THE VALIDATION AND APPLICATION OF A BISTATIC TWO-SCALE OF SURFACE ROUGHNESS SCATTERING MODEL

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The Validation and Application of a Bistatic Two-Scale of Surface Roughness Scattering Model

Bistatic configurations are being considered in several modern surveillance radar concepts. This introduces new clutter and target scattering cross section representations as a result of the more complex geometry. In this report three bistatic clutter topics are addressed. First, a bistatic two-scale of roughness terrain scattering model is validated by comparison with data. Second, the contributions from each roughness level are evaluated as a function of the scattering angle regimes. Third, comparisons of monostatic and bistatic clutter cross section maps for a loam surface are made for a bistatic radar configuration. Results showed generally good agreement between model and data except at low grazing angles where problems arise for experimental cross section measurements and single scattering assumptions in the model. Examination of the individual component contribution shows distinct behavior patterns and regions of dominance. Finally, the clutter mapping shows that for the configuration studied the bistatic cross sections were always much larger than the corresponding monostatic values.

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### ABSTRACT

- Bistatic configurations are being considered in several modern surveillance radar concepts. This introduces new clutter and target scattering cross section representations as a result of the more complex geometry. In this report three bistatic clutter topics are addressed. First, a bistatic two-scale of roughness terrain scattering model is validated by comparison with data. Second, the contributions from each roughness level are evaluated as a function of the scattering angle regimes. Third, comparisons of monostatic and bistatic clutter cross section maps for a loam surface are made for a bistatic radar configuration. Results showed generally good agreement between model and data except at low grazing angles where problems arise for experimental cross section measurements and single scattering assumptions in the model. Examination of the individual component contribution shows distinct behavior patterns and regions of dominance. Finally, the clutter mapping shows that for the configuration studied the bistatic cross sections were always much larger than the corresponding monostatic values.
Preface

This report represents a combined effort with individual contributions from both authors. Dr. Papa formulated the theory and compared the results with experimental data. Mrs. Woodworth developed the numerical methods and wrote the software that enabled the results to be obtained.
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The Validation and Application of a Bistatic Two-Scale of Surface Roughness Scattering Model

1. INTRODUCTION

Several new radar systems are being considered which operate in a bistatic mode. This offers the potential for increased target radar cross sections but has a more complicated clutter condition than typical monostatic operation would involve. This report addresses three topics related to this question. First, a bistatic terrain scattering model that includes two distinct sets of scattering phenomena\(^1\) is evaluated by comparisons with some bistatic scattering data.\(^2\) Secondly, the contributions from each of the levels of scattering are analyzed as a function of bistatic configuration. Finally, the validated bistatic scattering results are compared to a corresponding set of monostatic values representing a clutter map of a region where the surface is loam.

2. MODEL VALIDATION

In this section the two-scale-of-roughness bistatic scattering model will be described. Then the data base used for the comparisons will be discussed. Finally, the results for data and theory will be

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examined as a function of the bistatic scattering angles. Figure 1 shows the angles involved. \( \theta_g \) is the complement of \( \theta_i \), the incident elevation angle; \( \theta_s \) is the scattered elevation angle; and \( \phi_s \) is the azimuthal scattering angle. In the monostatic case \( \phi_s = 180^\circ \).

2.1 Theory

The model is quite complex. Details are given here to make the comparisons with data clearer in terms of the use of parameter values associated with the particular scattering processes. Two distinct roughness elements are assumed to contribute to the scattering cross section \( \sigma^\circ \) used in the scattering model. The large surface roughness is described by a model based upon physical optics (PO) assumptions. It can be shown that one sufficient condition for the validity of physical optics is that \( T_L >> \lambda \), where \( T_L \) is the surface correlation length associated with the large scale roughness. The form for \( \sigma^\circ \) is in terms of the Rayleigh parameter \( \Sigma = \frac{2\pi}{\lambda} \sigma_L (\cos \theta_i + \cos \theta_g) \). Here, \( \sigma_L \) = standard deviation in surface height for large scale roughness. When the conditions for the validity of physical optics are met, and the Rayleigh parameter \( \Sigma >> 1 \), the form of \( \sigma^\circ \) is equivalent to a high frequency, geometrical optics (GO) limit solution. The small scale surface roughness is described by the perturbation method (PM) solution.\(^1\) The conditions for the validity of the perturbation solution are that the rms surface height be small compared to a wavelength \( (2\pi/\lambda) \sigma_s < 1 \) and that the surface slopes be small \( \sigma_s/T_s < 1 \), where \( \sigma_s \) = standard deviation in surface height for the small scale roughness and \( T_s \) = surface correlation length for small scale roughness. In general, the surface can be quite complex; its scattering contribution may have to be integrated over segments with different geological features. Here, we are concerned only with the behavior of \( \sigma^\circ \). The surface areas are assumed to have Gaussian height statistics. The surface correlation function is assumed to be Gaussian. Surface shadowing effects are also included in the formalism.

