TERRAIN CLASSIFICATION IN TERMS OF RADAR REFLECTION PROPERTIES

by

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STUDIES IN RADAR CROSS SECTIONS

I "Scattering by a Prolate Spheroid", F. V. Schultz (UMM-42, March 1950), W-33(038)-ac-14222. UNCLASSIFIED.

II "The Zeros of the Associated Legendre Functions $P_n^m(\mu')$ of Non-Integral Degree", K. M. Siegel, D. M. Brown, H. E. Hunter, H. A. Alperin and C. W. Quillen (UMM-82, April 1951), W-33(038)-ac-14222. UNCLASSIFIED.

III "Scattering by a Cone", K. M. Siegel and H. A. Alperin (UMM-87, January 1952), AF-30(602)-9. UNCLASSIFIED.

IV "Comparison Between Theory and Experiment of the Cross Section of a Cone", K. M. Siegel, H. A. Alperin, J. W. Crispin, Jr., H. E. Hunter, R. E. Kleinman, W. C. Orthwein and C. E. Schensted (UMM-92, February 1953), AF-30(602)-9. UNCLASSIFIED.

V "An Examination of Bistatic Early Warning Radars", K. M. Siegel (UMM-98, August 1952), W-33(038)-ac-14222. SECRET.

VI "Cross Sections of Corner Reflectors and Other Multiple Scatterers at Microwave Frequencies", R. R. Bonkowski, C. R. Lubitz and C. E. Schensted (UMM-106, October 1953), AF-30(602)-9. SECRET - Unclassified when Appendix is removed.

VII "Summary of Radar Cross Section Studies Under Project Wizard", K. M. Siegel, J. W. Crispin, Jr., and R. E. Kleinman (UMM-108, November 1952), W-33(038)-ac-14222. SECRET.

VIII "Theoretical Cross Section as a Function of Separation Angle Between Transmitter and Receiver at Small Wavelengths", K. M. Siegel, H. A. Alperin, R. R. Bonkowski, J. W. Crispin, Jr., A. L. Maffett, C. E. Schensted and I. V. Schensted (UMM-115, October 1953), W-33(038)-ac-14222. UNCLASSIFIED.

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X "Scattering of Electromagnetic Waves by Spheres", H. Weil, M. L. Barasch and T. A. Kaplan (2255-20-T, July 1956), AF-30(602)-1070. UNCLASSIFIED.

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XV "Radar Cross Sections of B-47 and B-52 Aircraft", C. E. Schensted, J. W. Crispin, Jr., and K. M. Siegel (2260-1-T, August 1954), AF-33(616)-2531. CONFIDENTIAL.

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XXVI "Fock Theory", R. F. Goodrich, Scientific Report No. 3 (2591-3-T), AFCRC TN 58-350, AD 160790, AF 19(604)-1949 (July 1958). UNCLASSIFIED.

XXVII "Calculating Far Field Patterns from Slotted Arrays On Conical Shapes", R. E. Doll, R. F. Goodrich, R. E. Kleinman, A. L. Maffett, C. E. Schensted, and K. M. Siegel, (2713-1-F), AF 33(038)-28634 and AF-33(600)-36192 (February 1958). UNCLASSIFIED.

XXVIII "The Physics of Radio Communications Via the Moon", M. L. Barasch, H. Brysk, B. A. Harrison, T. B. A. Senior, K. M. Siegel and H. Weil, (2673-1-F), AF 30(602)-1725 (March 1958). UNCLASSIFIED.

XXIX "The Determination of Spin, Tumbling Rates, Sizes of Satellites and Missiles", K. M. Siegel, M. L. Barasch, W. E. Burdick, J. W. Crispin, Jr., B. A. Harrison, R. E. Kleinman, R. J. Leite, D. M. Raybin and H. Weil (2758-1-T), AF 33(600)-36793. To be published. CONFIDENTIAL.

XXX "The Theory of Scalar Diffraction With Application to the Prolate Spheroid", R. K. Ritt (Appendix by N. D. Kazarinoff) Scientific Report No. 4 (2591-4-T) AF 19(604)-1949, AFCRC TN-58351, AD 160791 (August 1958). UNCLASSIFIED.

