A Relook at Rocket Radar Ground Echo Data

B. L. Basore

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School of Electrical Engineering
Oklahoma State University
Stillwater, Oklahoma

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(* A refers to co-polarized channel A; B refers to cross-polarized channel B.)

I. Introduction.

In a NASA supported experiment conducted by JPL*, an Aerobee Rocket carried an L band radar to an altitude of 166 km over White Sands Missile Range in southern New Mexico. Data recorded during this flight included echos received both cross- and co-polarized with the transmitter. This paper described an analysis of a small fraction of the data in which an attempt has been made to understand the mechanisms producing cross-polarized return and how these mechanisms affect the data.

II. Mechanisms for Cross-Polarized Reflection.

One can readily describe a mechanism for producing a rotation of the plane of polarization for forward-scatter, and by combining this phenomenon with multiple reflection account for the cross-polarized component of back-scatter. Such a mechanism, a demonstration of which is described below, requires a surface roughness that intuition suggests is more pronounced as the amount of cross-polarized return is increased. It is probable that the relative cross-polarized return is greater for larger angles of incidence than for small (near verticle) ones. Why this should be so is perhaps evident if one notes that relatively shallow perturbations in a surface can nevertheless be of significant "depth" when viewed from a perspective approaching tangential. This is similar to the different impression of a mountain range gained from an aircraft high above the range as compared to that from the surface at

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* "Radar Studies of the Earth" paper presented at WESCON 68 by Walter E. Brown, Jr., Space Sciences Division, Jet Propulsion Laboratory, Pasadena, California.

same distance away.

The easiest demonstration of polarization rotation in forward scatter is that sketched below:

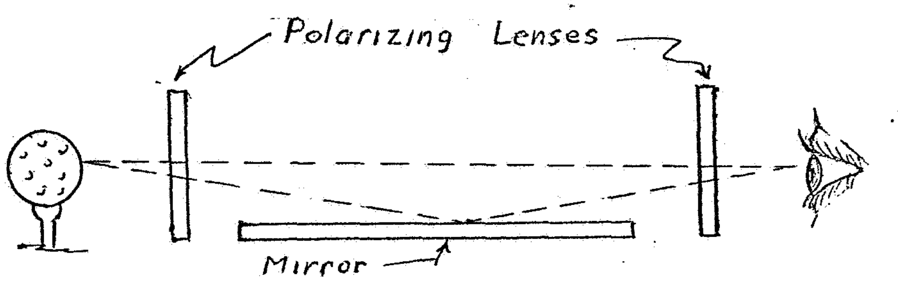


Figure 1

When the polarizing-analyzing filter near the object is <u>either</u> vertically or horizontally oriented, the direct and reflected paths are both observed to be polarized in the same direction. If the plane of polarization is inclined 45° to the vertical, the direct and reflected paths are observed to be cross-polarized. If the mirror is less than ideal, the plane of polarization is shifted more than 2θ(where θ is the original polarization angle) and there is also a loss in image intensity. It is observed, however, that if a single polarizer-analyzer is used to examine the image of one's own eye in a mirror held beyond the filter, there is no apparent shift of polarization. This is explained by noting the polarization angle is measured from the vertical plane containing the incident ray about an axis coincident with the ray. At normal incidence, the incident ray and the reflected ray are both vertical. Thus, the polarization angle is arbitrary, but whatever direction is used as a reference is also reversed in reflection, and the total shift of the polarization is 180°. As the angle of incidence is varied from grazing to vertical, two polarizer-analyzers adjusted plus and minus 45° to the vertical at grazing incidence will become co-polarized (180°) at an angle of incidence of zero.

