Defining the Sensitivity of Multi-frequency and Multi-polarized Radar Backscatter to Post-Harvest Crop Residue

H. McNairn[1], C. Duguay[2], J. Boisvert[3], E. Huffman[3] and B. Brisco[4]

Canada Centre for Remote Sensing[1]
588 Booth St., Ottawa, Ontario, Canada K2L 3Y7

Université Laval[2]
Département de géographie
Cité Universitaire, Sainte-Foy, Québec, Canada G1K 7P4

Agriculture and Agri-Food Canada[3]
Eastern Cereal and Oilseed Research Centre
Central Experimental Farm, Ottawa, Ontario, Canada K1A 0C6

Noetix Research Inc. [4]
403-265 Carling Ave., Ottawa, Ontario, Canada K1S 2E1

SUMMARY

Following harvest, agricultural fields are left with varying amounts of crop residue cover. The erodibility and health of the topsoil is determined, in part, by the amount and type of this residue cover. Although radar sensors could be useful for mapping residue and/or tillage in order to monitor soil conservation practices, little is understood about the relationship between residue and radar backscatter. Two ground-based microwave scatterometer experiments were conducted on agricultural plots at the Central Experimental Farm of Agriculture and Agri-Food Canada, in Ottawa (Canada). The experiments were designed to address the influence of residue type (corn and barley), residue moisture content and residue amount on radar backscatter, and to examine the effect of look direction on radar response. Scatterometer measurements (C- and L-Band in four linear transmit-receive polarization combinations) were taken of corn and barley plots where treatments varied in residue amount and moisture level. The experiments demonstrated that crop residue can retain significant amounts of moisture and that residue is not transparent to incident microwaves. Residue cover will impede the use of radar sensors for mapping soil moisture. Both residue amount and residue moisture content were correlated with radar backscatter, with the strongest correlations associated with corn residue treatments, C-Band cross-polarized backscatter and shallow incidence angles. Cross-polarized scattering was not sensitive to radar look direction effects. Results from these experiments indicate that cross-polarized backscatter could be used to provide information on conservation tillage practices.

RÉSUMÉ

Les taux de résidus laissés dans les champs varient beaucoup après la récolte. L'érodabilité et la santé de la couche arable sont en partie déterminées par la quantité et le type de résidus. Bien que les capteurs radar pourraient être utiles à la cartographie des résidus et/ou des méthodes culturales pour le suivi des pratiques de conservation des sols, la relation entre les résidus et le signal radar rétrodiffusé est peu connue. Deux expériences utilisant un diffusiomètre au sol ont été menées sur des parcelles de la Ferme expérimentale centrale d'Agriculture et agroalimentaire Canada, Ottawa (Canada). Les expériences ont été conçues pour évaluer l'influence du type (maïs et orge), de la teneur en eau et de la quantité de résidus sur le signal rétrodiffusé, et d'examiner l'effet de l'angle de visée sur la réponse radar. Les mesures du diffusiomètre (bandes C et L, dans quatre combinaisons linéaires de polarisation transmise-reçue) furent prises dans des parcelles de maïs et d'orge dont les traitements variaient en termes de quantité et de teneur en eau des résidus. Les expériences ont démontré que les résidus agricoles peuvent retenir des quantités significatives d'eau et qu'ils ne sont pas transparents aux hyperfréquences incidentes. Le couvert de résidus va entraver l'utilisation des capteurs radar pour la cartographie de la teneur en eau du sol. La quantité et la teneur en eau des résidus étaient correlées avec le signal radar rétrodiffusé, les corrélations les plus fortes étant associées aux traitements de résidus de maïs, la bande C croisée et les grands angles d'incidence. La diffusion polarisée n'était pas sensible aux effets de la direction de visée. Les résultats de ces expériences indiquent que la rétrodifussion croisée pourrait être utilisée pour obtenir de l'information sur les pratiques culturales de conservation.

INTRODUCTION

When preparing the soil for planting, agricultural fields are usually tilled in the fall following crop harvest, and/or in the spring prior to seeding. The tillage practices used, however, vary greatly in the frequency at which they are applied and in the tillage implements used. Tilling the soil affects the surface soil properties and is a determining factor in the susceptibility of the topsoil to erosion. Consequently, farmers are encouraged to reduce the number of tillage passes and to use conservation tillage implements, particularly on soils that are highly erodible. Adoption of conservation tillage also means that significant amounts of post-harvest crop residue are left on the field. Under this management approach, soil structure is maintained, organic matter levels are improved and the surface of the soil is left with a protective cover (Logan *et al*., 1991). On fields where conservation management is practised, the effects of wind and overland water runoff are minimized and erosion of the topsoil is significantly reduced.

A dramatic decrease in the amount of soil erosion occurs with the retention of even small amounts of crop residue. On surfaces with as little as 15% corn residue cover, soil loss is 75% of that on conventionally tilled surfaces (Ketcheson and Stonehouse, 1983). When larger percentages of residue are retained, as occurs under conservation tillage, even larger reductions in soil loss are realized (Moore *et al.*, 1988). Models that estimate soil erosion rates include the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965), the Wind Erosion Prediction Project (WEPP) (Laflen *et al.*, 1991), and the Wind Erosion Equation (WEQ) (Larney *et al.*, 1995). These models require information about post-harvest management practices. However, gathering tillage and crop residue information at a regional or even local scale is an enormous challenge because of the acres involved and the changing conditions on the fields between harvest and seeding. It is equally difficult to assess the success of programs designed to encourage adoption of conservation tillage practices.

A number of in-field approaches to measuring crop residue cover have been developed, including the knotted rope (Coleman and Roberts, 1987), residue meters and residue wheels (Morrison *et al.*, 1993). However, these techniques are labour intensive and time-consuming and are therefore at a significant disadvantage when regional level monitoring is required. Some success has been reported in the use of remotely sensed imagery for mapping crop residue levels. McNairn and Protz (1993), Haboudane *et al.* (1997) and Bannari *et al.* (2000) have demonstrated that optical sensors are sensitive to the amount of residue left on a field. In spite of the success in mapping residue cover at infrared wavelengths, acquisition of cloud free data during the spring and fall is problematic.

Microwave imaging through cloud cover is possible and as a result, the use of synthetic aperture radar (SAR) for mapping conservation management practices would be advantageous, if sensitivity could be established. Earlier research has demonstrated that when a field is tilled and the surface roughness changes, radar backscatter will also change (Brisco *et al.*, 1991; McNairn *et al.*, 1996). SAR backscatter also appears to have some sensitivity to post-harvest residue (Smith and Major, 1996; McNairn *et al.*, 1998). However, many questions remain regarding the relationship between backscatter and various residue parameters including residue type and residue moisture content. If this sensitivity can be demonstrated, then the development of a conservation monitoring system, based on both radar and optical remote sensing data, would be possible.

An understanding of target-microwave interaction suggests that residue type, amount and moisture content will likely affect SAR response. To test this hypothesis, a ground-based scatterometer was used to assess the sensitivity of radar backscatter to a number of residue characteristics. The experiments were designed to address the following questions:

1. What effect do residue characteristics – residue moisture content, type and amount of residue, and residue row direction – have on radar backscatter?
2. Does residue cover affect the sensitivity of radar to surface soil moisture?
3. Which sensor configurations – frequency, polarization and incidence angle – provide the greatest sensitivity to residue characteristics?

METHODOLOGY

Experimental plots with different residue treatments were set up at the Central Experimental Farm of Agriculture and Agri-food Canada, in Ottawa (Canada) (45° 24’ N; 75° 42’ W). The Canada Centre for Remote Sensing (CCRS) ground-based microwave scatterometer (Sofko *et al.*, 1989) acquired data over the plots in the spring of 1996, with a more detailed experiment following in the fall of 1996. Data were collected on two dates during the spring experiment (April 23 and April 29). During the fall experiment, data collection followed wetting and drying events and in all, data were acquired on nine dates (September 19, 24, 25; October 1, 3, 25, 29, 31; November 5).

The experimental plots were on a well-drained sandy loam field. Topographic variations across the field were minimal, thus eliminating any effects associated with local incidence angle variations. The entire site was planted in corn in 1995, but was split between corn and barley during the 1996 growing season. Consequently corn residue was the focus of the spring experiment. Both barley and corn residue treatments were examined in the fall experiment.

