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ABSTRACT

Airborne L- and C-band scatterometer data, taken over both vegetation-covered and bare fields, were systematically analyzed and theoretically reproduced, using a recently developed model for calculating radar backscattering coefficients of rough soil surfaces. The results show that the model can reproduce the observed angular variations of radar backscattering coefficient quite well via a least-squares fit method. Best fits to the data provide estimates of the statistical properties of the surface roushness, which is characterized by two parameters: the standard deviation of surface height, and the surface correlation length. In addition, the processes of vegetation attenuation and volume scattering require two canopy parameters, the canopy optical thickness and a volume scattering factor. Canopy parameter values for individual vegetation types, including alfalfa, milo and corn, were also determined from the best-fit results. The uncertainties in the scatterometer data were also explored. Best-fit results indicate that the scatterometer data probably have random uncertainties in the order of 2 dB, as indicated by the range of surface height standard deviation. In addition, supporting evidence shows that the C-band data should be systematically reduced by 3 dB for all measurements in order to produce reasonably good results, as expected.

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SECTION 1 - INTRODUCTION

Active remote sensing of Earth resources using radar has been studied theoretically and experimentally by many investigators [1-17]. It has been shown that the radar backscattering coefficient of Earth terrain depends on soil moisture, surface roughness and vegetation covers [2-17]. Analysis of the measured radar backscattering coefficients involves many parameters, values of which are usually difficult to obtain over natural and agricultural areas. Recently there have been accumulated many measurements of the microwave backscatter from the Earth's surface, using airborne scatterometers at various frequencies [12-15]. Mo et al., [6] have theoretically modeled the measured angular distributions of the radar backscattering coefficients of grass-covered watersheds (taken by Jackson et al., [12, 13]), using a newly developed model, which, in addition to the vegetation canopy scattering effect, includes both coherent and incoherent components of the backscattered radar signals from a vegetation-covered rough soil surface. Their model results [6] demonstrate excellent agreements with the airborne scatterometer data taken near Chickasha, Oklahoma in 1978 and 1980 at the 1.6 GHz (L-band) and 4.75 GHz (C-band) frequencies.

A large collection of scatterometer data given by Jones et al., [15] have not been similarly analyzed. These backscattering and soil moisture data were collected at two agricultural areas: Guymon, Oklahoma in 1978 and Dalhart, Texas in 1980 [14, 15]. The scatterometer data were taken over alfalfa-, milo- and corn-covered fields, in addition to bare soil surfaces.

This study represents a systematic analysis of these scatterometer data, using the theoretical model developed by Mo et al., [6]. It takes into account of the variability of soil moisture, surface roughness, canopy volume scattering and two-way attenuation of the vegetation layer. The main objectives of the study are to test the model on a large data base representative of a wide range of vegetation, terrain, and soil types, such as the one collected by Jones et al., [15], and to reproduce the observed angular variations of backscattering coefficients, using the least-squares fit method.

Best-fits to the scatterometer data of various vegetation-covered and bare soil surfaces produce numerical values of the soil surface statistical parameters: the standard deviation σ of surface height and its correlation length ℓ. These two parameters characterize the roughness of a soil surface. Detailed discussions of these parameters for each vegetation type will be presented in Section [illegible].

SECTION 2 - THE METHOD

In a recent paper, Mo et al., [6] developed a method for simulating the remotely sensed radar backscattering coefficient of grass-covered watersheds, and their model results show good agreements with the measured angular distributions of the radar backscattering coefficient for HH polarization at the L- and C-band frequencies. In this study, the same method is applied to model the scatterometer data collected by Jones et al., [15]. In the model the scattering of the radar waves from rough soil surfaces are effectively modeled by the Kirchhoff approach, as described by Fung and Eom [2, 3], and by Ulaby et al., [5].

The model includes both coherent and incoherent components of the backscattered radar waves from vegetation-covered rough soil surfaces, which are characterized by two parameters: σ, the standard deviation of surface height, and ℓ, the surface correlation length. The effect of vegetation canopy scattering and absorption (or attenuation) are also included in the model by a simple parametric formula, which contains two vegetation-dependent parameters: η, the canopy volume scattering factor, and τ, the canopy optical thickness. Only the main formulas of the model are presented below, and the detailed descriptions can be found in Reference [6].

For a radar pulse incident on a vegetation-covered soil surface at an angle θ from the nadir, the backscattering coefficient $\sigma^o(\theta)$ can be written in the form [6, 10].

$$\sigma^o(\theta) = \sigma_v^o(\theta) + \sigma_s^o(\theta)\, e^{-2\tau/\cos\theta} \tag{1}$$

where

$$\alpha_v^o(\theta) = \frac{\eta \cos \theta}{2\tau} (1 - e^{-2\tau/\cos \theta}) \tag{2}$$

and

$$\sigma_s^o(\theta) = \sigma_{coh}^o(\theta) + \sigma_{inc}^o(\theta) \tag{3}$$

where $\sigma_v^o(\theta)$ = vegetation backscattering coefficient

$\sigma_s^o(\theta)$ = soil surface backscattering coefficient

$\sigma_{coh}^o(\theta)$ = coherent component of backscattering coefficient of soil surfaces

$\sigma_{inc}^o(\theta)$ = incoherent component of backscattering coefficient of soil surfaces

The coherent scattering component occurs only in the specular direction and its magnitude along this direction can be approximated by [6],

$$\sigma_{coh}^o(\theta) = 4\pi \, |R_{pp}|^2 \cos \theta \exp(- h \cos^2 \theta) \tag{4}$$

where $h = 4k^2\sigma^2$, and the quantity $|R_{pp}|^2$ represents the reflectivity of a smooth surface for pp (= HH or VV) polarization. The $k = 2\pi/\lambda$ is the wave number of the incident wave and σ is the standard deviation of surface height.

The quantity $\sigma_{coh}^o(\theta)$ is important only when θ is small. It has been shown [6] that the contribution from $\sigma_{coh}^o(\theta)$ with $\theta \geq 15^o$ can be ignored, if an appropriate antenna gain pattern is adopted.

The incoherent scattering component $\sigma^o_{inc}(\theta)$ in Equation (3) depends on the statistical properties of the surface roughness: σ, the standard deviation of surface height, and ℓ, the surface correlation length. Assume that a rough soil surface has a Gaussian surface correlation function $\rho(\xi) = \exp(-\xi^2/\ell^2)$, then the incoherent backscattering coefficient $\sigma^o_{inc}(\theta)$ for polarization pp can be written in the form [6]

$$\sigma^o_{inc}(\theta) = (k\ell)^2 \left[|R_{pp}|^2 (1 + \sin^2\theta) + \mathrm{Re}(R_{pp}R^*_{pp1}) \sin 2\theta \right] \times e^{-h \cos^2\theta} \sum_{n=1}^{\infty} \frac{(h \cos^2\theta)^n}{n!n} \exp\left[- \frac{(k\ell \sin \theta)^2}{n} \right] \tag{5}$$

where R^*_{pp1} is the complex conjugate of R_{pp1}, which is a component of the reflectivity. For pp = HH, the explicit form of R_{HH1} is defined in Reference [6]. The quantity $|R_{pp}|^2$ was calculated from a radiative transfer model [18], using measured profiles of soil moisture and temperature.

For comparing with the data, the calculated backscattering coefficients need to be weighted with the antenna gain patterns and averaged over the illuminated target area bounded by the main antenna beam. Description of these treatments can be found in Reference [6].

SECTION 3 - THE DATA

The scatterometer data used in this study were collected by Jones et al., [15] at two agricultural areas: Guymon, Oklahoma in 1978 and Dalhart, Texas in 1980. The radar backscattering coefficients of alfalfa-, milo- and corn-covered and bare fields were taken with airborne scatterometers at L- and C-band frequencies from an altitude of 300 meter. The angular distributions of the backscattering coefficient were given in decibels (dB) at the incident angles of 5, 10, 15, 20, 25, 35, 40 and 45 degrees for each measurement. Soil moisture profiles and surface temperatures were also collected in conjunction with these aircraft data. Detailed descriptions of these data and field characteristics have been given elsewhere [14, 15].

Table 1 gives a summary of the main characteristics of the fields and some information related to the scatterometer data collection. During the data taking periods (August 1978 and 1980), most of the crops were near maturity, and some crops had high plant water contents, particularly those on the wet fields. One would expect that those plants with high water content have large canopy effect on the scattering and attenuation of the radar pulses.