If multiple reflection is simulated by a corner reflector (two mirrors at right angles), a single polarizer-analyzer rotated between the eye and its image will show that the reflection does become cross-polarized whenever the angle made by the plane of polarization is 45° with respect to the plane parallel to the incident ray that contains the line of intersection of the two mirrors. See Figure 2. Here, again, the polarization shift is modified if the mirrors are not ideal. An examination of the formula for reflection coefficients for

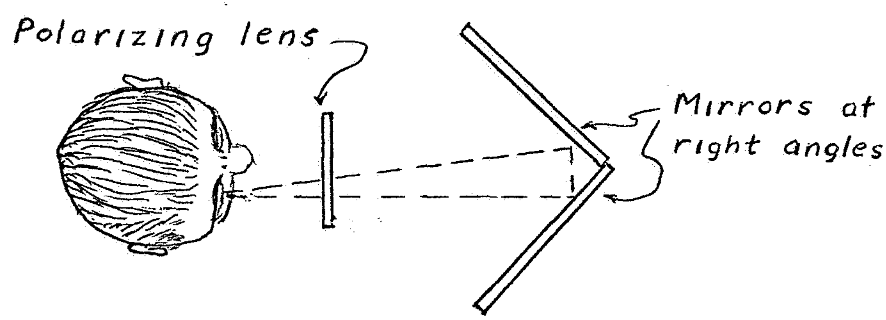


Figure 2

the two components of an arbitrarily polarized wave reveals that the ratio of the component parallel to the plane of incidence to the component perpendicular to the plane (considering E vectors) is always less than or equal to unity, the result being to shift the polarization angle away from the plane of incidence. This shift is, of course, accompanied in general by a reflection loss.

The mechanisms just described do not allow for a shift of polarization for waves striking a flat surface at normal incidence. A third kind of mechanism has been postulated that may account for the shift that appears to be present in the data to be described later. Here, we assume that conducting "grains" in or near the surface of the reflecting media are randomly oriented. The cross-polarized reflection from such a grain is proportional to cosθ sinθ where θ is the angle the grain axis makes with the plane of polarization. The co-polarized reflection from a single grain is proportional to $\cos^2\theta$, and is due to the projection of the induced current element onto the co-polarized axis, whereas the current induced is itself proportional to the projection of the axis of polarization onto the grain axis. Thus, for a given grain, we can let

$$E_y = \frac{E_i}{2}(1 + \cos 2\theta) \text{ for the co-polarized component ,}$$

and

$$E_x = \frac{E_i}{2} \sin 2\theta \text{ for the cross-polarized component.}$$

Where the angle θ is uniformly distributed from $-\pi/2$ to $\pi/2$, one can compute the quantities $\overline{E_y}$, $\overline{E_y^2}$, $\overline{E_x}$ and $\overline{E_x^2}$. They are

$$\overline{E_y} = \frac{E_i}{2} , \quad \overline{E_x} = 0 ,$$

$$\overline{E_y^2} = \frac{3}{8} E_i 2 , \quad \overline{E_x^2} = \frac{1}{8} E_i^2 ,$$

and

$$\sigma_x^2 = \sigma_y^2 \propto \frac{1}{8} E_i^2 .$$

Now if it is further assumed that grains are independent, then for N randomly oriented grains contributing within the reflection area corresponding to one Fresnel zone, we have

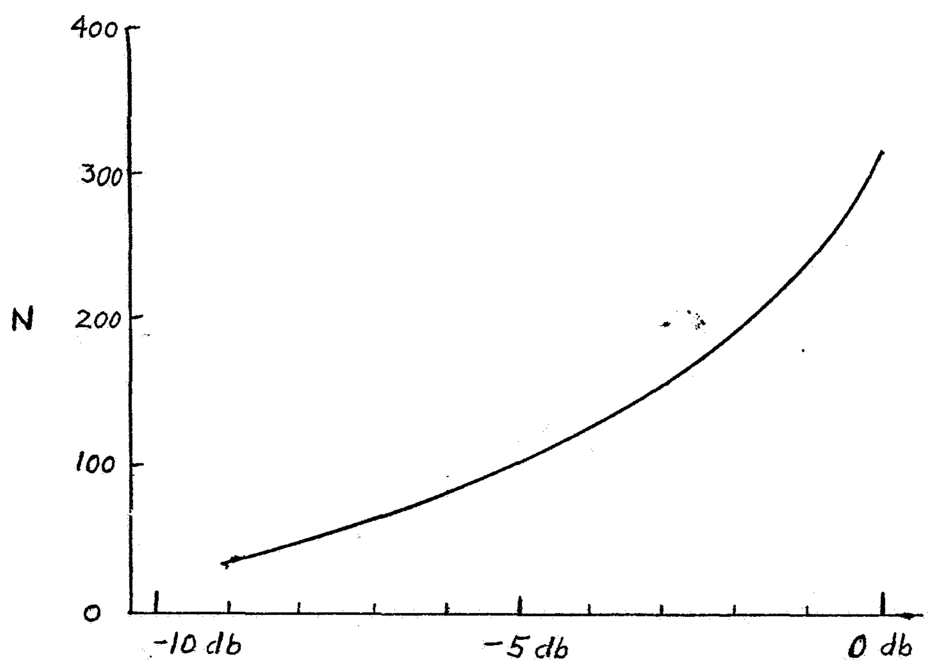
$$\overline{E_y(N)} \propto \frac{N}{2} E_i \qquad \overline{E_y(N)}^2 \propto \frac{N^2 E_i^2}{4}$$