PREFACE

For several years The University of Michigan has been conducting a major study of radar cross sections (i.e., radar reflection characteristics of specific shapes), antenna and radiation problems, and radar propagation phenomena.

The primary aims of the program in the study of radar cross sections are:

(1) To show that radar cross sections can be determined analytically.

(2) To develop means for computing cross sections of objects of military interest.

(3) To demonstrate that these theoretical cross sections are in agreement with experimentally determined values.

Intermediate objectives are:

(1) To compute the exact theoretical cross sections of various simple bodies by solution of the appropriate boundary-value problems arising from Maxwell's equations.

(2) To examine the various approximations possible in this problem, and determine the limits of their validity and utility.

(3) To find means of combining the simple body solutions in order to determine the cross sections of composite bodies.

(4) To tabulate various formulas and functions necessary to enable such computations to be done quickly for arbitrary objects.

(5) To collect, summarize, and evaluate existing experimental data.

This work has resulted in a series of Studies in Radar Cross Sections summarizing the results obtained for many problems of a relatively broad nature. Titles of the papers already published or presently in process of publication are listed on the preceding pages.

Since the material contained in this report will be of general interest to all individuals concerned with radar cross section problems, it is intended that the results reported here will be presented in a future paper in the Studies in Radar Cross Sections series.

TERRAIN CLASSIFICATION IN TERMS OF RADAR REFLECTION PROPERTIES

We wish to classify various types of terrain in terms of their properties as radar reflectors. This we do in terms pertinent to a range finding application which makes use of the correlation between signals received directly through the atmosphere and signals received by way of reflection from the ground. Certain simplifications will be made in order to facilitate the terrain classifications.

We have a transmitter T and a receiver R located at altitudes H and h above the earth and a distance L apart as in Figure 1.

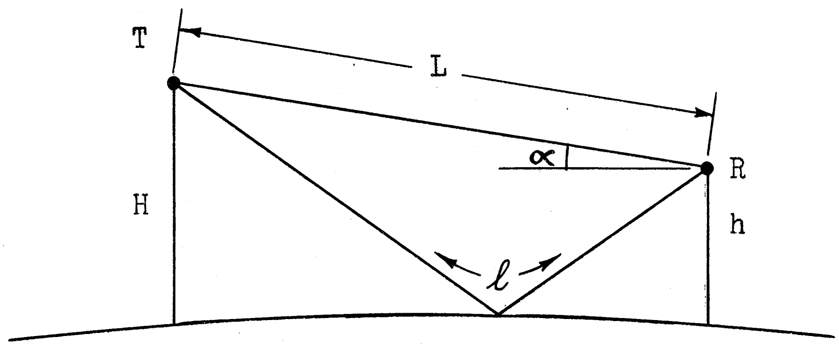

Figure 1.

The transmitter output is taken to be a continuous wave X-band carrier modulated by band-limited white noise. We consider the signal reaching the receiver as being made up of that transmitted directly, along path L, and that reflected by the ground, along path ℓ. If now the earth were a smooth plane, so that the reflection path

(path ℓ) would be primarily specular, the cross-correlation between the direct and ground return would give a measure of (ℓ -L), the path difference, which along with a knowledge of h and the elevation angle α would be sufficient to give information as to the range L.

We write x(t) for the transmitter output and $y_d(t)$ or $y_g(t)$ for the direct and reflected received signals respectively. We wish to examine the effect of various ground configurations on the cross-correlation of the functions y_d and y_g. In particular we wish to characterize the various types of terrain in terms of the effect of the departure from the ideal case - flat smooth earth - on the cross-correlation function. To this end we make the inessential simplifying assumptions that the transmitter and receiver are at the same altitude and that the earth is plane. The first assumption is justified since it will not essentially alter our description of the terrain in the above terms. The second assumption is justified since the ranges considered (L $\sim$ 50 mi) are sufficiently small that the curvature of the earth is a negligible effect.

We take the ground to be in the X-Y plane, the Z-axis upward and place the origin at the midpoint between the transmitter and receiver as in Figure 2.

