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RADAR SPECTRAL MEASUREMENTS OF VEGETATION

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RADAR SPECTRAL MEASUREMENTS OF VEGETATION

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ABSTRACT

4-8 GHz radar backscatter spectral data was gathered during the 1972 growing season at look angles between 0° and 70° and for all four possible polarization linear combinations. The data covers four crop types (corn, milo, alfalfa, and soybeans) and a wide range of soil moisture content. To insure statistical representation of the results, measurements were conducted over 128 fields corresponding to a total of about 40,000 data points. This paper investigates the use of spectral response signatures to separate different crop types and to separate healthy corn from blighted corn.

INTRODUCTION

Radar is unique among the sensors in that it can produce fine resolution images independent of time of day and nearly independent of weather. Furthermore its response is strongly dependent on moisture. Consequently the potential of radar as a vegetation sensor is high, since vegetation sensing is so dependent upon measurements being made at the right time in the growing cycle, and since moisture in plants and soil is so important to vegetation. In spite of this potential, however, radar has not been widely used for agricultural sensing because of a lack of adequate information as to what the radar senses in vegetation and what radar parameters are best for particular agricultural sensing needs.

Operational radar vegetation sensors will certainly use sidelooking radars, and many will use the synthetic aperture technique to obtain fine resolutions not feasible with real-aperture antennas carried on aircraft. Probably such systems will use multi-spectral, multi-polarization techniques in the same way that visible-IR sensors use these techniques for similar purposes—the difference is that the radar will be capable of imaging on demand and of better indications of moisture.

The lack of adequate past information on radar properties of vegetation is in line with the general lack of quantitative information on radar scattering properties¹. In fact, radar measurements of vegetation are more numerous than radar measurements of other earth surfaces, but nearly all the past radar measurements suffer because of limited resolution, or limited angle of incidence, or limited frequency range. Certainly all of them suffer from having been made at single frequencies rather than continuously over bands of frequencies, although several of the previous investigators have used frequency pairs or triads.

The Ohio State University measurements were made under carefully controlled conditions at three frequencies, but the resolvable cell was so small (about 30 cm in diameter) that only the smallest plants could be observed.² Goodyear Aerospace Corporation performed measurements on single-frequency images with realistic resolutions but with a limited range of conditions and incident angles, and with only a single incident angle for each field.³ de Loor in the Netherlands has performed many useful measurements from a TV tower, but the nature of the experiments confines most observations to angles very near grazing, and the fixed position of the equipment along with the monochromatic nature of the illumination made adequate

averaging of the signals difficult.⁴ Measurements were made in the Garden City, Kansas, area using a single frequency imaging radar⁵ and more recently with a dual-frequency imager⁶, but these also suffer from the inherent limitations of angle of incidence common to use of imagers for the fundamental measurements as well as from having been made with single frequencies. The sad state of the available information is highlighted by the frequent references to the data of Grant and Yaplee⁷, whose tri-frequency measurements were made over a short time interval with a radar mounted in a single position on a bridge with all that means in terms of limitations of potential materials and angles of incidence.

Some years ago we recognized that both broadband illumination and multi-spectral data were needed both for research and probably for operational systems⁸. Consequently efforts were started to demonstrate the need for broadband images^{9,10,11} and to develop a system to obtain continuous spectral responses at a wide range of angles of incidence and with multiple polarizations. The first system used a pulse radar, for that could also produce images with broad bandwidths, and observation with this system produced continuous response curves for the small range of objects visible from the system location at the top of a dormitory at Kansas University¹². For field use, however, it was deemed advisable to replace the pulse system with a frequency-modulated system, and the first octave-bandwidth crop responses were made with this system in the summer of 1971¹³.

Unfortunately, calibration of this system was difficult, so the reported responses were on a relative basis; furthermore it did not have the capability to measure cross-polarized returns which the imaging experiments at Garden City had shown to be significant. The system was rebuilt in time to make the observations reported here during the 1972 summer. In addition to these measurements of vegetation, soil moisture measurements were made in the summer of 1972¹⁴. During 1973 the system has been expanded from the original 3.75-7.50 cm spectral region to cover the region 1.67 to 15 cm wavelength.

SCATTERING COEFFICIENTS

The radar return signal from an area-extensive target is described in terms of the differential scattering coefficient σ^0 . This is a property of the area measured, and is only related to the system parameters in that it is a function of wavelength

and polarization, and may be a function of resolution if the resolution is so fine that it cannot encompass several plants at the same time.

