Laboratory Measurement of Microwave Scatter Coefficient: Calibration and Validation

***John W. Schultz*[1], *Stephen P. Blalock*[2], *Ed J. Hopkins*[3]**

[1]Georgia Tech Research Institute, 400 Tenth Street CRB 629, Atlanta GA 30318, USA, john.schultz@gtri.gatech.edu

[2]stephen.blalock@gtri.gatech.edu

[3]ed.hopkins@gtri.gatech.edu

Abstract

A laboratory method for measuring microwave scatter coefficient of rough surfaces and inhomogeneous material specimens is presented. This method uses a focused beam to simulate far-field plane-wave illumination and a calibration method is applied to quantify the scattering coefficient in units of dB-square meter per square meter. Two validation specimens, constructed from etched copper in a periodic array, supported on a dielectric substrate were constructed. These specimens were characterized with two different illumination beams with different widths, and comparisons of the measured data show that the incoherent, diffuse scatter levels are similar between the two different focused beam configurations.

1. Introduction

Radar-based remote sensing takes advantage of the varying backscatter properties of materials to provide information for applications ranging from agricultural monitoring to geological mapping to characterizing climate change. The measured backscatter coefficient is a function of surface roughness, spatial variations of dielectric or magnetic properties, and discontinuities at edges or joints. This paper presents a laboratory method for measuring backscatter coefficient from material specimens. This technique uses a focused microwave beam to illuminate a portion of a specimen and determine monostatic backscatter from the localized illumination. Since only a portion of the specimen is probed, the effects of scatterers within the illuminated area are measured separately from other scatterers on the specimen. Further, edge diffraction effects that can occur in compact range measurements are minimized in this technique.

Focused beam methods have been used to measure the microwave permittivity and permeability of materials at normal incidence [1,2,3]. These methods are accurate because the focused illumination minimizes edge diffraction effects from finite sample size, while still approximating plane wave illumination with a planar phase front. Petersson and Smith showed that this plane-wave approximation of Gaussian-beam illumination is reasonable as long as the beam is at least several wavelengths in diameter [4]. Similarly, Collin showed that Gaussian beam illumination could be applied to determine the scattering coefficient of a rough surface as long as a planar phase front is maintained and the correlation lengths of the rough surface are smaller than the illuminating beam diameter [5].

More recently, Schultz et al [6] described a new methodology for the focused beam method that provides quantitative measurement of the backscatter coefficient from laboratory samples. This paper reviews the experimental backscatter methodology and describes recent validation measurements of canonical samples of inhomogeneous surfaces.

.

2. Backscatter Method Description

A diagram of a focused beam system used for microwave backscatter characterization is shown in Figure 1. This system illuminates a confined area on a target or specimen with a finite-diameter beam focused by a dielectric lens. The apparatus consists of a 60 cm diameter biconvex lens made from Rexolite and fed by a broadband, ridged horn antenna. For typical 4-18 GHz operation, the separation between the horn aperture and the back surface of the lens is 48 cm, and the specimen is mounted 122 cm beyond the front surface of the lens. These values can vary when the beam diameter is changed. An Agilent 8510C network analyzer produced and detected microwave energy. The horn antenna could be configured for either vertical or horizontal electric field polarization so that the incident beam was either TM, with the magnetic field transverse to the plane defined by the sample normal and the incident beam direction, or TE, where the electric field was transverse to that plane. Specimens were mounted on a rotary stage, which allowed illumination at arbitrary azimuth incidence angles.

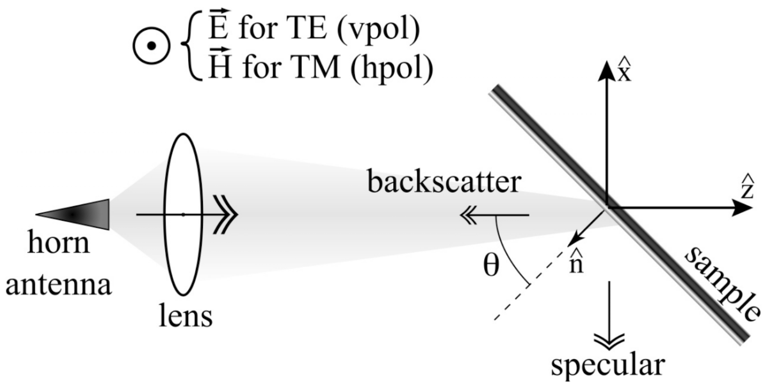

Figure 1 Overview of measurement geometry for diffuse backscatter with a focused incident beam