Since no known technique or mechanism was available to calibrate the scatterometers absolutely [14], the available scatterometer data [15] are in relative values of backscattering coefficients. They may differ from the absolute backscattering coefficients by a constant calibration factor. On the other hand, theoretical model calculation predicts the absolute values of the backscattering coefficient. For comparing the data with the calculated results, we assume the relative scatterometer data differ from the absolute backscattering coefficients by a constant factor α (dB) at all angles for each measured angular distribution. The α value is determined by least-squares fits to the data, as described in the next section.

Best-fit results show that one can assume $\alpha = 0$ for L-band data and $\alpha = -3$ dB for all C-band data.

Table 1. Characteristics of the Fields and Scatterometer Data Used in This Study

VEGETATION	DATE	LOCATION	FREQUENCY (GHz)	VEGETATION HEIGHT (m)	PLANT WATER (kg/m^2)	SM RANGE (cm^3/cm^3)
BARE	AUGUST 1978	GUYMON, OK	1.6, 4.75	–	–	5 – 22%
ALFALFA	AUGUST 1978	GUYMON, OK	1.6, 4.75	0.5	3	7 – 30%
MILO	AUGUST 1978	GUYMON, OK	1.6, 4.75	1.0	1	2 – 16%
CORN	AUGUST 1980	DALHART, TX	1.6, 4.75	3.0	5	5 – 42%

SECTION 4 - THE RESULTS

The formulae given in Section 2 was employed in this study to fit the scatterometer data [15] at L- and C-band frequencies. The 3-dB beamwidth of L-band antenna pattern was taken to be $\beta \simeq 9^{\circ}$ according to Wang [19], and that of the C-band scatterometer had a much smaller value of $\beta \simeq 2.5^{\circ}$. The model results are only sensitive at forward angles ($\theta < 10^{\circ}$) to the β values. In the formulae, there are four adjustable parameters (i.e., $k\sigma$, $k\ell$, η and τ) which can be varied to obtain the best fits to the data. The first two parameters (i.e., $k\sigma$ and $k\ell$) specify the characteristics of the soil surface, and the last two (i.e., η and τ) describes the features of the vegetation cover, which is assumed to cover the soil surface uniformly.

The canopy optical thickness τ has been shown to be directly proportional to the canopy water content W (kg/m^2), and it can be described by the empirical relation [20]

$$\tau \simeq cW \qquad (6)$$

where c is a frequency dependent proportionality constant.

For L-band, The c value varies from 0.1 to 0.24 [20]. The c value for C-band is not well known at the present time, however previous investigation [20] indicates that the τ values for C-band are probably several times larger than those for L-band. Since the canopy water contents W were not measured, one can not estimate the τ values from Equation (6). In the present study, we treat τ as an adjustable parameter to fit the data.

The parameters η and τ can be mutually compensating. This is due to the fact that only the ratio (η/τ) appears in the formula, as defined in Equation (2).

In addition, one needs to determine the scatterometer calibration constant α as described in Section 3. Exploratory least-squares fits to the data show that one can fit all the L-band data satisfactorily by setting $\alpha = 0$. The best-fit parameter values for $k\sigma$ and $k\ell$, as shown in Tables 2 to 5 for different vegetation covers and bare fields, are reasonable and comparable to previously reported results [6].

However, for the C-band scatterometer data, least-squares fit results are consistently inferior to the L-band cases, if $\alpha = 0$ is maintained, and also the 'best-fit' parameter values for $k\sigma$ and $k\ell$ would be unusually large in comparison to expected results [6]. This indicates, perhaps, that the C-band scatterometer data are normally larger than the absolute values of the backscattering coefficient. Evidence to support this indication can be found in a recent scatterometer cross-calibration experiment [21], which measured the radar backscattering coefficients from the three scatterometer systems developed at Jet Propulsion Laboratory (JPL), Johnson Space Center (JSC), and Kansas University (KU) for HH polarization at both L- and C-band frequencies. It was found that the C-band data from the JSC system are consistently 3 to 5 dB higher than the KU results, and that the L-band data from the JSC and KU systems are comparable within experimental errors, except for corn- and soybean-covered targets, where the JSC data are greater than the KU observations by 1 to 5 dB [21]. The relative differences between the JPL and KU measurements are of the same order of magnitude (3 to 4 dB).

Table 2. Best-Fit Parameters for Alfalfa-Covered Fields at Guy on, Oklahoma. SM_V is the Volumetric Soil Moisture within the 0 - [illegible] cm Surface Layer.

DATE	SITE	L-BAND				C-BAND				SM_V (%)
		$k\alpha$	$k\ell$	η	τ	$k\alpha$	$k\ell$	η	τ	
8/05/78	4	0.15	3.85	0.010	0.51	1.04	8.05	0.075	0.74	16.7
8/08/78	4	0.12	3.33	0.009	0.18	–	–	–	–	21.3
8/11/78	4	0.10	3.14	0.002	6.4×10^{-5}	–	–	–	–	9.9
8/17/78	4	0.14	3.61	0.004	7.8×10^{-5}	0.75	7.46	0.015	0.10	7.3
8/02/78	13	0.26	2.40	0.017	0.39	0.86	5.72	0.054	0.46	14.2
8/05/78	13	0.13	2.61	0.006	4.6×10^{-6}	0.73	6.30	0.141	0.85	29.8
8/08/78	13	0.16	2.73	0.004	4.6×10^{-6}	0.89	6.59	0.063	0.84	23.5
8/11/78	13	0.17	2.75	0.004	3.1×10^{-6}	0.85	5.48	0.059	0.51	14.1
8/17/78*	13	0.20	3.45	0.015	0.01	0.79	6.96	0.049	0.37	23.0

*DATA ARE SHOWN IN FIGURE 1.

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Table 3. Best-Fit Parameters for Milo-Covered Fields at Guymon, Oklahoma. SM_v is the Volumetric Soil Moisture within the 0 - 2 cm Surface Layer.

DATE	SITE	L-BAND				C-BAND				SM_v (%)
		$k\sigma$	$k\ell$	η	τ	$k\sigma$	$k\ell$	η	τ	
8/02/78	8	0.14	3.46	0.018	0.44	0.80	8.19	0.028	0.01	2.3
8/05/78	8	0.22	2.62	0.008	0.43	0.79	7.41	0.040	0.50	7.2
8/08/78	8	0.21	2.76	0.004	0.03	–	–	–	–	4.8
8/17/78	8	0.33	2.74	0.014	0.19	0.83	5.65	0.028	0.04	3.2
8/02/78	1A	0.37	2.21	0.016	0.46	0.85	7.31	0.061	0.04	6.1
8/05/78*	1A	0.27	2.61	0.021	0.73	0.80	8.88	0.078	0.38	5.8
8/08/78	1A	0.35	1.82	0.009	0.46	–	–	–	–	5.8
8/11/78	1A	0.22	2.62	0.016	0.45	–	–	–	–	4.9
8/14/78	1A	0.20	4.15	0.043	0.67	0.80	7.53	0.061	0.23	5.1
8/17/78	1A	0.35	1.91	0.014	0.24	0.80	7.48	0.050	0.13	4.5
8/02/78	2A	0.33	2.12	0.010	0.34	0.73	6.74	0.052	0.05	4.6
8/05/78	2A	0.44	1.80	0.000	0.27	0.87	9.16	0.091	0.39	6.7
8/08/78	2A	0.41	1.63	0.000	0.21	0.80	7.04	0.122	0.26	15.8
8/14/78	2A	0.24	3.12	0.014	0.11	0.83	7.38	0.052	0.03	6.1
8/17/78	2A	0.38	2.56	0.020	0.37	0.80	7.34	0.039	0.01	5.4

*DATA ARE SHOWN IN FIGURE 2.

Table 4. Best-Fit Parameters for Corn-Covered Fields at Dalhart, Texas. SM_v is the Volumetric Soil Moisture within the 0 - 2 cm Surface Layer.

