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June 1983

SEPARABILITY OF AGRICULTURAL CROPS WITH AIRBORNE SCATTEROMETRY

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16. Abstract Crop identification is an essential element of renewable resources remote sensing. Scientists have devoted much effort to crop discrimination with optical (visible and near-infrared) sensors, especially using spaceborne scanners. Other parts of the electromagnetic spectrum remain mostly unexplored in agricultural remote sensing. The goal of the present work is to assess the capability of microwave remote sensors to discriminate between crop classes.

Backscattering measurements were acquired with airborne scatterometers over a site in Cass County, North Dakota on four days in the 1981 crop growing season. Data were acquired at three frequencies (L-, C- and Ku-bands), two polarizations (like and cross) and ten incidence angles (5 degrees to 50 degrees in 5 degree steps). Crop separability is studied in an hierarchical fashion. A two-class separability measure is defined, which compares within-class to between-class variability, to determine crop separability.

The scatterometer channels with the best potential for crop separability are determined, based on this separability measure. Higher frequencies are more useful for discriminating small grains, while lower frequencies tend to separate non-small grains better. Some crops are more separable when row direction is taken into account. The effect of pixel purity is to increase the separability between all crops while not changing the order of useful scatterometer channels. Crude estimates of separability errors are calculated based on these analyses. These results are useful in selecting the parameters of active microwave systems in agricultural remote sensing.

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Row direction
Pixel Purity

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WITH AIRBORNE SCATTEROMETRY

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June, 1983

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ABSTRACT

Crop identification is an essential element of renewable resources remote sensing. Scientists have devoted much effort to crop discrimination with optical (visible and near-infrared) sensors, especially using spaceborne scanners. Other parts of the electromagnetic spectrum remain mostly unexplored in agricultural remote sensing. The goal of the present work is to assess the capability of microwave remote sensors to discriminate between crop classes.

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separability errors are calculated based on these analyses. These results are useful in selecting the parameters of active microwave systems in agricultural remote sensing.

INTRODUCTION

The ultimate goal of agricultural remote sensing is to estimate the production of crops on a regional as well as global basis. The ingredients of crop production estimates are the areal extent of planted crops and the crop yield (production per unit area). Identification of individual crops is an important facet of crop yield estimation. Much effort has been devoted to crop discrimination over the last decade or so.

The optical portion of the electromagnetic spectrum (visible, near- and mid-infrared) has received much of the attention. Various forms of optical sensors (multispectral cameras, visible and infrared radiometers, mechanical scanners) have been used from a variety of platforms (ground, helicopter, aircraft and spacecraft). A systematic program of ground truth collection has also been conducted for the past few years. Separability between two sufficiently dissimilar crops (corn and soybeans) has been fairly successful with optical data, albeit using a full season's worth of observations. However, discrimination between two similar crops (wheat and barley) has not been achieved with sufficient precision or accuracy.

Radio waves are generally recognized as a promising tool in crop separability, though very little research has been done in this area. In general, optical sensors respond to differences in the dielectric constant of crop canopies (water content, amount of chlorophyl), whereas active microwave sensors are affected by structural and architectural attributes of crop canopies, in addition to their electrical properties. This may be an advantage in using an active microwave sensor to discriminate agronomically similar vegetation canopies, compared to optical remote sensors. This hypothesis remains to be tested in a controlled experimental environment.

The purpose of the present research is to investigate the ability of active microwave remote sensors to accurately discriminate between agricultural crops. Specifically, we want to assess the usefulness of a multifrequency, multipolarization, multiangle airborne non-imaging radar system for crop separability. Our goal is to empirically determine the microwave sensor parameters most useful in crop separability, rather than an understanding of the physical interaction of microwave radiation with vegatation canopies.

DATA ACQUISITION

Scientists at NASA/Johnson Space Center conducted a remote sensing experiment in the summer of 1981 over an AgRISTARS supersite in Cass County, North Dakota. Data were acquired on four days in 1981 (June 3, June 24, July 16 and September 1) from a C-130 aircraft operated by NASA/JSC. The airborne sensor complement included three cw radar scatterometers operating simultaneously at 1.6 GHz (L-band), 4.75 GHz (C-band) and 13.3 GHz (Ku-band). Measurements were made at both like (HH) and cross (HV) polarizations at two lower frequencies (L- and C-bands) and at only like (VV) polarization for Ku-band. Multiangle measurements were made at ten incidence angles from 5 degrees to 50 degrees in 5 degree steps.

Simultaneous colour IR photographs were taken from the same C-130 platform. Periodic ground truth was collected by the US Department of Agriculture enumerators throughout the 1981 growing season. Agronomic characteristics such as canopy height, crop growth stage, and ground cover type and amount were among the ground truth gathered. Table 1 lists the ground cover types and their proportions within the Cass County site on each of the four days during the 1981 growing season.

The airborne sensors were flown on seven flight lines covering the test site on each of the four days. The aircraft navigational parameters (altitude, speed, heading, roll, yaw, pitch) were recorded on all flights. Though aware of the effects of these aircraft state parameters on the locations of radar

TABLE 1

GROUND COVER CLASSES

NUMBER OF PIXELS

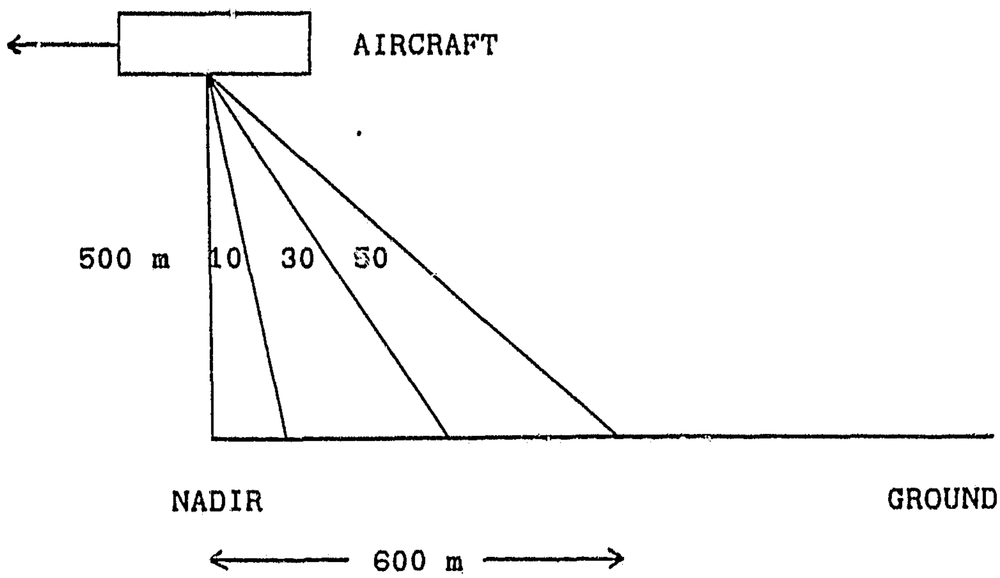
CLASS	DAY 1	2	3	4
Total	1043	1141	1121	1027
Non-Crops (NC)	212	50	49	539
Crops (C)	831	1091	1072	488
Small Grains (SG)	538	626	616	91
Barley (BR)	132	172	169	-
Durum Wheat (DW)	171	198	201	7
Oats (OA)	38	42	41	41
Spring Wheat (SW)	197	214	205	43
Non-Small Grains (NSG)	293	465	456	397
Dry Beans (DB)	25	63	65	66
Sugarbeets (SB)	110	165	170	147
Soybeans (SO)	52	102	94	67
Sunflower (SU)	106	135	127	117

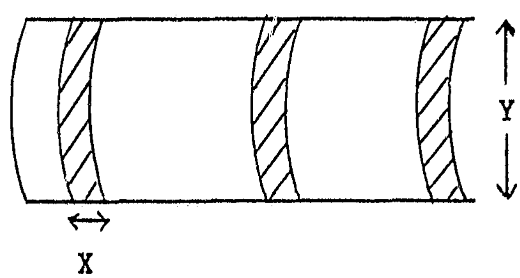
footprints at various incidence angles, we have assumed the aircraft to be flying at a constant altitude of 460 meters with a constant velocity (speed of 77 meters per second) and with no changes in attitude. This means that radar footprints at all angles are assumed to fall on the aircraft ground track behind the aircraft nadir.

PREPROCESSING

For the 1981 Cass County experiment, the scatterometer data preprocessing was performed by the NASA/JSC Experiment Systems Division. The scatterometers operated simultaneously at three frequencies and at both like and cross polarizations. Measurements at different incidence angles were obtained by dividing the instantaneous antenna footprint into ten sectors corresponding to ten incidence angles and calculating the radar backscatter in each of the sectors by Doppler filtering. Radar backscatter measurements were temporally (thus spatially for a moving platform) averaged such that we have a data point every 0.5 second along the flight line. For a moving sensor, the same location on ground is viewed at different times along the flight line for different incidence angles. Thus measurements at different angles were temporally adjusted so that they all refer to same spot on the ground at a given time. Figure 1 shows a sketch of the Doppler filtering concept and size of radar footprint on ground for the three scatterometers.

In order to determine radar signature of any of the ground cover classes, one has to know ground coordinates of radar footprints. This was done by photointerpreting low-altitude colour IR photographs. Using these photographs, each footprint was assigned to an agricultural field within the site. Then, from the USDA gathered in-situ information, a field number and a crop identification code were assigned to each footprint. Some of these footprints contain more than one ground cover class. For





SCATTEROMETER FOOTPRINT

FREQUENCY	X	Y
L	40 m	70 m
C	40 m	35 m
Ku	40 m	22 m

FIGURE 1

example, near a field boundary along a flight line, a part of a footprint may be in one field with one crop, while the rest may be in the next field with another crop class, resulting in what is known as a boundary or mixed pixel. To crudely identify these mixed pixels, distances were measured on colour IR photographs from the footprint center to the nearest boundary in both along track (east-west) and across track (north-south) directions. These distances, dubbed pixel purity measures, are used to determine the purity of a radar footprint and as a means of discarding the impure ones. (Note that the words radar footprint and pixel have been interchangeably used throughout this paper).

The result of scatterometer preprocessing is a computerized file containing radar backscattering coefficients, sigma0, with each footprint denoted by a time tag, field number, crop identification code (listed in Table 1), row direction (EW or NS) and pixel purity measures (defined above). The data set includes radar measurements at five frequency/ polarization combinations (L HH, L HV, C HH, C HV and K VV) and ten incidence angles, giving 50 scatterometer channels. A typical channel is denoted by C HV 35 (C-band, cross polarization at 35 degrees incidence angle) in rest of this report. It is to be noted that we have discarded scatterometer measurements at 5 degree incidence angle from the outset. As radar backscatter at very small incidence angle may not be calculated accurately with the Doppler filtering technique, we excluded the five scatterometer channels at 5 degree incidence angle (L HH 5, L HV 5, C HH 5, C

HV 5 and K VV 5) from further analysis. Thus we effectively have 45 scatteometer channels at our disposal.

In order to demonstrate the quality of the scatterometer data and to see whether there are any qualitative differences in the microwave signatures for different ground cover classes, one can look at sigma0 as a function of time for various scatterometer channels. An example is shown in Figure 2, where sigma0 is plotted against time for a set of incidence angles for K VV for one flight line on Day 3. Field boundaries are evident at most incidence angles and sigma0 values vary for different crops, indicating that various crops do indeed respond differently to microwave remote sensors.

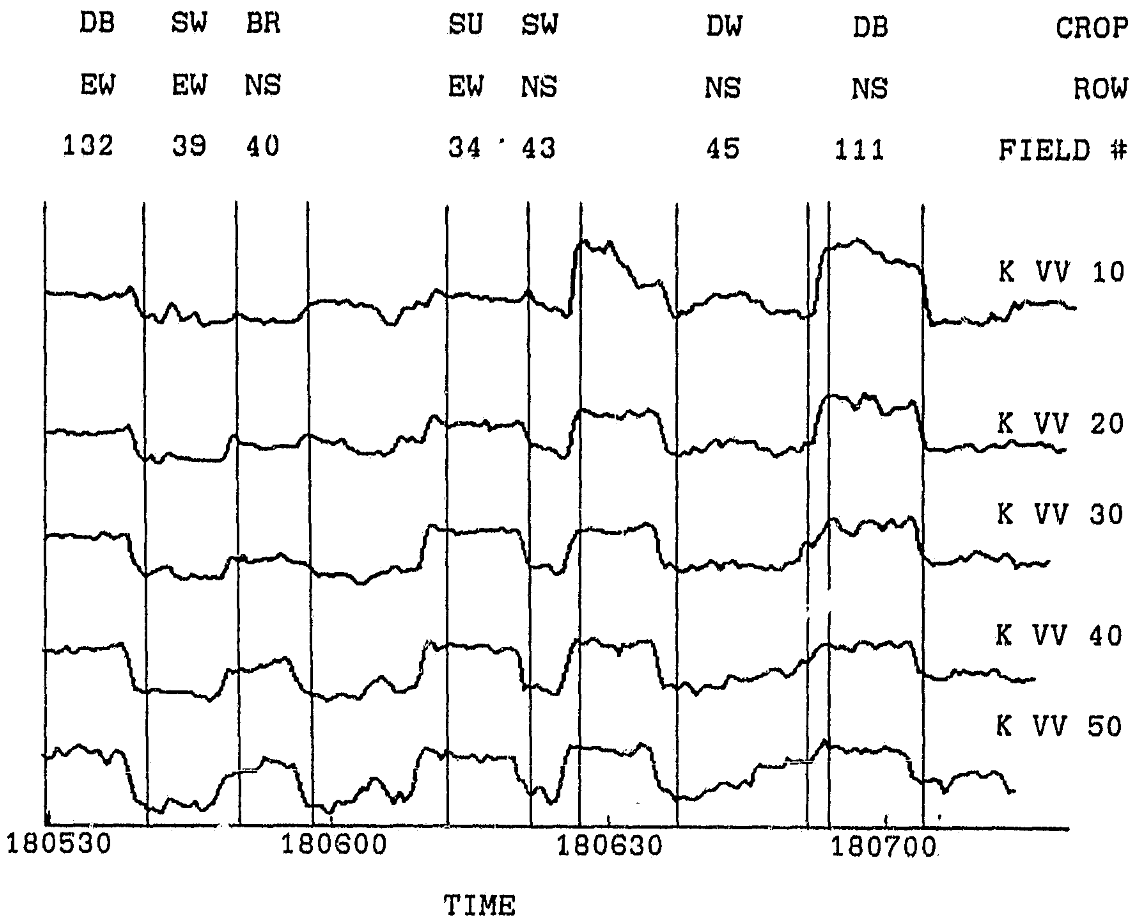

DB SW BR SU SW DW DB CROP
EW EW NS EW NS NS NS ROW
132 39 40 34 43 45 111 FIELD #
K VV 10
K VV 20
K VV 30
K VV 40
K VV 50
180530
180600
180630
180700
TIME

FIGURE 2

DATA ANALYSIS

The ground cover separability is studied in a hierarchical fashion, as shown in Figure 3. A hierarchical separability tree is a representation in which one separates classes at progressively more detailed levels. For example, one has to first separate crops from non-crops, after which one can separate small grains from non-small grains, barley from wheat and finally two kinds of wheat from each other. We have chosen to study eleven two-class pairs from this hierarchical separability tree, as listed in Table 2. These pairs cover all levels of the separability tree. We also selected one day (out of the four experimetal days in 1981) for each pair on the following grounds. It is evident from USDA ground truth that Day 1 was very close to planting of non-small grains and that by Day 4, most small grains were already harvested. There are very few data points on Day 3 for the non-crop class, as seen from Table 1. Thus we have selected Day 1 for small grains/non-crops, Day 4 for non-small grains/non-crops, Days 2 and 3 for small grains/non-small grains, Day 3 for all pairs containing small grains, and Day 4 for all pairs involving non-small grains.

