Methodology and Techniques for Highly-Precise Radar Cross Section Measurements at W-Band

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ABSTRACT This paper explores the challenges of radar cross section (RCS) measurements at W-band and proposes several techniques to overcome these challenges to obtain an accurate RCS measurement. This paper combines $S_{11}$ measurements collected using traditional radio frequency (RF) hardware with post-processing algorithms to extract RCS values with a single antenna. Vector background subtraction and time-gating suppress unwanted reflections while increasing the system’s dynamic range capability. Experiments are conducted at the University of Oklahoma’s mm-Wave Laboratory with a Vector Network Analyzer (VNA) and frequency extender to evaluate the proposed measurement techniques. The setup is calibrated with a metal sphere, and the RCS of a smaller metal sphere and an arrangement of four spheres is extracted. The single sphere’s RCS is measured with a 0.304 dBsm average error, and the distributed object under test (OUT) RCS is measured with a 1.60 dBsm average error from 80-90 GHz. Each OUT is placed on a 3D-printed pedestal, and the remainder of the test hardware is part of an existing mm-Wave antenna measurement configuration. The post-processing clutter cancellation techniques enable a flexible test configuration to isolate the OUT RCS without purchasing specialized hardware.

INDEX TERMS Calibration, electromagnetic scattering measurements, millimeter wave measurements, radar cross section, reflection coefficient.

I. INTRODUCTION
An object’s radar cross section (RCS) quantifies how much of an incident electromagnetic wave will be scattered back towards the radar by the object. This value is essential to design a radar receiver for the appropriate received power levels. RCS varies with the frequency, angle, and polarization of the incident wave and the object’s orientation, material, shape, and size. Analytical expressions of RCS make several simplifications and assumptions about the object’s material and shape. Even simple geometries can be very computationally intensive to solve [1], [2]. For this reason, RCS values are commonly obtained through measurement [3], [4]. RCS measurement is well-documented for a single frequency, but measuring RCS over a wide bandwidth presents additional challenges [5], [6], [7]. Rather than building a new measurement system to measure RCS at a single frequency, this work aims to apply measurement theory to an existing W-band system to extract RCS without purchasing additional hardware. With wide bandwidth capabilities and stepped frequency continuous wave (SFCW) radar principles, precise time-domain filtering is applied to extract the RCS of distributed targets accurately. Continuous-wave measurements traditionally measure RCS with a separate antenna for transmitting and receiving [8]. However, if two antennas are unavailable or the mutual coupling between two antennas is too high, a single antenna can be used to measure RCS [9]. RCS has been measured with a single antenna below 10 GHz without quantitative error analysis and at mm-wave with specialized hardware [10], [11]. Past wideband work has applied either time-gating or background subtraction to measure the RCS of a point target [12]. However, past
work does not combine clutter cancellation techniques to minimize error or discuss the challenges of distributed target measurements.

This paper presents a comprehensive measurement methodology to extract RCS from 80-90 GHz with a single antenna attached to a standard mm-Wave vector network analyzer (VNA) measurement system, as shown in Fig. 1. A highly accurate measurement is achieved with calibration, vector background subtraction, and time-gating in conjunction with a sensible measurement setup selection. The proposed methodology does not rely on specialized, expensive RCS measurement hardware such as an anechoic chamber configured specifically for backscatter measurements. The techniques can be applied to almost any VNA and antenna configuration because of the post-processing’s clutter suppression methods. This flexibility and lack of specialized equipment requirements make this methodology a more affordable option than many traditional RCS anechoic chamber setups [13]. The accuracy and robustness of the proposed measurement techniques are verified by comparing measurement results of a single-point and a distributed object under test (OUT) to analytically calculated and simulated values. The proposed procedures yield an average error of 3.62% for a 3.81 cm diameter metal sphere and 15.3% for a distributed OUT composed of four 2.54 cm spheres. This paper utilizes techniques from [9] and furthers the work by addressing challenges at W-band frequencies, including selecting the proper measurement geometry.

II. RCS EXTRACTION

With post-processing techniques based on several SFCW radar principles, an object’s RCS can be extracted with a vector network analyzer, as summarized in Fig. 2. First, the magnitude and phase of the reflection coefficient ($S_{11}$) are collected and converted to in-phase and quadrature ($I/Q$) components such that $S_{11} = I + jQ$. Then, vector background subtraction suppresses clutter by subtracting the I/Q values of the test setup without the OUT from the I/Q values of an OUT measurement. Even if the measurement system is calibrated at the antenna to minimize mismatch reflections, the power reflected by the OUT makes up a small fraction of the overall power received, making background subtraction essential to isolate the OUT return. Ideally, this process would remove the return from all scatterers except the OUT. However, background subtraction cannot eliminate all clutter perfectly due to shadowing effects and noise. Therefore, a time-gating window is also applied to isolate the response from the range bin(s) containing the OUT. This window is applied by first converting the background-subtracted measurement to the time domain with an inverse fast Fourier transform (IFFT), multiplying by the window, and then converting the time-gated signal back to the frequency domain with a fast Fourier transform (FFT). While a rectangular window is sufficient for most applications, adding a taper to the window will reduce edge effects in the frequency domain [14]. Moreover, the OUT may span multiple range bins in wideband measurements due to enhanced temporal resolution, so a standard tapered window such as a Hanning window will unevenly attenuate the return, causing an offset in the magnitude of the results [15]. In this work, a Tukey window is used because of its flat passband and cosine-tapered edges, so sufficient time-gating is achieved without attenuating the desired return signal.