For both experiments, plots measured at least 40 metres along each side. Six corn residue treatments were applied to the plots in the spring; four corn and four barley residue treatments were examined during the fall experiment (Table 1). Control plots with minimal residue (less than 10%) were also examined in each experiment. Different harvesting techniques (combine versus harvester) were used on each plot, thus leaving different amounts of residue. As well, the height at which the crop was cut during harvesting was varied and on some plots, the remaining standing residue was also mowed. These harvesting applications resulted in variations in the amount and orientation of residue from plot to plot. Creating residue treatments by varying the harvesting technique is preferable to creating these treatments by varying tillage. Although residue will vary when the soil is tilled, surface roughness will also vary, hence introducing another variable. Measurements collected using the chain method (Saleh, 1993) verified that differences in roughness among residue plots and between the residue and the control plots, were not significant.

Table 1. Description of the harvesting techniques and residue characteristics associated with the spring and fall scatterometer treatment plots

Treatment Number	Harvesting Technique	Residue Amount	Residue Position	Treatment Description
Spring 1996 – Corn Residue				
1	Harvester Low	Low (L)	Lying (L)	Crop harvested to leave 15 cm high residue. Residue cut with mot mower.
2	Harvester High	Intermediate (I)	Lying (L)	Crop harvested to leave 30 cm high residue. Residue cut with mot mower.
3	Bare (Control)			
4	Harvester Low	Low (L)	Standing (S)	Crop harvested to leave 15 cm high residue.
5	Harvester High	Intermediate (I)	Standing (S)	Crop harvested to leave 30 cm high residue.
6	Combine	High (H)	Standing (S)	Crop harvested to leave 50-90 cm high residue.
7	Combine	High (H)	Lying (L)	Crop harvested to leave 15 cm high residue. Residue cut with bush hogger.
Fall 1996 – Barley Residue				
1	Combine High	Intermediate (I)	Lying (L)	Crops harvested to leave 15-20 cm high residue. Cut straw was removed and remaining residue was mowed with bush hogger.
2	Combine High	Intermediate (I)	Standing (S)	Crops harvested to leave 15-20 cm high residue. Cut straw was removed.
3	Combine Low	High (H)	Lying (L)	Combine set low with straw spread over plot.
4	Combine Low	Low (L)	Standing (S)	Crops harvested to leave 2.5 cm high residue. Cut straw was removed.
5	Bare (Control)			
Fall 1996 – Corn Residue				
1	Harvester	Low (L)	Standing (S)	Crops harvested to leave 25-30 cm high residue.
2	Combine	High (H)	Standing (S)	
3	Combine	High (H)	Lying (L)	Standing residue cut with mower.
4	Harvester	Intermediate (I)	Lying (L)	Crop blown back onto plot.
5	Bare (Control)			

Coincident with scatterometer measurements, soil and residue ground data were collected on the experimental plots. Soil moisture measurements were taken at either 6 (spring experiment) or 16 (fall experiment) sites on each treatment plot (Table 2). A Time-Domain Reflectometer (TDR) (cable tester – Tektronix model 1502C) measured soil moisture at two depth ranges (0 to 5 cm and 0 to 10 cm) during both experiments. Soil core samples were gathered in the fall experiment to determine soil moisture from 0 to 3 cm. Soil samples were weighed wet and oven dried at 70°C for 48 to 72 hours, and then re-weighed to establish dry weight. Volumetric soil moisture for depths from 0 to 3 cm were then calculated using:

$$soil\ moisture = \frac{(wet\ weight\ -\ dry\ weight)}{volume\ of\ cylinder} \quad x \quad 100 \qquad [1]$$

To establish moisture levels in the residue, residue samples were gathered at all 16 sites in each plot, during the fall experiment (Table 2). At each site, all residue within a standard 0.5 m x 0.5 m square was collected. These samples were immediately weighed to establish wet weight, and then as with the soil samples, oven dried and re-weighed. Gravimetric residue moisture was calculated by:

$$residue\ moisture\ = \frac{(wet\ weight\ -\ dry\ weight)}{wet\ weight} \quad x \quad 100 \qquad [2]$$

The knotted rope (Coleman and Roberts, 1987) was used to estimate percent residue cover on each of the residue treatment plots for both experiments (Table 2). For the fall experiment, surface roughness estimates were also collected on the control plot. The SRM-200 (Johnson *et al.*, 1993) established a mean roughness (Root Mean Square) on this bare plot of 0.98 cm. Although the presence of residue prevented the use of this instrument on the other treatment plots, the chain method established that roughness among all plots was similar.

Table 2. Soil and residue ground data collected during the spring and fall scatterometer experiments

Parameter	**Technique**	**Depth (cm)**	**Measurements Taken Per Plot *Per Day***	**Measurements Taken Per Plot**	**Plots Measured**
Spring Experiment (2 Measurement Days)					
Soil Moisture	TDR	0-5 and 0-10	6		All
Percent Residue	Knotted rope			5	Residue
Fall Experiment (9 Measurement Days)					
Soil Moisture	Gravimetric	0-3	16		All
Soil Moisture	TDR	0-5 and 0-10	16		All
Percent Residue	Knotted rope			8	Residue
Residue Moisture	Sample		16		Residue
Surface Roughness	Chain			16	All
Surface Roughness	SRM-200			16	Control

The truck-mounted scatterometer of the Canada Centre for Remote Sensing collected data in C- (5.17 GHz) and L- (1.5 GHz) Bands and at a range of incidence angles (20°, 30°, 40°, 50°). Backscatter was recorded for all four transmit-receive linear polarization combinations (HH, VV, HV, VH). Reciprocity of HV and VH was assumed and consequently, data collected at only one cross-polarization was used in the analysis. The scatterometer collected data at a look direction perpendicular to the rows of corn residue during the spring experiment, but at both parallel and perpendicular look directions for the corn and barley residue plots in the fall. In this fall experiment acquisitions were timed to capture both moist residue conditions following rain events, as well as conditions during dry down of the residue and soil (Figure 1).

The scatterometer truck followed a track that was offset approximately three metres out from the plots for each successive incidence angle acquisition (from 20^o to 50^o). This adjustment helped to ensure that approximately the same area was illuminated at each incidence angle. As well, the size of the scatterometer foot print (approximately 1 metre at L-Band) relative to the plot dimensions meant there would be a minimum of 30 spatially independent scatterometer measurements per acquisition. This sampling strategy reduces the effects of fading inherent in radar systems and is consistent with recommendations by Sofko *et al.* (1989)

Prior to each acquisition, measurements were made over the same grassed area and the same asphalt area to test for consistent scatterometer operation. Also, once during each experiment the calibration of the scatterometer was checked using a corner reflector set up at the Experimental Farm. The corner reflector has a known radar cross-section and responses from the reflector are used to determine radar gain. Results indicated that the gain was constant with range and was consistent with previously measured gains, to within approximately 1 dB. Details of the system, its operation and calibration procedures are provided in Sofko *et al.* (1989).

Simple and multivariate regression analyses were used to establish the relationship between backscatter and the soil and residue characteristics. Separate correlations were generated for corn and barley treatments. Multiple range tests were used to test the statistical separability of the residue treatments. The Duncan's Multiple Range Test is similar to a simple t-test. However, multiple range tests take into account the fact that more than two samples were taken and thus these tests are a more conservative estimate of the significance of mean differences (Steel and Torrie, 1980).

RESULTS AND DISCUSSION

Results From the Spring Scatterometer Experiment

For the spring experiment, data were acquired over corn residue plots with a look direction perpendicular to the rows. Both percent corn residue and soil moisture (0 to 5 cm) data were collected coincident with the scatterometer acquisitions. In general, the amount of corn residue cover was significantly correlated with backscatter at both frequencies and all polarizations except C-VV (Table 3). A dominant vertical structure did not exist for most of the treatment plots. In particular, for plots harvested with a combine, the corn stalks were left in varying orientations.

For all polarizations, correlation coefficients were positive, indicating that increases in percent residue cover resulted in higher backscatter. In comparing coefficients generated for each incidence angle, the importance of incidence angle was not clear. For both C- and L-Bands, and particularly at shallower angles, HH and VH backscatter provided similar correlations with percent cover.

Simple correlations between surface soil moisture and backscatter were generally weak, although some coefficients for C-VV and C-VH exceeded 0.7 (Table 3). However, the strength of the correlation between backscatter and soil moisture was much weaker than expected, based on results reported in the literature from research on bare soil surfaces (Bruckler *et al.*, 1988; Bernard *et al.*, 1982). This suggests that the presence of residue cover impedes the interaction of microwaves with the soil surface. Residue is not transparent to incident microwaves and consequently, soil moisture cannot be mapped on fields with significant residue cover. The importance of residue to radar backscatter is likely dependent upon how much moisture is present in the residue (Smith and Major, 1996). Residue will be more of a factor in backscatter response when the residue is wet, as occurs immediately following a rain event and prior to dry down of the residue. Correlations between L-Band backscatter and soil moisture were either weak or were not significant, even though it was expected that this longer wavelength would penetrate the residue cover.