$$\sigma_y^2(N) \propto \frac{N}{8} E_i^2 \qquad \sigma_x^2(N) \propto \frac{N}{8} E_i^2$$

Thus, the ratio of co-polarized return to cross-polarized return is

$$\frac{\dfrac{N^2E_i^2}{4} + \dfrac{NE_i^2}{8}}{\dfrac{NE_i^2}{8}} = (2N + 1) .$$

One could thus interpret a cross-polarized component of return as being due to reflection from randomly oriented conducting scatters. It is more likely, however, that the echoes are made up of reflection from both conducting and non-conducting elements. Unfortunately, there is no way to decide how the separation should be made. For example, if one assumes that only part of the reflection is from conducting grains, the ratio of co-polarized to cross-polarized return is $\frac{1}{K}$ [2N+1] where K is the fraction of reflection due to conducting grains. This relationship is plotted below for values of K values from -10 db to 0 db, and a basic ratio of 25 db.



Ratio of Reflection from Conductors to Reflection from no Conductors
Figure 3

The numbers for N derived from the data do not appear to be large enough to account for the number of grains one's intuition would expect in typical soils. Perhaps "grain" ought to be interpreted in terms of regions of varying soil conductivity having dimensions of the order of several wavelengths. Such an interpretation would lead to the prediction that the ratio between co- and cross-polarized echo components varies rather widely. Based on horizontal velocity alone, a complete change in target geometry for the first Fresnel zone occurred roughly about every two seconds such that significant change in surface configuration is unlikely in each group of 100 pulses (2/3 second). We conclude, therefore, that target variability in the sense of changes other than the fine structure in the various contributions to the phase of the echo should be present in the data as recorded and processed.

IV. Some Inferences From the Data

One of the first results that can be inferred from the data, but as a speculation rather than with any great degree of confidence is related to the variability observed in the 100-pulse groups of data plotted in the standard data format. Here, we observe a variability of something like 3 or 4 db. This corresponds to a factor of perhaps 2 to 2½ in the fluctuations in N, which is adequate to support the theory of conducting grain reflections if grains are fairly large and relatively low in number. The fluctuation seems too large to fit well with the idea of small conducting grains in minerals, for example. Thus, we are led to conclude that if the randomly oriented grain model is to account for cross-polarized return from straight down, then rather large "grains" must be involved.

The second observation of significance is that at normal incidence, at least, the signals recorded in channel B are correlated to some extent with those in channel A. In an effort to determine the extent of this correlation, 1000 consecutive echoes recorded early in the flight were analyzed prior to any editing or averaging. When the recorded returns were reconverted to received signal amplitudes, a correlation coefficient of about 0.75 was observed. This correlation could have resulted from at least two relations. There is the evident possibility (and reality) of cross-talk between channels and there is also the fact that the target variations are common to the two channels. However, in the absence of a known and operative mechanism for generating cross-polarized return, it is not clear that the cross-polarized return fluctuations should necessarily correlate with the co-polarized return fluctuations. Thus, a first effort was made to determine the amount of cross-talk present. An estimate had already been made by observing the "up-fades" of the signal, but even for the strongest signal, a few db of fluctuation was evident in the difference between channels, and a means of incorporating the information present in more echoes to average the fluctuations was sought. A statistical model was employed that appears to offer a reasonable explanation of the behavior observed.