The scattering coefficient was determined from a series of voltage reflection coefficient, $V(\theta,f)$, measurements, where θ is the incidence angle and f is frequency. Included in the measured signal are undesired reflections from transmission path mismatches that corrupt the direct measurement of $V(\theta,f)$. Time-domain measurements have shown that the two largest mismatches are the discontinuities at the network analyzer port and at the input to the horn antenna. Interference from these mismatch reflections must be removed with calibration and data processing to allow measurement of small backscatter signal levels from the specimen.

The calibration technique uses two standards: an electrical short as the response ($V = 1$) and a matched load as the isolation ($V = 0$). The short was a flat aluminum plate with lateral dimensions much greater than the beam waist, oriented normal to the incident beam. The matched load was created by removing the aluminum plate and positioning pyramidal foam absorber at least a meter beyond the specimen position. The isolation standard was vector subtracted from the measured data and the ratio of this quantity to the response standard was calculated.

$$V_{\mathrm{cal}} = \frac{V_{\mathrm{meas}} - V_{\mathrm{load}}}{V_{\mathrm{short}} - V_{\mathrm{load}}}, \tag{1}$$

where V_{cal}, V_{meas}, V_{load}, V_{short} are the calibrated, measured, load (isolation), and short (response) voltage-reflection coefficients respectively.

The measured and calibrated voltage-reflection coefficients depend on the scattering properties of the material specimen as well as the illumination area of the incident beam. The relationship between the voltage-reflection coefficient and RCS can be derived by assuming the reflection from the response calibration (metal plate) is equivalent to the RCS of a flat metal plate with effective area corresponding to the illuminating beam area, $\left|V_{response}\right|^2 \propto 4\pi\left(A_{eff}^2/\lambda^2\right)$. Where λ is the wavelength and A_{eff} is the effective area of the illuminating beam, defined by the 3 dB diameter. Then the calibrated scatter from the sample, $|V_{cal}|^2$, is equal to the ratio of the sample RCS to the metal plate RCS. With algebraic rearrangement, the sample RCS is expressed by,

$$\sigma = 4\pi \frac{A_{eff}^2}{\lambda^2} \left|V_{cal}\right|^2 \tag{2}$$

For an inhomogeneous material or rough surface, the quantity of interest is not RCS, but scattering coefficient. The scattering coefficient (σ_o) is defined as RCS per unit physical area, where the illuminated (physical) area is the projected area divided by $\cos\theta$,

$$\sigma_0 = \frac{\sigma}{A_{\mathrm{eff}}/\cos\theta} = 4\pi\cos\theta \frac{A_{\mathrm{eff}}}{\lambda^2}\left|V_{\mathrm{cal}}\right|^2, \tag{3}$$

where θ is the angle between the surface normal and the direction of the illuminating beam.

In the measurements presented here, two different focal length lenses were used to obtain two different beam sizes. Figure 2a shows the half-power beam diameters for two different beam configurations. Thus the larger beam is approximately 50% larger than the smaller beam, and both beams follow an approximately 1/frequency size dependence. Figure 2b shows drawings of two validation samples measured in this work. The unperturbed array consists of a series of 4mm x 4mm metal squares on a dielectric (FR-4) substrate. The period of this array is 1.4 cm. The perturbed array is constructed similarly, but with random 2mm shifts of each metal square in the x and/or y (in-plane) directions.