DATE	SITE	L-BAND				C-BAND				SM_v (%)
		$k\sigma$	$k\ell$	η	τ	$k\sigma$	$k\ell$	η	τ	
8/14/80	7	0.35	2.49	0.041	1.71	1.05	9.76	0.246	0.81	14.4
8/16/80*	7	0.35	1.92	0.002	1.14	1.05	8.19	0.258	0.32	20.3
8/16/80	7	0.35	1.86	0.019	1.35	1.05	12.00	0.446	0.51	19.1
8/18/80	7	0.35	1.47	0.010	1.14	1.05	10.77	0.549	0.03	19.2
8/14/80	8	0.35	2.07	0.023	1.51	1.05	7.59	0.360	0.06	15.5
8/16/80	8	0.35	1.91	0.018	1.40	1.05	10.65	0.315	0.24	19.3
8/14/80	9	0.35	2.40	0.014	0.91	1.05	8.74	0.122	0.23	4.4
8/16/80	9	0.35	1.49	0.000	0.71	1.05	9.00	0.284	0.16	13.5
8/14/80	10	0.35	2.10	0.011	0.90	–	–	–	–	4.9
8/18/80	10	0.35	1.61	0.004	0.87	–	–	–	–	8.4
8/14/80	11	0.35	2.19	0.033	1.20	1.05	11.09	0.305	0.80	17.8
8/16/80	11	0.35	1.43	0.019	1.31	1.05	9.92	0.413	0.51	41.5
8/16/80	11	0.35	1.98	0.029	1.59	1.05	10.23	0.558	0.36	39.0
8/18/80	11	0.35	1.87	0.029	1.55	1.05	10.89	0.539	0.14	29.6
8/14/80	12	0.35	1.98	0.019	1.27	1.05	8.63	0.473	0.22	22.9
8/16/80	12	0.35	1.54	0.011	1.24	1.05	9.08	0.361	0.34	25.8

*DATA ARE SHOWN IN FIGURE 3.

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Table 5. Best-Fit Parameters for Bare Fields at Guymon, Ohlahoma. SM_v is the Volumetric Soil Moisture Within the 0 - 2 cm Surface Layer.

DATE	SITE	L-BAND		C-BAND		SM_v (%)
		ko	kℓ	ko	kℓ	
8/05/78	6	0.20	2.59	0.54	3.76	13.0
8/08/78	6	0.30	2.59	–	–	6.2
8/17/78*	6	0.31	2.53	0.92	5.05	5.7
8/02/78	14	0.23	2.55	0.66	3.54	22.3
8/05/78	14	0.24	2.65	0.65	3.83	20.0
8/08/78	14	0.22	2.50	0.67	4.26	10.8
8/11/78	14	0.23	2.42	0.74	3.81	5.4

*DATA ARE SHOWN IN FIGURE 4

This clearly confirms the fact that systematic measurement errors do exist in individual scatterometer systems, and that the magnitude of system errors in the scatterometer data can be up to 5 dB.

In this study, it was found that improvement in the best fits can be achieved if the C-band data were reduced by 3 dB at all incident angles (i.e., α = -3 dB). This α value is within the range of the scatterometer system errors, as given in Reference [21]. These modified data were taken as the 'absolute' values of the backscattering coefficient at the C-band frequency, and were used in this study to obtain the best-fit parameters as given in Tables 2 to 5, which show that the $k\sigma$ values at C-band are approximately 3 to 4 times larger than the corresponding ones at L- band. Also the $k\ell$ values correlate with the frequency variation. Therefore, one can conclude that α = -3 dB is, probably, an appropriate 'correction' factor, which gives the best fit to the C-band data for all flights. Some of the C-band data, which were labeled as questionable in accuracy (due to airplane flight problems) in References [14, 15], were omitted in Tables 2 to 5.

Representative best-fit results at both L- and C-bands are shown in Figures 1 to 4 for three types of vegetation covers and bare surface condition. Solid curves in these figures represent the best-fit results obtained with the parameter values listed at the top of each figure, and the asterisks denote the scatterometer data. The volumetric soil moisture content within the 0 - 2 cm surface layer and the date (month/day/year) of the data measurement are given in the lower part of each figure.

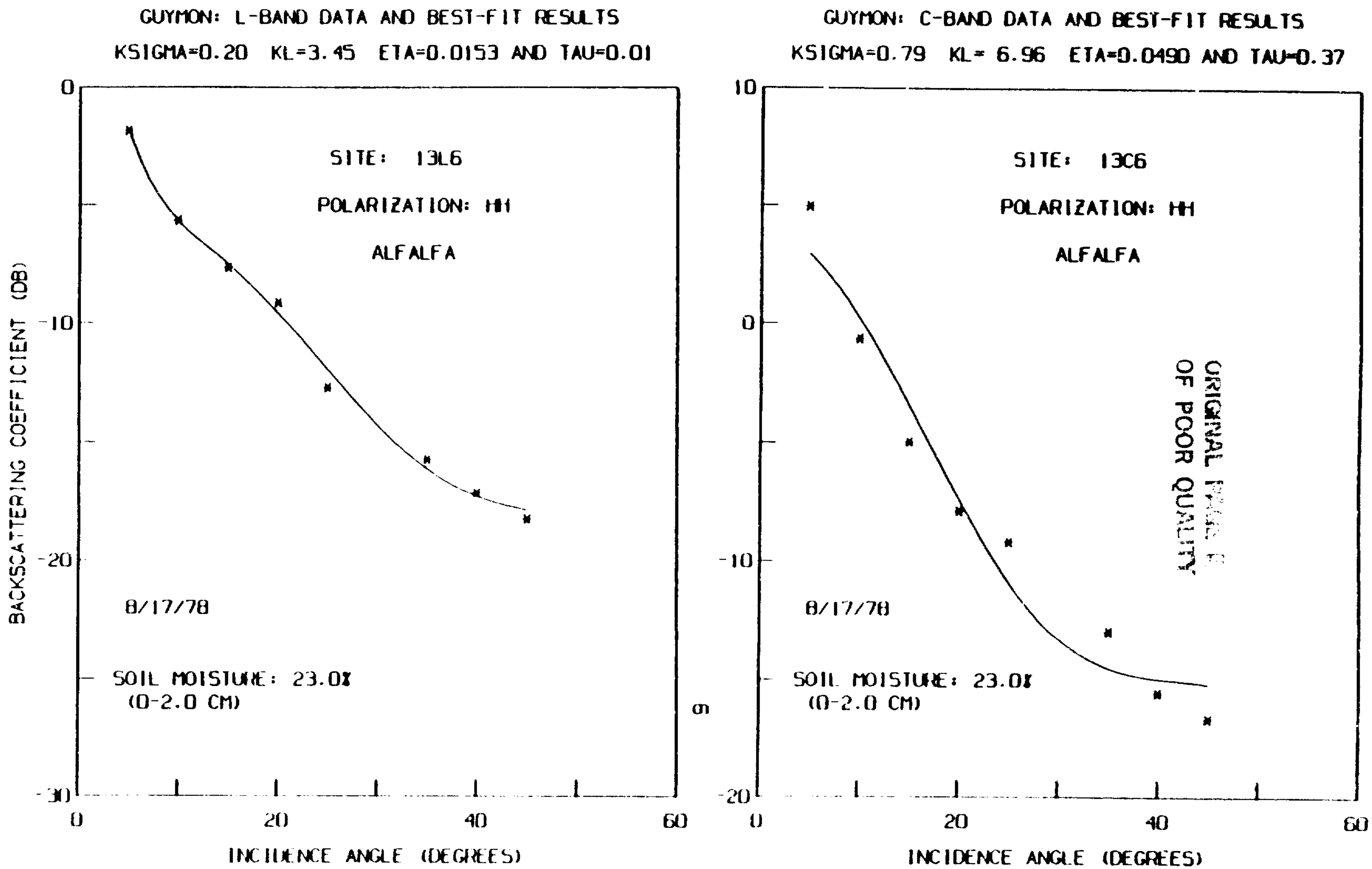

Figure 1. Comparison of Calculations (Solid Curves) and Scatterometer Data Taken at L- and C-Band Frequencies over an Alfalfa-Covered Field