The model first assumes that the signal in channel B is composed of two independent components. One of these is cross-talk from channel A; the other is cross-polarized echo energy and is thus desired signal. Cross-talk from channel B to channel A is a negligible contribution to the signal observed in channel A when, as in the apparent case here, the independent component in channel B is some 25 db or so below the signal in A, and it is further attenuated by the more than 25 db in the leakage path. From A to B, however, the signal A attenuated by the leakage path turns out to be about the same strength as the independent component.

In these circumstances, the signal in A can be treated as given in the statistical analysis of channel B signals. The leakage attenuation is assumed to be a constant to be determined. A family of probability contours are constructed of the probability of B, given αA as a parameter over a range such that αA varies from 20 db greater than the independent component of B to 20 db less. These contours are then plotted for probability values 2%, 16%, 50%, 84%, and 98%, on a db plot of A - B (in db) vs A (also in db). The choice of (A - B) as ordinate was determined by the format in which the data was readily available, and B alone might just as well have been used otherwise. (It does appear that this format accentuates the breaks in the data pattern as the cross-talk comes into play, and thus facilitates matching data to the contours.)

This probability of B, given A, is the "Rice" distribution,

$$P(B|A) = \int_{0}^{B} \frac{x}{\sigma^2} e^{-\frac{\alpha A^2+X^2}{2\sigma^2}} I_0 \left(\frac{\alpha AX}{\sigma 2}\right) dX ,$$

in which σ^2 is the variance of the independent component of B, measured in terms of radio frequency power and $I_0(\ )$ is the modified Bessel function of the first kind of order 0. A, B, and α are as defined previously. The figure below depicts a reference αA added to an independent normally distributed bivariate quantity assumed to be the independent component of B, to obtain the observed resultant quantity B.

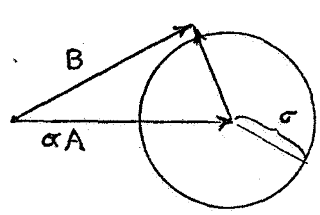


Figure 4

The contours corresponding to the five selected probabilities are illustrated in Figure 5.