The differential scattering coefficient is defined as

$$\sigma_0 = \frac{\text{Power scattered/unit solid angle-unit surface area}}{\text{Power incident/unit area}}$$

This is directly analogous with the optical quantity "bi-directional reflectance distribution function"¹⁵, although for radar the directions of incidence and observation are normally the same. This quantity can be greater than or less than unity depending on the absorption by the surface and the concentration of the reradiated energy; in fact, a specular reflector reradiates into a zero solid angle so these quantities are impulse functions at the specular reflection angle.

The value of differential scattering coefficient depends on both the dielectric properties of the object sensed and its geometry. A material with high dielectric constant or conductivity scatters more strongly in some direction (not necessarily back toward the radar) than one with low dielectric constant and conductivity. If the surface is rough, the scatter is relatively uniform; if it is smooth, most of the energy is scattered near the specular direction. Since the microwave signals penetrate significant distances into vegetation and soil, volume scatter is often as important, or even more so than surface scatter; this is particularly true for plants.

Both soil and plant scattering are strongly dependent on moisture content. The reason is that the dielectric constant of water is an order of magnitude or more higher than that of the dry materials, so the moisture content is the primary determiner of dielectric constant. Carlson¹⁶ demonstrated this for plant material, and Lundien¹⁷ did so for soil. With vegetation this is particularly important for the moisture content is a major constituent of the biomass and plant stresses that one may wish to observe often cause significant reductions in plant moisture content.

OBSERVATIONS

System Description

The 4-8 GHz (7.5-3.75 cm in wavelength) radar system used in this investigation utilizes two parabolic dish antennas mounted parallel on the same platform atop a 23-meter truck mounted boom¹⁸. The average effective illuminated area (over the 4-8 GHz band) varies from about 0.8m² at normal incidence to about 7.1m² at

70° incidence angle. The radar operates in an FM-CW mode producing a return averaged over 400 MHz for each of two orthogonal received polarizations, one of which is the same as that transmitted, by switching polarization ports at the antenna feeds. All switching modes are remotely controlled from the van accompanying the truck-mounted boom; this capability insures that the multi-polarized and multi-frequency data gathered at a given incidence angle are indeed from the same target area.

Spectral Response Data

The mobility of the radar system enabled us to investigate the spectral response of targets of interest under natural conditions. Spectral response data were obtained from corn, alfalfa, soybeans, and milo during August of 1972. Measurements were made at 8 incidence angles between 0° and 70° in 10° steps and for all three polarization modes: horizontal transmit-horizontal receive (HH), vertical transmit-vertical receive (VV), and cross (average of HV and VH). A total of 128 data sets was collected covering a wide range of soil moisture content but a comparatively narrower range of plant moisture content. In an effort to narrow down the number of variables, the data used in this paper will be limited to the "low soil moisture content range", defined for each crop type in Table 1. The soil moisture contents represent the average moisture in the top 5 cm of the soil whereas the plant moisture contents represent the average moisture of the entire plant. In addition to the aforementioned crops, a corn field infested with blight will also be considered.

HH-polarization scattering coefficient spectral responses are shown in Figure 1 for an incidence angle of 30°. The measured values have been normalized (by dividing by an appropriate normalization factor) such that the highest return for the four crops is 1.0, thereby presenting the data in a form analogous to reflectance in the optical region. This procedure has been applied to all subsequent figures. The curves represent visual best fits drawn within $\pm 1\sigma$ bounds. The standard-deviation-to-mean ratio varied between 0.12 and 0.21 for the 30° incidence angle data points (Figures 1 and 2) and 0.08 and 0.16 for the 60° data (Figures 3 through 6).

In addition to magnitude and spectral variation, classification of the four crop types shown in Figure 1 can be further enhanced by adding a third dimension: polarization. Except for alfalfa, the cross polarization spectra (Figure 2) appear to exhibit different shapes from the HH spectra, particularly at the higher end of the 4-8 GHz band. At the higher incidence angles, the magnitudes of the HH scattering coefficient responses of corn, milo and soybeans tend to overlap as

TABLE 1. SUMMARY OF FIELD CONDITIONS

Crop Type	Average Height in Meters	Soil Moisture Content*		Plant Moisture Content*		Number of Data Sets
		Range	Average	Range	Average	
Corn	2.4	7.0-12.2	10.65	332-395	355	18
Corn with Blight	2.4	9.2-12.3	10.75	207-217	212	6
Alfalfa	0.5	9.4-11.7	10.5	247-313	280	6
Soybeans	1.0	7.8- 8.3	8.1	298-314	305	9
Milo	1.0	6.0-10.6	8.2	186-224	203	10

* % by dry weight.