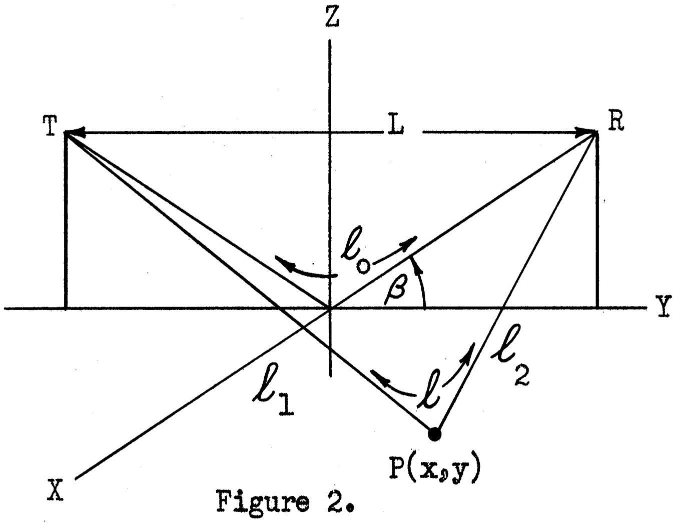

Figure 2.

We designate the specular path length as ℓ_o, the general path length as ℓ where

$$\ell = \ell_1 + \ell_2, \tag{1}$$

and ℓ_1 and ℓ_2 are the distances $\overline{TP}$ and $\overline{PR}$ respectively.

To find the ground return we note that the signal scattered from the point P and received at a time t had its origin at the transmitter at an earlier time $t - \frac{1}{c}\ell$. Hence, we write the return from a small area ΔS about P as

$$\frac{e^{ik\ell}}{\ell_1 \ell_2} A(P)\, x\, (t - \frac{1}{c}\ell) \Delta S \tag{2}$$

where the exponential gives the correct phase, the denominator $\frac{1}{\ell_1 \ell_2}$ accounts for the geometric attenuation, and for a field incident in the direction $\overline{TP}$ we write $A(P) \Delta S$ as the field scattered in the direction $\overline{PR}$ from the area ΔS about the point P. We choose to give a scalar treatment of the problem for reasons of simplification which we justify below. The total field from the ground is then this expression integrated over the X-Y plane, i.e.,

$$y_g(t) = \iint dS \frac{e^{ik\ell}}{\ell_1 \ell_2} A(P)\, x\, (t - \frac{1}{c}\ell). \tag{3}$$

We neglect the effects of atmospheric noise, again, because we are primarily interested in characterizing the types of ground.

The direct signal at a time t also will have its origin at an earlier time $t - \frac{L}{c}$ and will be of the form

$$y_d(t) = \frac{e^{ikL}}{L} x \left(t - \frac{1}{c} L\right). \tag{4}$$

Hence, the cross-correlation function will be

$$R_{y_d y_g}(\tau) = \frac{e^{-ikL}}{L} \iint dS \frac{e^{ik\ell}}{\ell_1 \ell_2} A(P) R_{xx}\left(\tau - \frac{\ell - L}{c}\right). \tag{5}$$

Because of the form of the integrand in Equation (3) we find it useful to express the integration in terms of the path length ℓ and a polar angle ϕ as the variables of integration. To do this we need the locus of constant ℓ in the X-Y plane.

The coordinates of the points T, R, and P are

$$T: \left(0, -\frac{L}{2}, h\right), \quad R: \left(0, \frac{L}{2}, h\right), \quad P: (x, y, 0). \tag{6}$$

Hence,

$$\begin{cases} \ell_1 = \overline{TP} = \left(x^2 + y^2 + y L + \frac{L^2}{4} \sec^2 \beta\right)^{\frac{1}{2}} \\ \ell_2 = \overline{PR} = \left(x^2 + y^2 - y L + \frac{L^2}{4} \sec^2 \beta\right)^{\frac{1}{2}}. \end{cases} \tag{7}$$