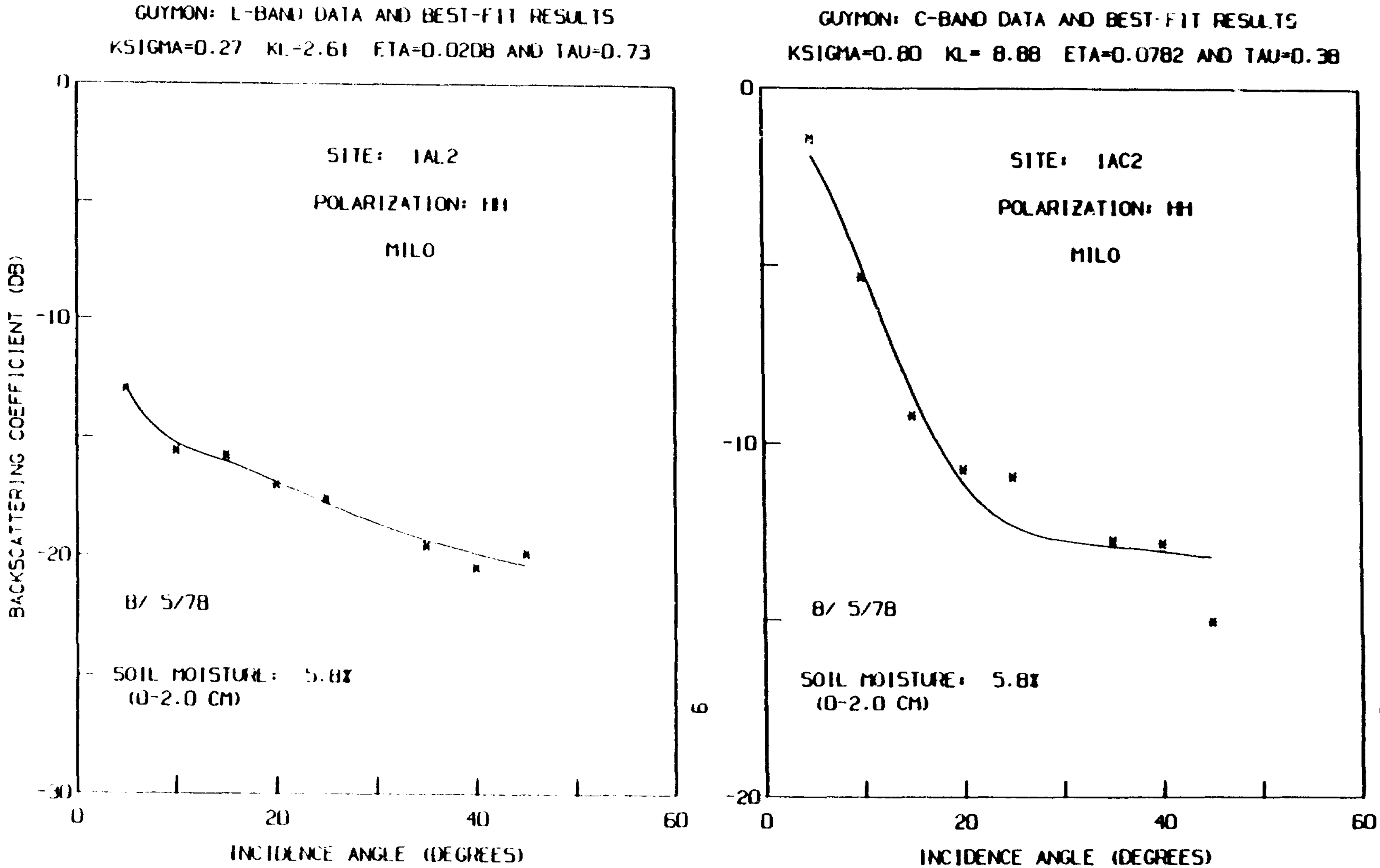

Figure 2. Comparison of Calculations (Solid Curves) and Scatterometer Data Taken at L- and C-Band Frequencies over a Milo-Covered Field

GUYMON: L-BAND DATA AND BEST-FIT RESULTS

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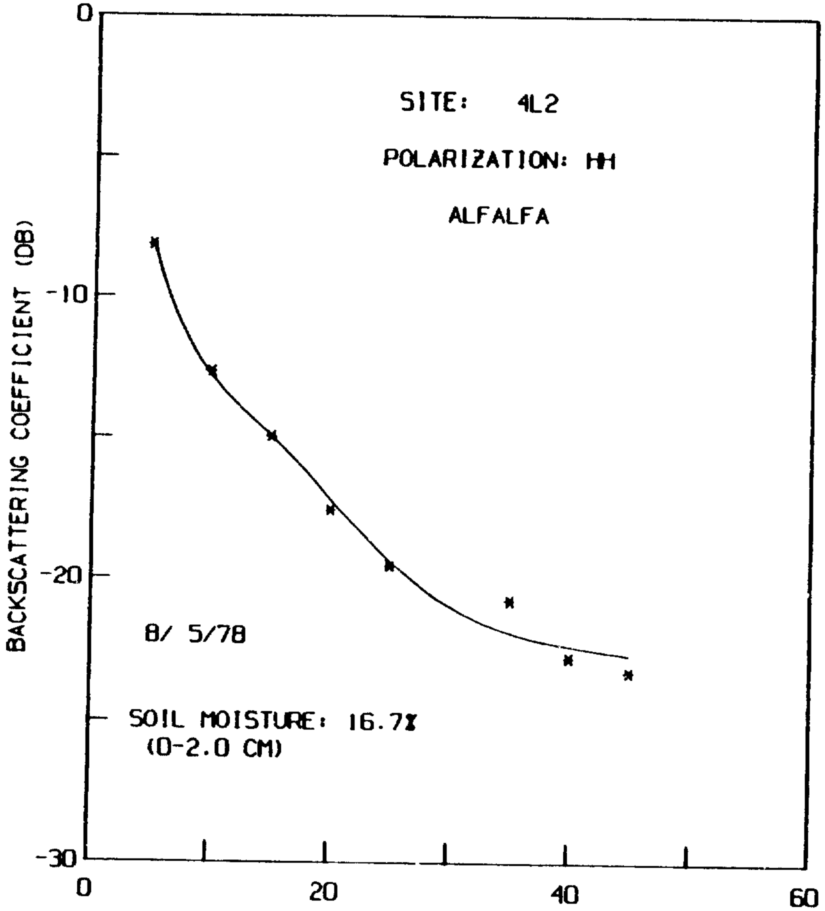

GUYMON: C-BAND DATA AND BEST-FIT RESULTS

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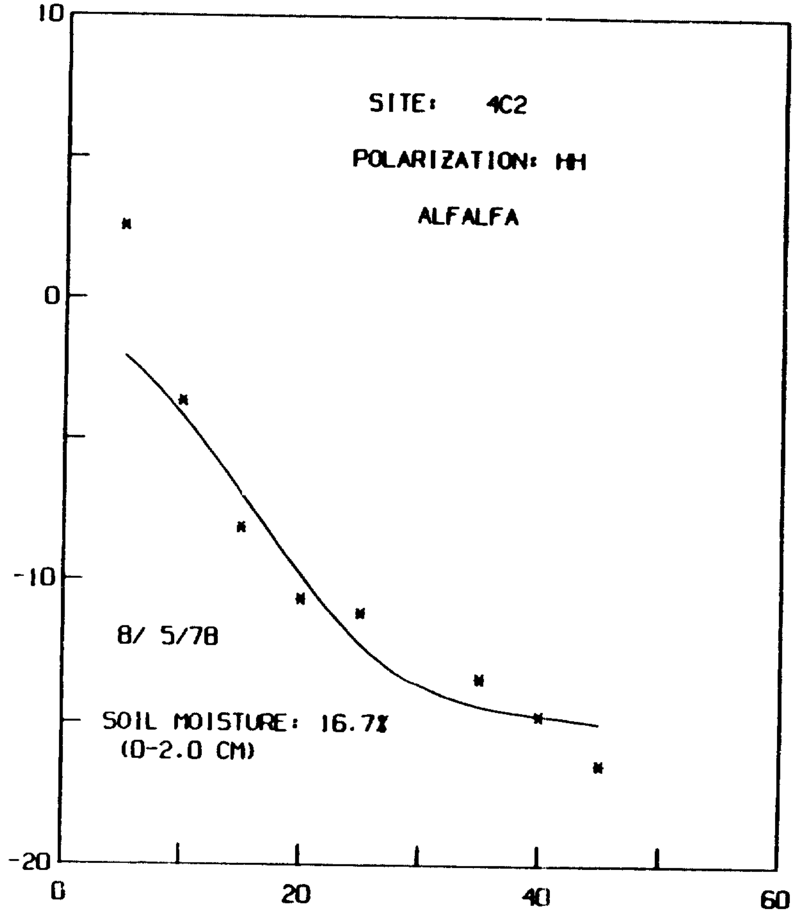