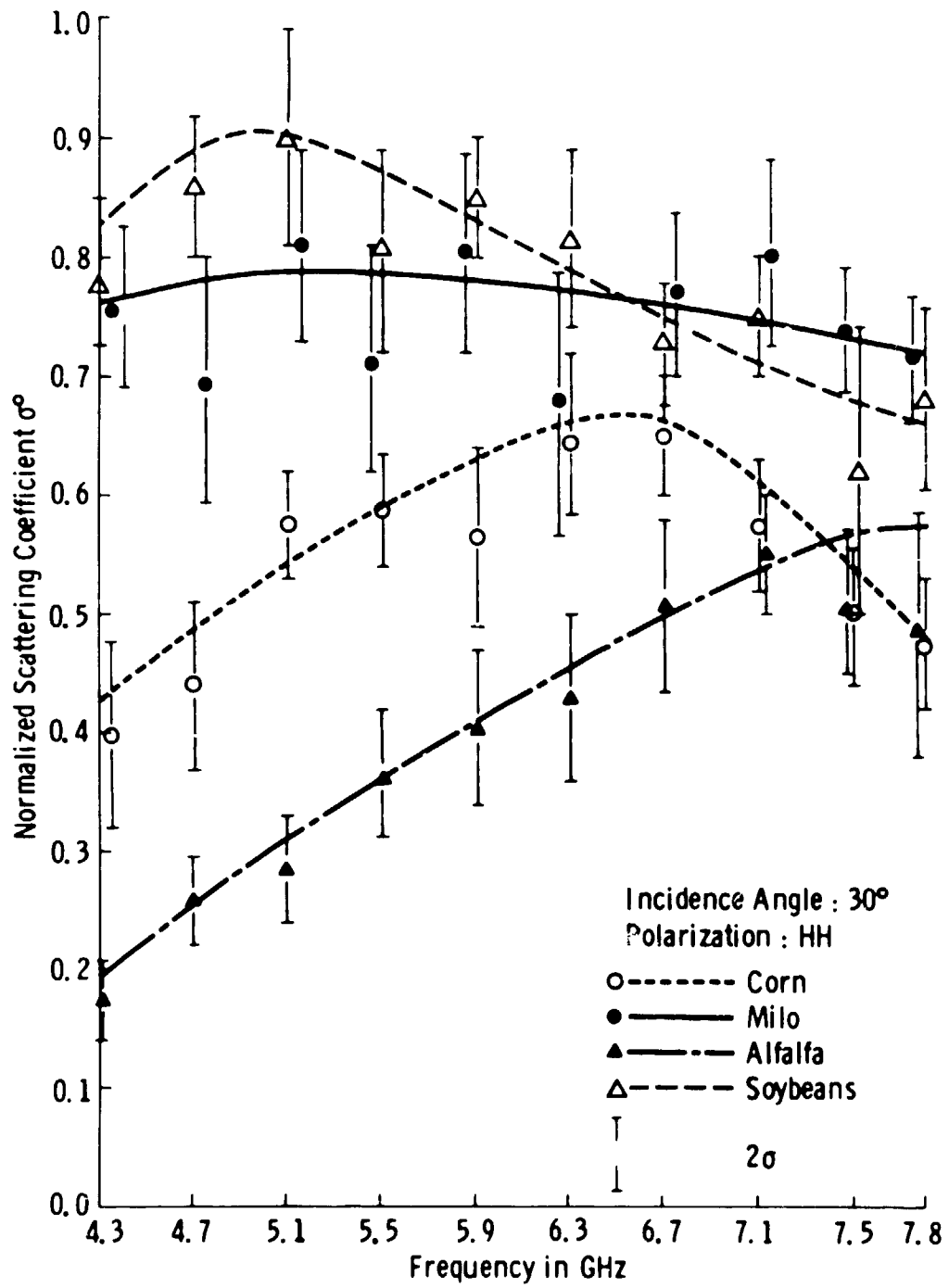


FIGURE 1. NORMALIZED SPECTRAL RESPONSE CURVES.
(Normalization factor = 0.516)