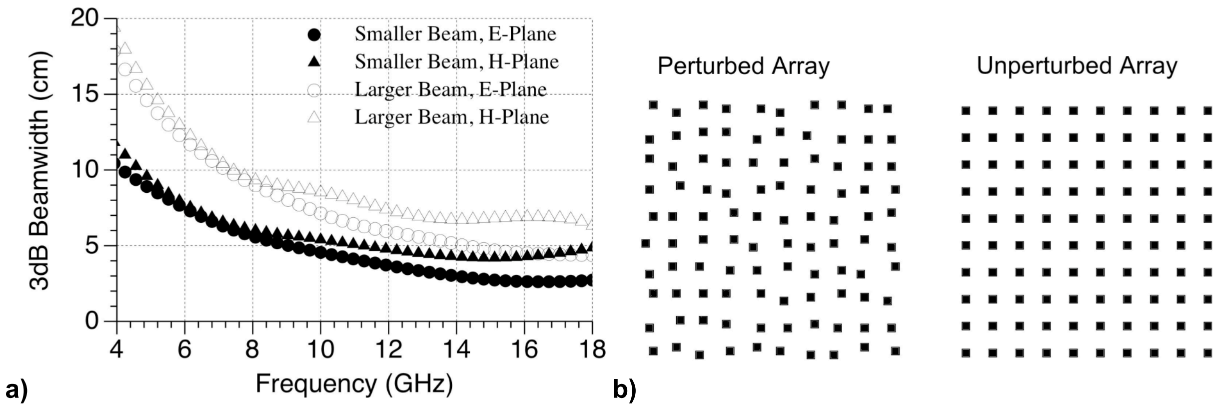

Figure 2 a) Measured half-power beam width of two focused beam configurations used. b) Drawings of perturbed and unperturbed periodic array panels measured as validation standards.

3. Measured Results

Utilizing the small and large diameter configurations of Figure 2, backscatter coefficient measurements were made of the perturbed and unperturbed arrays. Backscatter was measured by scanning across frequencies from 4-18 GHz and then azimuthally rotating the sample after each frequency scan. Data were obtained at angles from -80 degrees to +80 degrees, in 1-degree increments. Zero-degrees is defined as the angle when the focused beam is normally incident on the sample. In addition to the calibration procedures above, data were also process with time-domain gating to minimize the effects of reflections from other interfaces in the transmission path, including the network analyzer port, horn antennas, and reflections from the lens. In the data shown below a 3ns-wide gate was used.

Figure 3 shows the measured backscatter coefficient as a function of frequency and angle for both the perturbed array and unperturbed array validation specimens, measured with horizontal polarization (transverse magnetic wave). The data centered on 0 degree azimuth, corresponds to the specular reflection when the beam is normal incidence to the specimen. The width of this specular lobe is an indication of the plane wave spectrum of the finite sized focused beam. For a smaller, more tightly focused beam, the plane wave spectrum is broader while the larger diameter beam more closely approximates single plane-wave illumination by having a narrower plane wave distribution. Thus the larger beam provides a higher level of angular detail of backscatter behavior. Evident in these data is a grating lobe that occurs above 11 GHz and is a function of the 1.4 cm period of the array. The specular reflection lobe and grating lobe are coherent effects that provide useful reference points in the data, but don't validate the scattering coefficient calibration.

Comparisons between the unperturbed and perturbed array measurements show the effect of array perturbation, which provides an incoherent 'material noise' outside of the coherent grating lobe and specular reflections. The average levels of the incoherent scatter coefficient are in agreement between the smaller and larger beam measurements. Thus the perturbed array specimen provides a useful validation measurement for comparing focused beam configurations. Based on these measurements, a second-generation validation sample is planned with a smaller period and a greater degree of perturbation to provide a measurable incoherent scatter at lower frequencies.

4. Conclusion

A laboratory method for measuring microwave scatter coefficient of rough surfaces and inhomogeneous materials was presented. Backscatter measurements were performed with two validation samples, constructed from etched copper in a periodic array. The position of the elements of one of the arrays was 'perturbed' to simulate material inhomogeneity, while the other array was left 'unperturbed'. The measurements were done with two different focused beam configurations to investigate the effect of beam width. The larger diameter beam showed finer angular resolution in the measured data, corresponding to a narrower plane wave distribution. Comparison of the non-coherent or 'material noise' scatter of the perturbed array showed similar levels between the different beam configurations, indicating that the calibration procedure properly accounts for the experimental geometry.