For physical optics models, Ruck et al\(^1\) give expressions for the average bistatic rough surface cross section \( \sigma^\circ \) under the following assumptions: (1) the radius of curvature of the surface irregularities is larger than a wavelength; (2) the roughness is isotropic in both surface dimensions; (3) the correlation length is smaller than either the \( x \) or \( y \) dimension of the sample subregion; and (4) multiple scattering is neglected. Using their notation, one finds that the expression for \( \sigma^\circ \) becomes

\[
\sigma^\circ = | \beta_{pq} |^2 J S
\]

where \( \beta_{pq} \) represents the scattering matrix contributions, \( S \) is the local shadowing function, and the term \( J \) is related to the surface height distributions and the surface slopes. The shadowing function clearly depends on the roughness of the surface, and introducing this factor into the analysis can have significant effects on the diffuse scattered power.

In this report, the physical optics part of the theoretical cross section \( \sigma^\circ \) is not evaluated in the high frequency geometrical optics limit. Instead, it is evaluated by making the assumption of small surface slopes \( \sigma_s/T_s < 1 \) so that \( J \) is expressed as a single integral (Papa et al\(^3\)).

Figure 1. Surveillance Geometries for a Bistatic System or a Monostatic System
J = \frac{8\pi^2}{\lambda^2} \int_0^\infty J_0(v_{xy} \tau) \{x_2 - x_1 x_1^*\} \tau d\tau \tag{2}

where

\begin{align*}
v_{xy} &= \sqrt{v_x^2 + v_y^2} \\
v_x &= (2\pi/\lambda) \xi_x \\
v_y &= (2\pi/\lambda) \xi_y
\end{align*}

\begin{align*}
\chi_1 &= \epsilon^{1/2} \Sigma^2, \text{ univariate characteristic function of the surface height distribution function} \\
\chi_2 &= \exp \{-\Sigma^2(1 - e^{-\tau^2/T^2})\}, \text{ bivariate characteristic function (Gaussian in this report)} \\
J_0 \text{ is the zero order Bessel function.}
\end{align*}

\begin{align*}
\xi_x &= \sin \theta_1 - \sin \theta_s \cos \phi_s \\
\xi_y &= \sin \phi_s \sin \theta_s \\
\xi_z &= -\cos \theta_1 - \cos \theta_s
\end{align*}

It is in the scattering matrix term that the dielectric constant representing the respective moisture content levels is introduced. In that term, the matrix elements for linear polarization states are

\begin{align*}
\beta_{VV} &= [a_2 a_3 R \{\theta_1^{(*)}\} + \sin \theta_1 \sin \theta_s \sin^2 \phi_s R_{\perp}(\theta_1^{(*)})]/[a_1 a_4]. \\
\beta_{HV} &= \sin \phi_s \sin \theta_s \sin \theta_1 \sin \theta_s a_2 R_{\perp}(\theta_1^{(*)})]/[a_1 a_4]. \\
\beta_{VH} &= \sin \phi_s \sin \theta_1 \sin \theta_s a_3 R_{\perp}(\theta_1^{(*)})]/[a_1 a_4]. \\
\beta_{HH} &= [-\sin \theta_1 \sin \phi_s \sin \theta_1 \sin \theta_s a_2 a_3 R_{\perp}(\theta_1^{(*)})]/[a_1 a_4].
\end{align*} \tag{3}

Here, \( R \{\theta_1^{(*)}\} \) and \( R_{\perp}(\theta_1^{(*)}) \) are Fresnel reflection coefficients

\begin{align*}
R \{\theta_1^{(*)}\} &= \left[ \epsilon_r \cos \theta_1^{(*)} - \sqrt{\epsilon_r \mu_r - \sin^2 \theta_1^{(*)}} \right]/[\epsilon_r \cos \theta_1^{(*)} - \sqrt{\epsilon_r \mu_r - \sin^2 \theta_1^{(*)}}] \\
\text{and} \\
R_{\perp}(\theta_1^{(*)}) &= \left[ \mu_r \cos \theta_1^{(*)} - \sqrt{\epsilon_r \mu_r - \sin^2 \theta_1^{(*)}} \right]/[\mu_r \cos \theta_1^{(*)} + \sqrt{\epsilon_r \mu_r - \sin^2 \theta_1^{(*)}}].
\end{align*} \tag{4}
Note that $\varepsilon_r$ is the relative complex dielectric constant of the surface, the subscript $\parallel$ refers to the E-field in the plane of incidence, and the subscript $\perp$ refers to the E-field normal to the plane of incidence. The remaining angle-related terms are