Then, from Equation (1), we find the locus to be the ellipse

$$\frac{x^2}{\frac{\ell^2 - \ell_o^2}{4}} + \frac{y^2}{\frac{\ell^2(\ell^2 - \ell_o^2)}{4(\ell^2 - \ell_o^2 \cos^2\beta)}} = 1 . \tag{8}$$

To effect the change in variables we write

$$\begin{cases} x = \frac{1}{2} \sqrt{\ell^2 - \ell_o^2} \cos \phi \\ y = \frac{\ell}{2} \sqrt{\frac{\ell^2 - \ell_o^2}{\ell^2 - \ell_o^2 \cos^2\beta}} \sin \phi . \end{cases} \tag{9}$$

We now need to compute the Jacobian of the transformation and the denominator $\frac{1}{\ell_1 \ell_2}$. After a straightforward calculation we find

$$\frac{J}{\ell_1 \ell_2} = \frac{1}{\sqrt{\ell^2 - \ell_o^2 \cos^2\beta}} . \tag{10}$$

Substituting for the integrand in Equation (5)

$$R_{y_d y_g}(\tau) = \frac{e^{-ikL}}{L} \int_{\ell_o}^{\infty} d\ell \int_{0}^{2\pi} d\phi \frac{e^{ik\ell}}{\sqrt{\ell^2 - \ell_o^2 \cos^2\beta}} A(\ell, \phi) \cdot R_{xx}(\tau - \frac{\ell - L}{c}) . \tag{11}$$

We now recapitulate our description of the process. The signal received by way of the ground reflection at a given time t will have arisen in the transmitter at some earlier time $t - \frac{1}{c}\ell$ as we have pointed out above. The least time delay will correspond to the path length ℓ_o determined by the specular reflection point which in our case is the midpoint between the receiver and transmitter. Signals corresponding to a greater delay time, say $t - \frac{1}{c}\ell$ where $\ell > \ell_o$, will arrive at the receiver after having been scattered from the region of the ground given by $\ell = \ell_1 + \ell_2$. This is just the equation for the ellipse which we have finally put in parametric form in Equation (9). The center of the ellipse corresponds to $\ell = \ell_o$, hence, we can conceive of elliptical zones about the specular reflection point, each zone giving a contribution to the received signal. This is just the physical content of Equation (11). For a fixed ℓ we have that the ϕ-integration gives us the contribution from the ℓ'th elliptic zone as in Figure 3.

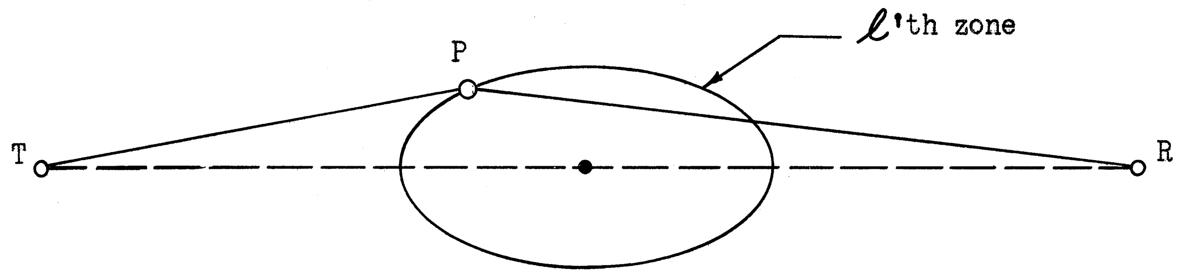

Figure 3.

Writing this explicitly, we find the contribution to the ground return from the ℓ'th zone to be

$$\Delta_{\ell} y_g(t) = \Delta \ell \frac{e^{ik\ell}}{\sqrt{\ell^2 - \ell_o^2 \cos^2\beta}} x(t - \frac{\ell - L}{c}) . \int_0^{2\pi} d\phi \, A(\ell, \phi) \ . \qquad (11a)$$

or for the cross-correlation function

$$\Delta_{\ell} R_{y_d y_g}(\tau) = \frac{e^{-ikL}}{L} \frac{e^{ik\ell} \Delta \ell}{\sqrt{\ell^2 - \ell_o^2 \cos^2\beta}} R_{xx}(\tau - \frac{\ell - L}{c}) \int_0^{2\pi} d\phi \, A(\ell, \phi) \qquad (11b)$$

We now turn to a detailed consideration of the amplitude function $A(\ell, \phi)$. We first note the extremes of the behavior of $A(\ell, \phi)$. If the ground behaves like a perfectly reflecting smooth plane A is essentially the delta function $\delta(\ell - \ell_o)$. This is a case given very approximately by a quiet sea. On the other hand, if A is independent of the variables ℓ and ϕ, i.e., diffuse reflection, we have a case given approximately by say a green uniformly forested area.