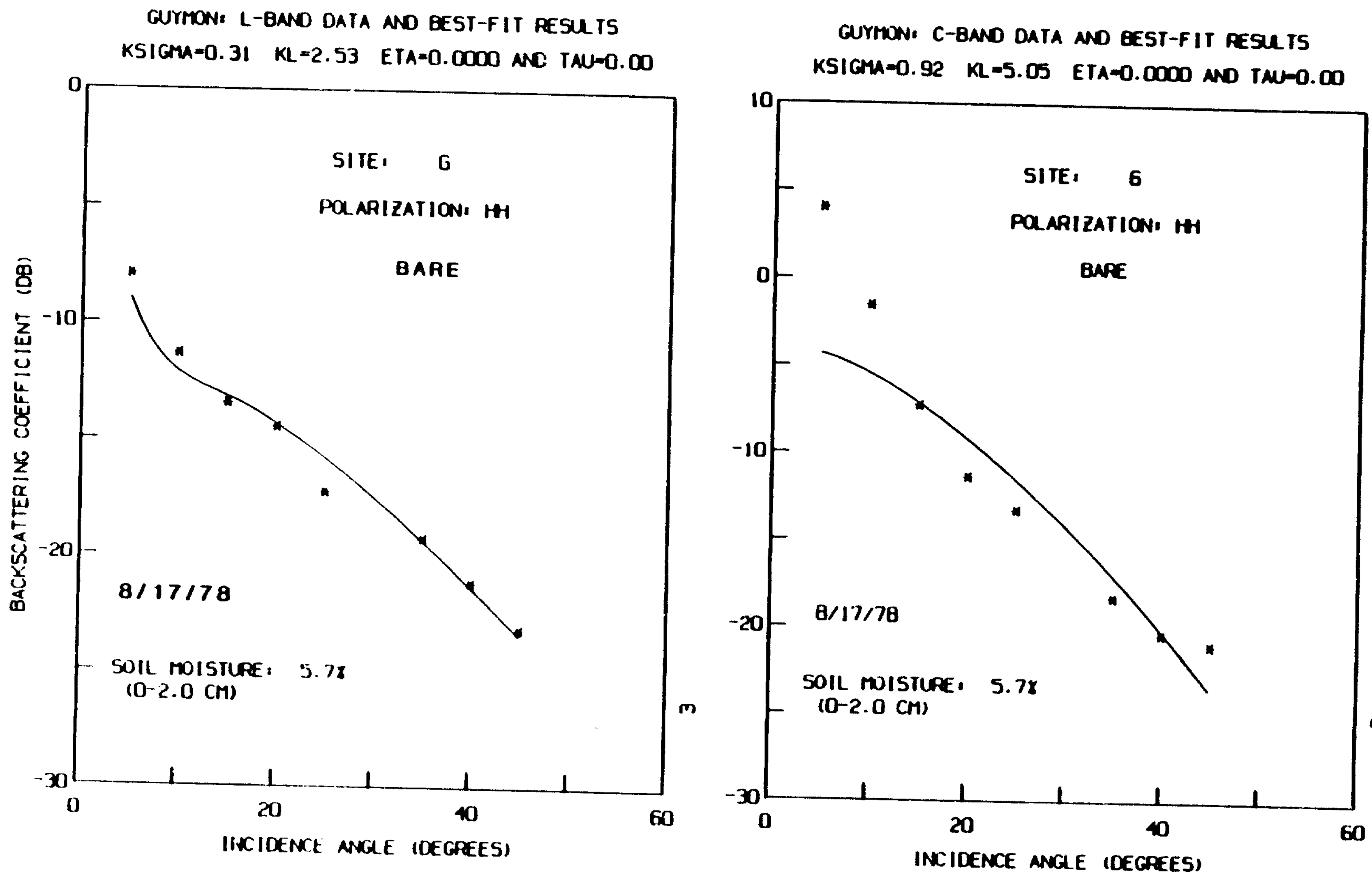

Figure 4. Comparison of Calculations (Solid Curves) and Scatterometer Data Taken at L- and C-Band Frequencies over a Bare Field

There are some variations in the $k\sigma$ values, as shown in Tables 2 to 4, for the same field. This can be probably attributed to measurement errors in the day-to-day operations of the scatterometers. It has been shown [6] that a measurement error of 2 dB can produce 50 percent changes in the best-fit $k\sigma$ values.

Figure 1 shows the best-fit results and comparison with the scatterometer data of alfalfa-covered field near Guymon, Oklahoma in 1978. The L-band results are shown on the left hand side and the C-band on the right handside. Figure 1 demonstrates that the calculations (the solid curves) can reproduce the observed angular variations (the asterisks) at both frequencies.

Figure 2 shows the calculations and data of the milo-covered field at Guymon, Oklahoma. The field was dry on the data collection date. The agreement between calculation and data is reasonably good.

A typical case for a corn-covered field is displayed in Figure 3. The scatterometer data taken over corn-covered fields are somewhat different from other fields. The variation in magnitude as a function of incident angle is much smaller than those of other vegetation cases. Table 6 gives the 16 measurements of the L-band scatterometer data from corn fields used in this study, and it shows that the backscattering coefficients are essentially independent of surface soil moisture contents, which are also listed in the third column (Table 6). This is contrary to other types of vegetation-covered fields, which exhibit soil moisture dependence of measured radar backscattering coefficient. Perhaps, this is due to the fact that the radar pulses can not fully penetrate the 'thick' corn canopies.

Table 6. Scatterometer Data of Corn-Covered Fields (L-Band)

DATE	SITE	SM_v (%)	5°	10°	15°	20°	25°	35°	40°	45°
8/14/80	7	14.4	-18.3	-14.6	-18.0	-17.2	-17.2	-19.1	-21.5	-22.1
8/16/80	7	20.3	-12.1	-14.2	-17.3	-18.7	-17.8	-21.1	-24.4	-25.1
8/16/80	7	19.1	-14.7	-17.2	-15.4	-19.8	-16.7	-19.5	-22.6	-22.4
8/18/80	7	19.2	-13.4	-19.2	-14.3	-20.2	-17.0	-21.6	-21.5	-22.6
8/14/80	8	15.5	-16.7	-16.6	-18.4	-16.7	-17.8	-19.8	-23.0	-23.0
8/16/80	8	19.3	-15.4	-16.8	-16.9	-18.9	-16.5	-20.4	-22.4	-23.2
8/14/80	9	4.4	-16.9	-15.2	-18.7	-18.6	-17.7	-20.7	-22.7	-23.0
8/16/80	9	13.5	-11.7	-16.4	-14.9	-18.6	-15.7	-19.5	-21.7	22.3
8/14/80	10	4.9	-16.6	-16.6	-18.6	-19.5	-18.6	-20.3	-22.6	-24.3
8/18/80	10	8.4	-15.4	-18.1	-19.3	-20.6	-19.6	-21.5	-24.2	-24.8
8/14/80	11	17.8	-14.7	-12.7	-15.4	-15.9	-14.4	-17.1	-19.9	-21.2
8/16/80	11	41.5	-12.2	-17.0	-13.5	-18.9	-15.0	-18.6	-19.9	-21.7
8/16/80	11	39.0	-14.2	-14.8	-15.0	-18.1	-16.1	-18.3	-20.9	-22.4
8/18/80	11	29.6	-14.4	-16.6	-15.2	-18.2	-16.7	-18.8	-21.3	-21.7
8/14/80	12	22.9	-13.3	-14.5	-15.5	-17.1	-16.6	-18.6	-21.2	-22.1
8/16/80	12	25.8	-13.1	-16.3	-16.1	-19.2	-16.8	-19.2	-22.4	-22.6

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The fact that there are no forward-angle peaks in the observed angular distributions of L-band frequency (see Figure 3 and Table 6) indicates the $\sigma^{o}_{coh}(\theta)$ component being heavily attenuated by the thick corn canopy τ values. Best-fit results as listed in Table 4 indeed show large τ values at L-band, but only moderate values at C-band. This indicates that the corn canopy is less effective in attenuating the shortwave radar pulses. Another possibility is that the L-band signals can penetrate deeply into the corn canopy, while the c-band waves can only pass through the top layer, where leaves are the major portion of the vegetation. Thus the two sensors are responding to two different volumes of the vegetation. Since leaves are most likely to producing scattering rather than attenuation, thus it might explain why the η values for C-band are much larger than the corresponding ones of L-band, as shown in Table 4. Also, the large τ values render the fits insensitive to the variation in the surface parameters. Therefore an estimated value of $k\sigma = 0.35$ was used for the L-band, and $k\sigma = 1.05$ for C-band.

The results shown in Figure 3 demonstrate that the calculations are in excellent agreement with the observations at both frequencies.