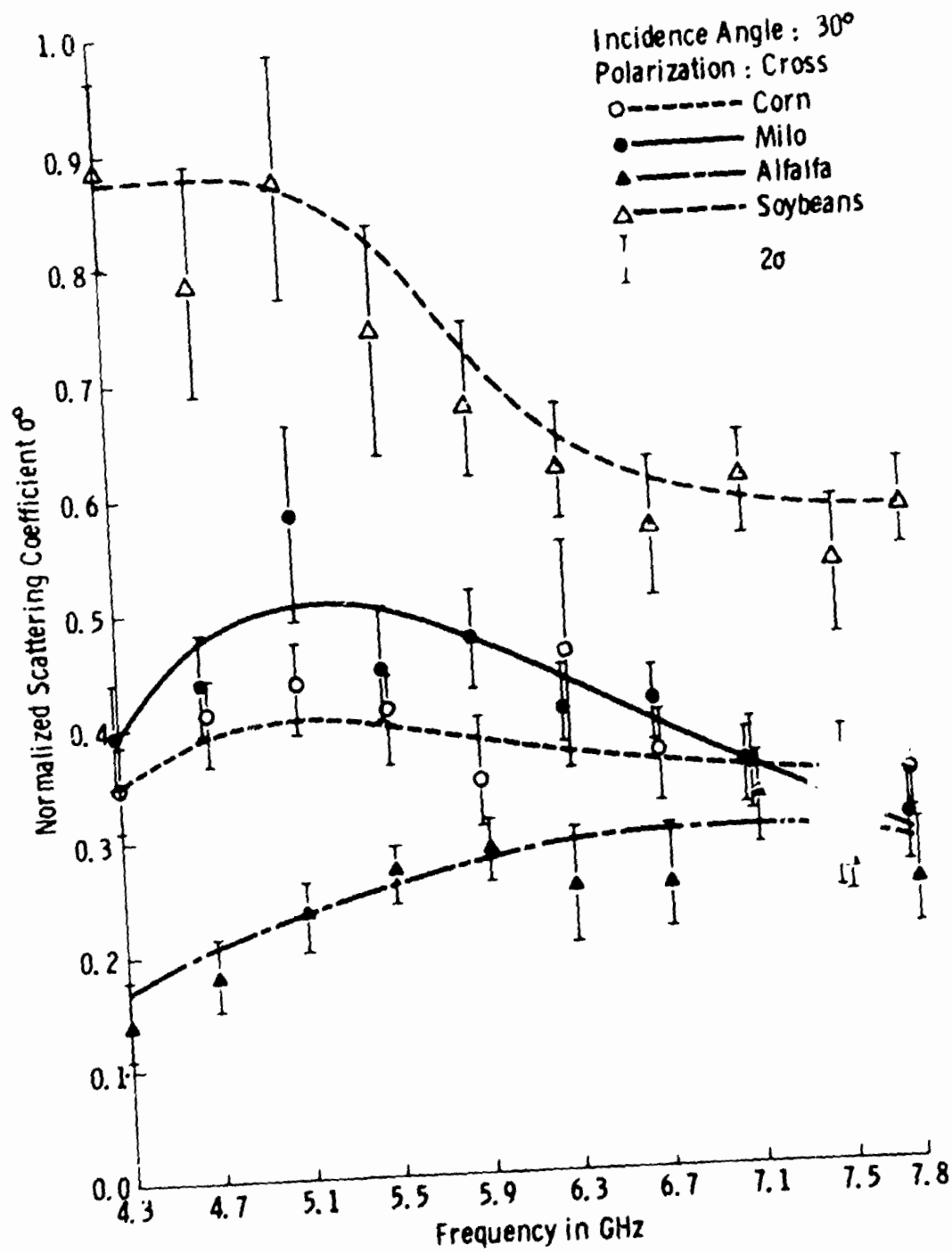


FIGURE 2. NORMALIZED SPECTRAL RESPONSE CURVES.
(Normalization factor = 0.118)