PRELIMINARY ANALYSIS

To obtain an indication of separability of various ground cover classes using radar measurements, we can examine sigma0 distribution in a scatterometer channel. The overall sigma0 distribution for K VV 10 is shown in Figure 4 in the form of a histogram of individual footprints. Two additional

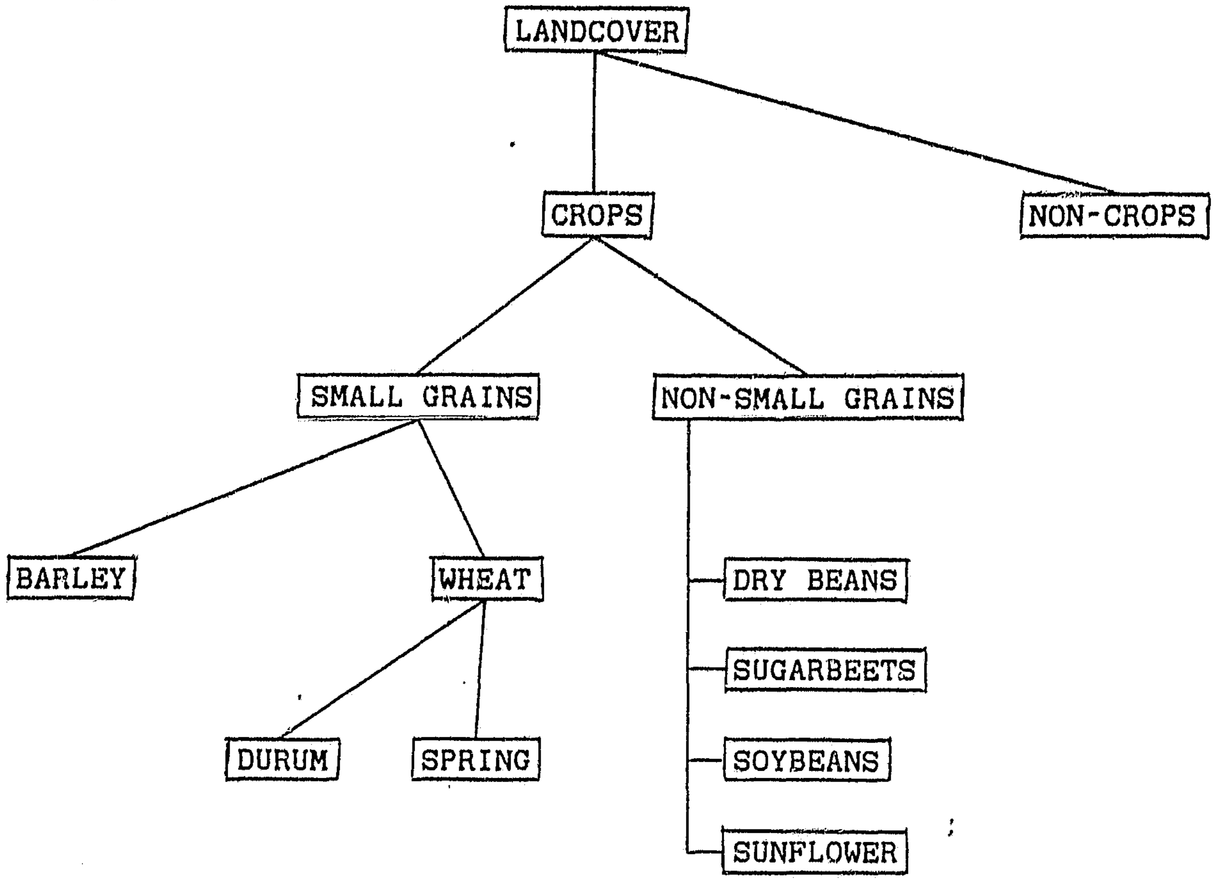

LANDCOVER
CROPS
NON-CROPS
SMALL GRAINS
NON-SMALL GRAINS
BARLEY
WHEAT
DURUM
SPRING
DRY BEANS
SUGARBEETS
SOYBEANS
SUNFLOWER

FIGURE 3

TABLE 2

TWO-CLASS SEPARABILITIES

Small Grains/Non-Crops	SG/NC	Day 1
Non-Small Grains/Non-Crops	NSG/NC	Day 4
Small Grains/Non-Small Grains	SG/NSG	Day 3
Barley/Wheat	BR/Wheat	Day 3
Durum Wheat/Spring Wheat	DW/SW	Day 3
Dry Beans/Sugarbeets	DB/SB	Day 4
Dry Beans/Soybeans	DB/SO	Day 4
Dry Beans/Sunflower	DB/SU	Day 4
Sugarbeets/Soybeans	SB/SO	Day 4
Sugarbeets/Sunflower	SB/SU	Day 4
Soybeans/Sunflower	SO/SU	Day 4

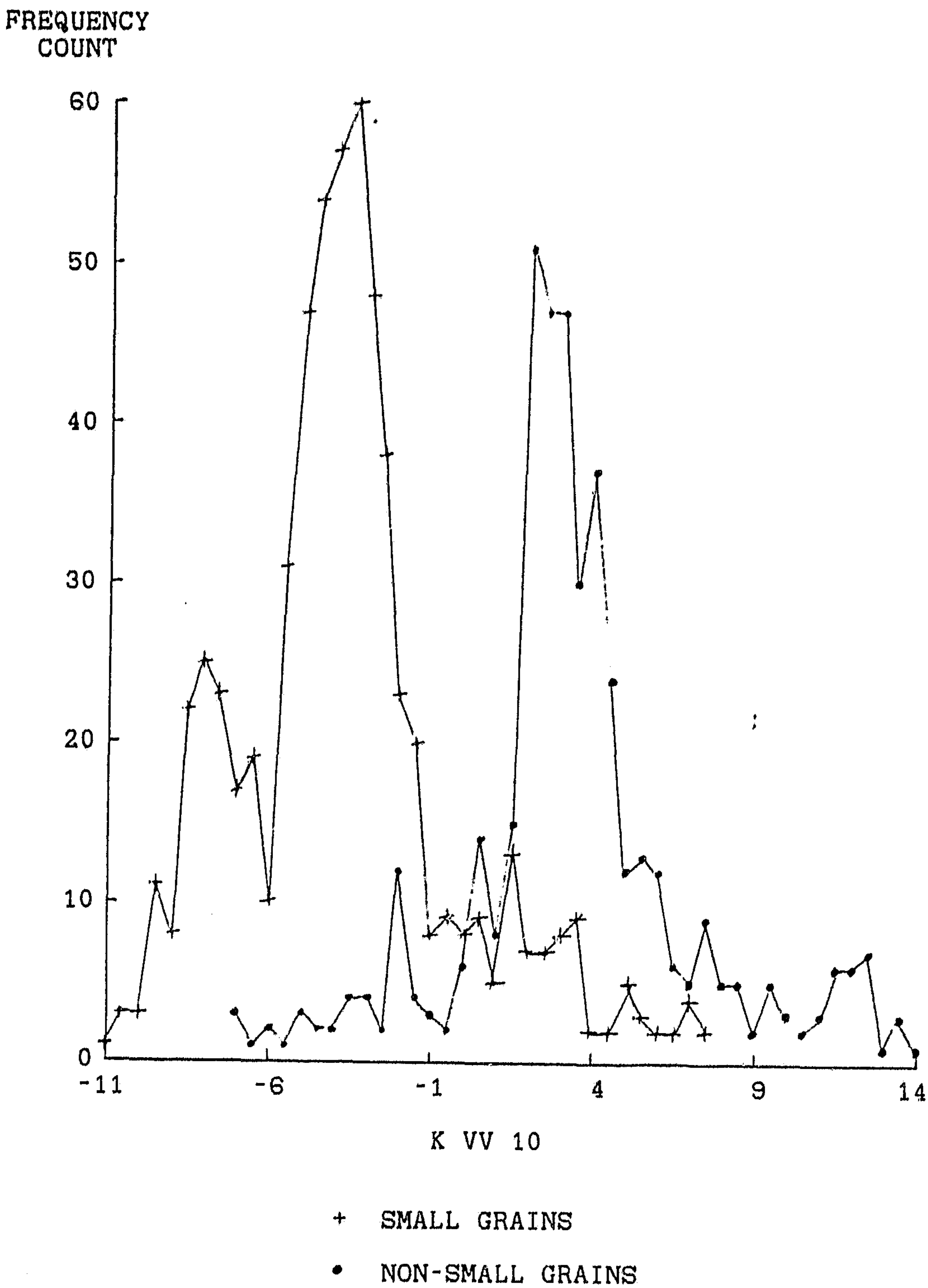

FREQUENCY
COUNT
60
50
40
30
20
10
0
-11
-6
-1
4
9
14
K VV 10
+ SMALL GRAINS
• NON-SMALL GRAINS

FIGURE 4

distributions for small grains and non-small grains are also shown. An alternate way of displaying the same qualitative assessment of ground cover separability is a two-channel scatter plot. An example is shown in Figure 5, where field averages of scatterometer backscatter in channels K VV 10 and C HH 50 are plotted. Field averages are categorized in four major classes of small grains EW, small grains NS, non-small grains EW and non-small grains NS. It is clear from Figures 4 and 5 that scatterometer channel K VV 10 can separate small grains from non-small grains rather well. Furthermore, Figure 5 shows no indication of row direction difference in either crop class for K VV 10. Figure 6 presents a similar scatter plot of L HH 10 vs C HH 50 for the same four major classes. It is seen that row direction is discernible in L HH 10, but not the crop classes of small grains and non-small grains.

This sort of qualitative examination of histograms and scatter plots for all 45 scatterometer channels was made for the four major classes of small grains EW and NS, and non-small grains EW and NS. As already demonstrated, some scatterometer channels are capable of separating crop classes, while others can discriminate between row directions. These observations are summarized in Table 3, which lists qualitative assessment of small grains/non-small grains separability and row direction separability for 15 scatterometer channels for all four days. Lower frequencies (L- and C-bands), like polarization (HH) and low incidence angles (10-30 degrees) seem to discriminate between row directions of planted crops, whereas good crop