Calculations and data for the cases of bare fields are illustrated in Figure 4 and Table 5. Only two parameters, $k\sigma$ and $k\ell$, are required to fit the data in this case. The calculated results, as shown in Figure 4, agree reasonably well with the observations. Also the $k\sigma$ values vary with frequency as expected.

Additional calculations and comparisons with the data are given in Appendix A.

SECTION 5 - SUMMARY AND DISCUSSION

We have systematically simulated a series of recently measured radar backscattering coefficients of vegetation-covered and bare fields, using a simple electromagnetic wave scattering model developed in Reference [6]. The model takes into consideration coherent and incoherent scattering from rough soil surface, in addition to vegetation volume scattering and attenuation. The data used in this study were collected with airborne scatterometers at the L- and C-band frequencies. Radar instrumental characteristics, such as 3-dB beamwidth and scatterometer gain pattern were also taken into consideration in the simulated results, which are presented according to types of vegetation covers, including alfalfa, milo, corn and bare soil surfaces.

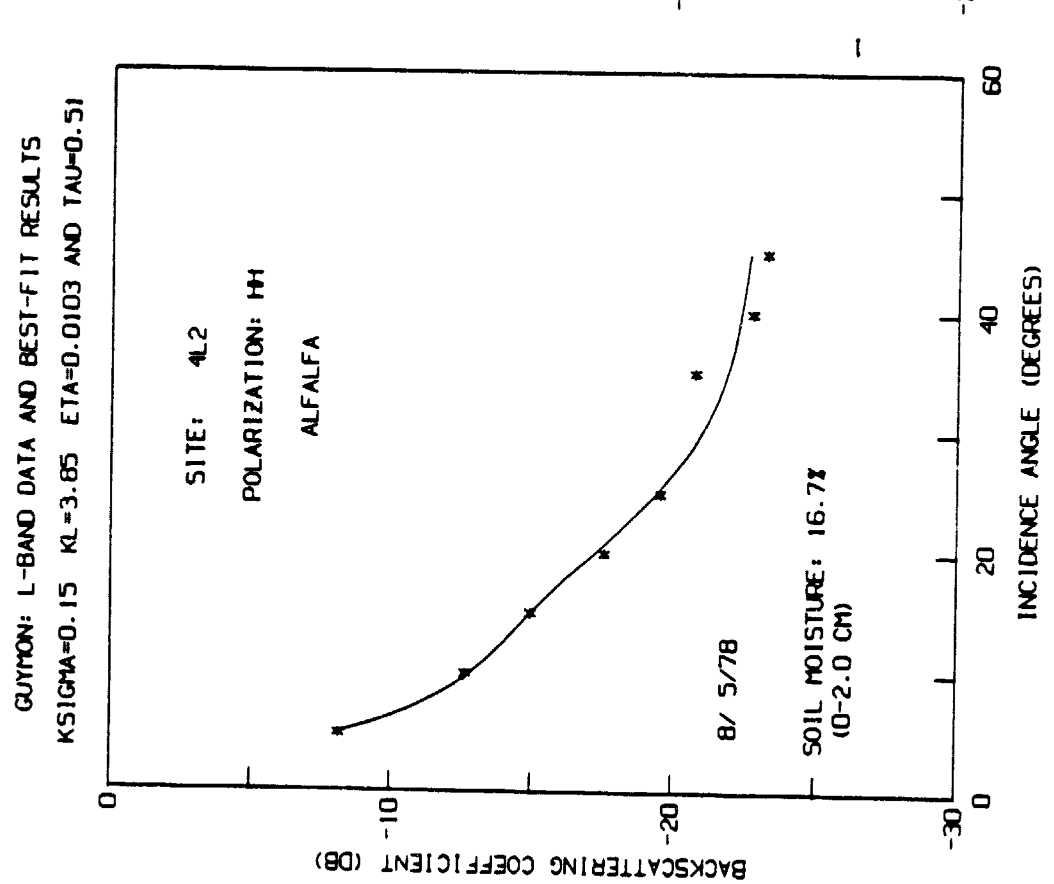
The objective of this study is to test the theoretical model on a large data base of wide range of vegetation, terrain and soil types. The model results, as shown in Figures 1 to 4, demonstrate that the model can satisfactorily reproduce the measured angular distribution of radar backscattering coefficients of all fields within experimental errors, as discussed in Section 4. The best-fit parameter values are reasonable over a wide range of vegetation, and are consistent with previously reported results [6], except for the corn field, of which the data show no sensitivity to the variation in the soil moisture. This is perhaps, due to the thick corn canopy, which heavily attenuates the radar signal.

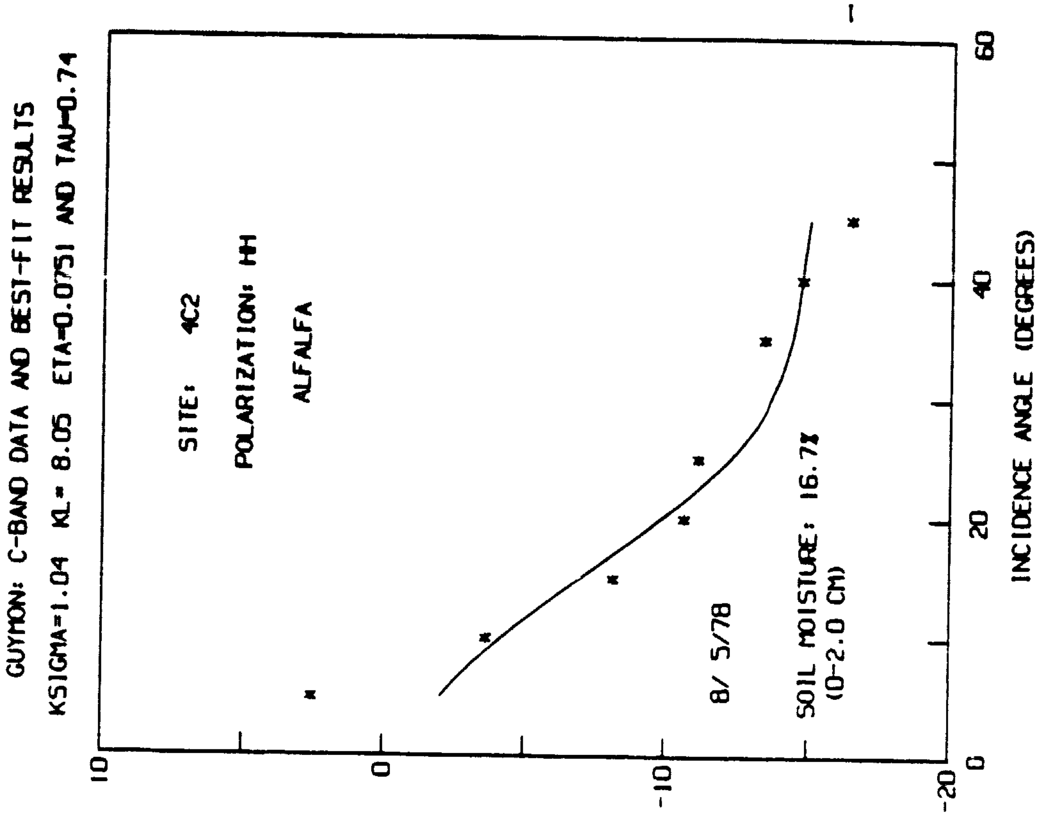
There seems a major difference in the C-band data between the Chickasha measurements (which were used in Reference 6) and the Guymon and Dalhart results [15], used in this study. The former does not need modification of the absolute value to obtain the best-fit results, but the later requires a reduction of 3 dB in the C-band scatterometer data, as given in Reference [15], in order to produce reasonably best-fit results. At the present time, we do not fully understand why this difference occurs, and more study of this problem is urgently needed.

APPENDIX A

This appendix presents additional calculations and comparisons of scatterometer data of backscattering coefficients for HH polarization as described in the main text of this study.

Each set of calculated and observed results is plotted as a function of incidence angle. The parameters used in the calculations are listed at the top of each plot. These parameters are also listed in Tables 2 to 4. The Asterisks (*) denote the scatterometer data, and the solid curves represented the calculated results. The type of vegetation cover is marked on each figure.