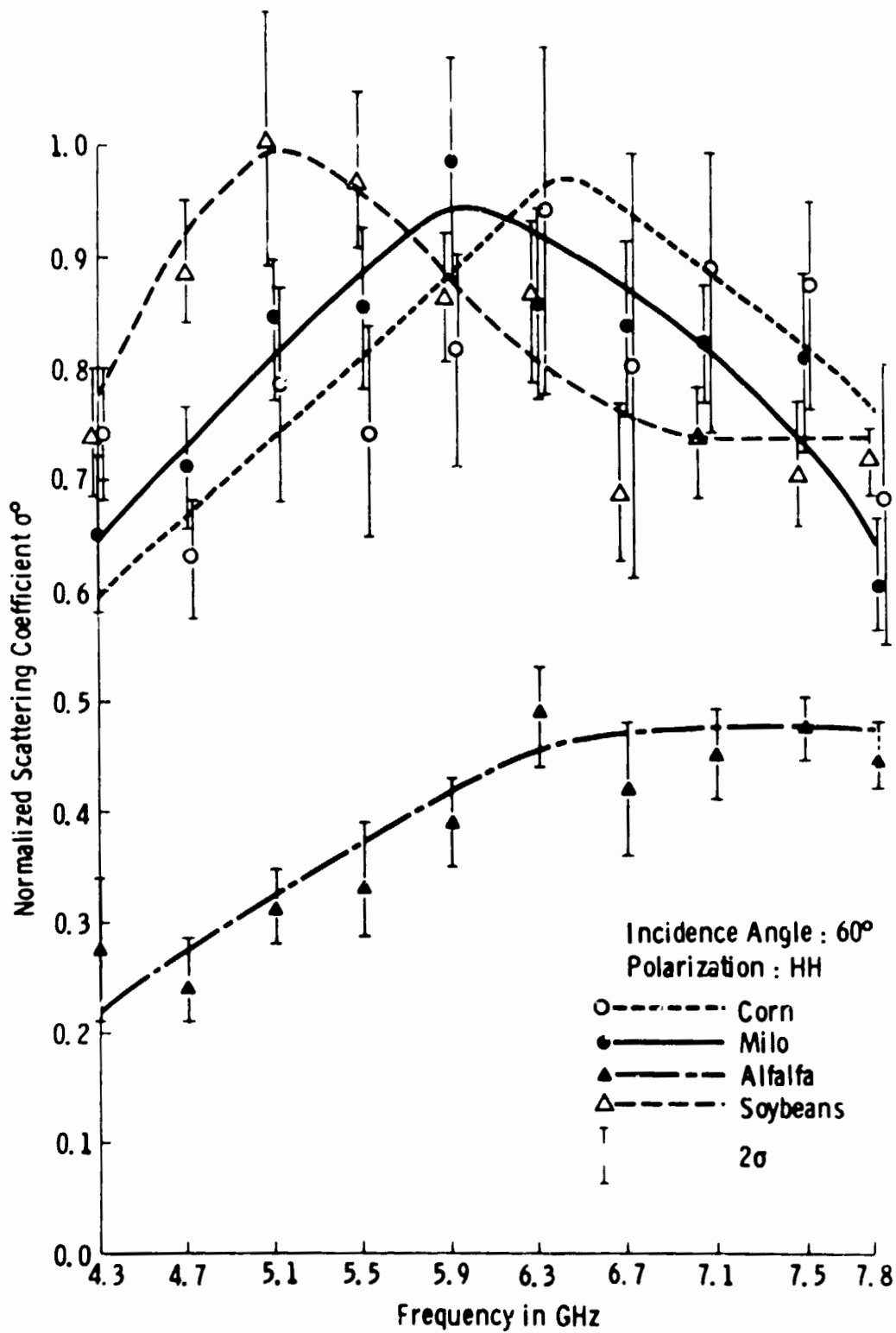


FIGURE 3. NORMALIZED SPECTRAL RESPONSE CURVES.
(Normalization factor = 0.23)