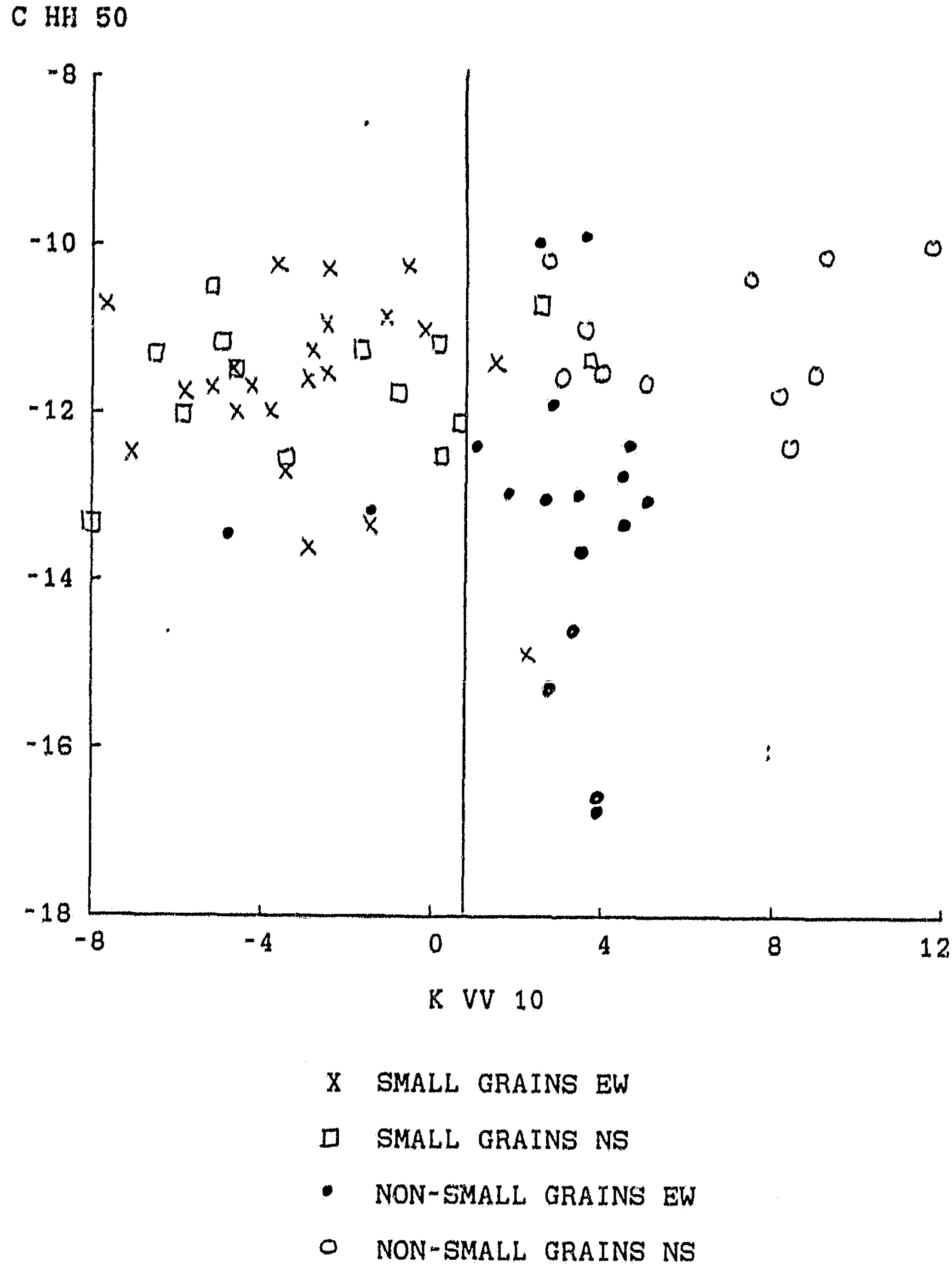
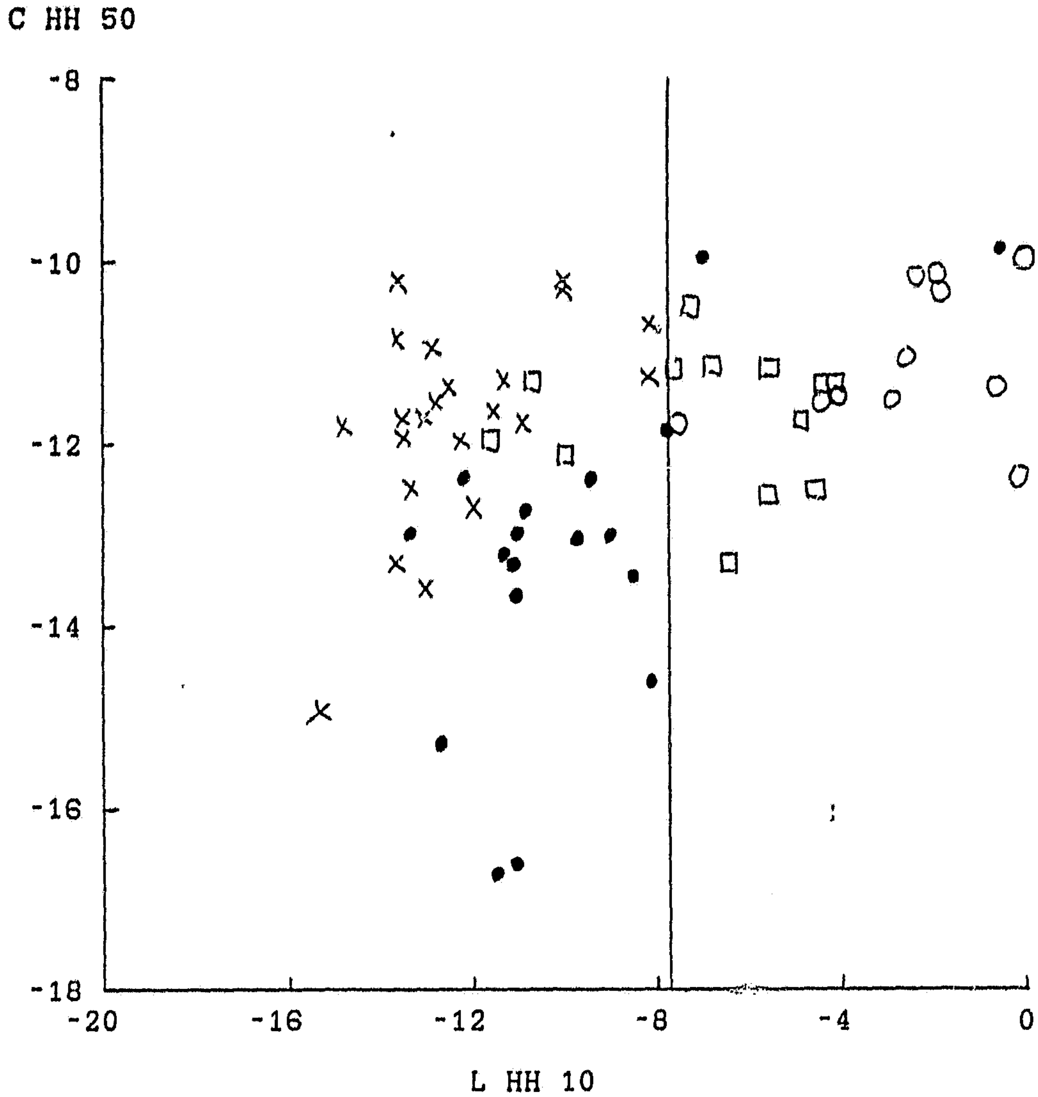

C HH 50
-8
-10
-12
-14
-16
-18
-8
-4
0
4
8
12
K VV 10
X SMALL GRAINS EW
□ SMALL GRAINS NS
• NON-SMALL GRAINS EW
○ NON-SMALL GRAINS NS

FIGURE 5



X SMALL GRAINS EW

□ SMALL GRAINS NS

• NON-SMALL GRAINS EW

○ NON-SMALL GRAINS NS

FIGURE 6

TABLE 3

QUALITATIVE GROUND COVER SEPARABILITY

CHANNEL	SMALL GRAINS/NON-SMALL GRAINS				ROWS EW/NS			
Day	1	2	3	4	1	2	3	4
L HH 10	P	P	P	-	G	F	F	G
L HH 30	P	P	P	-	F	F	F	P
L HH 50	P	P	P	-	P	P	P	P
L HV 10	P	P	P	-	P	P	P	P
L HV 30	P	P	P	-	P	P	P	P
L HV 50	P	P	P	-	P	P	P	P
C HH 10	P	P	P	-	G	F	F	P
C HH 30	P	P	P	-	F	F	P	P
C HH 50	P	P	P	-	P	P	P	P
C HV 10	G	P	P	-	P	P	P	P
C HV 30	G	P	P		P	P	P	P
C HV 50	G	P	P	-	P	P	P	P
K VV 10	G	F	F	-	P	P	P	P
K VV 30	G	P	P	-	P	P	P	P
K VV 50	P	P	P	-	P	P	P	P

P - Poor

F - Fair

G - Good

separability is achieved at all angles for C HV and for small incidence angles for K VV.

TWO-CLASS SEPARABILITY MEASURE

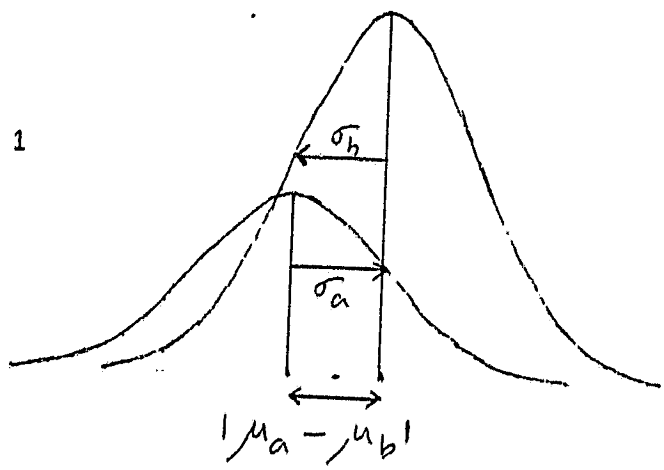
In order to conduct a more quantitative appraisal of the capability of microwave remote sensors for crop separability, we define a two-class separability measure S as

$$S = \frac{|\mu_a - \mu_b|}{\sigma_a + \sigma_b},$$

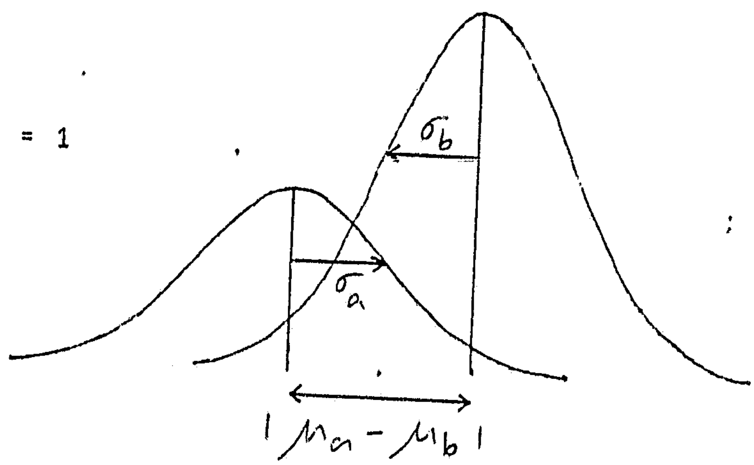
where μ_a, μ_b are means of classes a,b and σ_a, σ_b are standard deviations of classes a,b. The separability measure compares the between-class variability (numerator) to the within-class variability (denominator) for a given data set. Figure 7 sketches the range of S for crop classes with normal (Gaussian) distributions. Clearly higher values of S indicate better separability between two classes.

An appropriate way to judge crop discrimination is to look at separability measures for all 45 channels. Figures 8 to 19 show angular behavior of S for the eleven two-class pairs. Figure 8 gives the small grains/non-crops separability measures, where C HV seems to give best separability at all angles. In addition, C HH and K VV do well at large angles, while L-band seems less useful in separating these two classes. Figure 9 shows separability measures for non-small grains/non-crops. Again, C HV performs well at all angles and C HH at incidence angles greater than 20 degrees. But K VV approaches C-band separability