GUYMON: L-BAND DATA AND BEST-FIT RESULTS
KSIGMA=0.15 KL=3.85 ETA=0.0103 AND TAU=0.51
SITE: 4L2
POLARIZATION: HH
ALFALFA
8/ 5/78
SOIL MOISTURE: 16.7%
(0-2.0 CM)
BACKSCATTERING COEFFICIENT (DB)
INCIDENCE ANGLE (DEGREES)
0
-10
-20
-30
0
20
40
60


GUYMON: C-BAND DATA AND BEST-FIT RESULTS
KSIGMA=1.04 KL= 8.05 ETA=0.0751 AND TAU=0.74
SITE: 4C2
POLARIZATION: HH
ALFALFA
8/ 5/78
SOIL MOISTURE: 16.7%
(0-2.0 CM)
INCIDENCE ANGLE (DEGREES)
10
0
-10
-20
0
20
40
60

GUYMON: L-BAND DATA AND BEST-FIT RESULTS
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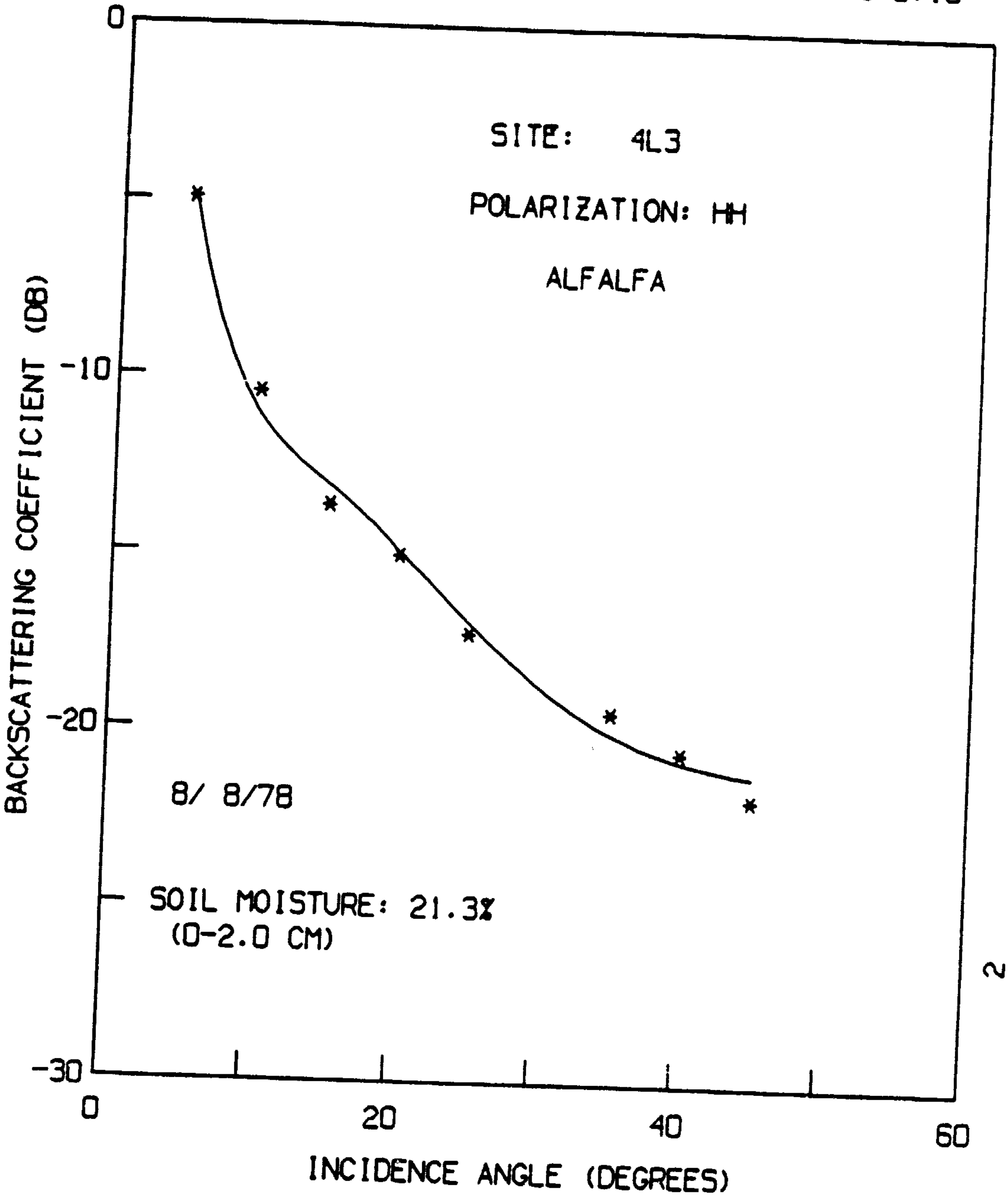

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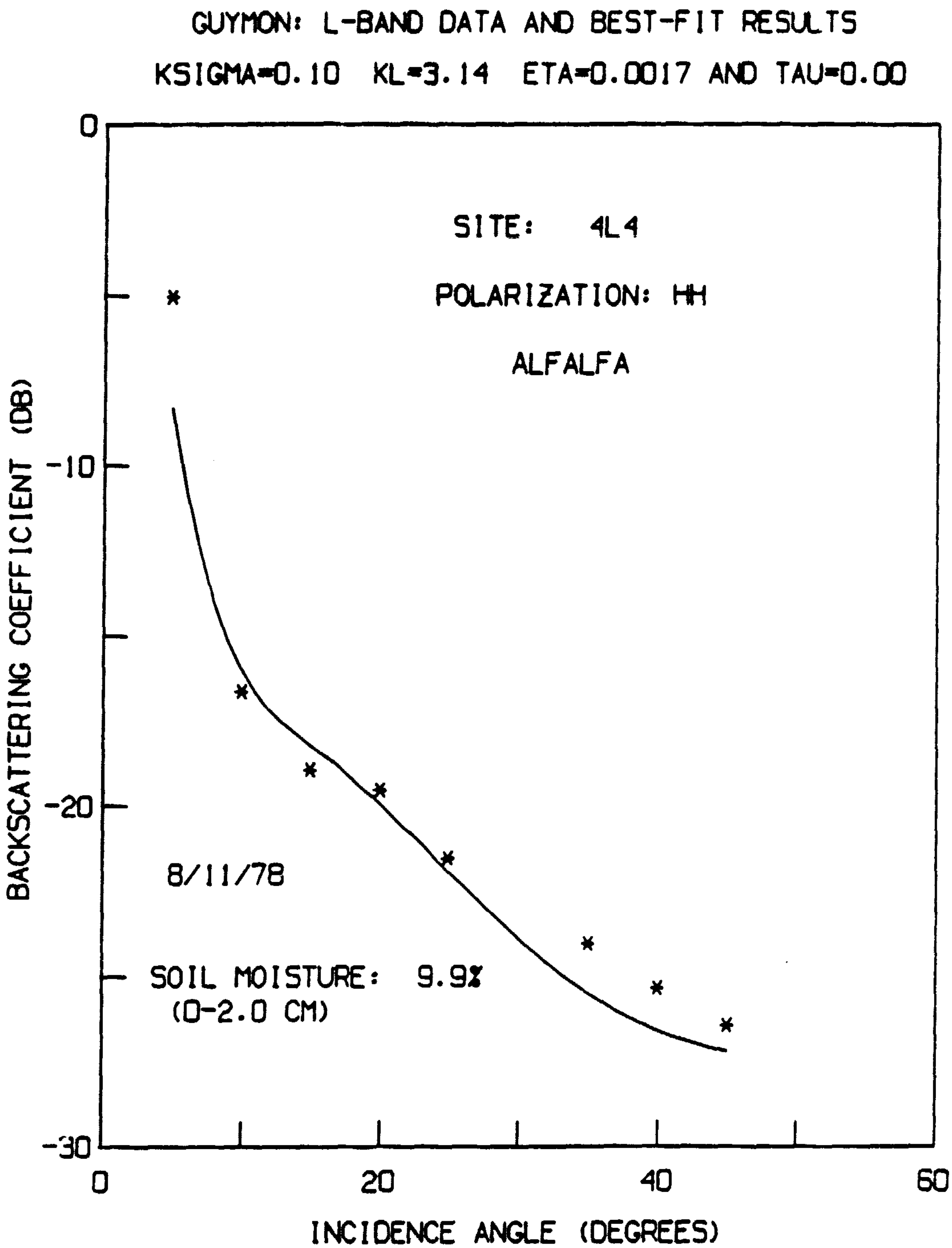