When both percent residue and soil moisture were included as independent variables, strong multivariate correlations were generated for all cases except C-VV. C-Band cross-polarized backscatter provided correlation coefficients (R-values) close to or exceeding 0.90 (Table 3). L-VH correlation coefficients were lower but generally greater than 0.75. For C-VH at steep angles, soil moisture was the dominant variable, although as the microwaves interacted more with the residue cover at shallower angles both variables contributed equally. The strong correlations with cross-polarized backscatter suggest that multiple scattering during target-microwave interaction is an important scattering mechanism. Both simple and multivariate correlation coefficients indicated that although residue contributions were important, soil moisture still contributed to the backscatter for some configurations.

Table 3. Simple and multivariate correlation results derived from regression of backscatter against soil and residue properties (results from the spring scatterometer experiment)

		Multivariate Regression Results (R-values) (independent variables are % residue and % soil moisture)				**Simple Regression Results (R-values)**							
						Percent Residue Cover				**Soil Moisture (0 to 5 cm)**			
		Incidence Angle (Degrees)				**Incidence Angle (Degrees)**				**Incidence Angle (Degrees)**			
		20	**30**	**40**	**50**	**20**	**30**	**40**	**50**	**20**	**30**	**40**	**50**
CHH	**Multiple R-value**	**.625**	**.871**	**.751**	**.833**	NS	**.717**	**.585**	**.723**	**.588**	NS	NS	NS
	Beta coefficient (soil)	**.607***	**.502**	**.478**	**.419**								
	Beta coefficient (residue)	NS	**.804***	**.667***	**.769***								
CVV	**Multiple R-value**	**.687**	**.783**	**.620**	**.510**	NS	NS	NS	NS	**.680**	**.767**	**.617**	**.475**
	Beta coefficient (soil)	**.697***	**.795***	**.628***	**.508***								
	Beta coefficient (residue)	NS	NS	NS	NS								
CVH	**Multiple R-value**	**.911**	**.913**	**.881**	**.842**	**.651**	**.686**	**.688**	**.669**	**.760**	**.733**	**.682**	**.639**
	Beta coefficient (soil)	**.760***	**.733***	**.682**	**.639**								
	Beta coefficient (residue)	**.651**	**.686**	**.688***	**.669***								
LHH	**Multiple R-value**	**.891**	**.794**	**.826**	**.772**	**.783**	**.596**	**.667**	**.697**	NS	NS	NS	NS

	Beta coefficient (soil)	**.431**	**.533**	**.495**	**NS**								
	Beta coefficient (residue)	**.858***	**.668***	**.752***	**.775***								
LVV	**Multiple R-value**	**.922**	**.567**	**.908**	**.897**	**.779**	**NS**	**.575**	**.632**	**NS**	**.521**	**.593**	**.518**
	Beta coefficient (soil)	**.501**	**.560***	**.714***	**.647**								
	Beta coefficient (residue)	**.865***	**NS**	**.698**	**.744***								
LVH	**Multiple R-value**	**.807**	**.792**	**.754**	**.733**	**.775**	**.703**	**.625**	**.707**	**.395**	**.506**	**.543**	**NS**
	Beta coefficient (soil)	**.395**	**.506**	**.543**	**NS**								
	Beta coefficient (residue)	**.775***	**.703***	**.625***	**.707***								

NS = not statistically significant at a probability level (p) < 0.05

Note: The asterisk (*) indicates the independent variable that provided the largest contribution to the multivariate model. The Beta coefficients generated during the multivariate analysis provide a relative measure of the significance of each variable (percent residue and soil moisture) to the full multiple regression model.

Results From the Fall Scatterometer Experiment

Assessing Residue Moisture Content

In research related to radar remote sensing of agricultural soil surfaces, residue contributions to backscatter have often been assumed to be negligible. The assumption is that as dry matter, residue holds insignificant amounts of moisture and is thus transparent to incident microwaves. Radar theory dictates that moisture must be present in such targets for significant scattering to occur.

Results from the spring experiment demonstrated that residue is not transparent to microwaves and it was hypothesized that residue moisture content was important in determining the sensitivity of radar to residue cover. In the fall experiment, residue moisture derived from samples collected from the barley and corn treatment plots indicated that crop residue can hold significant amounts of moisture. However, moisture levels were strongly dependent upon meteorological conditions and residue type (Figure 2). Corn residue retained as much as 50 to 60% moisture following a rain event. Under similar soil moisture conditions corn residue contained 5 to 10% more moisture than barley residue. Observations also suggested that moisture in the residue tended to increase and decrease relatively quickly in response to wetting and drying events. However, the residue moisture data also revealed that once the finer barley residue was relatively dry (less than 20% moisture content) further losses in residue moisture were small.

Assessing Radar Look Direction Effects

The direction from which the scatterometer views the target can significantly affect backscatter response. In the case of tillage effects, tillage row direction is a factor, and backscatter is significantly greater when the scatterometer look direction is perpendicular to the row direction (McNairn *et al.*, 1996). To examine backscatter dependence on residue row direction, a Duncan's Multiple Range Test was applied to the C-Band data from the fall experiment. In this experiment, the scatterometer acquired data with the look direction both perpendicular and parallel to the residue rows.

Results indicated that for corn residue, like-polarized backscatter was particularly sensitive to row effects, although residue row direction for barley was a factor only at steep incidence angles (Table 4). Even at an incidence angle of 20°, backscatter differences associated with barley residue row direction were not significantly above the calibration accuracy of the instrument. These differences between barley and corn residue row effects suggested that sensitivity to row direction is a function of the size of the residue relative to the wavelength. Both Cihlar *et al.* (1987) and Brisco *et al.* (1991) also reported that row direction effects associated with tillage and residue were significant for like-polarized backscatter.

For both types of residue, cross-polarized backscatter was not sensitive to row direction effects. These polarization responses are a result of multiple scattering within the target, and in contrast with like-polarized behaviour, are less dependent upon the orientation of the target components. For imagery acquired using like-polarizations, the dependence of backscatter on look direction as occurs in the "bow tie" effect, will impede the use of radar for operational monitoring. However, the lack of sensitivity to residue row direction for cross-polarized backscatter suggests that the use of this polarization for operational residue mapping would provide an advantage over like-polarizations, especially for residues such as corn.

Table 4. Comparison of C-Band backscatter acquired at look directions both parallel and perpendicular to row directions during the fall scatterometer experiment

	C-HH	**C-VV**	**C-VH**
Corn Residue			
20°	✓	✓	NS
30°	✓	✓	NS
40°	✓	✓	NS
50°	✓	✓	NS
*Difference**	3-4 dB	2-4 dB	
Barley Residue			
20°	✓	✓	NS
30°	NS	NS	NS
40°	NS	NS	NS
50°	NS	NS	NS
*Difference**	1-2 dB	1-2 dB	

✓ = difference in backscatter was statistically significant (at a probability level (p) < 0.05) when backscatter from parallel and perpendicular look directions were compared
(NS indicates differences between parallel and perpendicular look directions were not significant)

*denotes how much higher backscatter was at a perpendicular look direction relative to a parallel look direction

Correlations Between Residue, Soil Characteristics, and Radar Backscatter

Backscatter is plotted as a function of incidence angle and residue treatment in Figures 3a and 3b. For corn residue, backscatter at angles of 40° or 50° was higher for most of the residue plots relative to backscatter from the control plot . For grain residue plots, separation among the various treatments was more difficult, particularly at steep angles. Like-polarized backscatter was higher for the control plot relative to the grain residue plots. At these very steep angles, like-polarized backscatter is responding to soil moisture on the bare plot, but is less affected by the residue covering the other treatment plots. As shown in Figure 3, like-polarized backscatter at incidence angles of 30^o or less may be useful in separating bare surfaces from those with barley residue cover. However this figure also demonstrates that at steep angles, further separation among barley residue levels may be very difficult if like-polarizations are used. Both the scatterometer calibration and the variance associated with the target characteristics must be considered when discussing the significance of backscatter differences among the residue treatments. For C-Band, the standard deviation associated with backscatter measurements was on the order of 1.8 dB, suggesting that differences in backscatter less than this cannot be considered significant. For L-Band, differences in the order of 2.5 dB would be required. Both the regression analysis and the multiple range tests applied to these data consider this variance when establishing statistical significance.

For both barley and corn residue cover, Figure 3 demonstrates the sensitivity of cross-polarized backscatter to residue treatments, particularly when data are gathered at shallower incidence angles. These results indicate that both C- and L-Band cross-polarized backscatter may be used to discriminate among corn residue management practices. For finer residues, like barley, fewer classes of residue would be discriminated.