S < 1



S = 1



S > 1

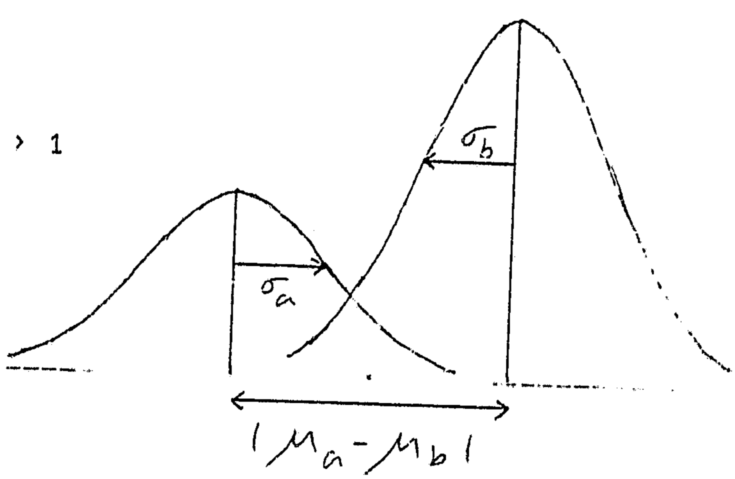


FIGURE 7

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SMALL GRAINS/NON-CROPS

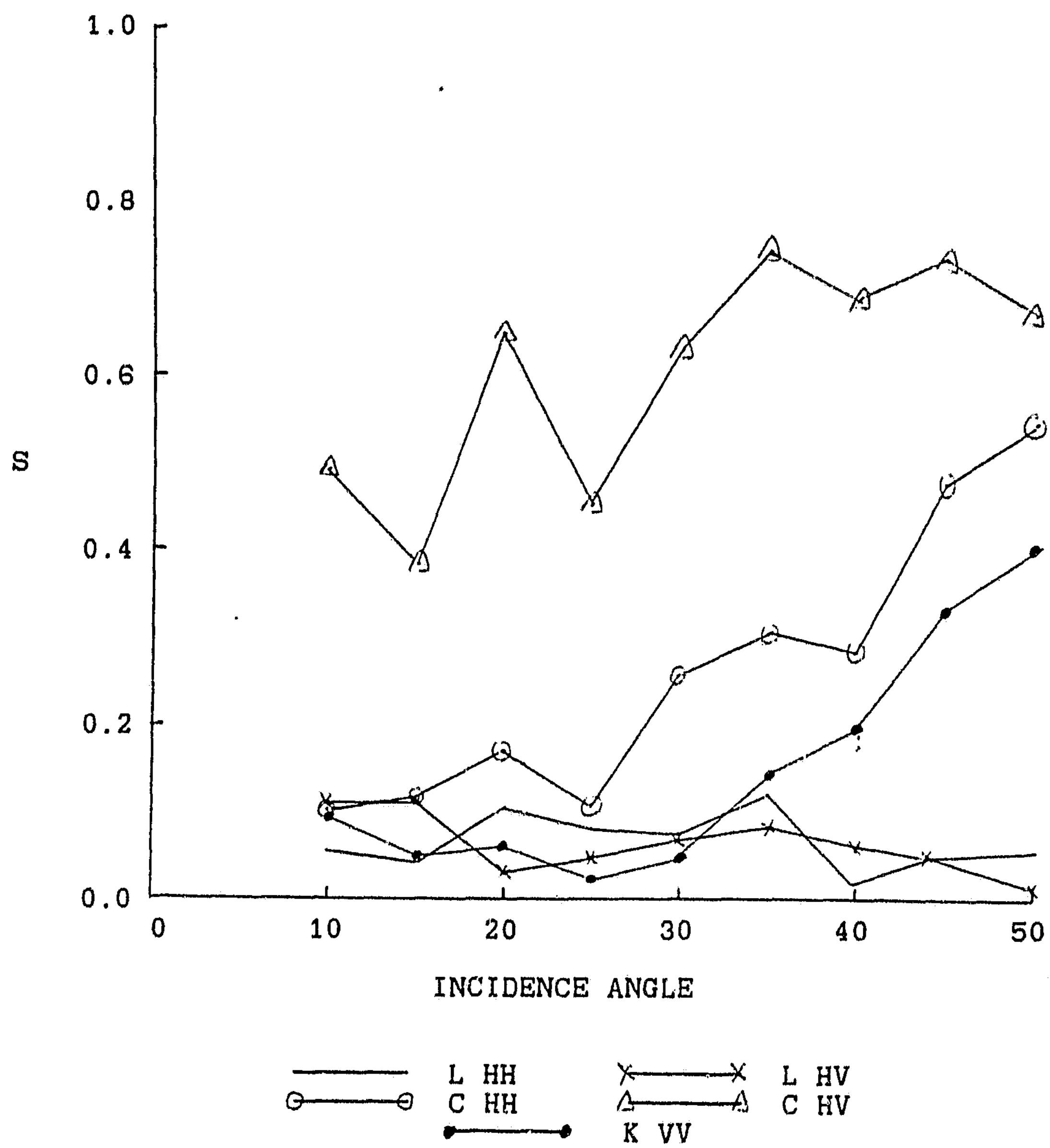

FIGURE 8

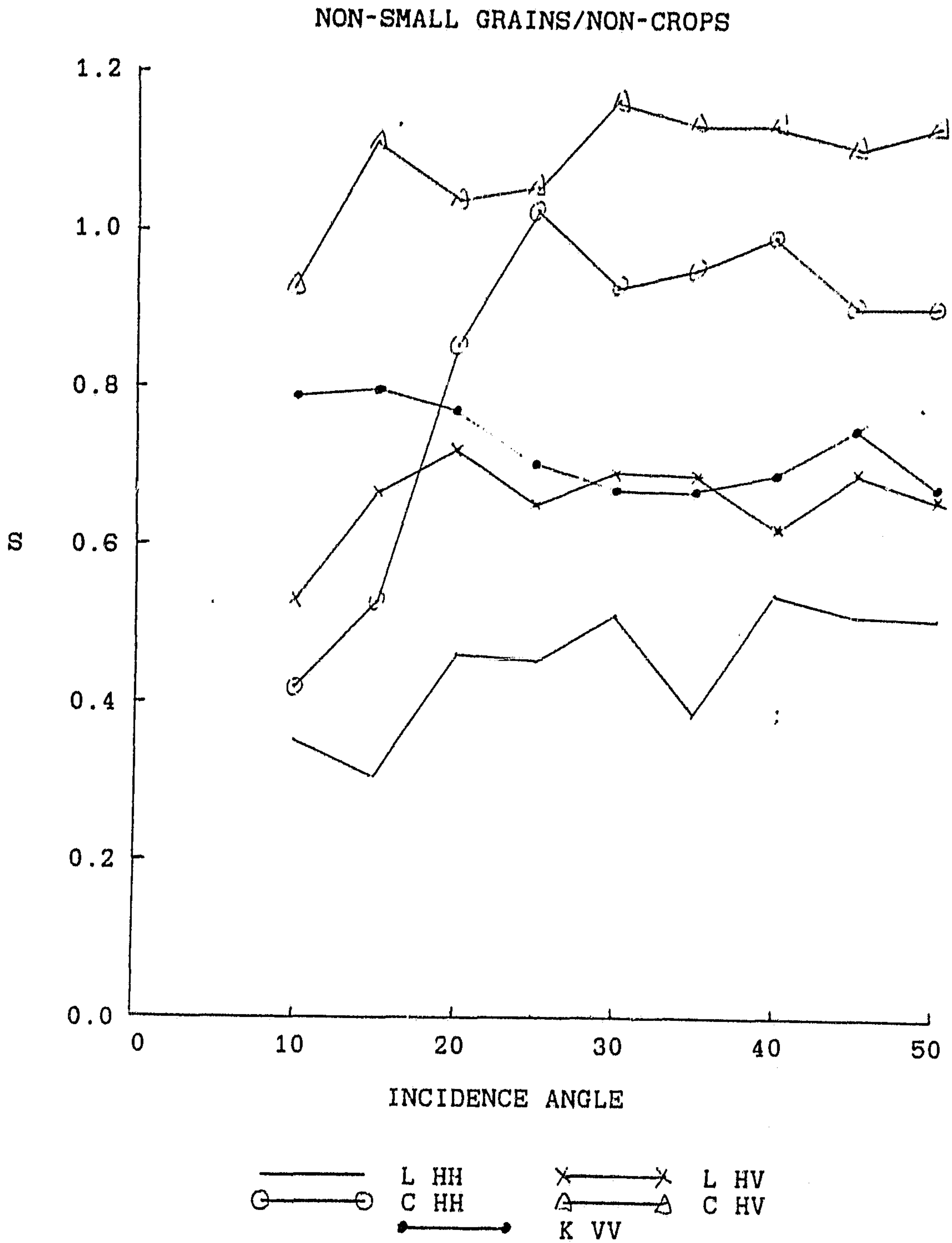
NON-SMALL GRAINS/NON-CROPS
S
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
INCIDENCE ANGLE
L HH
C HH
K VV
L HV
C HV

FIGURE 9

only at higher angles. The L-band S values are again the least useful for these two classes. Note that S values for non-small grains/non-crops (Figure 9) are higher overall than those for small grains/non-crops (Figure 8).

Once crops are separated from non-crops, the next step is to separate two major crop classes - small grains and non-small grains. This separability is shown in Figure 10 for Day 2 and in Figure 11 for Day 3. On both days, K VV stands out at mid-angles (20-45 degrees), with Day 3 performance a little better. On Day 2, C HV 10-25 seems almost as good as K VV, while L-band data show poor results. In comparison, on Day 3, L HV 15-25 and L HH 40-45 may be acceptable, but C-band performs very poorly.

Within the small grains class, Figure 12 gives barley/wheat separability. Clearly, C HV is better than other frequency-polarization combinations at all incidence angles. In addition, L HV 10 and K VV 45-50 are slightly better than the rest. It is encouraging to note that separability between two similar crops like barley and wheat is reasonably good, which is indicated by an S value of about 0.7. Figure 13 shows an attempt to separate two kinds of wheat - durum and spring. Not surprisingly, two wheat species are not separable in any of the 45 scatterometer channels, with the best value being less than about 0.3.

Figure 14 presents two-class separability of dry beans/sugarbeets. K VV has the widest range of angles over which dry beans/sugarbeets separability is good. In addition, L HH does well at 35-50 degrees and L HV is useful in the 25-40

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SMALL GRAINS/NON-SMALL GRAINS

DAY 2

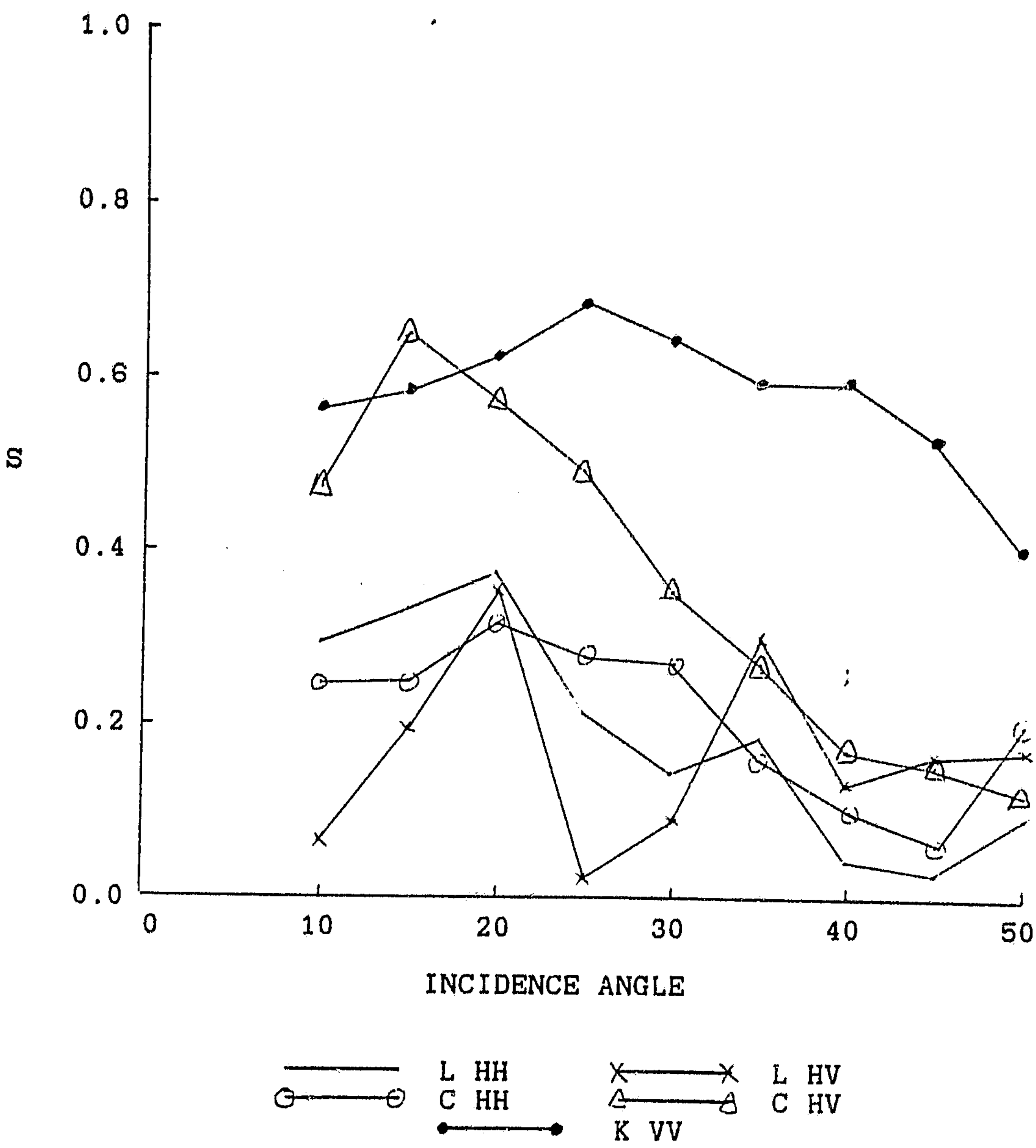

FIGURE 10

SMALL GRAINS/NON-SMALL GRAINS

DAY 3

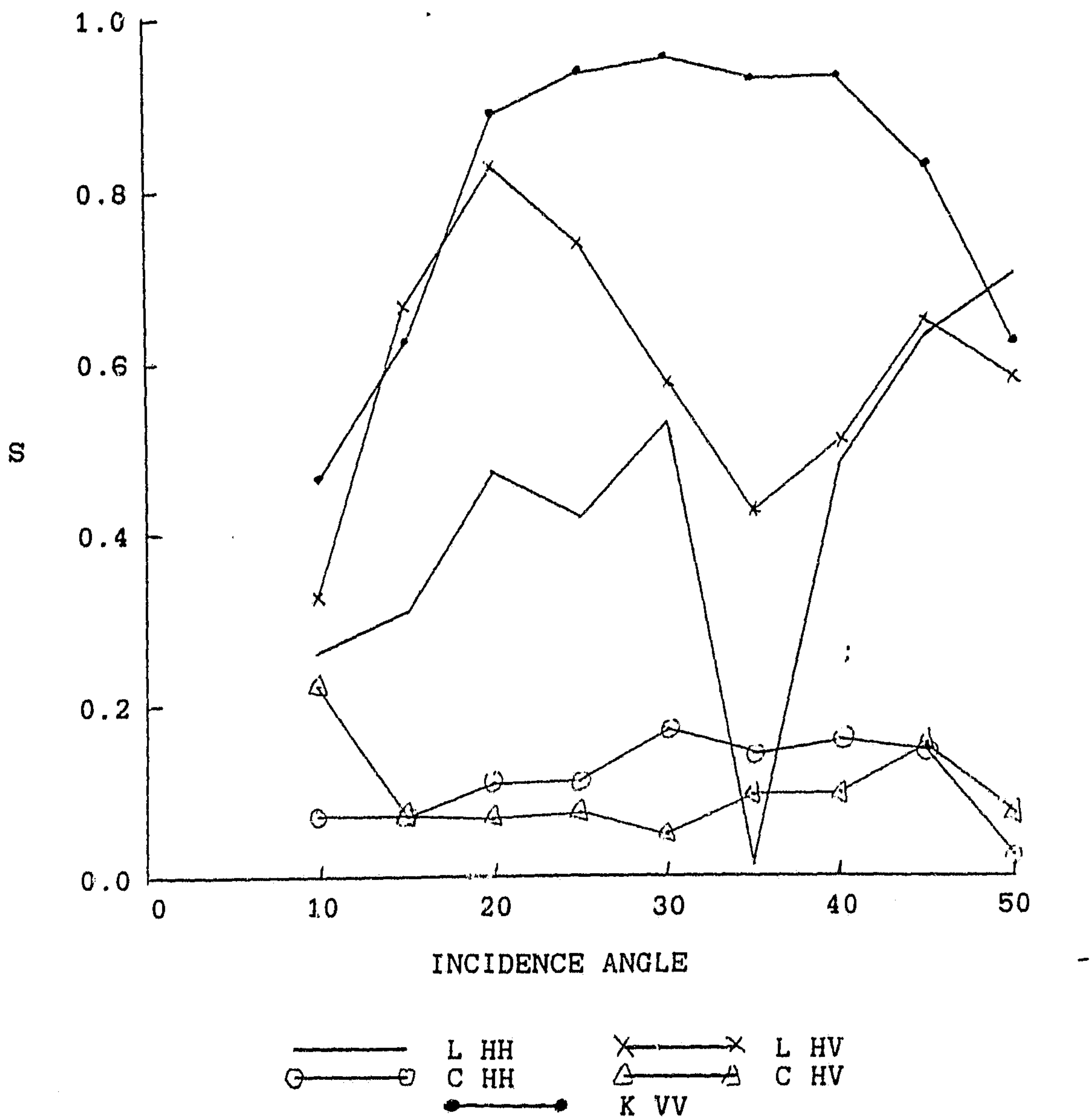

FIGURE 11

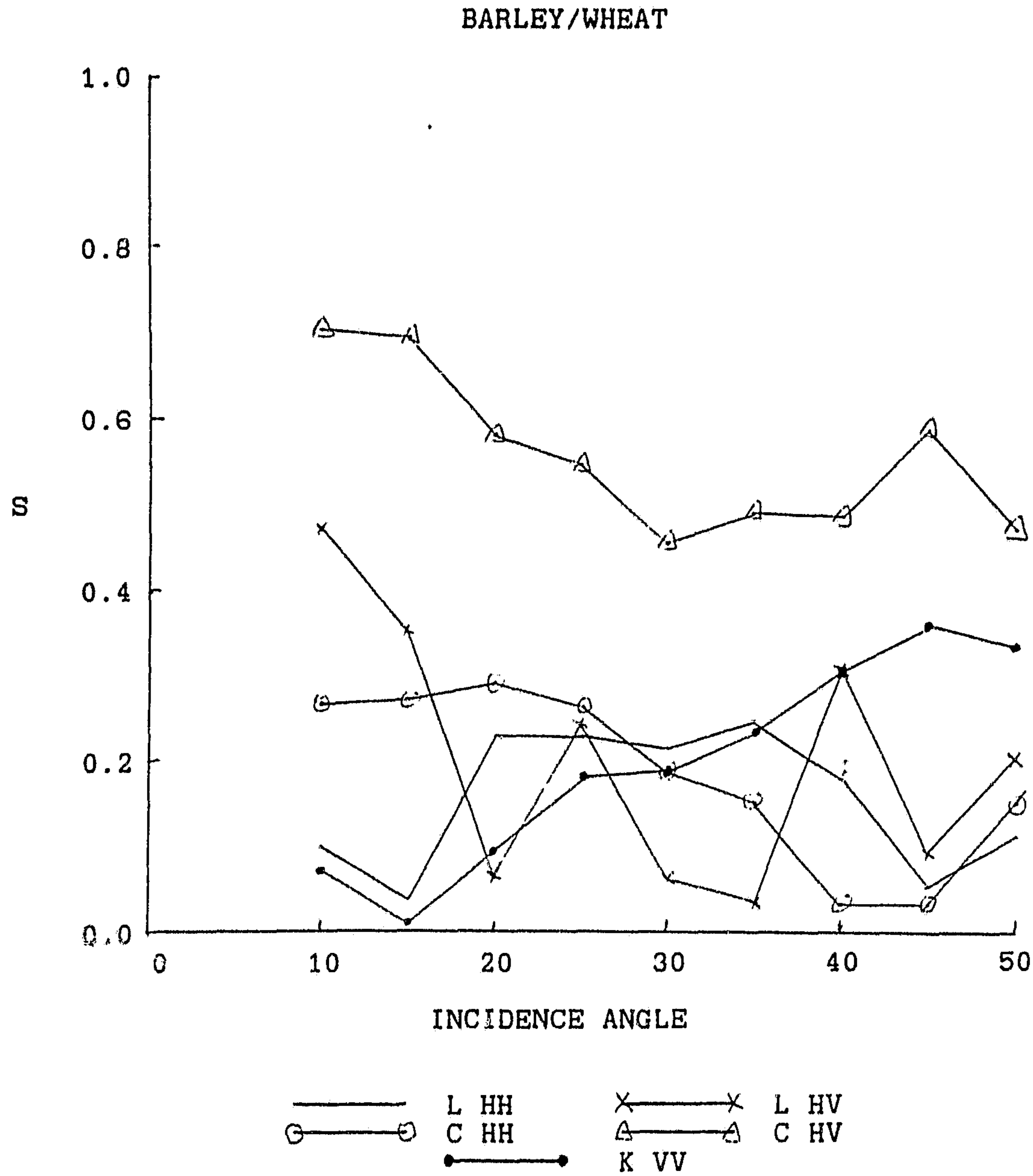
BARLEY/WHEAT
1.0
0.8
0.6
0.4
0.2
0.0
S
0
10
20
30
40
50
INCIDENCE ANGLE
L HH
L HV
C HH
C HV
K VV