In terms of the cross-correlation function we give a qualitative description of the various forms of the amplitude function. In the smooth plane case the cross-correlation function will be sharply peaked at the value $\tau = \tau_o = \frac{\ell_o - L}{c}$. For rough but plane ground there will be two effects on the cross-correlation function; the magnitude of the peak will be less and the peak will be broadened as we have pictured qualitatively in Figure 4.

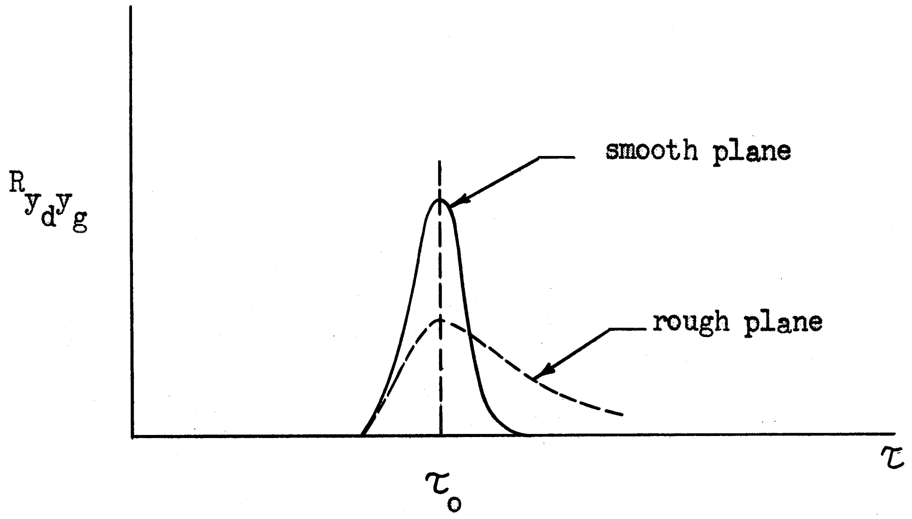

Figure 4.

The rough plane presents no essential problem since, as we show below, the cross-correlation function will still be a maximum at $\tau = \tau_o$; however, the amplitude may be so low as to make the peak undetectable. It is this case that should concern us and we shall propose a simple method for classifying various terrain in terms of the size of the cross-correlation peak.

The behavior of $A(\ell, \phi)$ is most efficiently determined experimentally. However, we will give an example of how we might arrive at a given A from a local analysis of the ground. Suppose we have a grassy area with a distribution of rocks which are large with respect to the wavelength. The grassy patches will scatter diffusely giving some average return per unit area, say a_g. The rocks will scatter according to geometric optics, the scattered field being proportional to some average value of the characteristic dimension of the rocks, say $\langle r \rangle$. This will then be multiplied by the distribution ρ the number per unit area. This then gives us a function $A = a_g \langle r \rangle \rho$ where we have assumed that the phase correlation between scatterers is random, i.e. all phases are equally likely, and we have neglected interactions between the scatterers.

This gives a constructive but not very useful method of determining the amplitude function. We say this since what would be involved in such an analysis would be first a determination of the individual behavior of the various ground scatterers, i.e. the return from individual rocks, grassy patches, etc. and then an averaging over some collection of these scatterers; however, this averaging is just what is done in performing an experimental determination of the ground return. We claim it is much better to make use of the large body of experimental data or ground returns using X-band radar.