(a) Barley Residue Results

Using data acquired during the fall experiment, the contribution of residue moisture to backscatter was assessed. Simple correlation results presented in Table 5 indicate that C-HH and C-VV backscatter were not significantly correlated with barley residue moisture at incidence angles steeper than 50^o and even at shallow angles, correlations were weak ($R < 0.6$). Smith and Major (1996) concluded that moisture on or in the barley residue was required in order to classify residue cover. Consequently, the low correlations with residue moisture suggest that using C-HH or C-VV backscatter for mapping fine residue classes may be difficult.

C-Band backscatter from the barley residue plots was significantly correlated with soil moisture at most incidence angles. However, as with the results of the spring experiment, correlation coefficients were lower than would be expected for bare agricultural fields, especially for data acquired at steeper incidence angles. For example, early RADARSAT-1 results established a correlation of 0.875 between surface soil moisture measured on bare fields and C-HH backscatter (Brisco *et al.*, 1996). Even though residue moisture was not strongly correlated with like-polarized backscatter, the residue cover affects the interaction between the microwaves and the soil surface. In almost all cases, simple correlations were strongest between backscatter and soil moisture at depths of 0 to 3 cm when compared to results for moisture measured at depths of 0 to 5 or 0 to 10 cm. These results suggest that on a residue-covered surface, C-Band microwaves were penetrating only the very top surface of the soil.

C-Band cross-polarized backscatter was significantly positively correlated with barley residue moisture at all incidence angles, although the strength of the relationship was only moderate (R-values between 0.58 and 0.67). This significant correlation indicates that volume scattering is important for these surfaces. Multiple scattering from within the volume is expected to result in depolarization of the incident electric field vector thus producing a significant cross-polarized response. Although surface soil moisture (0 to 3 cm) was significantly related to C-VH backscatter for some angles, correlation coefficients were weak. The sensitivity of cross-polarized backscatter to surface soil moisture for bare fields has been previously demonstrated (Hirosawa *et al.*, 1978). Consequently, these weak correlations suggest that even fine residues are not transparent to microwaves.

When percent soil moisture, percent residue cover and percent residue moisture were included in the regression model, differences in regression results as a function of polarization decreased significantly. For C-Band, multiple R-values generally fell in the range from 0.7 to 0.8 (Table 6). Soil moisture contributions appeared to be most important for like-polarized returns. Conversely, for cross-polarized backscatter the most important variable was residue moisture although soil moisture was still significant, particularly at a look direction parallel to residue rows. Multivariate models derived for cross-polarized backscatter were significant at all incidence angles. With inclusion of all three independent variables, as much as 60% of the variance in cross-polarized response was explained.

When compared to C-Band results, correlations between L-Band backscatter and measurements made on barley plots were generally weaker, particularly for the like-polarizations (Table 5). Like-polarized L-Band backscatter had no significant correlation with residue measurements at steep incidence angles and only a weak and inconsistent correlation at shallower angles. Interaction of microwaves is dependent on the relationship between elements in the scattering volume and the wavelength. Barley residue is generally much smaller than the incident L-Band microwaves (20 cm), suggesting reduced sensitivity to residue characteristics. The highest correlations were obtained for cross-polarized backscatter acquired at shallower incidence angles (exceeding 40^o). L-Band correlations with surface soil moisture were weak and generally poor relative to C-Band results. This weak dependence of backscatter on soil moisture was observed at all polarizations and incidence angles, and suggests that barley residue cover still impedes the interaction of the microwave signal with the soil surface, even at longer wavelengths.

Multiple regression results for the L-Band data indicated that for cross-polarized backscatter, barley residue characteristics (either percent cover or moisture) were the dominant contributors to variations in backscatter (Table 6). However, as with C-band, soil moisture was still important at a parallel look direction. The best correlations were again achieved for cross-polarized backscatter at shallow incidence angles. More than 60% of the variance in backscatter is then explained. Despite this observation, however, L-Band multivariate results were generally poor, especially for like-polarized backscatter.

Table 5. Simple correlation results derived from regression of backscatter against soil and residue properties (fall 1996 experiment on barley and corn residue treatments)

	Soil Moisture (0-3 cm)				Residue Moisture				Percent Residue			
	Incidence Angle				Incidence Angle				Incidence Angle			
	20	30	40	50	20	30	40	50	20	30	40	50
Barley Treatments – Correlation Coefficients (R) for Look Direction Parallel to Row Direction (n=40)												
CHH	.560	.620	.442	.493	NS	NS	NS	.414	NS	NS	NS	.499
CVV	.544	.733	.607	.761	NS	NS	NS	NS	NS	-.48	NS	NS
CVH	.506	.441	.478	.475	.617	.665	.628	.582	.407	.582	.524	.563
LHH	.365	.364	.438	.406	NS	NS	NS	NS	NS	NS	NS	.636
LVV	.383	.474	.403	.463	NS	NS	NS	NS	NS	NS	NS	.387
LVH	.532	.516	.618	.536	.537	.574	.635	.498	.442	.582	.584	.680
Barley Treatments – Correlation Coefficients (R) for Look Direction Perpendicular to Row Direction (n=40)												
CHH	.545	.368	NS	NS	NS	NS	NS	.563	NS	-.36	NS	NS
CVV	.447	.492	.591	.718	NS	NS	NS	.360	-.53	NS	NS	NS
CVH	.487	NS	NS	NS	.660	.672	.636	.608	NS	.428	.454	.439
LHH	NS	NS	NS	NS	NS	NS	.409	.525	NS	NS	NS	NS
LVV	NS	.328	NS	.438	NS	NS	NS	NS	NS	NS	NS	NS
LVH	.363	.329	NS	NS	.426	.424	.654	.611	NS	NS	NS	NS
Corn Treatments – Correlation Coefficients (R) for Look Direction Parallel to Row Direction (n=32)												
CHH	NS	NS	NS	NS	NS	.606	.705	.755	NS	NS	NS	.369
CVV	NS	NS	NS	NS	NS	.628	.652	.740	-.69	NS	NS	NS
CVH	NS	NS	NS	NS	.758	.767	.800	.812	NS	NS	.392	.408
LHH	NS	NS	NS	NS	.695	.538	.740	.712	.535	NS	.417	.467
LVV	NS	NS	NS	NS	.698	.377	.726	.739	.476	NS	NS	NS
LVH	NS	NS	NS	NS	.696	.622	.740	.731	NS	NS	.371	.378
Corn Treatments – Correlation Coefficients (R) for Look Direction Perpendicular to Row Direction (n=32)												
CHH	NS	NS	NS	NS	NS	NS	.441	.570	NS	NS	NS	NS
CVV	NS	NS	NS	.376	NS	NS	.466	.478	NS	NS	NS	NS
CVH	NS	NS	NS	NS	.679	.609	.611	.618	.408	.546	.430	.394
LHH	NS	NS	NS	NS	NS	NS	NS	.517	NS	NS	NS	NS
LVV	NS	.428	NS	.392	NS	NS	NS	NS	NS	-.38	NS	NS
LVH	NS	NS	NS	NS	.451	.468	.454	.544	.406	.374	NS	NS

NS = not statistically significant at a probability level $(p) < 0.05$

Table 6. Multiple regression results for barley residue plots (fall experiment)

Scatterometer Configuration		Multiple Regression Coefficient (R)	Independent Variables		
			Soil Moisture (0-3 cm)	Residue Moisture	Residue Cover
Look Direction Parallel to Residue Row Direction					
C-HH	**20°**	**0.701**	✓ *	✓	
	30°	**0.758**	✓ *		
	40°	NS			
	50°	**0.499**	✓		✓ *
C-VV	**20°**	**0.717**	✓ *	✓	
	30°	**0.827**	✓ *	✓	
	40°	**0.752**	✓ *	✓	
	50°	**0.825**	✓ *	✓	
C-VH	**20°**	**0.741**	✓ *	✓	
	30°	**0.777**	✓	✓ *	✓
	40°	**0.751**	✓	✓ *	
	50°	**0.745**	✓ *	✓	
L-HH	**20°**	NS			
	30°	NS			
	40°	**0.454**	✓ *		
	50°	**0.700**	✓		✓ *
L-VV	**20°**	NS			
	30°	**0.496**	✓ *		
	40°	NS			
	50°	**0.592**	✓ *	✓	
L-VH	**20°**	**0.670**	✓ *		
	30°	**0.740**	✓		✓ *
	40°	**0.782**	✓ *		✓
	50°	**0.792**	✓		✓ *
Look Direction Perpendicular to Residue Row Direction					
C-HH	**20°**	**0.802**	✓ *	✓	✓
	30°	**0.573**	✓ *		✓
	40°	NS			
	50°	**0.532**		✓ *	
C-VV	**20°**	**0.797**	✓ *	✓	✓
	30°	**0.775**	✓ *		✓
	40°	**0.705**	✓ *		✓
	50°	**0.740**	✓ *		
C-VH	**20°**	**0.717**	✓	✓ *	
	30°	**0.686**		✓ *	
	40°	**0.660**		✓ *	
	50°	**0.663**		✓ *	
L-HH	**20°**	NS			
	30°	NS			
	40°	NS			
	50°	**0.487**		✓ *	
L-VV	**20°**	NS			
	30°	NS			
	40°	NS			
	50°	NS			
L-VH	**20°**	**0.484**		✓ *	
	30°	**0.499**		✓ *	
	40°	**0.590**		✓ *	
	50°	**0.612**		✓ *	