FIGURE 12

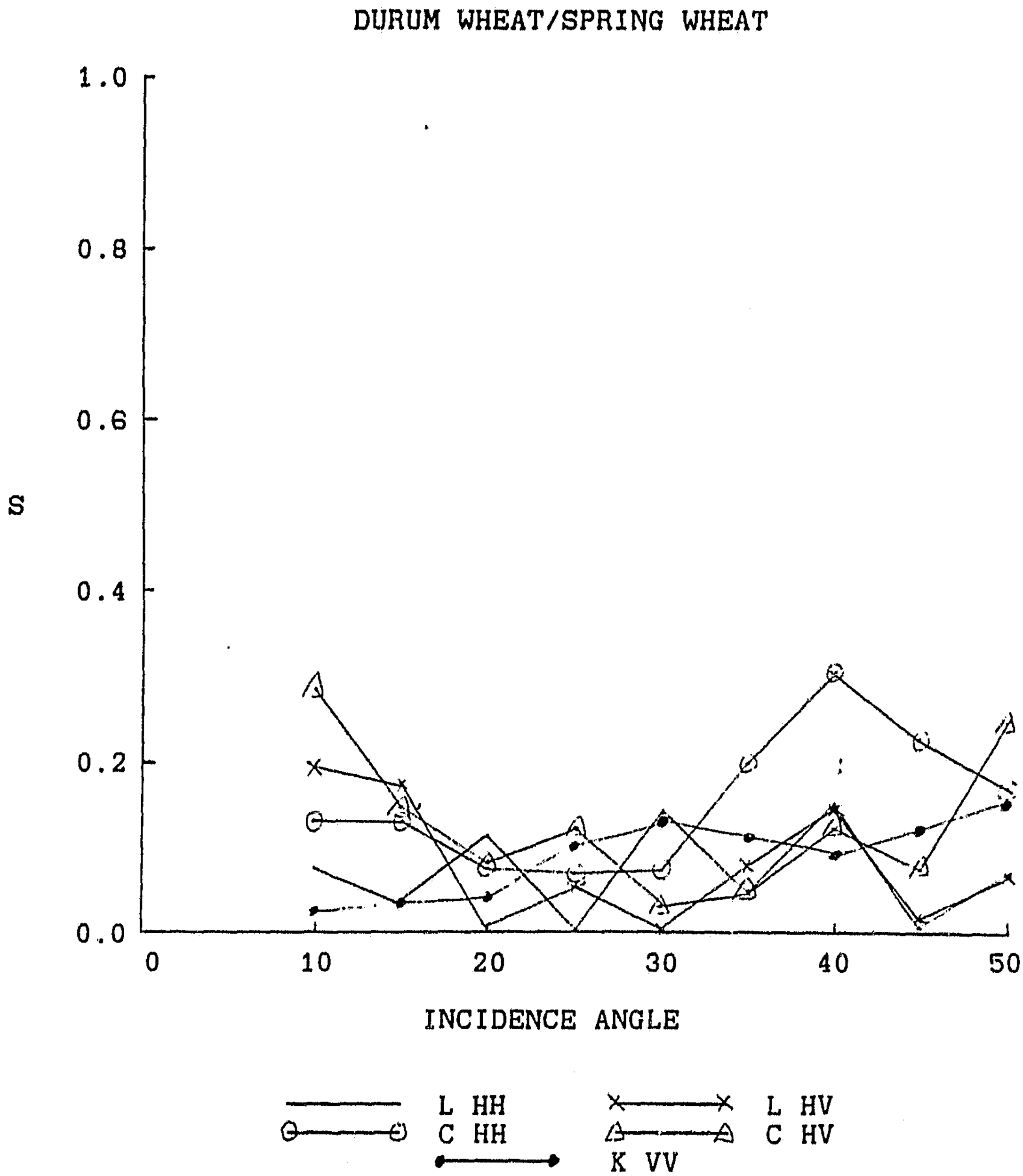
DURUM WHEAT/SPRING WHEAT
1.0
0.8
0.6
0.4
0.2
0.0
S
0
10
20
30
40
50
INCIDENCE ANGLE
L HH
C HH
K VV
L HV
C HV

FIGURE 13

DRY BEANS/SUGARBEETS

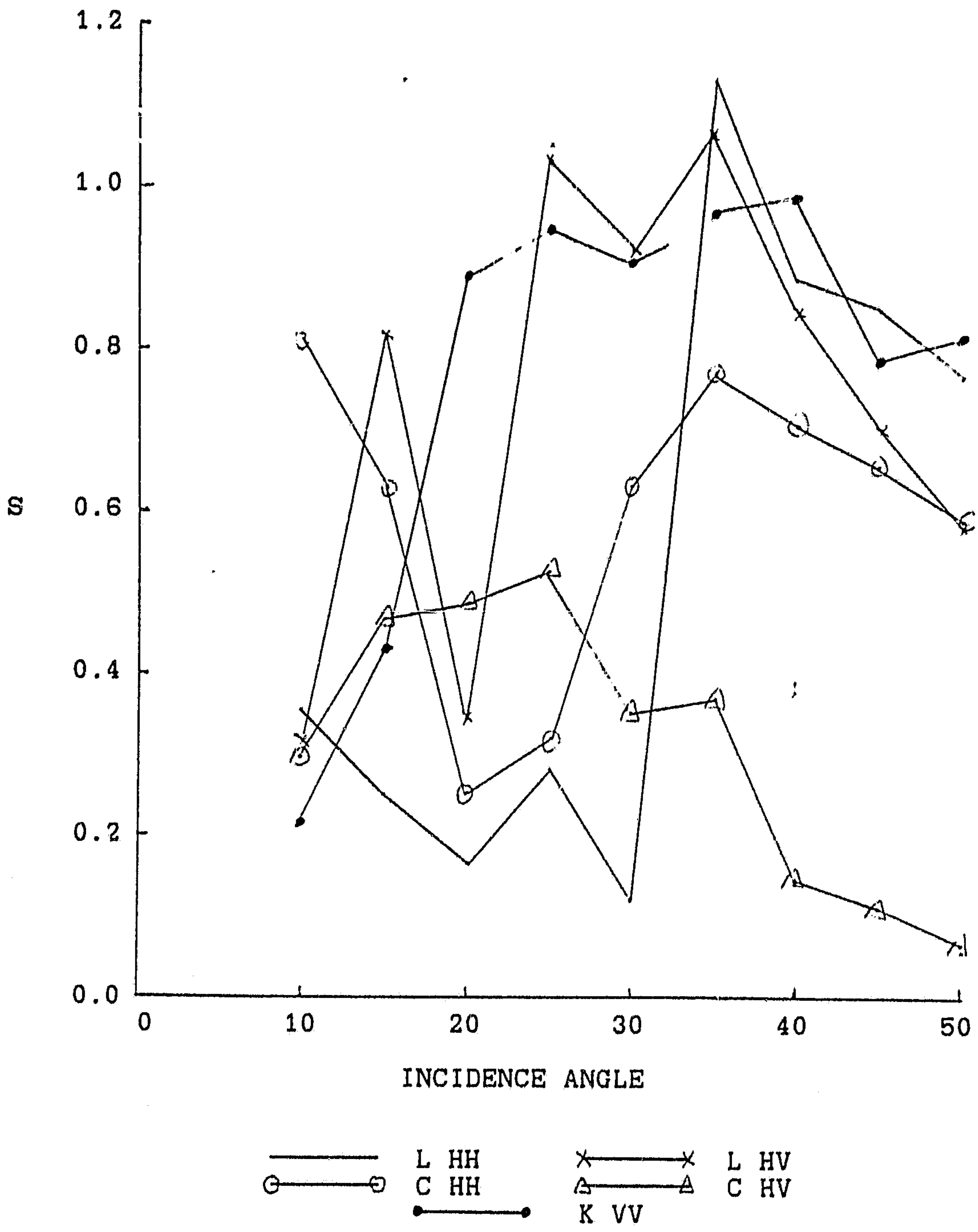

FIGURE 14

degree range. C-band does rather poorly except at C HH 10. The best S values are of the order of 1.0. The dry beans/soybeans separability is shown in Figure 15. In this case, like polarizations at low angles are clearly the best performers. The largest S values are for L HH 10, C HH 10 and K VV 10. The separability measure drops off with increasing angle. Interestingly, L HH improves its performance in the 40-50 degree range. Figure 16 displays dry beans/sunflower separability. The L-band is the best performer; the separability is good for L HV all angles and for L HH 35-50. Moreover, C HH and K VV do well at large angles (30-50 degrees), while C HV is good for 10-25 degrees. The S values are as high as 1.5 for the dry beans/sunflower crop classes.

The sugarbeets/soybeans separability is shown in Figure 17. K VV ia superior at all angles with S values of the order of 1.5. L HV does well for incidence angles of 15-35 degrees, while C HH is good for 40-50 degrees. We show the sugarbeets/sunflower separability in Figure 18. The overall separability of these two crops is relatively poor in all channels, with the best S value of about 0.85. Again, K VV does well, at least for 15-25 degrees. The performance of remaining channels is poor, less than 0.5. Finally, for the crop classes of soybeans/sunflower, Figure 20 gives the separability measures. C HV and K VV give good results at all angles with the highest S value of about 1.7. In addition, C HH 45-50 and C HV 10-15 do well.

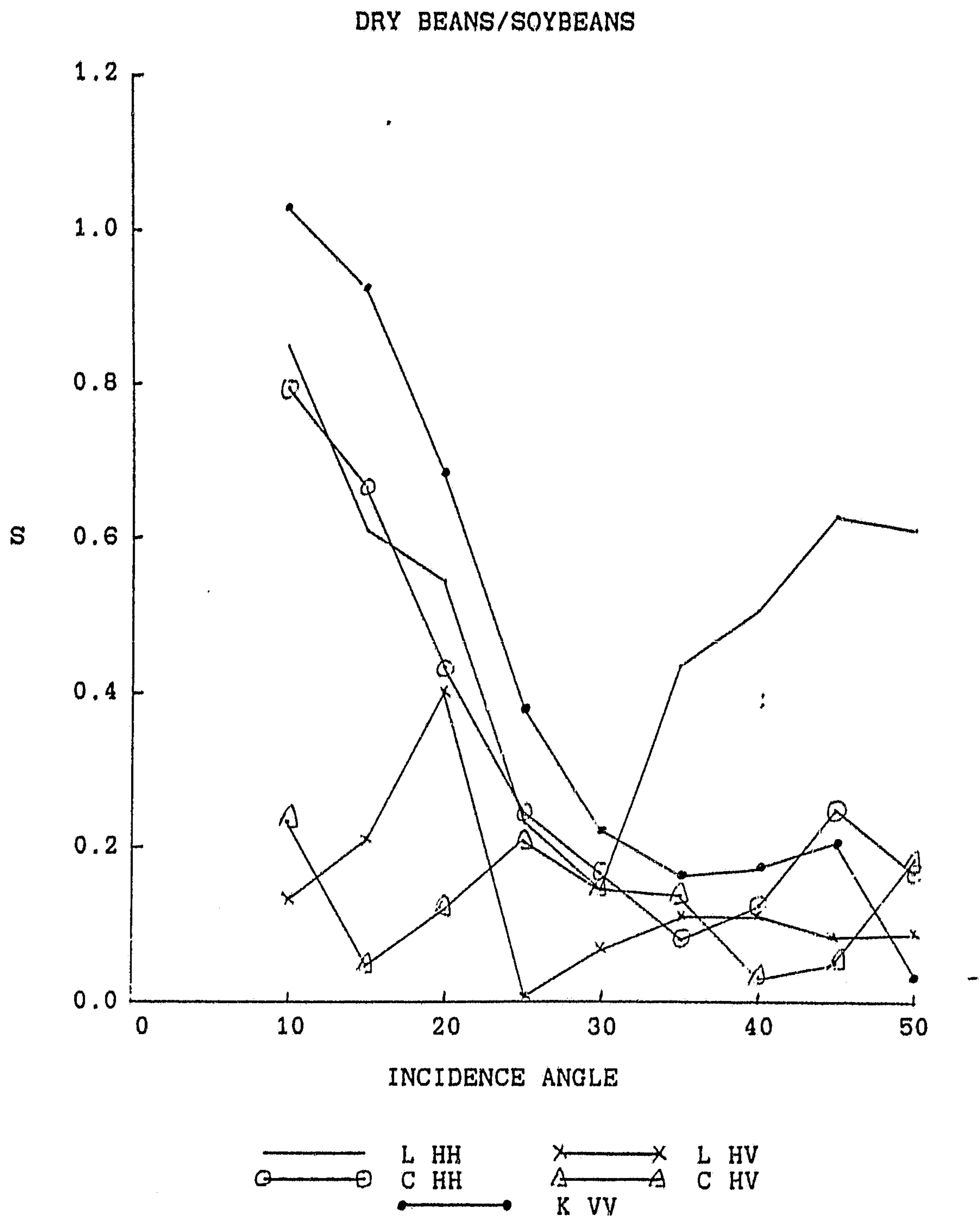
DRY BEANS/SOYBEANS
1.2
1.0
0.8
S
0.6
0.4
0.2
0.0
0
10
20
30
40
50
INCIDENCE ANGLE
L HH
C HH
K VV
L HV
C HV