\[
\cos \theta_i^* = \left( \frac{1}{\sqrt{2}} \right) \sqrt{1 - \sin \theta_i \sin \theta_s \cos \phi_s + \cos \theta_i \cos \theta_s}
\]
\[
a_1 = 1 + \sin \theta_i \sin \theta_s \cos \phi_s - \cos \theta_i \cos \theta_s.
\]
\[
a_2 = \cos \theta_i \sin \theta_s + \sin \theta_i \cos \theta_s \cos \phi_s.
\]
\[
a_3 = \sin \theta_i \cos \theta_s + \cos \theta_i \sin \theta_s \cos \phi_s.
\]

and
\[
a_4 = \cos \theta_i + \cos \theta_s.
\]

For small scale roughness the cross section, $\sigma^{ss}$ is obtained by a perturbation method solution to Maxwell's equations. The fundamental assumptions for this case are small roughness ($k_r \sigma_s < 1$) and small surface slopes ($|\partial z_s/\partial x|, |\partial z_s/\partial y| < 1$) with isotropic roughness. Here, $k = 2\pi/\lambda$, and $z_s$ is the surface height.

For this model we have
\[
\sigma^{ss} = \frac{4}{n^2} \left( \frac{1}{2} \right) \left( \frac{1}{2} \right) \frac{a_{pq}^2}{l}
\]

where $a_{pq}$ is proportional to the scattering matrix element and, for a Gaussian surface with Gaussian correlation
\[
1 = \pi T^2 \exp \left[ -0.25k^2T^2 (\xi_x^2 + \xi_y^2) \right].
\]

The $a_{pq}$ terms are given by
\[
\alpha_{III} = \frac{[\varepsilon_r(\mu_r - 1)(\mu_r \sin \theta_i \sin \theta_s - \cos \phi_s \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_s}}) + \mu_r(\varepsilon_r - 1) \cos \phi_s]}{[\mu_r \cos \theta_i + \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i} \sin \theta_s + \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_s} \sin \theta_s].}
\]

\[
\alpha_{VII} = \sin \phi_s \frac{\varepsilon_r(\mu_r - 1) \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i} - \mu_r(\varepsilon_r - 1) \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i}}{[\mu_r \cos \theta_i + \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i} \sin \theta_s + \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_s} \sin \theta_s].}
\]

\[
\alpha_{IV} = \sin \phi_s \frac{\varepsilon_r(\mu_r - 1) \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i} - \mu_r(\varepsilon_r - 1) \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i}}{[\mu_r \cos \theta_i + \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i} \sin \theta_s + \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_s} \sin \theta_s].}
\]

and
\[
\alpha_{VV} = \frac{[\varepsilon_r(\mu_r - 1)(\varepsilon_r \sin \theta_i \sin \theta_s - \cos \phi_s \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_s}}) + \varepsilon_r(\mu_r - 1) \cos \phi_s]}{[\varepsilon_r \cos \theta_i + \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_i} \sin \theta_s + \sqrt{\varepsilon_r \mu_r - \sin^2 \theta_s} \sin \theta_s].}
\]
In the previous equations, $\varepsilon_r$ is the relative permittivity of the surface and $\mu_r$ is the relative permeability. They may be either real or complex (for a lossy surface). Here we take $\mu_r = 1$.

We have derived individual expressions for the cross section of the surface of each of the two levels of roughness to be considered. It has been shown that, as long as $\sigma_L/T_L < 1$ for the large scale roughness, the total scattering cross section is just the sum of the two components. If that is not the case, Brown\textsuperscript{4} has shown that the calculation of the composite cross section is no longer that simple. For our purposes we will address only cases that do satisfy the criterion, $\sigma_L/T_L < 1$, so that summation can be applied.