✓ indicates which independent variables were significant ($p < .05$) in the multiple regression equation
*** indicates the independent variable with the largest contribution to the multiple regression model**

(b) Corn Residue Results

Correlations between backscatter and residue moisture were significant for the corn residue treatments (Table 5). C-Band backscatter was significantly dependent upon corn residue moisture at incidence angles shallower than 40^o for both C-HH and C-VV, and at all incidence angles for cross-polarized backscatter. The highest R-values were generated for C-VH with a look direction parallel to the row direction. Fifty-five to sixty-five percent of variance in C-VH backscatter on these corn plots was explained by differences in residue moisture content. Corn residue is comparable in size to the C-Band wavelength, resulting in an increased sensitivity when compared to the finer barley residues. In addition, a greater volume of corn residue is also present within the scatterometer footprint and corn residue holds more moisture relative to barley residue. Cross-polarized backscatter results indicated that multiple scattering from within the corn residue volume was important.

In general, C-Band backscatter and soil moisture on the corn residue plots were not significantly correlated, regardless of polarization or incidence angle. Corn residue has an even stronger masking effect, and consequently mapping soil moisture on fields covered with larger residues like corn is expected to yield poor results. Contributions from percent corn residue were significant for cross-polarized backscatter, although even at this polarization the relationship was generally weak.

Within the multivariate regression model, corn residue moisture was usually the largest contributor to C-Band backscatter (Table 7), with cross-polarized backscatter provided the highest correlations. Looking parallel to the rows of residue at shallow angles, as much as 79% of the variance in C-Band cross-polarized responses was explained by the three independent variables. Although percent residue and soil moisture had some effect on backscatter, residue moisture content was the most important factor. Again, look direction effects were not obvious for cross-polarized backscatter. However, for C-HH and C-VV, parallel look directions provided more significant results. Correlations tended to be slightly higher at shallow incidence angles, although improvements were small.

Simple regression results indicated that in almost all cases, the correlation between corn residue characteristics and L-Band backscatter was only weak to moderate (Table 5). About half the variance in backscatter could be attributed to residue moisture content. Percent residue cover, however, made only a small contribution to explained variance and only for some polarizations. Nevertheless, simple correlations for the corn residue plots were stronger than results derived for the barley residue plots, again suggesting that the amount and the size of the corn residue components are important parameters in the microwave interaction. The suggestion that the size of the residue relative to the wavelength is important was supported by the fact that L-Band results were generally weaker than results derived from the C-Band data. The strongest coefficients were associated with shallower incidence angles of 40 to 50^o. As with C-Band interactions with corn residue, L-Band backscatter was not correlated with soil moisture at most incidence angle – polarization combinations.

When multiple independent variables were regressed against L-Band backscatter, R-values generally fell between 0.6 and 0.8 (Table 7). Correlations using L-Band cross-polarizations were generally lower than those reported at C-Band. However, coefficients were still moderate (0.60) to strong (0.88) for cross-polarized backscatter. This result suggests that at L-Band multiple scattering with the corn residue and between the residue and the soil was still an important scattering mechanism. As with C-Band, corn residue moisture content had the highest contribution to backscatter for most radar configurations. The improved correlations at shallow incidence angles observed for the simple regressions were not obvious here. This multivariate model incorporated the contributions of both surface soil moisture and residue cover. Since the total backscatter from both soil moisture and residue was considered in this multivariate model, incidence angle effects were less apparent.

Table 7. Multiple regression results for corn residue plots (fall experiment)

Scatterometer Configuration		**Multiple Regression Coefficient (R)**	**Independent Variables**		
			Soil Moisture (0-3 cm)	**Residue Moisture**	**Residue Cover**
Look Direction Parallel to Residue Row Direction					
C-HH	**20°**	**0.448**			✓ *
	30°	**0.678**	✓	✓ *	
	40°	**0.833**	✓	✓ *	
	50°	**0.813**	✓	✓ *	
C-VV	**20°**	**0.764**		✓	✓ *
	30°	**0.714**	✓	✓ *	
	40°	**0.746**		✓ *	
	50°	**0.763**		✓ *	
C-VH	**20°**	**0.838**	✓	✓ *	
	30°	**0.843**	✓	✓ *	
	40°	**0.887**	✓	✓ *	✓
	50°	**0.865**	✓	✓ *	✓
L-HH	**20°**	**0.832**	✓	✓ *	✓
	30°	**0.623**	✓	✓ *	
	40°	**0.847**	✓	✓ *	
	50°	**0.826**	✓	✓ *	✓
L-VV	**20°**	**0.807**	✓	✓ *	✓
	30°	**NS**		✓ *	
	40°	**0.809**	✓	✓ *	
	50°	**0.751**		✓ *	
L-VH	**20°**	**0.835**	✓	✓ *	
	30°	**0.797**	✓	✓ *	
	40°	**0.876**	✓	✓ *	✓
	50°	**0.823**	✓	✓ *	✓
Look Direction Perpendicular to Residue Row Direction					
C-HH	**20°**	**0.597**	✓		✓ *
	30°	**NS**			
	40°	**0.670**	✓	✓ *	
	50°	**0.695**	✓	✓ *	
C-VV	**20°**	**0.561**	✓ *		✓
	30°	**0.567**	✓ *		✓
	40°	**0.579**		✓ *	

	50°	0.523		✓ *	
C-VH	20°	0.787		✓ *	✓
	30°	0.820	✓	✓ *	✓
	40°	0.811	✓	✓ *	✓
	50°	0.704		✓ *	✓
L-HH	20°	NS			
	30°	NS			
	40°	NS			
	50°	0.537		✓ *	
L-VV	20°	NS			
	30°	0.777	✓ *	✓	✓
	40°	NS			
	50°	0.629	✓ *		✓
L-VH	20°	0.733	✓	✓ *	✓
	30°	0.671	✓	✓ *	✓
	40°	0.647	✓	✓ *	✓
	50°	0.600		✓ *	

✓ indicates which independent variables were significant ($p < .05$) in the multiple regression equation
* indicates the independent variable with the largest contribution to the multiple regression model

Separating Corn and Barley Residue Treatment Plots Using C- and L-Band Backscatter

Regression results from both the spring and the fall experiments suggested that radar backscatter may be useful in classifying residue levels. To further investigate this potential, multiple range tests were used to determine whether plot average backscatter among the residue treatments, as well as between the residue treatments and the control plot, were statistically significant. All dates were pooled for this analysis and the test was run separately for each radar configuration.

After reviewing initial results from the multiple range tests, data acquired on the driest date were dropped from the analysis. Virtually no difference in backscatter was observed among the various barley residue plots on this date, when residue moisture was generally at or below 20%. Separation among residue treatments significantly improved after this date was removed from the analysis. This observation supports the importance of residue moisture in separating residue classes. Data acquired on all other dates were used in this analysis.

(a) Barley Residue Results

Using C-HH or C-VV configurations, in most cases barley residue plots were significantly different from the bare control plot at incidence angles of 30° or less (Table 8). Among the residue plots, for most incidence angles less than half of the treatments could be separated using C-HH or C-VV backscatter. Cross-polarized backscatter at shallower incidence angles could separate most residue treatments.

Regression analysis and multiple range test results were not consistent with respect to the importance of look direction. This observation, coupled with the results presented in Table 4, suggests that differences in backscatter as a function of radar look direction are likely not a significant factor for barley residue, beyond a 30^o incidence angle.

At an incidence angle of either 20 or 30^o, in many cases the presence of residue could be distinguished using either L-HH or L-VV (Table 8). However, L-Band like-polarized backscatter differences among many residue treatments were not statistically significant. L-VV, in particular, was not useful for separating the four residue treatments. Separation of residue treatments was significantly improved using cross-polarized backscatter at L-Band. At a shallow angle, cross-polarized backscatter was statistically different for almost all treatment pair comparisons. Differences in treatment separability as a function of radar frequency appears to be less important for cross-polarizations.