FIGURE 15

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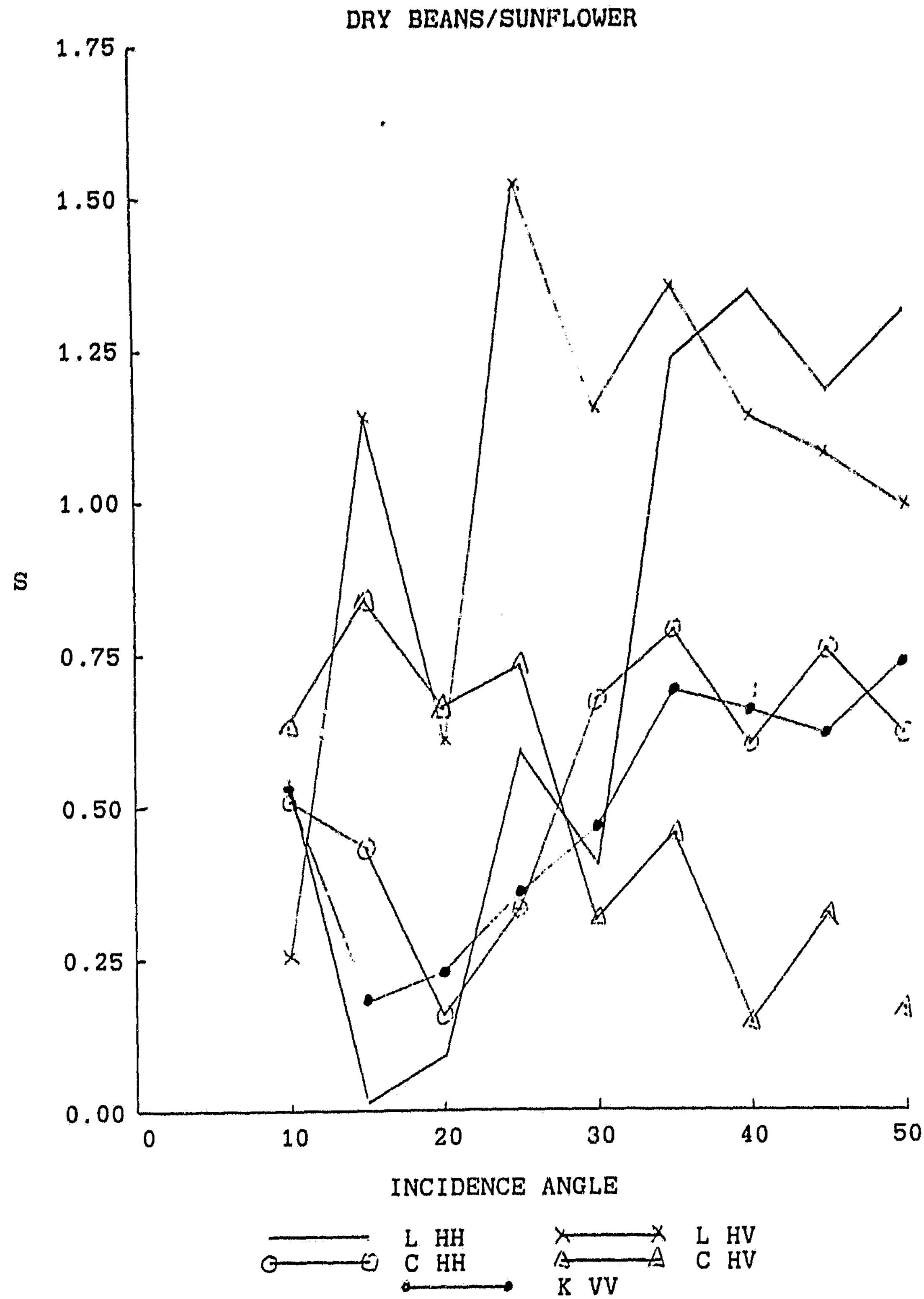

FIGURE 16

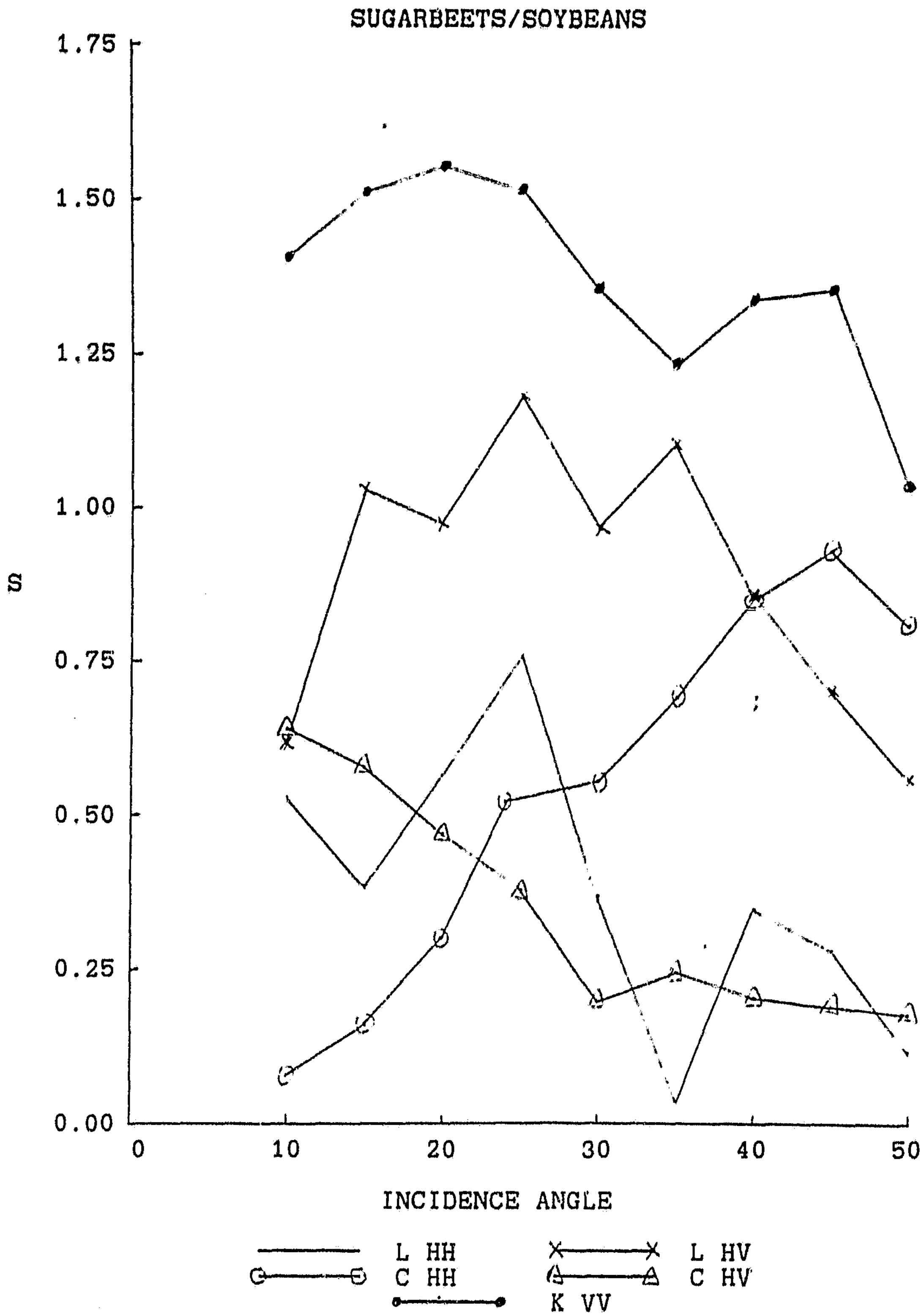
SUGARBEETS/SOYBEANS
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
S
0
10
20
30
40
50
INCIDENCE ANGLE
L HH
C HH
K VV
L HV
C HV

FIGURE 17

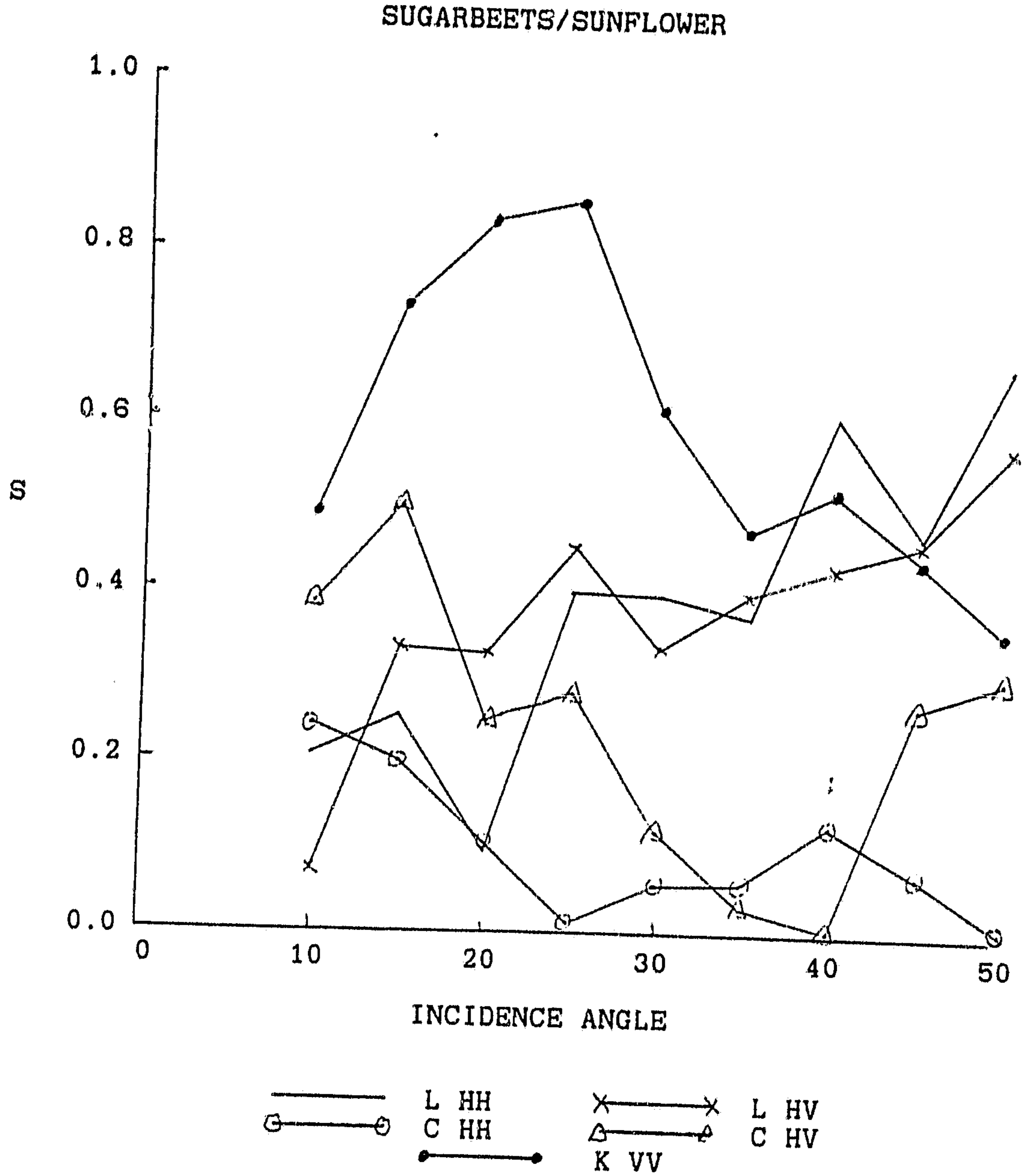
SUGARBEETS/SUNFLOWER
1.0
0.8
0.6
0.4
0.2
0.0
S
0
10
20
30
40
50
INCIDENCE ANGLE
L HH
C HH
L HV
C HV
K VV

FIGURE 18

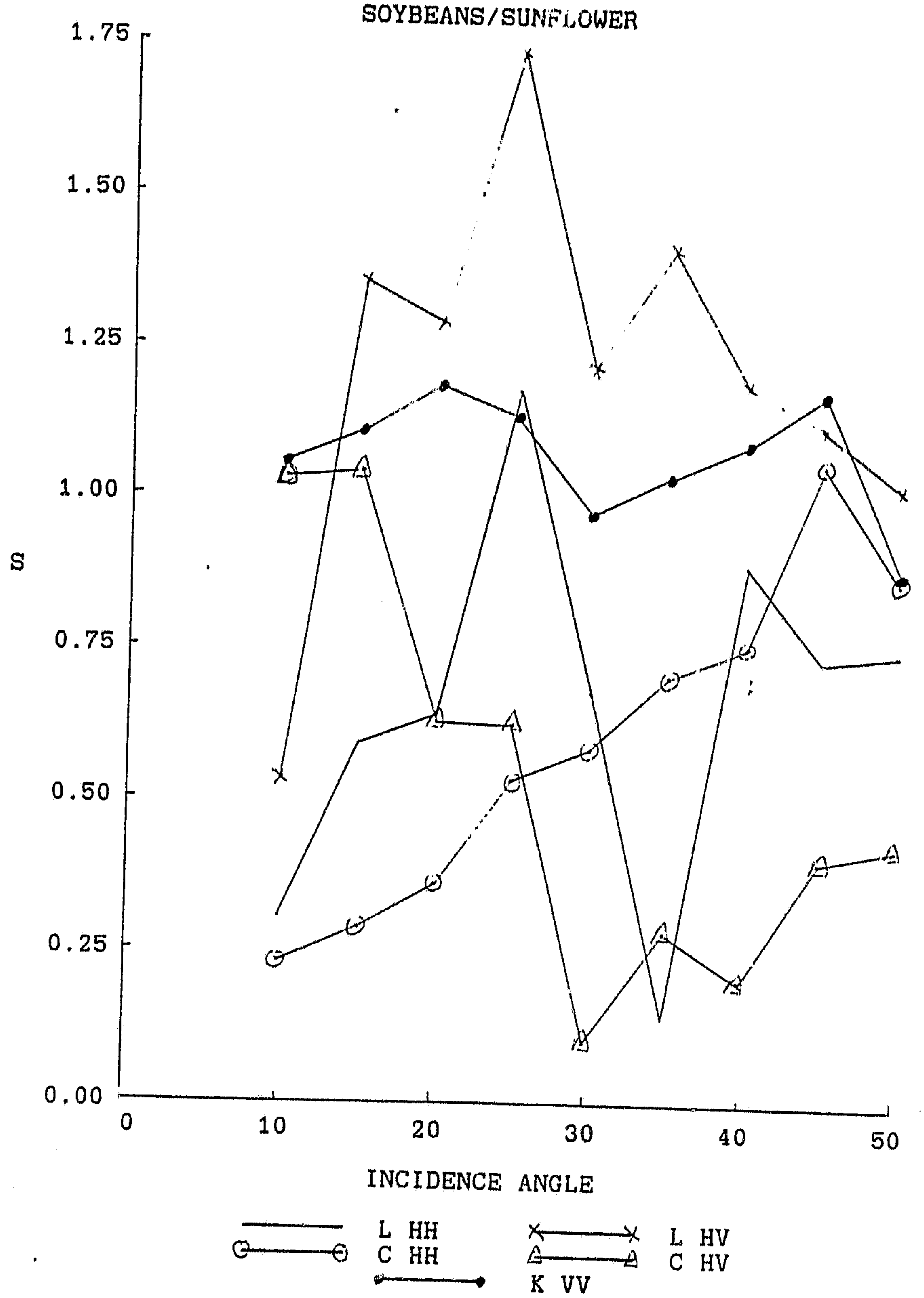
SOYBEANS/SUNFLOWER
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
S
0
10
20
30
40
50
INCIDENCE ANGLE
L HH
C HH
L HV
C HV
K VV

FIGURE 19

SEPARABILITY ERRORS

Once the best performing scatterometer channel for a two-class pair is selected based on separability measure described above, one can make estimates of separability errors. An example is shown in Figure 20, where a histogram is shown for small grains/non-small grains for K VV 30 on Day 3. A subjective linear decision boundary can be drawn as shown and misclassified footprints can be counted for each class. Figure 21 gives a second example for Day 3 barley/wheat separation. These results can be summarized in a tabular form as shown in Table 4. All two-class separabilities are given with sample sizes and misclassified proportions. The combined separability error ranges from about 5% for soybeans/sunflower to more than 35% for two kinds of wheat. In terms of separating individual crops, it is interesting to note that while 33% of barley is identified as wheat, only 11% of wheat is misclassified as barley. Similarly, 22% of sugarbeets are taken for soybeans, whereas only 4% of soybeans are confused with sugarbeets. Note that the linear decision boundary in each two-class pair is drawn subjectively to minimize the combined separability error. It is also to be noted that the estimates of separability errors for some two-class pairs may not be completely reliable as sample sizes for these classes are rather small, particularly for non-small grains. Finally, one must remember that the separability errors discussed here are not directly comparable to classifiaction (omission and comission) errors one obtains by applying formal classifiers, commonly used in pattern recognition.