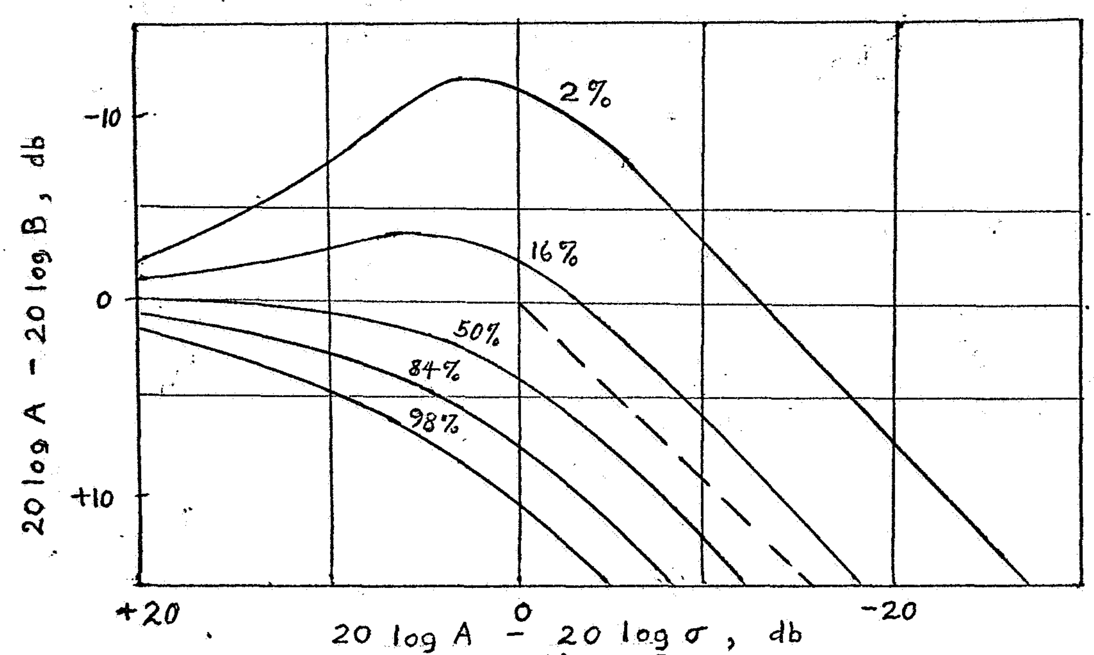


Figure 5

When these contours are plotted with the same scales as the plot presenting the recorded data, i.e., channel A - channel B (in db) vs channel A (in db), it can be translated (without rotation) until the contours best fit the data. The phenomenon of the pinching down of the distribution of data points at the left of a typical scatter-plot, indicating the presence of significant amounts of cross-talk, is most evident and useful in performing the curve fitting. For distributions in which cross-talk plays a minor role, the scatter of points fits rather well into the more or less parallel diagonal lines at the right, except that the unit slope in the theoretical curves, indicating complete independence, it is not quite matched by the slope of the axis of a typical scatter plot. This smaller slope indicates a correlation in the magnitudes of the A and B vectors even when cross-talk is not a factor. The spread of observed points in these cases indicates that the conditional variance of B is nearly equal to the unconditional variance, which in turn suggests the correlation coefficient is of the order of 0.5 or less. (When the correlation coefficient is 0.5, the conditional variance is 75% of the unconditional variance, i.e., in terms of standard deviation the percentage is 87%.)

A match of probability contours was made with data observed at words no.40, 41, 42, 43, and 44 which are five points covering the specular echo of the transmitted pulse. In each case approximately one thousand data points had been plotted. The results are presented in Figure 5, in which the plot of channel A, reduced by 25½ db is plotted with the mean value of the "independent" component of B as determined by the location of the contours for a best fit. The mean value is derived by adding 2 db to the result obtained when the "axis" of the contours (the 10 db/decade line passing through 0 - 0 in Figure 5) is used with any A ordinate to obtain a corresponding level for A - B. The 2 db is the amount that the mean of the Rayliegh distribution is displaced from σ_x, which corresponds to the "axis" of the contour plot.

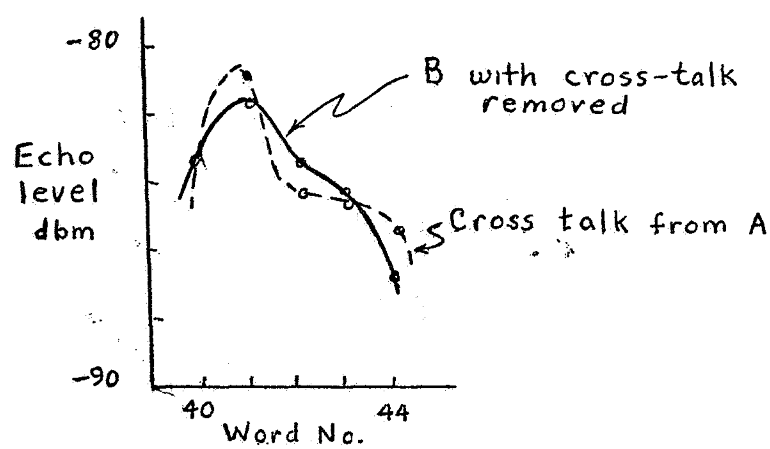


Figure 6

The principal conclusion to be drawn from the waveforms sketched in Figure 6 is that the independent component of B appears to be specular, i.e., a replica of the transmitted pulse, rather than scattered return. The characteristic for the initial build-up in the case of scattered return is a relatively slow-rising leading edge corresponding to the increase in illuminated area as the transmitted pulse reaches the reflection surface and spreads out until, as the trailing edge reaches the surface, the illuminated area becomes an annular ring. This property, i.e., appearing to be specular in nature, argues against a multiple reflection scattering model for this return from vertical incidence. This is consistent with our intuition that the multiple scattering model would not readily account for a cross-polarized component from straight down.

Thus, this analysis leads us to conclude that there is indeed a cross-polarized component, exhibiting specular characteristics, that conceivably could be accounted for by the "conducting grain" model. The case for the conducting grain model is not well established, however, and a search for a better explanation continues to be justified.