After the OUT return has been isolated, the RCS value is extracted with the radar range equation. This equation relates the ratio of received power to transmitted power ($\frac{P_r}{P_t}$) to RCS ($\sigma$), given by:

$$\frac{P_r}{P_t} = \frac{G^2\lambda^2\sigma}{(4\pi)^3R^4L} = k\sigma$$

where $\frac{P_r}{P_t}$ is the reflection coefficient ($S_{11}$), $G$ is the antenna gain, $\lambda$ is the wavelength, $R$ is the distance to the OUT, and $L$ is system losses [16]. All the variables on the right side of (1) except for $\sigma$ are independent of the OUT, so they are combined into a single, frequency-dependent calibration set ($k$). The calibration set is created by subtracting the calibration object’s actual RCS from the magnitude of the time-gated measurement of the calibration object. Metal
spheres are a common calibration object since the RCS can be calculated with the Mie series, and the RCS value is angle-agnostic. The calibration set is then subtracted from the time-gated OUT measurement to yield the OUT’s RCS.

Several parameters are adjusted to achieve the desired measurement functionality. The frequency step size ($\Delta f$) is selected to ensure that any substantial scatterers do not lie beyond the maximum unambiguous range ($R_{\text{max}}$) given by:

$$R_{\text{max}} = \frac{c}{2\Delta f \sqrt{\varepsilon_r}}$$

where $c$ is the electromagnetic wave’s velocity of propagation in free space and $\varepsilon_r$ is the medium’s relative permittivity [17]. Returns from scatterers beyond this range will alias down into a closer range bin and distort the time-domain response, potentially overlapping with the desired OUT response despite being temporally separated. The range resolution ($\Delta R$) is given by:

$$\Delta R = \frac{c}{2B}$$

where $B$ is the measurement bandwidth [18]. A finer resolution helps separate the clutter and desired OUT response into different range bins and allows more control to shape the time-gating window. In addition, a lower intermediate frequency (IF) bandwidth setting on the VNA reduces the measurement’s thermal noise in exchange for a longer measurement time. Point averaging may also be implemented to overcome thermal noise limitations; however, averaging does not reduce multiplicative noise such as multi-path reflections [16].

In addition to clutter cancellation, calibration, and VNA settings, the measurement accuracy also relies on the proper geometry. For a single antenna measurement, the range ($R$) between the antenna and the OUT must be large enough for the entire OUT to be included in the antenna’s main beam. The criterion is given by:

$$R \geq \frac{D}{2 \tan \left( \frac{\theta}{2} \right)}$$

where $\theta$ is the half-power beamwidth of the antenna. Antenna beamwidths are relatively narrow at W-band frequencies; therefore, including the OUT within a single antenna’s main beam is more attainable than ensuring that the OUT lies within the main beam of two antennas separated by some distance. Another consideration for the measurement geometry is the shape of the transmitted wave incident upon the OUT and the wave reflected by the OUT incident upon the antenna. Because RCS is a far-field quantity, the incident wave must be approximately planar. Therefore, the far-field criterion gives the distance the wave must travel before it is approximately planar. This far-field range ($R_{\text{FF}}$) is given by:

$$R_{\text{FF}} = \frac{2D^2}{\lambda}$$

where $D$ is the maximum dimension of the OUT or the antenna, whichever is larger [19]. While the OUT must be far enough to be in the antenna’s beamwidth and within the far-field, selecting an $R$ much larger than the minimum increases the spherical spreading loss proportional to $R^4$ in (1), reducing the signal-to-noise ratio (SNR). This trade-off is especially challenging at high frequencies because $R_{\text{FF}}$ increases with frequency while $\frac{P_c}{P_i}$ decreases with frequency. While adding a low-noise amplifier could help resolve SNR issues, this is more challenging in a single antenna setup since multiple circulators may be required to accommodate the wideband, bi-directional measurement and is therefore non-ideal for this experiment.