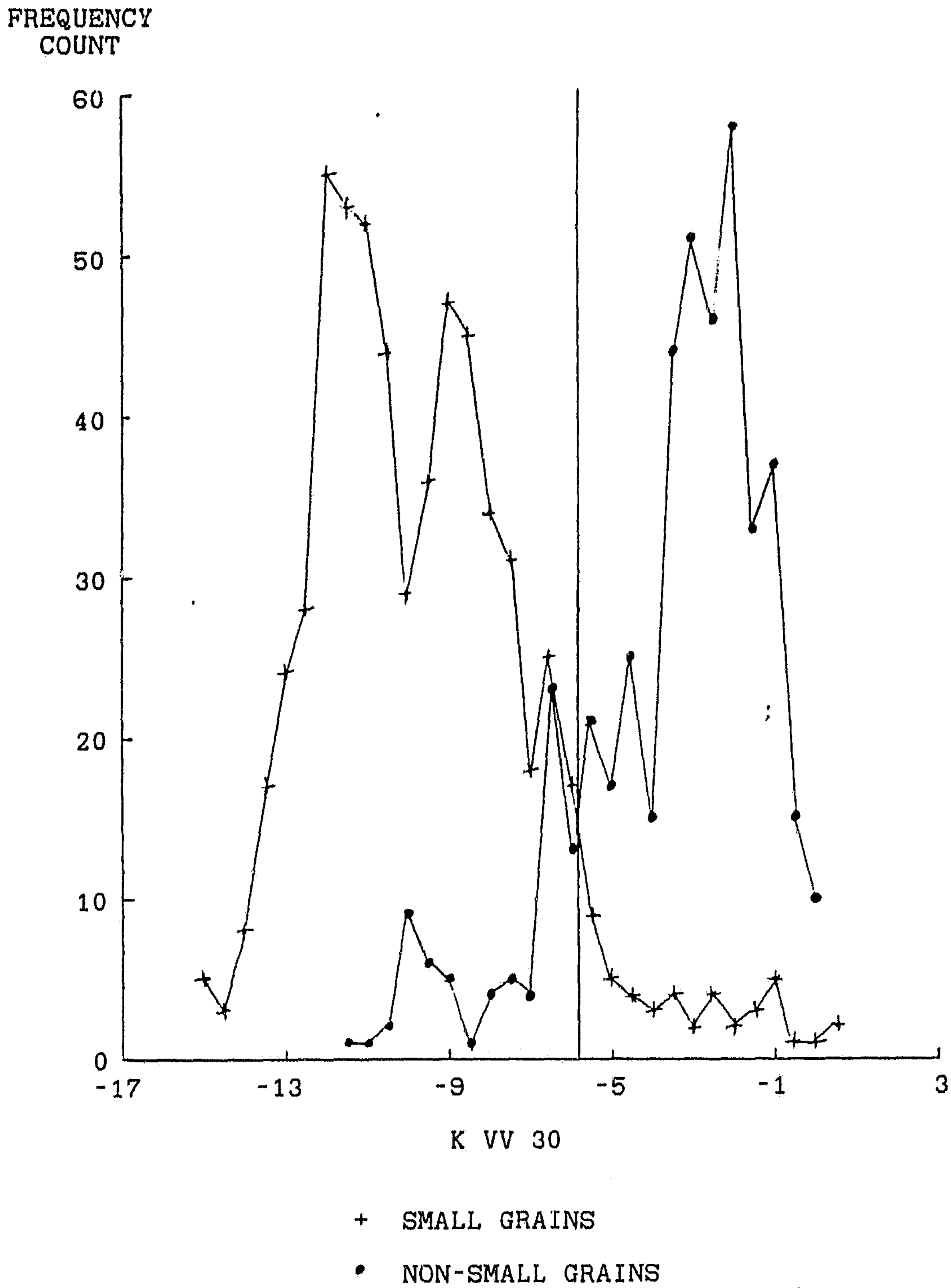
FREQUENCY
COUNT
60
50
40
30
20
10
0
-17
-13
-9
-5
-1
3
K VV 30
+ SMALL GRAINS
• NON-SMALL GRAINS

FIGURE 20

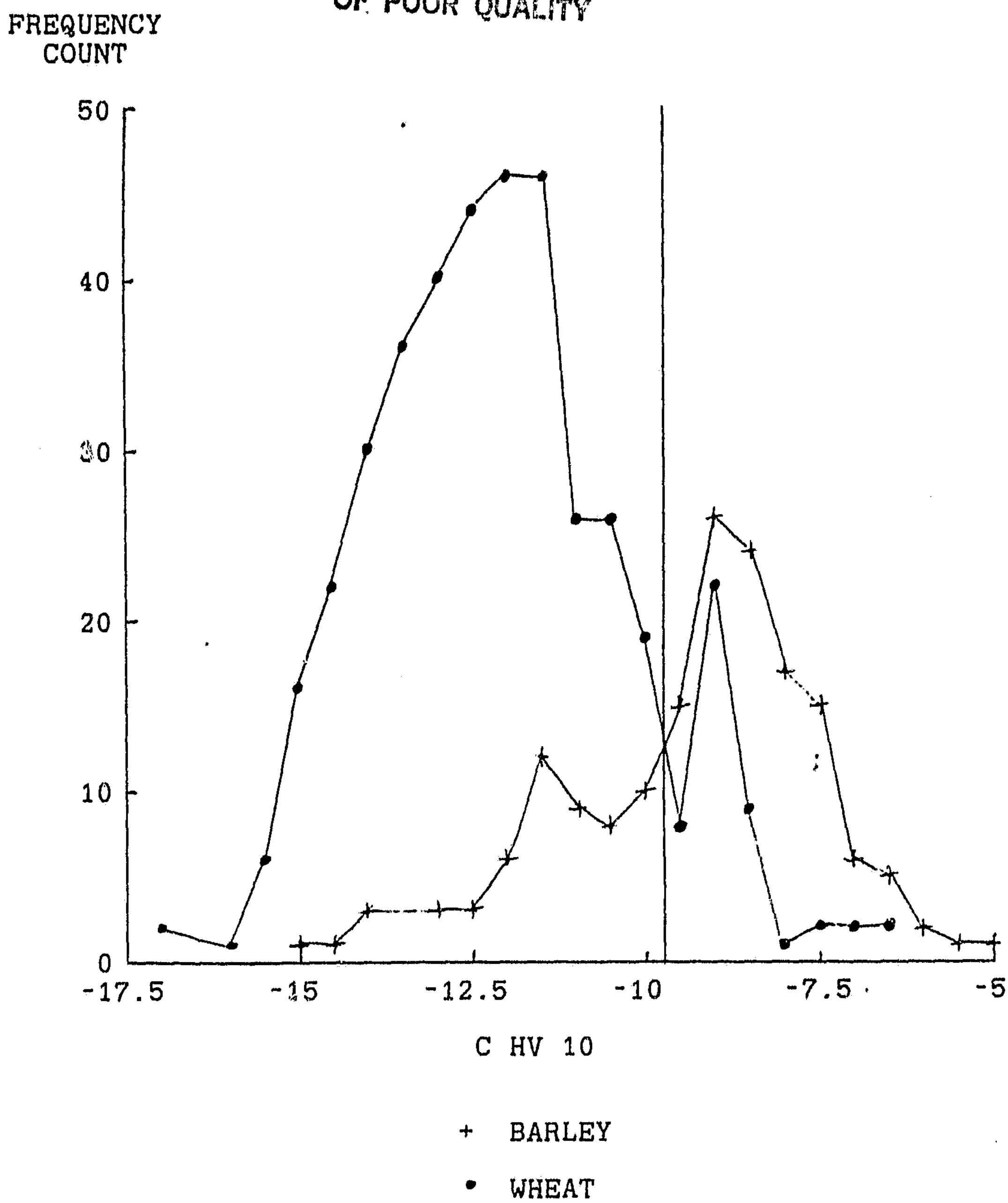
FREQUENCY
COUNT
50
40
30
20
10
0
-17.5
-15
-12.5
-10
-7.5
-5
C HV 10
+ BARLEY
• WHEAT

FIGURE 21

TABLE 4

CLASSIFICATION ERRORS

TWO-CLASS PAIRS	SAMPLE SIZE	MISCLASSIFIED PIXELS	MISCLASSIFIED %	COMBINED PIXELS	COMBINED %
(A) Small Grains	474	37	7.8	103	15.2
Non-Crops	206	66	32.0		
(B) Non-Small Grains	397	45	11.3	99	10.6
Non-Crops	539	51	9.5		
(C) Small Grains	616	45	7.3	119	11.1
Non-Small Grains	456	74	16.2		
(D) Barley	169	56	33.1	102	17.7
Wheat	406	46	11.3		
(E) Durum Wheat	198	83	41.9	145	35.2
Spring Wheat	214	62	29.0		
(F) Dry Beans	66	13	19.7	23	10.8
Sugarbeets	147	10	6.8		
(G) Dry Beans	66	6	9.1	13	9.8
Soybeans	67	7	10.5		
(H) Dry Beans	66	2	3.0	12	7.4
Sunflower	97	10	10.3		
(I) Sugarbeets	147	18	12.2	27	12.6
Soybeans	67	9	13.4		
(J) Sugarbeets	170	33	22.5	38	13.2
Sunflower	117	5	4.3		
(K) Soybeans	67	2	3.0	9	5.5
Sunflower	97	7	7.2		

EFFECT OF PIXEL PURITY

One of the factors affecting crop separability is the proportion of mixed or impure pixels in the data set. In theory, these mixed pixels widen the distribution in a scatterometer channel, creating longer tails. Discarding mixed pixels should narrow the distributions (reducing the denominator of separability measure S) and improve the separability between two crops. We will consider two cases of pure and superpure pixels. A scatterometer pixel is pure if there is no field boundary within it. No boundary exists within twice the size of a regular footprint, for a superpure pixel. Note that scatterometer footprints are different in physical size for the three frequencies, as shown in Figure 1.

We will show an example of the effect of pixel purity on crop separability. Figure 22 presents separability measures for small grains/non-small grains for Day 3 for pure pixels, while Figure 23 shows those for superpure pixels. These plots of pure and superpure pixels should be compared with Figure 11, where separability measures for all pixels were given. An important point to note is that the best performing scatterometer channels are the same in all three figures. In other words, pixel purity has no influence on the selection of best scatterometer channels for crop separability. The S values in all channels are higher for pure pixels and still higher for superpure pixels. For example, the largest S value in all three plots is for K VV 30. The value of S for K VV 30 for all pixels is 0.96, while that

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SMALL GRAINS/NON-SMALL GRAINS