In this report, the surface heights are assumed to have a Gaussian distribution. Hence, the shadowing can be described (in the high frequency limit $\lambda \to 0$) by a shadowing function $S$ derived by Sancer.\textsuperscript{5}

\begin{align}
(1) & \quad \text{For } \phi_s = 180^\circ,
S &= 1/(1 + C_0) \quad \text{when } \theta_s < \theta_L;
S &= 1/(1 + C_2) \quad \text{when } \theta_s \geq \theta_L; \text{ and} \\
(2) & \quad \text{For } \phi_s = 180^\circ,
S &= 1/(1 + C_0 + C_2).
\end{align}

In these expressions,

$$C_0 = \left[\sigma_L \tan \theta_L / (T_L \sqrt{\pi})\right] \exp \left\{-\left[T/(2\sigma_L \tan \theta_L)\right]^2\right\} + (1/2) \text{erfc} \left\{T/(2\sigma_L \tan \theta_L)\right\}$$

and

$$C_2 = \left[\sigma_L \tan \theta_s / (T_L \sqrt{\pi})\right] \exp \left\{-\left[T/(2\sigma_L \tan \theta_s)\right]^2\right\} + (1/2) \text{erfc} \left\{T/(2\sigma_L \tan \theta_s)\right\}$$

Brown\textsuperscript{4} has shown that this shadowing function $S$ multiplies the cross section for both large scale roughness and the cross section for the small scale roughness.

### 2.2 Data and Model Parameters

Cost\textsuperscript{2} presents bistatic data in two formats. For $\phi_s = 0^\circ$, values of $\sigma^e$ are plotted as a function of elevation scattering angle $\theta_s$, for fixed incident elevation angles $\theta_L$. In the second series of data sets the values of $\sigma^e$ are plotted as a function of azimuthal scattering angle for fixed values of $\theta_L = \theta_s$. Both vertical-vertical and horizontal-horizontal polarized signals were considered and the data are for a

\begin{thebibliography}{9}


\end{thebibliography}
wavelength $\lambda = 3$ cm. (X-band). Only limited ground truth was given for the data. For the azimuthal variations we will show comparisons for loam. Cost gives the standard deviation in surface heights for his loam data to be on the order of a wavelength. The $\phi_s = 0^\circ$, elevation angle $\sigma^\circ$ comparisons in this report are for sand. Cost gives the standard deviation of the surface heights for sand as several wavelengths. For the loam comparisons, three sets of elevation angles were considered: $\theta_1 = \theta_2 = 60^\circ$, $\theta_1 = \theta_2 = 70^\circ$, and $\theta_1 = \theta_2 = 85^\circ$. The $\phi_s = 0^\circ$ sand comparisons are made for two sets of incident angles, $\theta_1 = 20^\circ$ and $\theta_2 = 40^\circ$.

The model parameters have to be related to the scattering surfaces that resulted in the experimental data sets. The parameters must have physically realistic values and are required to satisfy a series of constraints imposed by the model. First, the surface must be very large compared to the large scale correlation length. Next, the large scale surface slopes must be small, so that $T_L > \sigma_L$. The small scale surface parameters must satisfy the requirements that $T_s << T_L$ and $\sigma_s < \sigma_L$. Also, the small scale surface parameters must satisfy two additional constraints: (1) $\frac{2\pi}{\lambda} \sigma_s < 1$ and $\sigma_s/T_s < 1$. Subject to all these conditions, some variation in the surface is possible and there was no additional ground truth supplied by Cost. The principal model parameter of interest is the correlation length $T_L$. The constraints for this parameter for loam are such that $0.06 \, \text{m} < T_L < 0.6 \, \text{m}$ and for sand $0.15 \, \text{m} < T_L < 0.6 \, \text{m}$. The final selection of parameters was made by considering several possibilities and checking agreement with a limited data set. The same parameters were then used to predict behavior for other cases and the results are assessed in the next section. As an example, for the azimuthal cases, small incident elevation angle cases with horizontally polarized signals were used to establish the basic parameter set consistent with the parameter constraints of the model. For loam the final parameter values are $\sigma_L^2 = 0.03 \, \text{m}$ (given); $T_L = 0.15 \, \text{m}$ (mid-range); $\sigma_s = 0.0045 \, \text{m}$; $T_s = 0.025 \, \text{m}$; and $\epsilon = 30.0 + j \, 2.0$. For sand, the corresponding baseline parameters are slightly different. Here, $\sigma_L^2 = 0.09 \, \text{m}$ (given); $T_L = 0.45 \, \text{m}$ (mid-range); $\sigma_s = 0.0001 \, \text{m}$; $T_s = 0.0005 \, \text{m}$; and $\epsilon = 3.0 + j \, 0.2$.