**III. TEST SETUP**

Measurements are conducted in the mm-Wave laboratory at the University of Oklahoma to evaluate the proposed methodology. A 3.81 cm diameter G25 chrome steel bearing ball is used for calibration, and a single G25 2.54 cm diameter chrome steel bearing ball and a distributed arrangement of four 2.54 cm bearing balls, shown in Fig. 3, are used as the two OUTs. The “true” RCS is calculated with the Mie series for the single spheres, and the RCS of the distributed sphere arrangement is simulated in Altair FEKO [20].

A calibrated Copper Mountain C4209 VNA and a Keysight N5295AX03 Frequency Extender are attached to an Eravant SAR-2013-10-S2 horn antenna to collect $S_{11}$ measurements from 80-90 GHz. This antenna has a 3-dB beamwidth of 16° at the center frequency. The VNA is set to a frequency step size of 10 MHz and an IF bandwidth of 100 Hz. The height of the OUT’s center is laser-aligned to lie in the center of the antenna beamwidth at a range of 0.84 m, as shown in Fig. 1. Each OUT is placed on a resin support structure 3D printed with a Formlabs Form 3 Stereolithography (SLA) 3D printer. Each OUT’s support pedestals height is designed...
to hold the center of the OUT in the middle of the beamwidth. For example, the support column for the 2.54 cm sphere is 0.64 cm taller than the 3.81 cm sphere, so the equator of both spheres will be at the same height. The top of the pedestal is narrow to minimize its interaction with the OUT, and the pedestal’s diameter increases towards the base. This taper directs reflected waves away from the antenna [15]. Empty chamber measurements for each support structure are collected to ensure accurate background subtraction.

IV. MEASUREMENT AND ANALYSIS
First, the RCS of a single 2.54 cm sphere is extracted with the procedure described in Section II, including background subtraction, time-gating, and calibration set creation. The resultant measured RCS is shown in Fig. 4, and the average error is 3.59% or 0.304 dBsm. The calculated RCS is derived assuming that the sphere is a perfect electric conductor, which is not the case for the measured chrome spheres and contributes to some of the errors. The remainder is attributed to measurement errors and assumptions, including the incident wave’s phase error and the potential for minor misalignment between the antenna and OUT.

Next, a distributed target composed of four 2.54 cm spheres and a 3D-printed pedestal, shown in Fig. 3, is measured to verify the robustness of the proposed measurement techniques. There is a 42 mm distance between the center of the two spheres on the left. The measured RCS is compared to a FEKO simulation, and the results are shown in Fig 5. The average error is 15.6%, or 1.60 dBsm. Some of the error originates from imperfections in the simulation. Due to finite computational resources, the simulation model is composed of PEC spheres and does not include the 3D-printed support structure. Vector background subtraction removes the scattering from the support structure in the measurement. However, none of the measurement post-processing accounts for the support structure’s impact on the incident wave propagation on and around the spheres.

Distributed targets are more challenging to measure because, by definition, the target response spans multiple range bins. As a result, a wider window is needed in time-gating, which incorporates more clutter. Furthermore, slight misalignment in the measurement setup of a distributed target can create significant changes in the resultant RCS values because of the small wavelength at W-band. The consequences of misalignment are demonstrated in Fig. 6, where a 1° rotation changes the shape and magnitude of the RCS response. Not only must the OUT be centered in the beam and azimuthally aligned, but the far-field approximation also contributes to the error. At a range of $R_{FF}$, there is still a $22.5^\circ$ phase error across the OUT. Therefore it may be necessary to place the OUT farther into the far-field than $R_{FF}$ if higher levels of accuracy are needed. Given the above considerations, there are clear indications that the measured RCS is reasonable and accurate.

Several relevant RCS measurement configurations are summarized in Table 1. The majority of mm-Wave work only presents results at a single frequency. However, because
RCS can vary with frequency, particularly for distributed targets, wideband measurement results are necessary to inform a radar design accurately [21]. Therefore, this work characterizes RCS over a wide bandwidth to capture the behavior of the targets across frequency. Moreover, a quantitative analysis of the measurement results is included for efficacy transparency of the measurement setup and techniques.

V. CONCLUSION

This paper proposes a method to accurately measure the RCS of objects at W-band with a single antenna. This single antenna technique is well-suited for this frequency range as W-band antennas are expensive and have very narrow beamwidths. The ratio of reflected power to incident power is acquired across frequency with a single port reflection coefficient measurement on a VNA. By selecting the proper measurement setup and applying a calibration set, vector background subtraction, and time-gating, the RCS of both single-point and distributed targets is accurately extracted with a standard far-field mm-Wave VNA configuration. The techniques are verified by measuring a 3.81 cm diameter metal sphere as a calibration target to obtain the RCS of a single 2.54 cm sphere and a distributed arrangement of four 2.54 cm spheres. The RCS values of the 2.54 cm sphere are measured with an average error of 0.304 dBsm, and the distributed target RCS is extracted with a 1.60 dBsm average error from 80-90 GHz.

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