = \text{reflected field strength at the receiving antenna} \]

\[ E_i = \text{strength of incident field at the target} \]

The most common radar configuration uses a single antenna for both transmission and reception, and the corresponding RCS is termed monostatic. All other configurations are denoted as bistatic. Characterization of the target RCS requires, in addition, specification of both the transmitted and received polarizations. Since \( \sigma_0 \) is an area, the relation between target and model RCS is

\[ \sigma_o = \left( \frac{A}{\lambda_m^2} \right)^2 \sigma_m. \]  

(3)

Exact scaling theory also requires that the model surface conductivity be greater than that of the actual target by the ratio \( (\lambda / \lambda_m) \). However, the difference in reflectance between surfaces of infinite conductivity and those of the common metals is very small at microwave through submillimeter wavelengths. Therefore, the assumption can be made that both the model and the full size target are perfect conductors, i.e. have infinite conductivity.

The modeling technique generally allows the acquisition of accurate cross section data from a variety of complex man-made targets including ships, planes and tanks in a relatively inexpensive and rapid manner, and in a laboratory environment. Details can be faithfully preserved and model size held to a manageable level at scale factors between roughly 1:1 and 100:1 depending upon the type of target. It follows that the requisite region for modeling the millimeter includes the entire submillimeter (1mm-100μm) and extends into the far infrared (100μm-10μm).

Submillimeter model measurements have been made by the EMI group in Great Britain, using mainly the 891 GHz HCN laser. With the discovery and development of optically pumped lasers the potential for modeling in this region has greatly expanded. Hundreds of frequencies distributed throughout the submillimeter and far infrared are now available using a single experimental setup. Thus, it is possible to choose a laser frequency appropriate for modeling almost any millimeter wavelength for an arbitrary scale model. This often allows the use of commercial models which are inexpensive, readily obtainable and, in some cases, remarkably faithful. Consider, for example, the use of a 35:1 scale model for obtaining real target information at the atmospheric windows in the millimeter, i.e., 35 GHz, 94 GHz, 140 GHz and 220 GHz. Table I lists a set of optically pumped laser sources which could be applied to the task. The transfer of operation from one laser line to another is straightforward and can be accomplished with virtually no change in system performance. Thus, it is possible to make meaningful comparisons of target scattering at different wavelengths of interest.

<table>
<thead>
<tr>
<th>Optical Pumped Laser</th>
<th>CO₂ Laser Pump Line</th>
<th>Submillimeter Frequency (GHz)</th>
<th>Modeled Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₂H₅OH</td>
<td>9.33</td>
<td>4573</td>
<td>131</td>
</tr>
<tr>
<td>CH₃OH</td>
<td>9.35</td>
<td>7379</td>
<td>228</td>
</tr>
</tbody>
</table>

**Experimental apparatus**

The apparatus used for scan imaging and RCS measurements are shown in Figs. 1 and 2, respectively. Imaging measurements delineate the separate scatterers on the target, and provides information on the magnitude of their return and the angular extent over which they scatter radiation in the direction of the receiver. As depicted in Fig. 1, a diffraction limited CW submillimeter laser beam, generated by CO₂ laser optical pumping, is directed by a mylar beamsplitter to an 8° diameter, off-axis parabolic mirror. The target is positioned in the waist region of the resulting Gaussian beam. The typical spot size on the target is 3 mm diameter which, for a 35:1 scale model, corresponds to 10 cm resolution on the actual target. The gimbaled mounted mirror is driven in azimuth and elevation by computer controlled stepping motors. The stepping distance and dwell time of the mirror are controlled by software, instructions, which are chosen to be compatible with spot size and receiver time constant, respectively. For monostatic reception, the detector and collecting optics are positioned behind the beamsplitter, as shown in Fig. 1. As noted in the introduction, several types of submillimeter detectors are available. For these preliminary studies a cooled (2K) germanium bolometer was used because of its broadband capability.
Figure 1. Experimental arrangement for scan imaging of model target in the monostatic configuration.

Figure 2. Schematic of setup for bistatic RCS measurements.
and relatively high sensitivity. The option of using coherent detection with room tem-
perature Schottky diodes in quasi-optical mounts has not yet been employed but would pro-
vide greater receiver sensitivity and allow for more rapid data acquisition rates.

Figure 2 is a schematic of the experimental arrangement for model RCS measurements.
The submillimeter beam is expanded roughly tenfold in diameter in order to achieve complete
target illumination with near plane wave radiation. The wavefront at the target is
approximately plane since it is located near the waist of the large Gaussian beam formed by
the beam expander. A beamsplitter is used to direct backscattered radiation to a detector
for the monostatic RCS, and a separate mirror positioned at some finite angle relative to
the outgoing beam provides for bistatic RCS measurements. Both monostatic and bistatic
signals can be recorded at the same time. The target is mounted on a turntable which can
be driven by stepping motors in either aspect or depression angle. The procedure used to
acquire RCS data is to maintain the target at a fixed depression angle and rotate it around
the full 360° of aspect.

The data is displayed in real time on the minicomputer graphics terminal, and a hard
copy is available at the completion of a run. The data can then be stored on magnetic
disks for future retrieval and processing.