### 2.3 Comparisons of Model Results with Data

The two-scale-of-roughness model predictions are compared to the X-band data taken by Cost. The loam data allows azimuthal variations to be examined while the sand results show scattering elevation variations for $\phi_s = 0^\circ$.

Figures 2 through 7 show Cost’s data for loam as points for $\theta_1 = \theta_2 = 60^\circ$, 70°, and 85° for both HH and VV polarizations. The solid lines show the theoretical model results with the two scales of roughness parameters chosen by judicious variations over a range of conditions. The dots show the experimental data. The final selection of parameters has been cited previously. The agreement between the experimental data and the theoretical model is, in general, good, considering the large variations in angles of incidence, scattering angles and polarizations. It should be noted that the general trend of $\sigma^\circ$ vs $\phi_s$ is followed by both the experimental data and the theoretical model. For small $\phi_s$ ($\phi_s = 0^\circ$), $\sigma^\circ$ is at a maximum; as $\phi_s$ increases, $\sigma^\circ$ reaches a minimum ($20^\circ < \phi_s < 100^\circ$); and then $\sigma^\circ$ increases and reaches a plateau beyond $\phi_s = 100^\circ$. This is true for $\theta_1 = \theta_2 = 60^\circ$ and 70°, in terms of both the experimental data and the theoretical model, for both polarizations. The agreement between the experimental data and the theoretical model is the least good for $\theta_1 = \theta_2 = 85^\circ$. This is probably due to the fact that here multiple scattering plays a role, and the two-scale model (with shadowing) doesn’t
Figure 2. RCS vs. $\phi_s$ for Loam
Figure 3. RCS vs. $\phi_s$ for Loam

\begin{align*}
\theta_i &= 70.00 \\
\theta_s &= 70.00 \\
\lambda &= 0.03 \\
\sigma_L^2 &= 0.300E-01 \\
T_L &= 0.150 \\
\sigma_S^2 &= 0.450E-02 \\
T_S &= 0.250E-01 \\
\varepsilon &= (30., 2.)
\end{align*}

HH Polarization
Shadowing
Gaussian Correlation
Large Scale
Small Scale
Figure 4. RCS vs. $\phi_s$ for Loam
Figure 5. RCS vs. $\phi_s$ for Loam

\[ \begin{align*}
\theta_i & = 60.00 \\
\theta_s & = 60.00 \\
\lambda & = 0.03 \\
\sigma_	ext{L}^2 & = 0.300 \times 10^{-1} \\
T_L & = 0.150 \\
\sigma_	ext{S}^2 & = 0.450 \times 10^{-2} \\
T_S & = 0.250 \times 10^{-1} \\
\epsilon & = (30., 2.) \\
\text{VV Polarization} \\
\text{Shadowing} \\
\text{Gaussian Correlation} \\
\text{Large Scale} \\
\text{Small Scale}
\end{align*} \]
Figure 6. RCS vs. $\phi_s$ for Loam

LOAM

- $\theta_i$ = 70.00
- $\theta_s$ = 70.00
- $\lambda$ = 0.03
- $\sigma_t^2$ = 0.300E-01
- $T_L$ = 0.150
- $\sigma_s^2$ = 0.450E-02
- $T_S$ = 0.250E-01

VV Polarization
Shadowing
Gaussian Correlation
Large Scale
Small Scale
Figure 7. RCS vs. $\phi_s$ for Loam

\begin{align*}
\theta_i &= 85.00 \\
\theta_s &= 85.00 \\
\lambda &= 0.03 \\
\sigma_L^2 &= 0.300E-01 \\
T_L &= 0.150 \\
\sigma_S^2 &= 0.450E-02 \\
T_S &= 0.250E-01 \\
\varepsilon &= (30, 2) \\
\end{align*}
account for multiple scattering. Also, the nulls in \( \sigma^o \) shown in the theoretical curves near \( \phi_s = 30^\circ \) in Figures 5 and 6 do not appear in the experimental data. This may occur because the nulls are narrow and there are simply not enough experimental data points in this region.

Figures 8 through 11 show Cost’s data for sand as points for \( \theta_i = 20^\circ \) and \( 40^\circ \) for both HH and VV polarizations. Again, the solid lines show the theoretical model results for the two scales of roughness parameters chosen in accord with Cost’s data. The agreement between the experimental data and the theoretical model is quite good, and, in general, better than the agreement for loam. The greatest discrepancy between the experimental data and the theoretical model occurs for \( \theta_s \rightarrow 90^\circ \). This discrepancy again may be attributed to the effects of multiple scattering, which mostly occur near small grazing angles. Also, there may be large errors in the experimental data when \( \phi_s = 90^\circ \), because it is difficult to define precisely the radar footprint on the earth’s surface.