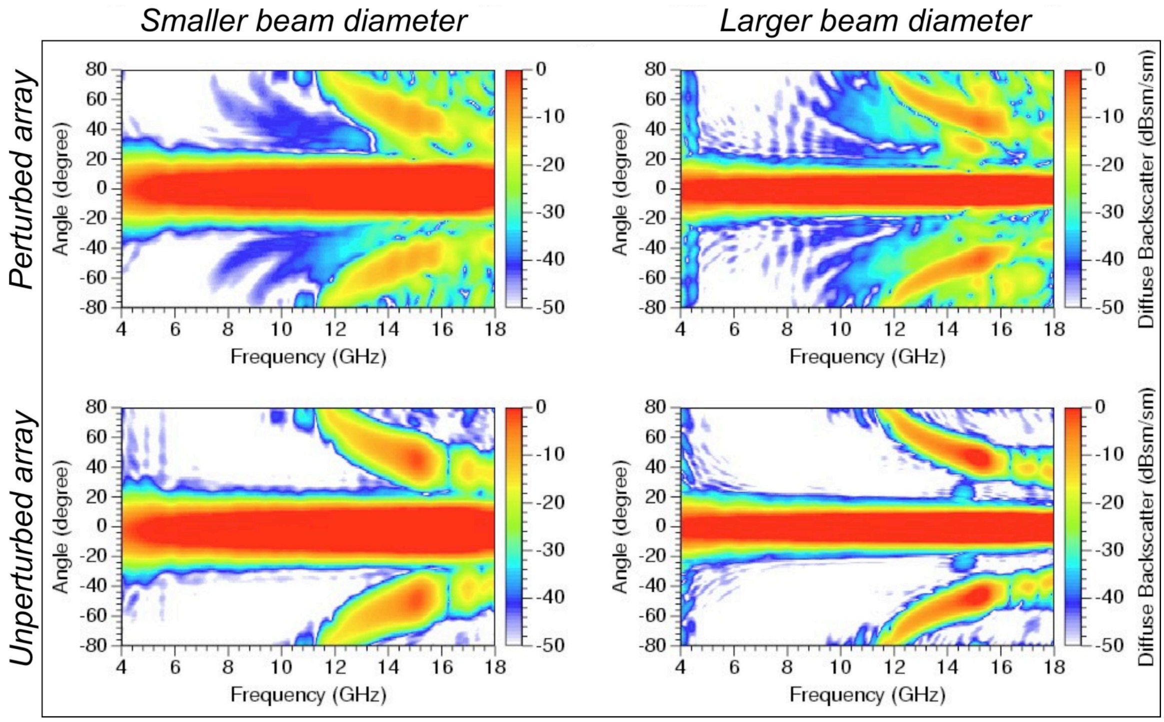

Figure 3 Measured backscatter coefficient as a function of frequency and angle. Data are show for both the perturbed array and unperturbed array, measured with two different diameter beams.

5. References

1. J. Musil, and F. Zacek, *Microwave Measurements of Complex Permittivity by Free Space Methods and Their Applications*, Elsevier Science Publishing, New York, 1986

2. D.K. Ghodgaonkar, V.V. Varadan, V.K. Varadan, "A free-space method for measurement of dielectric constants and loss tangents at microwave frequencies," *IEEE Trans. Instrum. Meas.*, vol. 37, 1989, pp. 789-793

3. P. Friederich, R. Moore, E. Kuster, "Free-space electromagnetic measurement system," *URSI Radio Science Meeting, Seattle*, WA, 1994, p. 390

4. L.E. Rickard Petersson, Glenn S. Smith, "An Estimate of the Error Caused by the Plane-Wave Approximation in Free-Space Dielectric Measurement Systems," *IEEE Trans. Antennas and Propagation*, vol. 50, 2002, pp. 878-887

5. R.E. Collin, "Scattering of an incident Gaussian beam by a perfectly conducting rough surface," *IEEE Trans. Antennas and Propagation*, vol. 42, 1994, pp. 70-74

6. J.W. Schultz, E.J. Hopkins, J.G. Maloney, E.J. Kuster, M.P. Kesler, "A Focused Beam Methdology for Measuring Microwave Backscatter," *Microwave and Opt. Tech. Lett.,* vol. 42, 2004, pp. 201-205

7. G.T. Ruck, D.E. Barrick, W.D. Stuart, C.K. Krichbaum, *Radar Cross Section Handbook*, Volume 1, Pleneum Press, New York, 1970