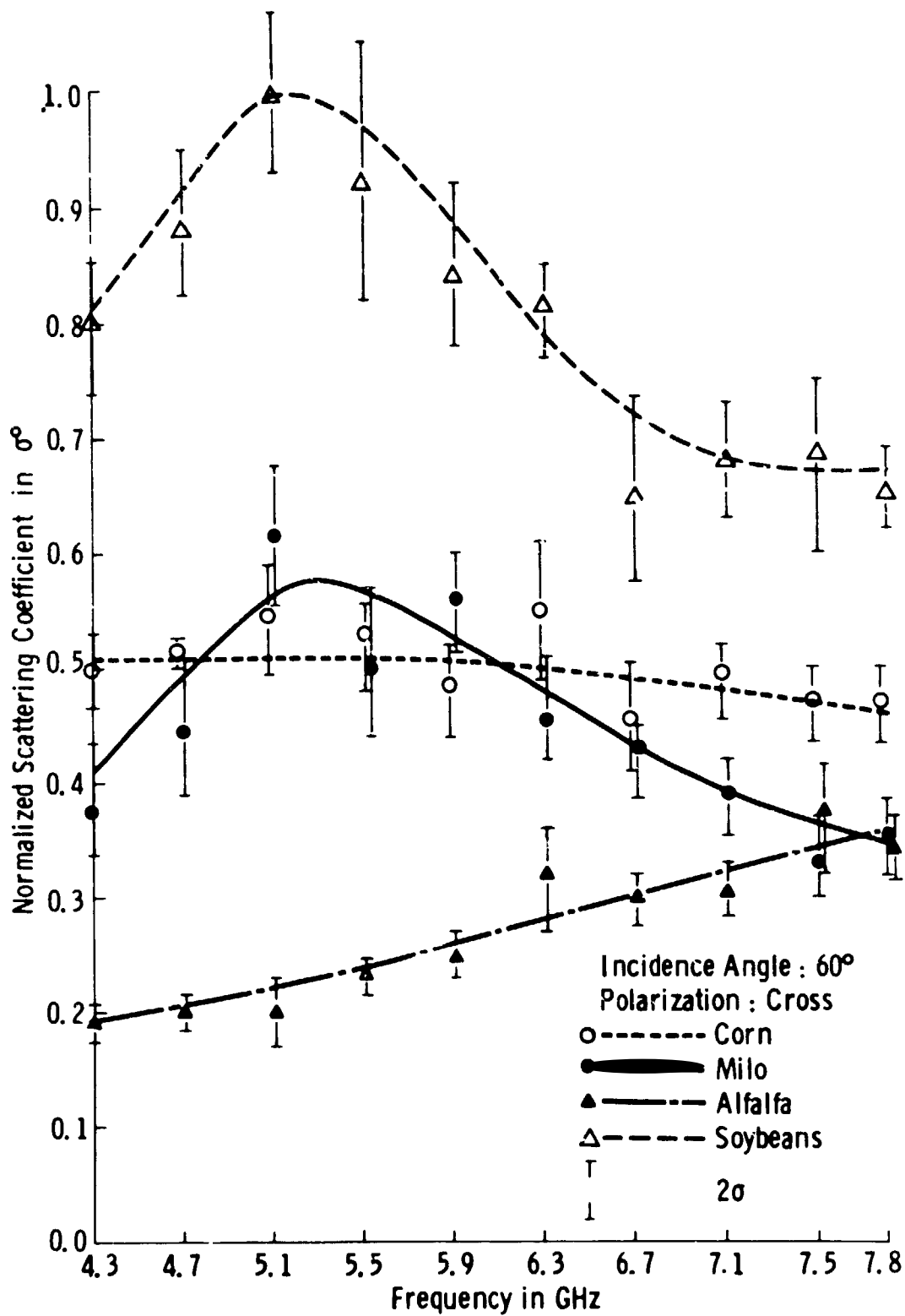


FIGURE 4. NORMALIZED SPECTRAL RESPONSE CURVES.
(Normalization factor = 0.08)