3. ASSESSMENT OF SURFACE ROUGHNESS CONTRIBUTIONS

In the previous section we have shown how the two-scale model scattering predictions behave as a function of geometry. In this section we will examine the results more explicitly. The predictions will be examined with the contribution of each level of roughness isolated from the other so that the regions where one or the other scattering mechanism dominates the cross section can be seen and analyzed. Only horizontal-horizontal (HH) polarization results will be considered, since the behavior for the vertical-vertical (VV) polarization is very similar. Figures 12 through 20 show \( \sigma^o \) vs \( \phi_s \) plots for HH polarization for the large scale of roughness only (loam is the dielectric surface). Here, the surface slopes are small, \( \sigma_i/T_L = 0.333 \) for Figures 12, 13, and 14; and \( \sigma_i/T_L = 0.577 \) for Figures 15, 16, and 17.

The figures show, in general, a characteristic trend. The normalized cross section \( \sigma^o \) starts out at a relatively high value at \( \phi_s = 0^\circ \), drops down to some minimum value as \( \phi_s \) increases, and then rises to a plateau as \( \phi_s \) further increases. This behavior is not always exhibited when \( \theta_i = \theta_s = 85^\circ \), where \( \sigma^o \) often exhibits a monotonic decrease as \( \phi_s \) increases. The more general behavior which is shown at \( \theta_i = \theta_s = 60^\circ \) and \( 70^\circ \) follows what is observed experimentally. Comparing Figure 15 with Figure 12, Figure 16 with Figure 13, and Figure 17 with Figure 14, one may observe another general trend in behavior. As the surface slope \( \sigma_i/T_L \) increases, \( \sigma^o \) decreases near \( \phi_s = 0^\circ \) and \( \sigma^o \) increases for \( \phi_s > \) the null angle.

Figures 18, 19, and 20 summarize clearly the effects of \( \sigma_i \) and \( T_L \) on the graphs of \( \sigma^o \) vs. \( \phi_s \) for fixed \( \theta_i \). Comparing Figure 19 with Figure 18, one may observe a general trend: as \( T_L \) increases, the right hand side (backscatter) decreases and the left hand side (forward scatter) increases (for \( \sigma_i \) constant, both HH and VV polarizations). Comparing Figure 20 with Figure 19, we may note that as \( \sigma_i \) decreases, the right hand side (backscatter) decreases and the left hand side (forward scatter) increases. Thus, for the large scale roughness, both \( T_L \) and \( \sigma_i \) control the shape of the \( \sigma^o \) vs. \( \phi_s \) curves.

In Figures 21 through 29, only the small scale roughness, \( (\sigma_s, T_s) \) contributes to the normalized cross section \( \sigma^o \). Comparing Figure 24 with Figure 21, Figure 25 with Figure 22, and Figure 26 with Figure 23, one may observe a trend in behavior that is analogous to the large-scale-of-roughness case. As \( T_s \) decreases and \( \sigma_s/T_s \), the slope, increases, \( \sigma^o \) decreases near \( \phi_s = 0^\circ \) and \( \sigma^o \) increases for \( \phi_s > 30^\circ \).
Figure 8. RCS vs. $\theta_s$ for Sand
Figure 9. RCS vs. $\theta_s$ for Sand
Figure 10. RCS vs. $\theta_s$ for Sand

\begin{itemize}
  \item $\theta_i \quad 20.00$
  \item $\phi_s \quad 0.00$
  \item $\lambda \quad 0.03$
  \item $\sigma_L^2 \quad 0.900E-01$
  \item $T_L \quad 0.450$
  \item $\sigma_S^2 \quad 0.100E-03$
  \item $T_S \quad 0.500E-02$
  \item $\epsilon \quad (3.0, 0.2)$
\end{itemize}

VV Polarization
Shadowing
Gaussian Correlation
Large Scale
Small Scale
Figure 11. RCS vs. $\theta_s$ for Sand

Parameters:
- $\theta_i = 40.00$
- $\phi_s = 0.00$
- $\lambda = 0.03$
- $\sigma_L^2 = 0.900E-01$
- $T_L = 0.450$
- $\sigma_S^2 = 0.100E-03$
- $T_S = 0.500E-02$
- $\varepsilon = (3.0, 0.2)$