Imaging measurements and calibration techniques

Plastic scale models (35:1) of tactical targets were spray-lacquered to reduce surface
roughness and aluminized with several 1000 Å layers by vacuum deposition. The models have
a bright, shiny appearance, and the RMS surface roughness is estimated to be no more than a
few microns. Scattering from tactical targets at microwave and millimeter frequencies is
specular rather than diffuse. Thus, an image at these frequencies may bear little
resemblance to its optical counterpart. However, if the target's surface is sufficiently
complex, radiation will be backscattered from many discontinuities and irregularities,
and with sufficient dynamic range an image is created which in some cases may provide for
target identification. For example, images of tanks at millimeter frequencies are clearly
identifiable when viewed near broadside at a shallow depression angle, primarily because
the periodic pattern of the wheels, which is a prominent spatial feature in the optical
image, is also found in the specular return. Figure 3 shows such a view of a model tank
using the 236 μm CH₄/₂ line to simulate 36 GHz. Nonlinear techniques have been used to
process the displayed data in order to provide sufficient dynamic range to allow
identification. Figure 4 is an image of the same vehicle at a steeper depression angle
where the specular features differ significantly from those at optical frequencies, making
target discrimination difficult.

The purpose of obtaining target image data is the identification of scatterers and
measurement of their cross section. Identification is achieved by overlaying the sub-
millimeter image with a photograph of the target made at the completion of each run.
Matching the two images is achieved using an array of small corner reflectors which frame
the model. Figure 3 shows the target surrounded by 9 such reflectors, which have been
fabricated to have cross sections spanning the range of those from the individual scat-
ters on the target. This provides a guide for intensity, as well as spatial, calibration
points. The corner reflectors are themselves calibrated against an array of spheres which
provide rotationally invariant targets. Imaging of spheres has proven to be an excellent
method of primary calibration. In the "optical" limit, (λ << a, where a = sphere radius)
the sphere backscatters only over a small central region, and as long as the focussed beam
dimension exceeds the size of this region, the integrated return will be proportional to the
known cross section of a sphere.

![Image 3](image_url_3)
Figure 3: Image of model tank viewed near broadside, Calibrated corner reflectors are located to the sides and below the target.

![Image 4](image_url_4)
Figure 4: Image of the same vehicle viewed at a steeper depression angle than shown in Fig. 3. Calibrated corner reflectors are located on each side of the model.
RCS measurements of targets are a function of signal bandwidth. Interference among the scattering centers causes rapid angular variation in the RCS for the case of broadband radiation. A broadband signal, $\Delta f > c/2L$, decorrelates scatterers separated in range by a distance $L$. Frequency-agile systems are widely used to reduce such interference, which produces deep nulls in the target cross section and severely degrades ($\Delta f < 0.1$ MHz). However, the system's optics can be utilized to average over a sufficient angular extent to remove the rapid variation in target return. The effect, known as aperture averaging, decorrelates scatterers separated in cross-range by a distance $S > \lambda/\alpha$, where $\alpha$ is the field-of-view of the optical system. A radar receiver using coherent detection is limited to a field-of-view of approximately $\lambda/D$, where $D$ is the antenna aperture. While aperture averaging has been observed in radar measurements, the process is much more pronounced in the present modeling system, which employs an incoherent detector.

To demonstrate aperture averaging, two corner reflectors, 10 cm apart in cross-range, were positioned in the beam where the target is normally located. One reflector was mounted on a translation stage and driven slowly in range while the return from the two reflectors was recorded. The field-of-view of the system was then decreased by stopping down the entrance aperture of the bolometer, which is located at the focal plane of the optical system, and the run repeated. The data are shown in Figs. 5a and 5b and demonstrate the nearly complete averaging of interference effects at this separation. Further tests indicate significant decorrelation exists for scatterers separated in cross range by as little as 2 cm (100$\lambda$), even at the longest modeling wavelength used, so that scatterers on the target are nearly completely decorrelated.

Preliminary results indicate that aperture-averaged model RCS data agree reasonably well with broadband measurements on actual targets despite the basic difference in the averaging process indicated in the previous discussion. Nevertheless, it would be desirable to directly model frequency-agile radars. This requires a submillimeter source with a bandwidth $\Delta f_m = ps \Delta f_0$. Here $\Delta f_0$ is the frequency range of the actual radar system, typically 500 MHz, and $p$ is the model scale factor. It is probable that within the next few years submillimeter sources with the requisite bandwidths (10-30 GHz) will become available. Two promising techniques, both of which have been demonstrated, are the generation of submillimeter Raman radiation by high-intensity optical pumping, and mixing in a nonlinear element. At the present time significant problems remain in developing such systems to the level where they could be applied to model measurements.

![Figure 5a](image1.png)  
![Figure 5b](image2.png)  

Figure 5. Demonstration of aperture averaging in RCS measurements: (a) Monopulse from two corner reflectors located 10 cm in cross range as a function of field-of-view. (b) Same measurement as (a) except receiver field-of-view reduced. The signal is periodic in a distance $R_2 - R_1 = \lambda/2$. 

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Conclusions

A submillimeter laser facility has been developed for the purpose of modeling millimeter wavelengths. High resolution images and RCS data from models of tactical targets have been obtained. Other useful measurements such as target tracking and radar centroid determination are within the capability of the present modeling technique. As advances in submillimeter source, detector and component technology occur additional measurements relevant to proposed millimeter radar systems can be undertaken.

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References