It is now useful to make an assumption as to the functional behavior of $A(\ell, \phi)$. We assume that near the specular reflection direction $A(\ell, \phi)$ is describable as a function of the angle the line $\overline{PR}$ makes with the specular direction. This is illustrated in Figure 5, A ray from T to P, characterized by the vector $\vec{\ell}_1$, will be specularly reflected in the direction $\vec{\ell}_{sp}$. We now take $A(\ell, \phi)$ to be a function of θ alone as long as the angle θ is small.

There is much to be criticized in this assumption. However, we again insist that for our purposes this is a sufficiently good characterization of the ground return, since, as we will see below the particular form of our characterizations of the ground, i.e., in terms of the cross-correlation function, we need only consider small values of the angle θ.

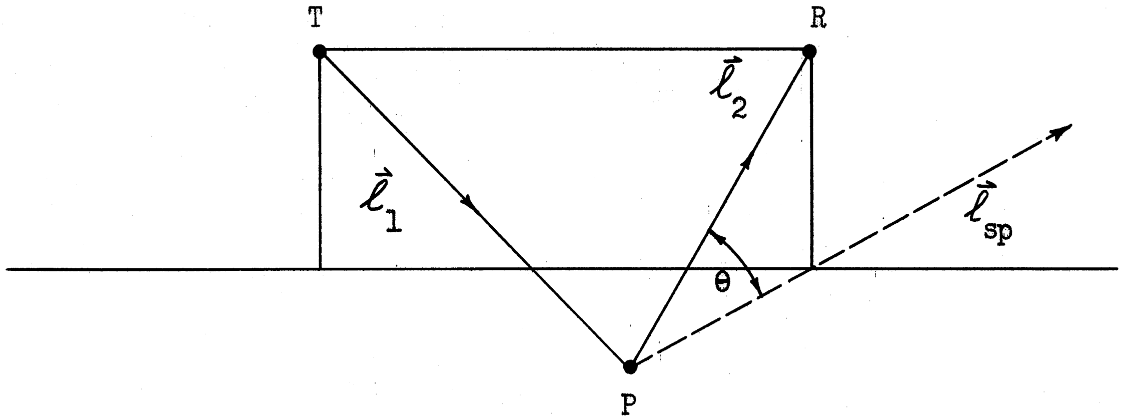

Figure 5.

Under our assumption we write

$$A(\ell, \phi) = \mathcal{a}(\theta), \tag{12}$$

where θ is the angle between $\overline{PR}$ and the specular direction. If we define $\vec{\ell}_1$ and $\vec{\ell}_2$ as the vectors from T to P and P to R respectively we have the vector in the specular direction given by

$$\vec{\ell}_{sp} = (\ell_1^x , \ell_1^y , - \ell_1^z). \tag{13}$$

Hence,

$$\cos\theta = \frac{1}{\ell_1 \ell_2} \vec{\ell}_{sp} \cdot \vec{\ell}_2 . \tag{14}$$

After some straightforward manipulations, we have

$$\cos\theta = 1 - \frac{1}{2} \frac{\ell^2 - \ell_o^2}{\ell_1 \ell_2} . \tag{15}$$

We now examine the cross-correlation function in more detail. The integrand in Equation (5) is made up of three factors: The geometric factor $\dfrac{e^{ik\ell}}{\sqrt{\ell^2 - \ell_o^2 \cos^2\beta}} \equiv g(\ell)$, the amplitude factor $\mathcal{A}(\theta)$ where $\theta = \theta(\ell, \phi)$ and the autocorrelation function $R_{xx}(\tau - \frac{\ell - L}{c})$.

The geometric factor has its maximum at $\ell = \ell_o$, in fact

$$\left| g(\ell) \right| \leqslant \frac{1}{\ell_o \sin\beta} .$$

The amplitude factor also is a maximum at $\ell = \ell_o$, i.e. at $\theta = 0$, except for certain extraordinary events. These extraordinary events could arise from say a single large reflector which could dominate the return at a given instant or say from the rare case that a number of obstacles be so distributed that they scatter coherently. That is to say in Equation (11b) the amplitude from the ℓ'th zone

$$\int_0^{2\pi} d\phi \, A(\ell, \phi)$$

as a function of ℓ could have a maximum for some $\ell \neq \ell_0$ due to coherent scattering from the elements in this zone or due to the specular return of some large smooth obstacle which lies at some position (ℓ, ϕ), $\ell \neq \ell_0$. We propose not to consider such cases since in the application envisaged the number of trials will be large enough to make their consideration of no importance.