- VV Polarization
- Shadowing
- Gaussian Correlation
- Large Scale
- Small Scale
Figure 12. RCS vs. $\phi_0$ for Loam
Figure 13. RCS vs. $\phi_S$ for Loam
Figure 14. RCS vs. $\phi_S$ for Loam
Figure 15. RCS vs. $\phi_S$ for Loam
Figure 16. RCS vs. $\phi_s$ for Loam
Figure 19. RCS vs. $\phi_s$ for Loam
Figure 20. RCS vs. $\phi_s$ for Loam
Figure 21. RCS vs. $\phi_s$ for Loam
Figure 22. RCS vs. $\phi_s$ for Loam
Figure 23. RCS vs. $\phi_s$ for Loam
Figure 24. RCS vs. $\phi_s$ for Loam
Figure 25. RCS vs. $\phi_s$ for Loam

Parameters:

- $\theta_i = 70.00$
- $\theta_s = 70.00$
- $\lambda = 0.03$
- $\sigma_s = 0.450E-02$
- $T_s = 0.500E-01$

Note:

- HH Polarization
- Shadowing
- Gaussian Correlation
- Small Scale Only
LOAM

\[ \theta_i = 85.00 \]
\[ \theta_s = 85.00 \]
\[ \lambda = 0.03 \]
\[ \sigma_s = 0.450E-02 \]
\[ T_s = 0.500E-01 \]
\[ \varepsilon = (30., 2.) \]

HH Polarization
Shadowing
Gaussian Correlation
Small Scale Only

Figure 26. RCS vs. \( \phi_s \) for Loam
Figure 28. RCS vs. $\phi_s$ for Loam
Figures 27, 28, and 29 summarize the effects of the small scale roughness on the $\sigma^0$ vs. $\phi_s$ curves. Comparing Figure 28 with Figure 27, one may note a general trend; as $T_s$ increases, the right hand side (backscatter) decreases and the left hand side (forward scatter) increases and the entire angular extent where $\sigma^0$ contributes becomes narrower (for $\sigma_b$ constant, both HH and VV polarizations). Thus, $T_s$ controls the shape of the $\sigma^0$ vs. $\phi_s$ curve. Comparing Figure 29 with Figure 27, one may note that as $\sigma_b$ decreases, the entire $\sigma^0$ vs. $\phi_s$ curve moves down (decreases) and does not change shape (for $T_s$ constant, both HH and VV polarizations).

4. BISTATIC AND MONOSTATIC CLUTTER MAPS

One question of interest is how the clutter cross section map of a region would change if a bistatic map were considered instead of a monostatic one. We will use our validated bistatic $\sigma^0$ model to demonstrate the differences for a particular scattering configuration. The region will consist of a loam surface extending some 200 nmi down range and 400 nmi cross range. A monostatic system is assumed to be at a grazing angle of about 6° with the front center of the region and about 2° with the rear. (The grazing angle is the complement of $\theta_l$). These conditions apply to the scattered elevation angle values of the bistatic system. The bistatic incident elevation angle is taken with respect to the center of the region, $\theta_l = 70°$. For both cases the $\sigma^0$ maps are constructed by dividing the region into 5 nmi by 5 nmi boxes and assigning a $\sigma^0$ value to the center of each box. Since the region is so extensive, the further refinement of a spherical geometry was introduced. The four-thirds earth radius concept then takes into account tropospheric refraction effects.

For this section the frequency is considered to be L-band ($f = 1$ GHz). The terrain is considered to be very rough but the constraint $\sigma_L/\tau_L < 1$ is maintained. Here $\sigma_L = 1.0$ m; $\tau_L = 1.1$ m; $\sigma_b = 0.0045$ m, $T_s = 1$ m; and $\varepsilon = 30.0 \pm 2.0$.

In Figure 30, the bistatic clutter map for loam is shown for horizontal-horizontal polarization, with the wavelength equal to 30 cm. The first observation to be noted is that the clutter cross section $\sigma^0$ is, in general, greatest in the direct forward, near specular, direction. This is due to the scattering in the forward, near specular direction (small slopes, $\sigma_L/\tau_L < 1$). The decrease in clutter cross section $\sigma^0$ with increasing range is due primarily to shadowing. The surface irregularities cause less of the rough surface to be illuminated by the incident rays as the elevation scattering angle $\theta_s$ decreases.

In Figure 31, the monostatic clutter map for loam is shown for horizontal-horizontal polarization. It may be noted immediately that, for a given clutter cell, the monostatic cross section $\sigma^0$ is, in general, at least 50 dB less than the corresponding bistatic cross section. Since the monostatic cross section $\sigma^0$ has a fixed azimuthal scattering angle ($\phi_s = 180°$), the monostatic clutter map is circularly symmetric about the radar position. The behavior of the monostatic cross section $\sigma^0$ with range is similar to the bistatic cross section; $\sigma^0$ decreases as the range increases primarily because of shadowing.