(b) Corn Residue Results

C-HH backscatter from the bare plot was significantly different than backscatter from the residue plots at both steep and shallow angles (Table 8). Again, in differentiating among residue treatments, shallower angles tended to be better. Results from C-VV were not as promising as results using C-HH, although in many cases backscatter from the bare plot was different from that of the residue plots. C-VV did not perform as well in identifying residue treatments, particularly for a look direction parallel to the rows.

At shallow angles, C-VH backscatter was able to differentiate almost all of the residue treatments. In addition, at incident angles of 40 or 50^o, C-VH backscatter could separate each residue plot from the bare plot, regardless of look direction. The improved separability of residue treatments with cross-polarized responses is supported by the regression results. These results reinforce the importance of cross-polarizations for this application.

As with barley residue plots, like-polarized L-Band backscatter was able to distinguish residue plots from the bare plot at a steep incidence angle. From data collected at these steep angles, most treatment pairs could be separated. L-Band cross-polarized backscatter from most corn plots was statistically different at incidence angles of either 40 or 50^o. In contrast with L-Band like-polarizations, separation of the bare plot from the residue treatment plot was improved at shallower incidence angles. Using backscatter acquired at a look direction perpendicular to the row direction only slightly improved treatment separation. These results support the conclusion that cross-polarized backscatter is not sensitive to look direction effects.

Table 8. Statistical separability of residue plots based on C- and L-Band multi-polarized backscatter (fall scatterometer experiment)

	Percentage of Treatment Comparisons That Were Statistically Separable (at p < 0.05)							
BARLEY RESIDUE	***Look Direction Perpendicular to Row Direction***				***Look Direction Parallel to Row Direction***			
	20°	**30°**	**40°**	**50°**	**20°**	**30°**	**40°**	**50°**
C-HH								
Among Residue Treatments	**67%***	**50%**	**33%**	**67%**	**33%**	**17%**	**50%**	**50%**
Control vs Residue	*100%***	*100%*	*50%*	0	*75%*	*100%*	*25%*	*25%*
C-VV								
Among Residue Treatments	**67%**	**50%**	**50%**	**17%**	**33%**	**33%**	**50%**	**0**
Control vs Residue	*100%*	*100%*	*75%*	0	*50%*	*100%*	*75%*	0
C-VH								
Among Residue Treatments	**50%**	**83%**	**83%**	**83%**	**50%**	**83%**	**67%**	**67%**
Control vs Residue	*75%*	*25%*	*50%*	*50%*	*25%*	*50%*	*50%*	*50%*
L-HH								
Among Residue Treatments	**50%**	**50%**	**83%**	**67%**	**67%**	**33%**	**67%**	**33%**
Control vs Residue	*100%*	*25%*	*50%*	*50%*	*50%*	*75%*	*50%*	*25%*
L-VV								
Among Residue Treatments	**50%**	**50%**	**33%**	**0**	**33%**	**17%**	**33%**	**33%**
Control vs Residue	*100%*	*25%*	*25%*	*100%*	*50%*	*100%*	*50%*	*50%*
L-VH								
Among Residue Treatments	**67%**	**83%**	**83%**	**83%**	**83%**	**83%**	**83%**	**100%**
Control vs Residue	*100%*	*75%*	*75%*	*100%*	*75%*	*75%*	*50%*	*100%*
CORN RESIDUE	**20°**	**30°**	**40°**	**50°**	**20°**	**30°**	**40°**	**50°**
C-HH								
Among Residue Treatments	**17%**	**50%**	**83%**	**67%**	**33%**	**50%**	**83%**	**83%**
Control vs Residue	*100%*	*75%*	*50%*	*100%*	*100%*	*100%*	*100%*	*100%*
C-VV								
Among Residue Treatments	**50%**	**67%**	**50%**	**0**	**33%**	**17%**	**33%**	**17%**
Control vs Residue	*75%*	*75%*	*100%*	*100%*	*100%*	*100%*	0	*25%*
C-VH								
Among Residue Treatments	**50%**	**67%**	**83%**	**50%**	**83%**	**83%**	**83%**	**83%**
Control vs Residue	*100%*	*100%*	*100%*	*75%*	*50%*	*50%*	*100%*	*100%*
L-HH								
Among Residue Treatments	**50%**	**17%**	**50%**	**50%**	**67%**	**50%**	**83%**	**83%**
Control vs Residue	*100%*	*100%*	*100%*	*100%*	*100%*	*50%*	*50%*	*50%*
L-VV								
Among Residue Treatments	**50%**	**50%**	**33%**	**0**	**67%**	**50%**	**50%**	**50%**
Control vs Residue	*100%*	*50%*	*100%*	*100%*	*100%*	*75%*	*75%*	*25%*
L-VH								
Among Residue Treatments	**100%**	**83%**	**83%**	**83%**	**50%**	**83%**	**100%**	**83%**
Control vs Residue	*75%*	*75%*	*100%*	*100%*	*50%*	*75%*	*75%*	*100%*

* **67%** indicates, for example, that for 4 out of 6 residue treatment comparisons, backscatter between the residue treatment plots was statistically different

** *100%* indicates, for example, that backscatter from the control plot was statistically different from backcatter for each of the 4 residue plots

CONCLUSIONS

Results from two microwave scatterometer experiments conducted on the Central Experimental Farm of Agriculture and Agri-food Canada clearly demonstrated that crop residues can hold significant amounts of moisture, as much as 60% for large corn residues and 40 to 50% for finer barley residues. Residue moisture content was very dynamic, and moisture levels changed significantly during wetting and drying events. Correlation analysis determined that backscatter increased with increasing residue moisture levels and increasing percent residue cover. The strength of this correlation was clearly dependent upon the sensor configurations and the characteristics of the residue. Relative to barley residue, stronger correlations were associated with the corn residue treatments. In comparing results generated for all radar configurations, the highest coefficients were achieved with C-Band cross-polarized backscatter acquired at shallower incidence angles. Radar will provide good information on corn residue. However, it will likely be more difficult to distinguish among finer residue classes.

Cross-polarizations were sensitive to both corn and barley residue treatments and were strongly correlated with residue conditions. The sensitivity of cross-polarized backscatter suggests that significant depolarization of incident microwaves occurs within the residue cover. Cross-polarized backscatter has the added advantage of being insensitive to radar look direction relative to residue row direction. For these reasons, cross-polarized backscatter appears to be particularly attractive for use in conservation tillage mapping.

This study demonstrated that residue cover is not transparent to microwaves. For most radar configurations, correlations between surface soil moisture under a residue cover, and backscatter, were either weak or not significant. Consequently, significant residue cover will impede the use of radar sensors for surface soil moisture mapping.

Like-polarized backscatter (C- and L-Band) at steep incidence angles (20 to 30^o) was useful for separating residue from bare soil plots. This suggests that current spaceborne SAR systems can provide some information on residue management practices. For fine residue such as barley, RADARSAT-1 (at steep incidence angles) and ERS-2 could be used to differentiate bare surfaces from those with residue cover. If RADARSAT-1 data are acquired at shallower incidence angles and the residue is wet, some additional information will be provided on residue cover. For larger residues such as corn, C-HH backscatter can be used to identify if the surface is covered with residue and may provide additional information about harvesting techniques and amount of residue. For all residue types, cross-polarized backscatter appears promising for mapping residue characteristics, and consequently the use of RADARSAT-2 or ENVISAT’s ASAR sensor for this application should be investigated.

If SAR imagery is to be used for residue mapping, careful attention must be given to the timing of data acquisition, as well as the SAR configurations used. Separation of residue classes is likely to be better after a rain event when residue is wet. From the results presented here, steeper incidence angles may be able to mask out or separate bare fields from fields with residue cover. Data acquired at shallower angles could then provide separation among those fields identified as residue-covered.

An earlier study used RADARSAT-1 imagery and concluded that three classes of residue could be derived from these images (McNairn *et al*., 1996). The scatterometer results presented in this paper confirm that radar backscatter is sensitive to crop residue. However conditions on agricultural fields are complex, with soil and residue characteristics changing temporally, varying across fields, and varying from one field to the next. Although these scatterometer results are encouraging, care must be taken in extrapolating results from controlled experiments to operationally mapping exercises. In particular, identifying residue cover will be complicated if significant surface roughness is present, as occurs following primary soil tillage. In these cases, very rough surfaces could be confused with surfaces having high residue cover. This confusion will likely be most pronounced for finer residues. Less confusion between residue and roughness would exist following secondary and tertiary tillage when surface roughness is reduced. It is still unclear whether radar can provide the level of detail on residue cover conditions that is required for erosion modelling. Nevertheless, radar imagery will be able to provide some information on residue management practices for use in monitoring soil conservation practices.