PURE PIXELS

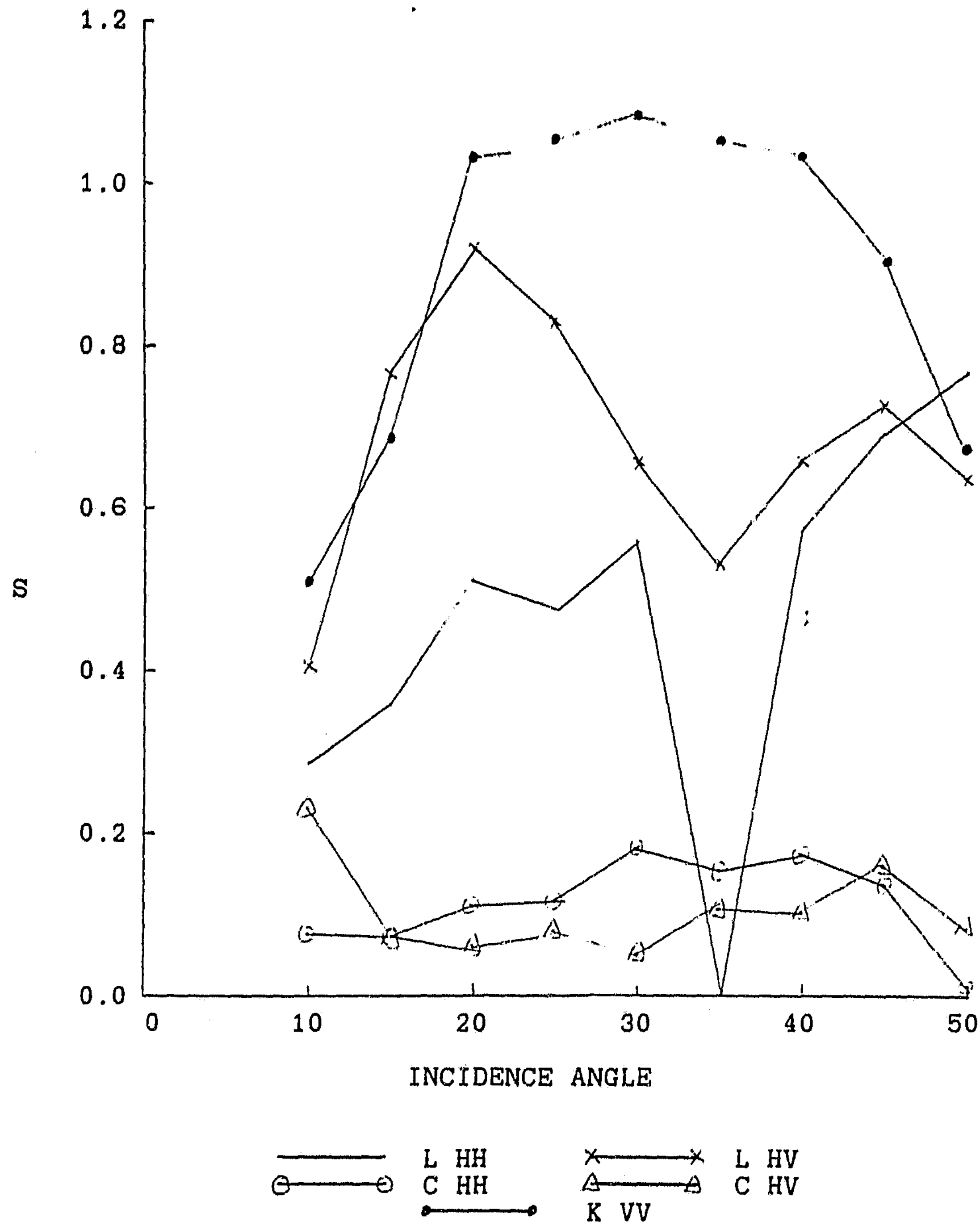

FIGURE 22

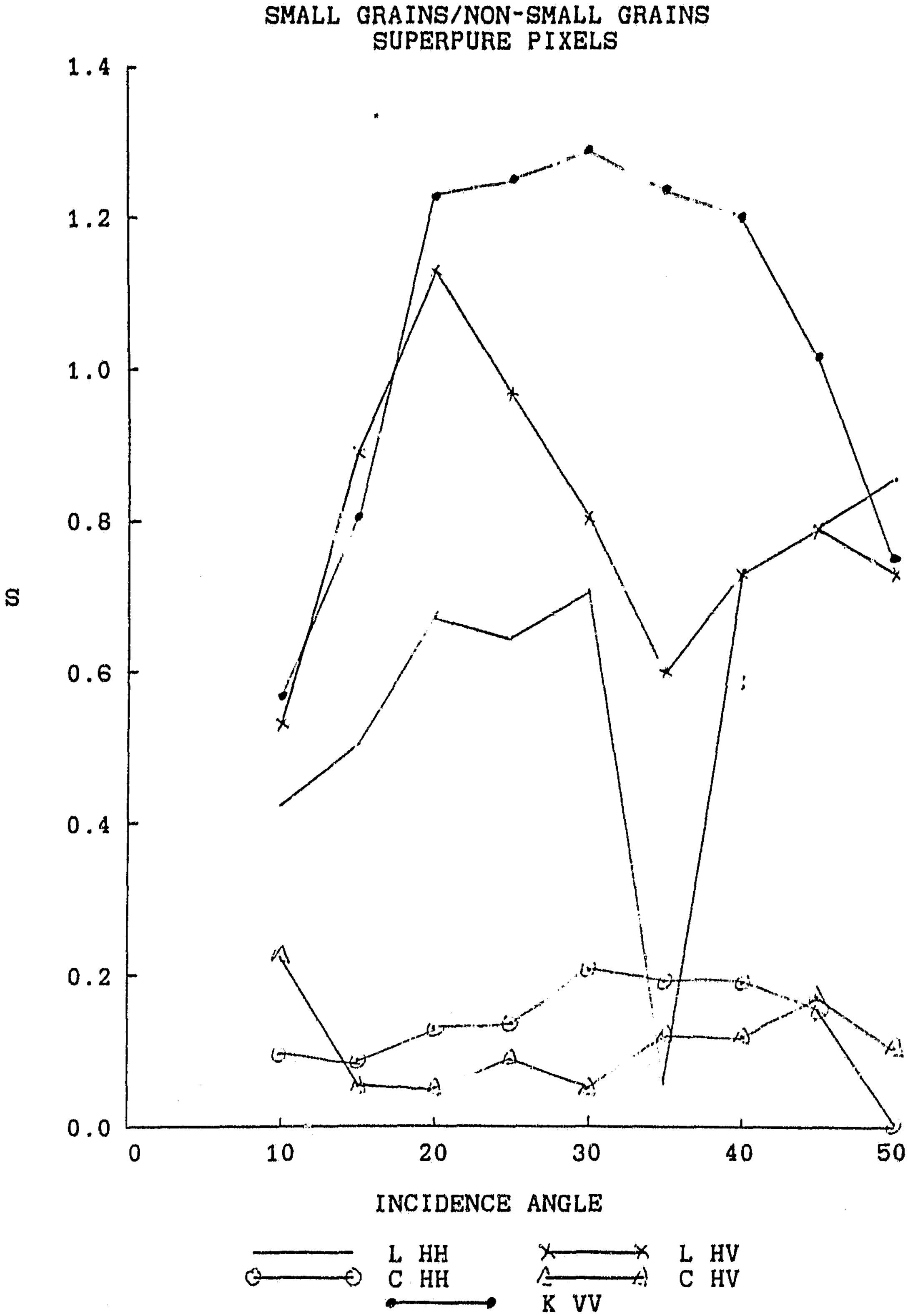
SMALL GRAINS/NON-SMALL GRAINS
SUPERPURE PIXELS
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
S
0
10
20
30
40
50
INCIDENCE ANGLE
L HH
L HV
C HH
C HV
K VV

FIGURE 23

for pure pixels is 1.08 (an improvement of 13%) and is 1.29 (a 35% improvement) for superpure pixels. A similar improvement in the separability measure is seen for other two-class pairs.

The effect of pixel purity on separability errors is determined for only two cases; the results are given in Table 5. The combined separbility error for small grains/non-small grains is reduced from about 11% for all pixels to less than 9% for pure pixels (improvement of 22.5%) and futher reduced to 7% for superpure pixels (a 37% improvement over all pixels). The improvement in barley/wheat separability because of pixel purity is much smaller. Retaining only pure pixels gives an improvement of about 9% (separability error of 18% forr all pixels to that of 16% for pure pixels), while an improvement of 10% is achieved in keeping only superpure pixels (16% separability error for superpure pixels).

SEPARABILITY OF ROW CROPS

Since row direction affects the radar signature, it is logical to ask whether knowledge of row direction would improve crop-separability. We can investigate this effect by dividing a crop class into EW and NS rows and calculating separability measures for row crops. Table 6 shows results of such an exercise. Separability measures are calculated for four subclasses - two crops and two row directions. For the case of small grains/non-small grains, one obtains better discrimination by considering row crops separately compared to rows considered together. The separability measure between small grains EW and non-small

TABLE 5

EFFECT OF PIXEL PURITY ON CLASSIFICATION ERRORS

PIXEL PURITY	SAMPLE SIZE	MISCLASSIFIED PIXELS	MISCLASSIFIED %	COMBINED PIXELS	COMBINED %
(A) SMALL GRAINS/NON-SMALL GRAINS:					
All	616	45	7.3	119	11.1
	456	74	16.2		
Pure	548	23	4.2	82	8.6
	406	59	14.5		
Superpure	477	47	9.9	58	7.0
	351	11	3.1		
(B) BARLEY/WHEAT:					
All	169	56	33.1	102	17.7
	406	46	11.3		
Pure	149	44	29.5	82	16.1
	360	38	10.6		
Superpure	123	35	28.5	68	15.8
	307	33	15.9		

TABLE 6

SEPARABILITY OF ROW CROPS

TWO-CLASS PAIRS	'BEST' CHANNEL	S	SAMPLE SIZE
Small Grains/Non-Small Grains	K VV 30	0.958	616/456
SG EW / NSG EW	K VV 20	1.257	443/339
SG EW / NSG NS	K VV 20	1.323	443/117
SG NS / NSG EW	L HV 45	1.208	104/127
SG NS / NSG NS	K VV 40	0.939	173/117
Barley/Wheat	C HV 10	0.706	169/406
Barley EW / Wheat EW	C HV 10	0.726	112/290
Barley EW / Wheat NS	L HH 30	1.455	41/66
Barley NS / Wheat EW	L HV 15	0.901	38/167
Barley NS / Wheat NS	C HV 45	0.952	57/116

grains NS is 1.32 (a full 38% better than both rows together). Note that separability between NS rows of small grains/non-small grains is slightly worse than both rows combined.

For the case of barley/wheat, we get higher S values when we consider the two row directions separately for both crop classes. We get surprisingly good separability (S value of 1.45) for barley EW/wheat NS. This is a factor of 2 improvement over the two row directions combined.

CONCLUDING REMARKS

As mentioned in the beginning, the primary goal of this research was to assess the capability of airborne radars for crop separability and to provide information in determining specifications of future multiparameter microwave remote sensors in the study of vegetation canopies. It was not possible to address the issues of interaction of microwave radiation with crop canopies in any quantitative fashion, primararily because of the lack of appropriate ground truth such as canopy geometry and soil background. Thus, given the limited scope of present study, our general approach was to empirically investigate crop separability with multiparameter radar scatterometers.

An electromagnetic sensor typically responds to features on the scale size comparable to its wavelength. In addition, for microwave sensors, wave polarization is important as it is affected by the orientation of various features. Finally, sensor look angle (incidence angle for radar scatterometers) plays a role because the projected area of a target determines the radar backscatter. Overall, radar signature in a sensor channel (frequency/polarization/incidence angle combination) results from a complex interaction of incident microwave radiation with vegetation canopy structure (number, size and shape of various components) and architecture (orientation of these components). Moreover, if radar energy penetrates through a vegetation canopy, the backsctterred signal is also affected by the properties of soil background. The variability of the dielectric constant is a second order effect for radar backscatter, as there are probably no significant differences in the dielectric properties of various crop species.

We have seen that high frequency channels (C- and Ku-bands) are more useful in separating small grains, while non-small grains are more easily discriminated at lower frequencies (L-band). This implies that there are differences on the order of a few cms (2 to 6 cms) among small grains, at least at certain growth stages, represented on Day 3 in our analysis. More importantly, two agronomically similar crops like barley and wheat look different to a 6 cm radar, but they are indistinguishable at larger wavelengths. The differences among most non-small grains are of the order of 20 cms, with the exception of two cases involving sugarbeets, where Ku-band (2 cms) seems more useful.

Cross polarization seems more useful in most cases, both for small grains and non-small grains. Perhaps this is because of a specific leaf angle distribution for a crop canopy. A leaf angle distribution peaking at about 45 degrees from horizontal direction will have pronounced effect on cross polarization. There is no preference for a particular incidence angle in all but one cases, except that mid angles are better in crop separability. For one exception, that of dry beans/soybeans, incidence angle of 10 degrees is significantly better than larger angles for like polarization for all three frequencies. This may be caused by a leaf angle distribution predominently horizontal and vertical which shows up only at small incidence angles. One has to keep in mind the complication of soil background, at least at L-band, in interpreting radar signatures in this case.

It is well-known that lower frequencies tend to penetrate more deeply into a crop canopy than higher frequencies. Therefore, it is unlikely that Ku-band microwaves can penetrate a full canopy and be affected by the soil background, particularly at large incidence angles. On the other hand, L-band radar can penetrate a full canopy and 'see' the underlying soil, even at large incidence angles. This behavior is evident in Table 6. One can see that small grains are planted in a different row structure than non-small grains, as S value for SG EW/NSG EW is larger than overall SG/NSG separability, even for K VV 20. But for NS rows of both crop classes, the S value is similar to the overall separability measure. For the case of barley/wheat, row structure plays a relatively minor role, as evidenced by separability of EW rows being very similar to the overall separability.

The effect of pixel purity is to increase the separability between two ground cover classes. For the two cases we considered, there is a 15-25% improvement in crop separability for pure pixels and about 35% increase for superpure pixels. It is important to note that the relative ordering of scatterometer channels in crop separability performance is not affected by pixel purity; separability measure in each channel improves by discarding mixed pixels.

Separability measure S, defined in a previous section, is a direct indicator of a sensor's ability to discriminate between two classes; the higher the S value, the better the two-class separability. It is good to note that multiparameter scatterometers do a fairly decent job of crop separability, as indicated by S values of the order of 1. Separability measure for small grains is less than 1, indicating that it is harder to discriminate within the small grains class. Separability between two agronomically similar crops like barley and wheat is fairly good, of the order of 0.7. It is not surprising to see that this set of scatterometers are unable to distinguish between two kinds of wheat. Separability within non-small grains is better with S values greater than 1 in most cases. For some non-small grains, S value is greater than 1.5, with soybeans/sunflower separability of 1.73. This indicates that this set of scatterometers are well capable of discriminating between non-small grains.

Only L HH active microwave remote sensors have been flown from space so far, at 20 degree incidence angle for Seasat SAR and with 47 degree angle with SIR-A. A variable angle L HH SAR will be flown in 1984 under the SIR-B program. It may be a few years before a multifrequency/multipolarization/multiangle microwave remote sensor is flown in space. The logical question in the present context is how a multiangle L HH sensor would perform the task of crop separability. Table 7 compares best separability measures for L HH with overall best S for the eleven two-class pairs. Clearly, for all pairs containing small

TABLE 7

TWO-CLASS SEPARABLITIES FOR L HH

TWO-CLASS PAIRS	L HH CHANNEL	L HH S	OVERALL CHANNEL	OVERALL S
Small Grains/Non-Crops	L HH 35	0.119	C HV 35	0.743
Non-Small Grains/Non-Crops	L HH 40	0.539	C HV 30	1.165
Small Grains/Non-Small Grains	L HH 50	0.700	K VV 30	0.958
Barley/Wheat	L HH 35	0.242	C HV 10	0.706
Durum Wheat/Spring Wheat	L HH 40	0.151	C HH 40	0.303
Dry Beans/Sugarbeets	L HH 35	1.130	L HH 35	1 130
Dry Beans/Soybeans	L HH 10	0.848	K VV 10	1.029
Dry Beans/Sunflower	L HH 40	1.340	L HV 25	1.522
Sugarbeets/Soybeans	L HH 25	0.756	K VV 20	1.552
Sugarbeets/sunflower	L HH 50	0.663	K VV 25	0.857
Soybeans/Sunflower	L HH 25	1.177	L HV 25	1.729

grains, L HH channels perform very poorly compared to the other channels, as pointed out earlier. For two-class pairs involving non-small grains, L HH channels do rather well in most cases; an L HH channel is close to the best performing channel, if not the most useful.

In summary, the set of airborne multiparameter radar scatterometers are capable of separating various ground cover classes with fair degree of accuracy, even in the presence of such confusion factors as row direction and mixed pixels. It is important to note that we have used radar measurements only from a single date; we have not investigated the utility of a multidate data set. (Multidate analysis has proved to be fairly successful in corn/soybeans separbility using spaceborne optical remotely sensed data). We have clearly demonstrated the desirability of multiparameter microwave remote sensors for the study of agricultural crops. It is important to continue this line of research with an investigation of multidate measurements and by conducting a controlled experiment to study the effects of canopy geometry and soil background on radar signatures.

ACKNOWLEDGEMENTS

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