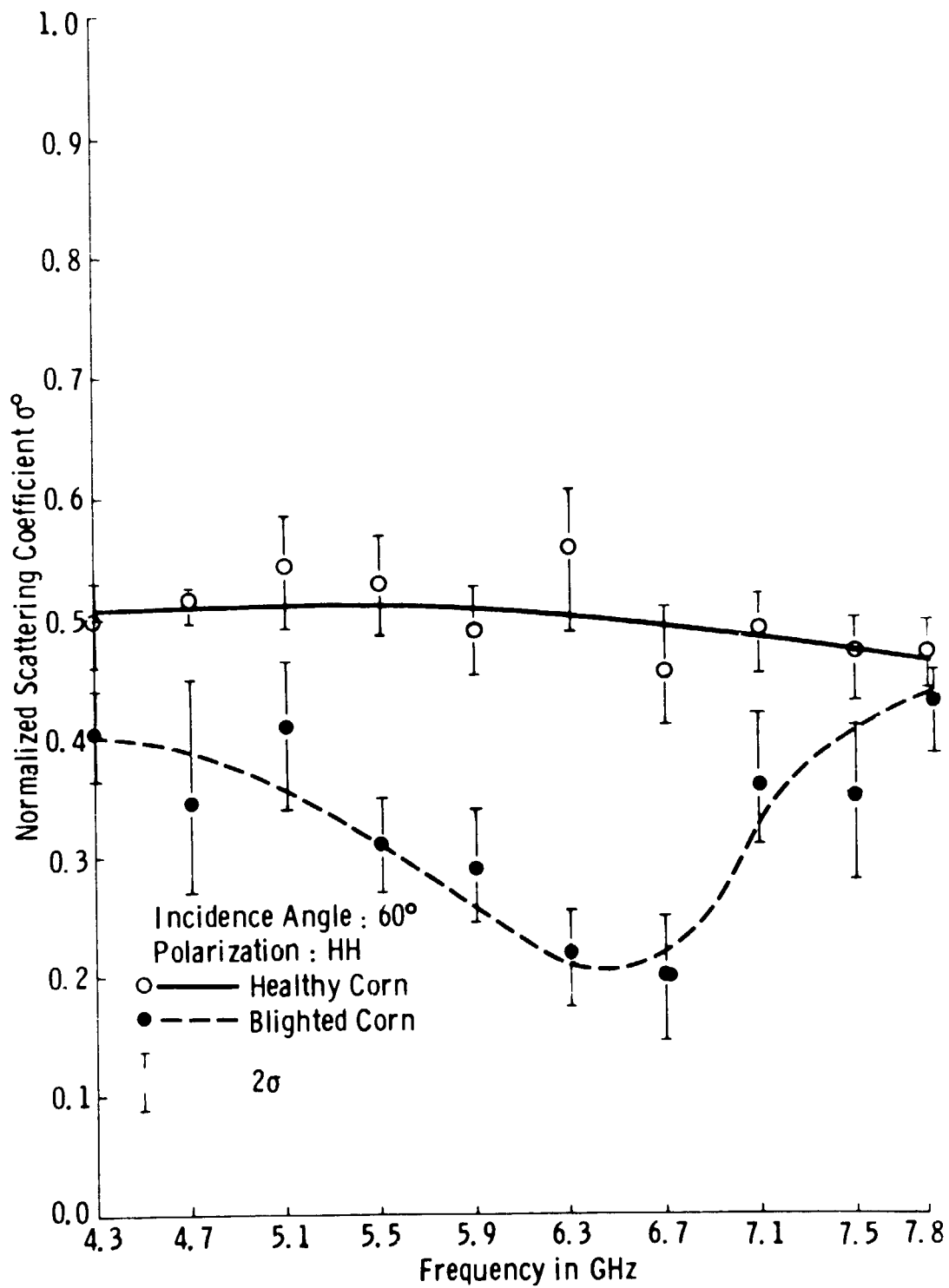


FIGURE 5. NORMALIZED SPECTRAL RESPONSE CURVES.
(Normalization factor = 0.23)