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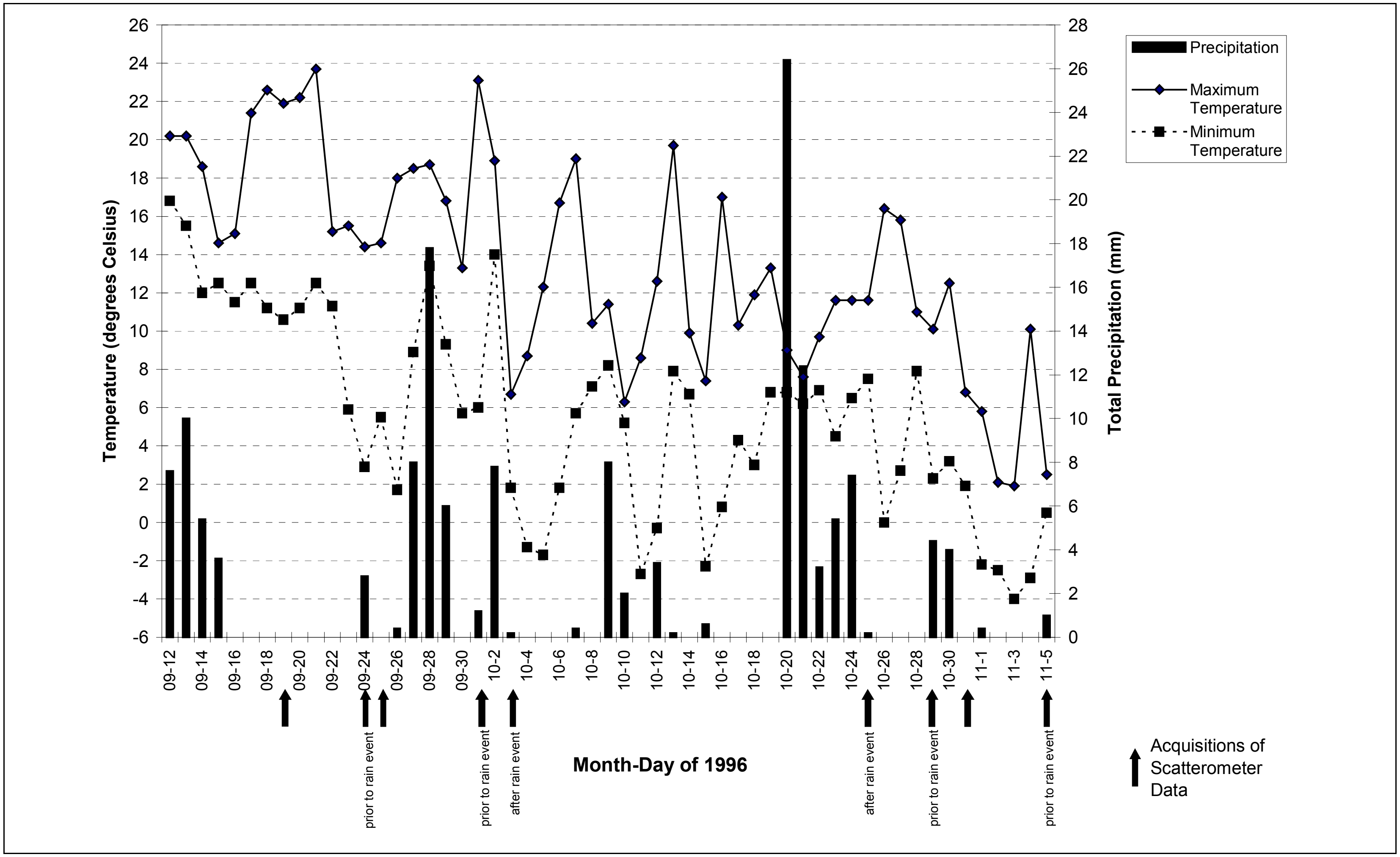

Figure 1

Total precipitation (mm), maximum temperature (^{o}C) and minimum temperature (^{o}C) for each day during the fall scatterometer experiment (September 12, 1996 to November 5, 1996). Days on which scatterometer measurements were taken are indicated with an arrow.

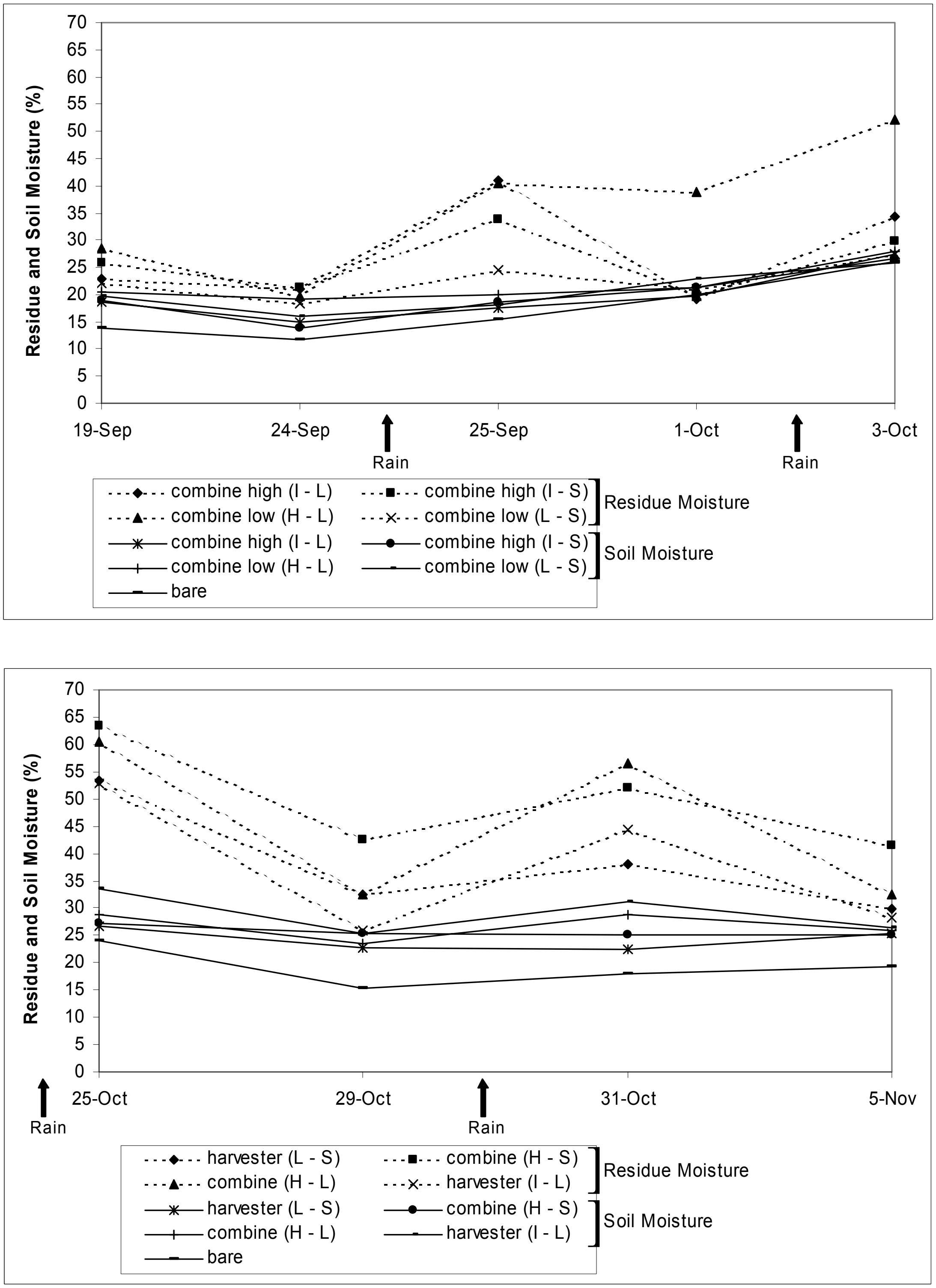

Figure 2
Moisture levels for soil and residue associated with wetting and drying events. In these graphs, changes in residue moisture (dashed lines) and soil moisture (solid lines) are presented for the fall scatterometer experiment. Results are given for barley residue (top graph) and corn residue (bottom graph) for each of the five treatment plots. Treatments are identified by the harvesting implement, as well as the amount of residue left (H = high; I = intermediate; L = low) and whether the residue was mowed (L = lying) or left standing (S = standing).