The autocorrelation function for white noise taking the frequency band to be $(0, \omega)$ and the power spectral density to be W_0 is given by

$$R_{xx}(\tau) = \frac{2W_0}{\tau} \sin \omega \tau .$$

This has its maximum value at $\tau = 1$; in fact

$$\left| R_{xx}(\tau) \right| \leq 2W_0 \omega , \quad R_{xx}(0) = 2W_0 \omega .$$

Hence, because of the behavior of the other factors in the integrand, we have that the cross-correlation will be a maximum, excluding the extraordinary events, at the value,

$$\tau_0 = \frac{\ell_0 - L}{c} .$$

What we now do is to examine the cross-correlation at $\tau = \tau_o$ and estimate the relative size for various types of terrain. Now $R_{xx}(\tau_o - \frac{\ell - L}{c})$ is half-maximum for

$$\left| \omega(\tau_o - \frac{\ell - L}{c}) \right| \sim 2, \tag{16}$$

or rewriting, for

$$\frac{\ell}{\ell_o} = 1 + \frac{2c}{\omega \ell_o} . \tag{17}$$

Taking the upper limit of the modulation frequency to be 1 Mc and measuring ℓ_o in meters, Equation (17) becomes

$$\frac{\ell}{\ell_o} \cong 1 + \frac{10^2}{\ell_o} . \tag{18}$$

The corresponding value for θ we get from Equation (18)

$$\cos \theta = 1 + 0 \left(\frac{10^2}{\ell_o} \right) . \tag{19}$$

Hence, for any reasonable value of the range or ℓ_o we are justified in writing

$$\left| R_{y_d y_g}(\tau_o) \right| \leqslant \left| a(0) \right| \left| \int_0^\infty d\ell \int_0^{2\pi} d\phi \frac{e^{ik\ell}}{\sqrt{\ell^2 - \ell_o^2 \cos^2\beta}} R_{xx}\left(\frac{\ell - L}{c}\right) \right| . \tag{20}$$

We see then that we can compare the various types of terrain in terms of the magnitude of the return in the specular direction.

It only remains now to experimentally determine the amplitude for specular reflection from various types of terrain. Unfortunately the large body of experimental data is for monostatic ground return. We can, however, make the reasonable assumption that the bistatic specular returns which we need are scaled in the same way as the monostatic specular return from the same types of terrain. This we propose to do classifying the various ground returns in terms of power in decibels below the return from a calm sea. This is done in Table 1 using the data of Grant and Yaplee (Reference 1).

Finally we note that only a relatively small region of the ground about the specular reflection is of importance in determining the cross-correlation. This fact, then, is a justification of our scalar treatment of the problem since the angle the polarization vector makes with the ground will change very little over this small region about the specular reflection direction. Since polarization effects will be of little importance for our purposes the vector treatment will be only a complicating encumbrance adding little to the solution.

The effect of rolling or sloping terrain will introduce a bias error independent of the type of terrain; hence, for the purposes of terrain classification, we need not consider this effect.

Type	Power	Shape of $A(\theta)$
calm sea	0	sharply peaked
rough sea	-9 db	peaked
marsh	0	peaked
grass and sand	0	peaked
green grass	-10 db	peaked
short dry grass	-25	isotropic
green forest	-25	isotropic

Table 1

In conclusion we can say that the usefulness of this approach is limited primarily by the discrimination of the receiver. If the cross-correlation is detectable in the difficult cases of diffuse reflection the device will be successful. We suggest, therefore, that the most useful experimental check need be made over heavily forested areas. If the cross-correlation is there detectable we are assured that the results of a run will not be negative, although the bias error introduced by sloping ground will need be considered in any case.

We now make more precise what we mean by sloping ground. We use the term to describe very large obstacles as for example, a large hill. In this case the departure of the ground from flat occurs over much larger areas than previously considered. The effect on the cross-correlation function will be to introduce a bias error as we indicate qualitatively in Figure 6.