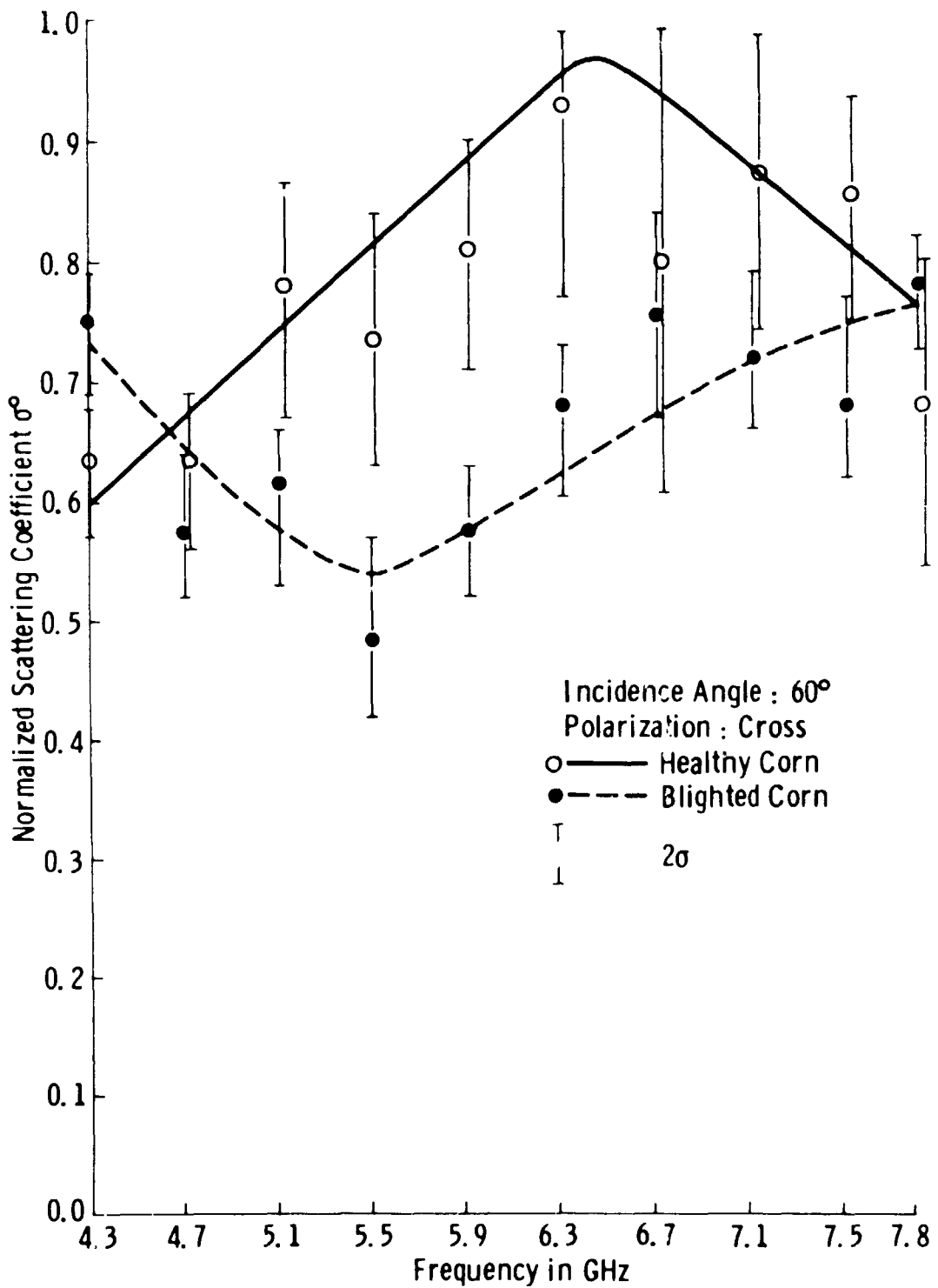


FIGURE 6. NORMALIZED SPECTRAL RESPONSE CURVES.
(Normalization factor = 0.08)

evidenced in Figure 3 at an incidence angle of 60° . The cross polarization spectra (Figure 4), on the other hand, clearly illustrates how soybeans can be separated from corn and milo. As would be expected, corn and milo are the most difficult to separate of the four categories since their geometries (except for height) are the most similar.

Using the same normalization factors employed in Figures 3 and 4, the 60° spectra of healthy and blighted corn are compared in Figures 5 and 6 for HH and cross polarizations, respectively. The difference in magnitude can be attributed to differences in plant moisture content, which in turn is related to the blight.

Color Combination Technique

The observations were combined to produce "radar color". For each angle and polarization the normalized spectral response curves (like those shown in Figures 1-4) were divided into three equal sub-bands. The calculated average scattering coefficients over the three sub-bands were then used to set the intensity-levels of a three-beam color combiner. The low, medium and high frequency sub-bands were assigned to the red, green, and blue beams, respectively. The color signature of the four crop types were then grouped by look angle and polarization. The test was repeated for three data groupings corresponding to low, medium and high soil moisture contents (13%, 13.1-23%, and 23.1% by dry weight). The soil moisture ranges were chosen such that the distribution of gathered data sets over the three moisture ranges is approximately even for each crop type. The following results were obtained:

- a) For each moisture range, the combination of color intensity and hue can separate all four crop categories at all angles of incidence between 0° and 70° if a combination of HH or VV polarization and cross polarization is used. In general VV appears to exhibit greater differences than HH. Between 50° and 70° , hue appears to be the same for corn and milo and the difference in intensity is small; in several cases the two crops could only be separated by a light meter pointed at the color combiner screen.
- b) A comparison of the color signatures (for each crop, angle, and polarization) corresponding to the three soil moisture ranges indicates a wide range of variations in hue and intensity at 0° - 20° incidence angles, a slight change in hue (increase in the red band intensity as

the soil moisture is increased) at 30° and only minor changes in either hue or intensity at the higher angles.

- c) The optimum incidence angles for separating healthy corn from blighted corn are 40° - 60° . Over this range of angles it appears easier to separate healthy corn from blighted corn than from milo!

CONCLUSIONS

Classification of crop types can be greatly enhanced through the use of dual polarization octave band spectral data. For the crops tested the combination of VV and cross polarizations yield the best results. Being highly sensitive to soil moisture, the interfering radar return component from the underlying soil limits the use of radar crop identification to incidence angles larger than about 30° . Among the four crop types, alfalfa is the easiest to distinguish from the rest at almost any frequency and polarization due to its consistently smaller scattering coefficient. The combination of either VV or HH and cross polarizations can distinguish soybeans from milo and corn at all incidence angles greater than 30° . Corn and milo are best separated using VV and cross polarizations at 30° and 40° and only slight differences in intensity can separate them at 50° - 70° . Separation of healthy corn from blighted corn is best achieved in the 40° - 60° angular range. These conclusions only apply for this spectral region. Since imaging radars in common use have shorter wavelengths, conclusions for them might be different.

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