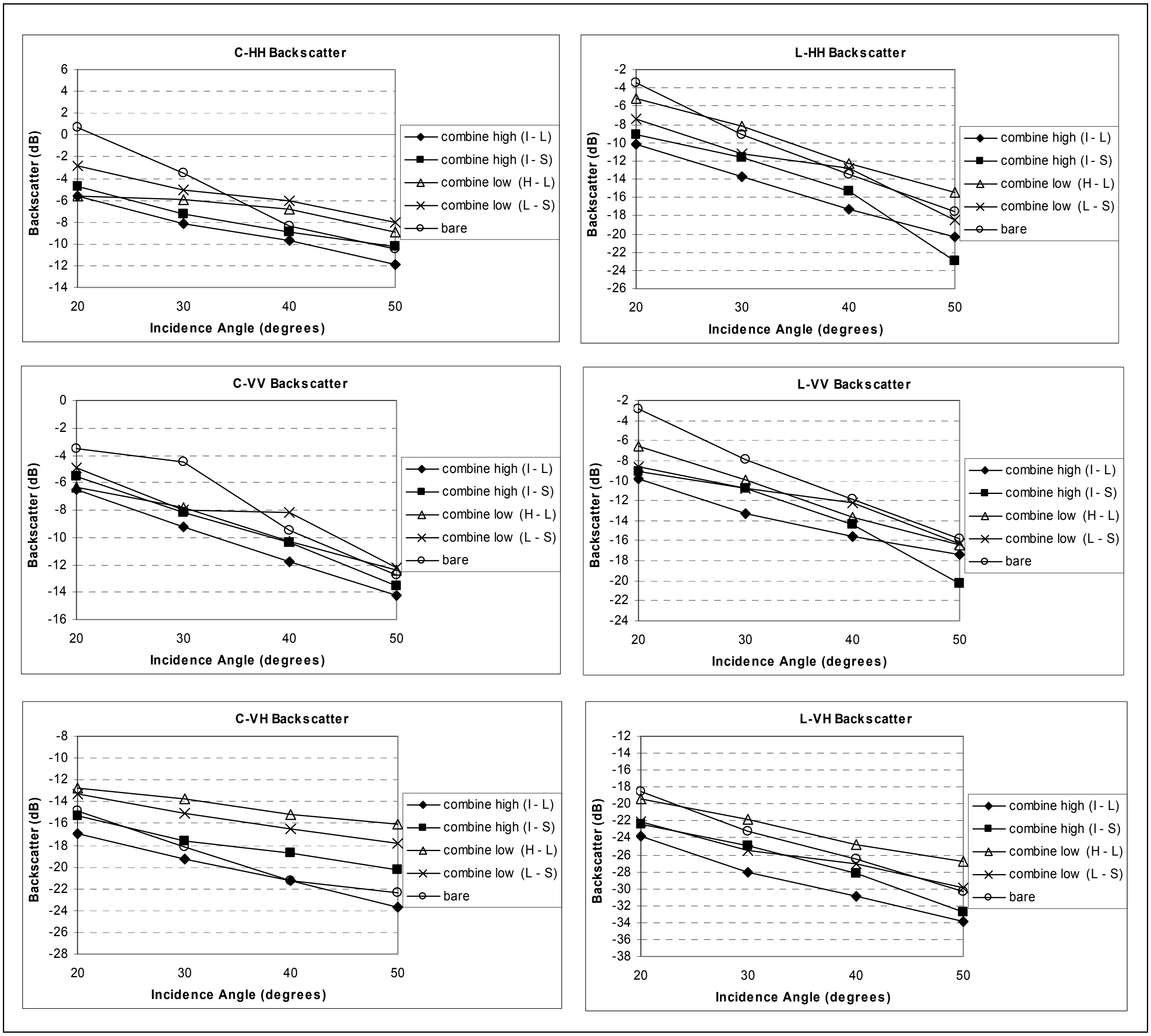

Figure 3a
Backscatter acquired on barley residue plots, at a look direction parallel to the residue row direction. In the line graphs presented in this figure, backscatter is plotted as a function of incidence angle for each residue treatment. Only data acquired on September 25 are presented here. Treatments are identified by the harvesting implement, as well as the amount of residue left (H = high; I = intermediate; L = low) and whether the residue was mowed (L = lying) or left standing (S = standing). On average, the standard deviation associated with the backscatter measurements was 1.84 dB for C-Band and 2.44 dB for L-Band.

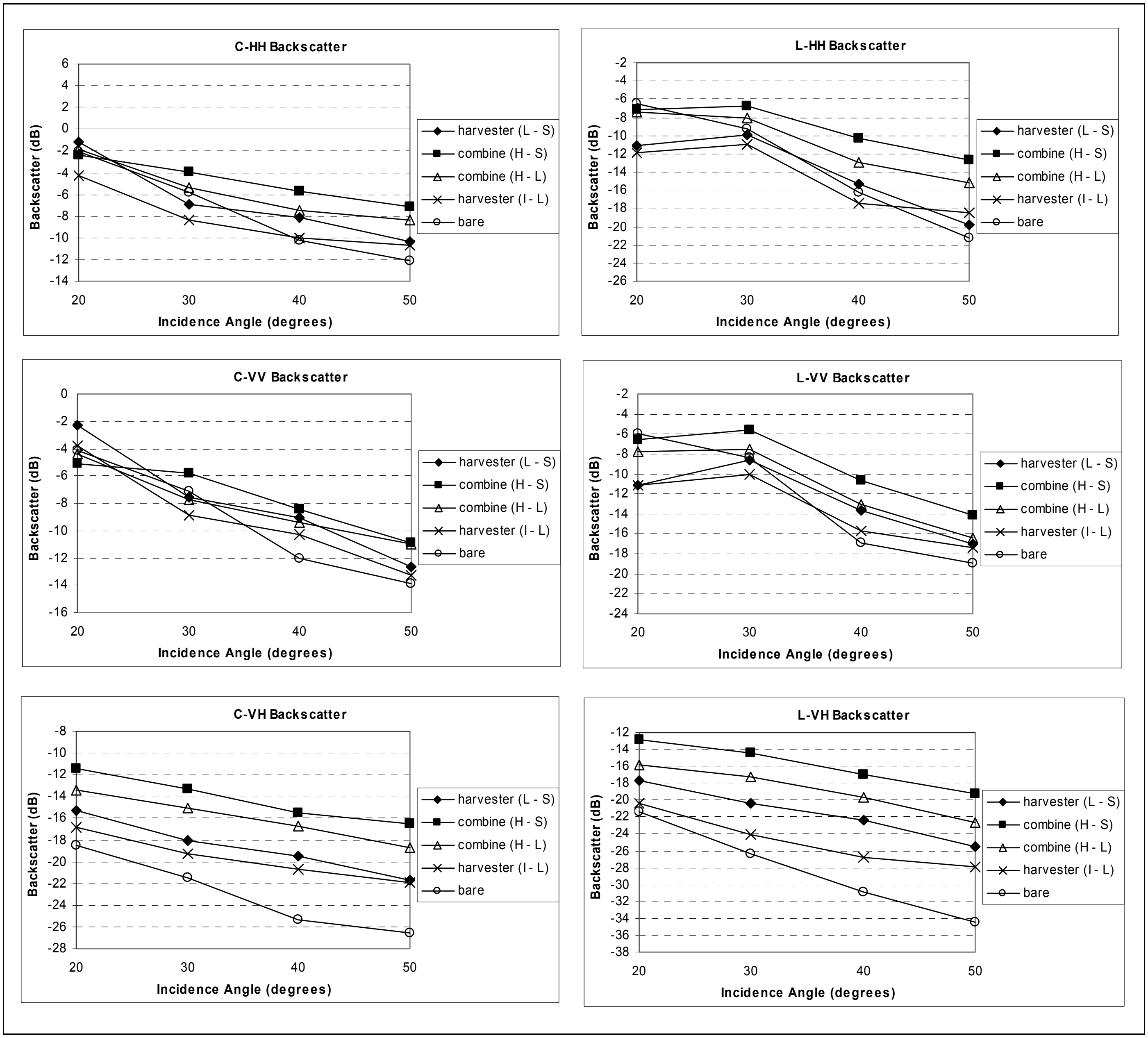

Figure 3b
Backscatter acquired on corn residue plots, at a look direction parallel to the residue row direction. In the line graphs presented in this figure, backscatter is plotted as a function of incidence angle for each residue treatment. Only data acquired on October 29 are presented here. Treatments are identified by the harvesting implement, as well as the amount of residue left (H = high; I = intermediate; L = low) and whether the residue was mowed (L = lying) or left standing (S = standing). On average, the standard deviation associated with the backscatter measurements was 1.88 dB for C-Band and 2.53 dB for L-Band.