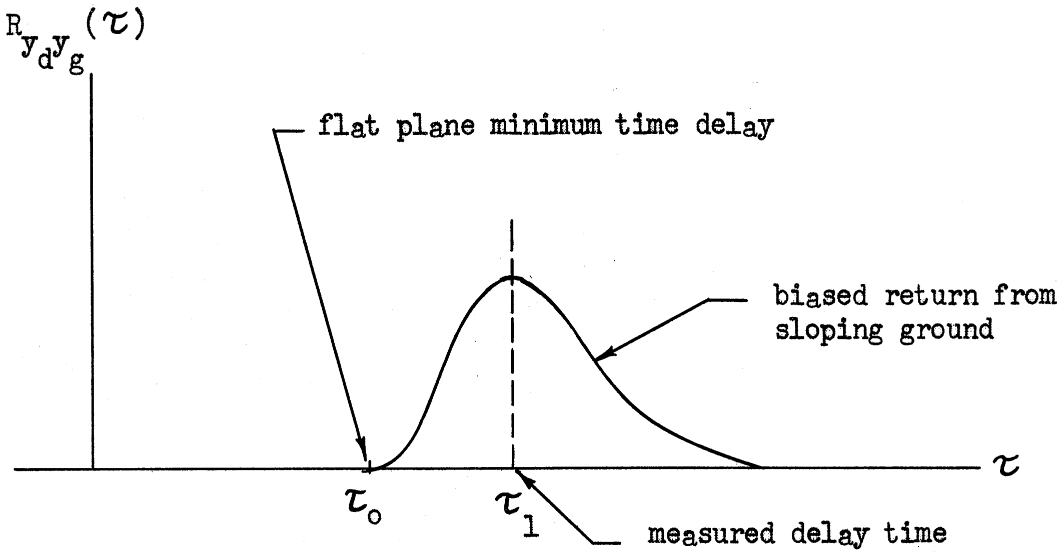

Figure 6.

This bias error will be partially corrected in application since the transmitter and receiver will be in motion and, hence, the specular reflection point will be also in motion. The effect of this is to cause the cross-correlation function to jitter back and forth in time so that the problem becomes that of determining the minimum time delay, presumably τ_o.

The simplest means of correcting for this bias error is then to take a large enough sample in time that many "hills" have been passed over. Then, on the average the return will appear isotropic and the above analysis is applicable. To characterize sloping ground we need count the number of hills per unit area. We then decide on the number of samples necessary to establish the minimum time delay, and finally, we take a large enough sample in time so that the agreed number of hills have been passed over.

The limitations imposed by sloping ground would seem to be on the rapidity with which a range determination can be made. For single slopes of many miles the system fails. For uniformly hilly regions in which there are a sufficiently large number of peaks per unit area so that the return is isotropic on the average for a reasonable duration of the sample the systems can be expected to work.

Inhabited areas will behave much like the sea in terms of the cross-correlation function. This obtains since there will be a large number of flat, level specular reflectors such as flat roofs, paved areas, and graded areas. The only important departure would arise in the case of a large number of pitched roofs, e.g. a heavily built-up subdivision. In this latter case, depending upon whether or not there is preferred orientation of the pitched roofs, there will or will not be a bias error introduced. This bias error would be of the same form as that cited above for single slopes. As in that case, the system fails if the array of oriented pitched roofs is of many miles extent.

We have considered various types of terrain in terms of their radar reflection properties. These considerations have been somewhat qualitative because of the lack of experimental data necessary for this particular application. We have, however, pointed out the type of experiments which would most usefully be performed for this application. We repeat our suggestions for experiments. You need two classes of information to check these results.

1. The relative magnitude of the cross-correlation for the types of terrain as, for example, those presented in Table 1.
2. The duration of a sample in order to get a "good" reading over sloping or hilly ground.

Reference

Grant, C. R. and Yaplee, B. S., "Back Scattering from Water and Land at Centimeter and Millimeter Wavelengths", Proceedings of the IRE, Vol. 45, No. 7, pp. 976 - 982, July 1957.