Figure 32 is not a clutter map, rather, it is a clutter ratio map, that is, $\sigma^0_{HH}$ (monostatic)/$\sigma^0_{HH}$ (bistatic). It may be noted immediately from Figure 32 that for any cell, the monostatic cross section is at least 50 dB less than the corresponding bistatic cross section $\sigma^0$.

Figure 33 is a bistatic clutter map for loam for vertical-vertical polarization. Comparing Figure 33 with Figure 30 shows that in the forward scatter direction, the bistatic cross section $\sigma^0_{VV}$ is
Figure 30. Bistatic Clutter Map for Loam (HH Polarization)
Figure 31. Monostatic Clutter Map for Loam (HH Polarization)

MONOSTATIC CLUTTER
LOAM
HH POLARIZATION
GAUSSIAN CORRELATION FUNCTION
Figure 32. Monostatic/Bistatic Ratio Map for Loam (HH Polarization)
Figure 33. Bistatic Clutter Map for Loam (VV Polarization)
about 20 dB less than $\sigma_{HH}^2$. For larger azimuthal scattering angles, corresponding to a cross range > 50 nmi, the bistatic cross section $\sigma_{VV}^2$ is, in general, greater than $\sigma_{HH}^2$. The behavior of $\sigma_{VV}^2$ with range is similar to $\sigma_{HH}^2$; it decreases as the range increases because of shadowing.

Figure 34 is a monostatic clutter map for loam for vertical-vertical polarization. Comparing Figure 34 with Figure 31, we may note that the monostatic cross section $\sigma_{VV}^2$ for a given clutter cell is very nearly identical to $\sigma_{HH}^2$.

Figure 35 is a map of the ratio $\sigma_{VV}^2$ (monostatic)/$\sigma_{VV}^2$ (bistatic). It may be noted immediately that the monostatic cross section $\sigma_{VV}^2$ is at least 45 dB less than the bistatic $\sigma_{VV}^2$ for any given clutter cell. Comparing Figure 35 with Figure 32, it may be noted that the two map ratios $\sigma^{2\text{(monostatic)}}/\sigma^{2\text{(bistatic)}}$ for the two polarizations are quite distinct. This is due primarily to the differences in the two bistatic cross sections.

5. CONCLUSIONS

Reasonable agreement was obtained between the bistatic scattering model with two scales of roughness and the X-band data. Both elevation plane comparisons for sand and azimuthal results for loam were considered. Considering the sparseness of the data and the limited nature of the ground truth, it appears that sufficient accuracy and trend preservation can be obtained using the theoretical model. It should be noted that, where the agreement is poorest (small incident grazing angle), both the data and the model are suspect. The uncertainty in the data is caused by the footprint determination requirement while the physical optics model does not allow multiple scattering which is more likely to occur at those conditions.

The parametric studies in which each level of roughness was treated separately allowed us to evaluate the model performance. The physical optics terms were dominant in the forward scattering directions and in those cases the results were controlled by the surface slope. As the scattering extended beyond these regions, the physical optics results were not as significant and the behavior was no longer slope dependent. Different patterns occurred depending on whether the standard deviation in heights or the correlation length was varied. The perturbation theory (small scale) results do not show any direct slope related pattern. For all cases there is a distinct difference in behavior to the curves when either $\sigma_s$ or $T_s$ is varied. $\sigma_s$ affects the magnitude and $T_s$ affects the shape of the small scale pattern.

When the validated bistatic scattering model was used to compare bistatic and monostatic clutter cross sections for a loam covered surface subdivided into 5 nmi boxes the results showed that the bistatic $\sigma^2$ values for the configuration used in the analysis always exceed the corresponding monostatic values by 50 dB for horizontal polarization and by 45 dB for vertical polarization. Shadowing, as expected, played a more significant role for the furthest down range cells. For this type of geometry, any enhanced target detection using bistatics has to come from greatly increased target cross sections at bistatic angles.
Figure 34. Monostatic Clutter Map for Loam (VV Polarization)

MONOSTATIC CLUTTER

LOAM
VV POLARIZATION
GAUSSIAN CORRELATION FUNCTION

10-OCT-89
Figure 35. Monostatic/Bistatic Ratio Map for Loam (VV Polarization)
References


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