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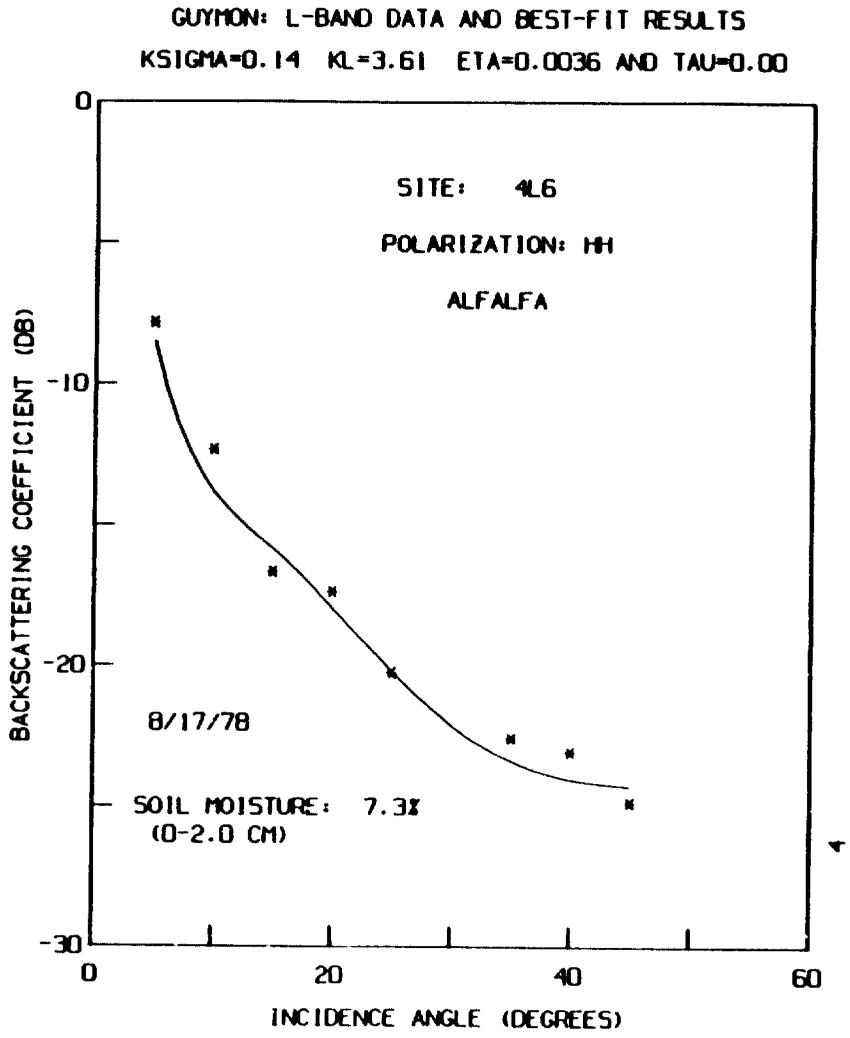

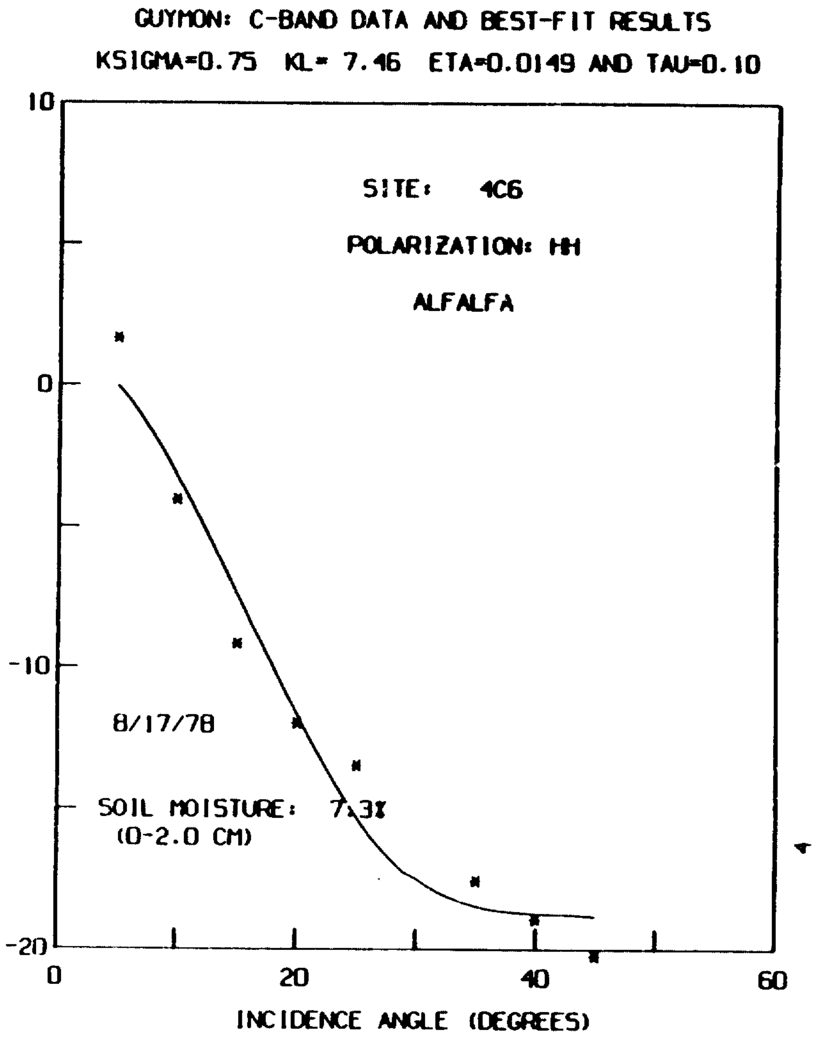

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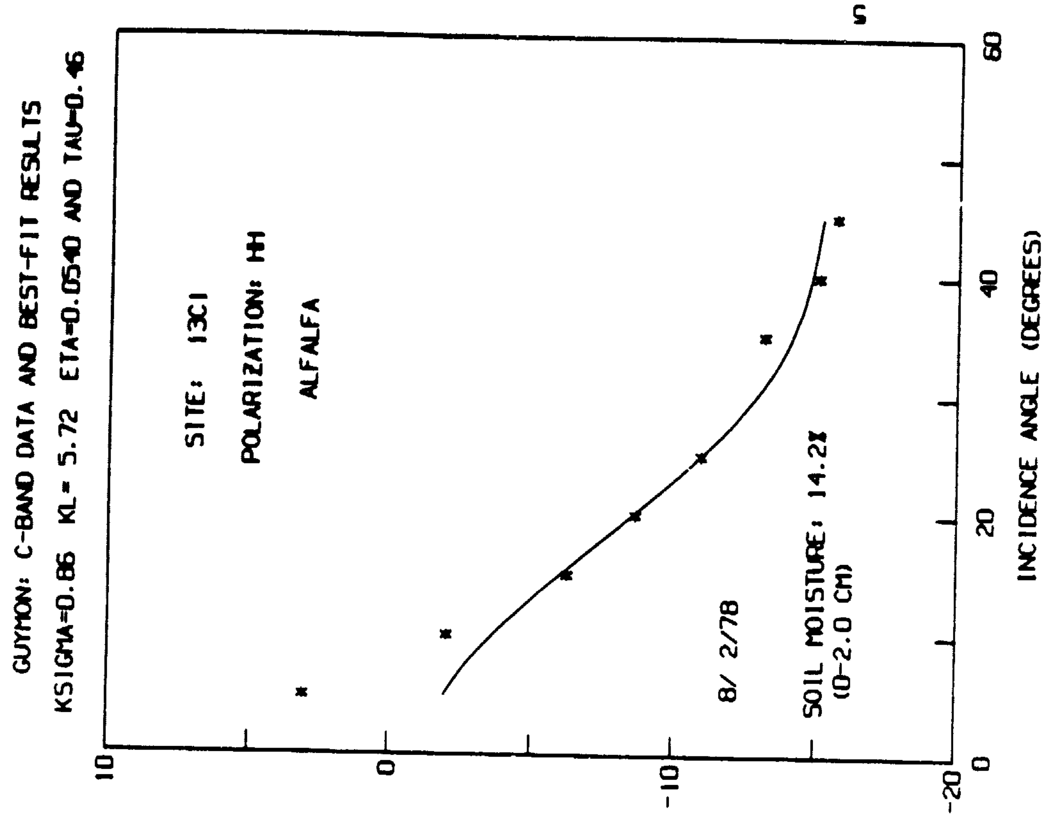

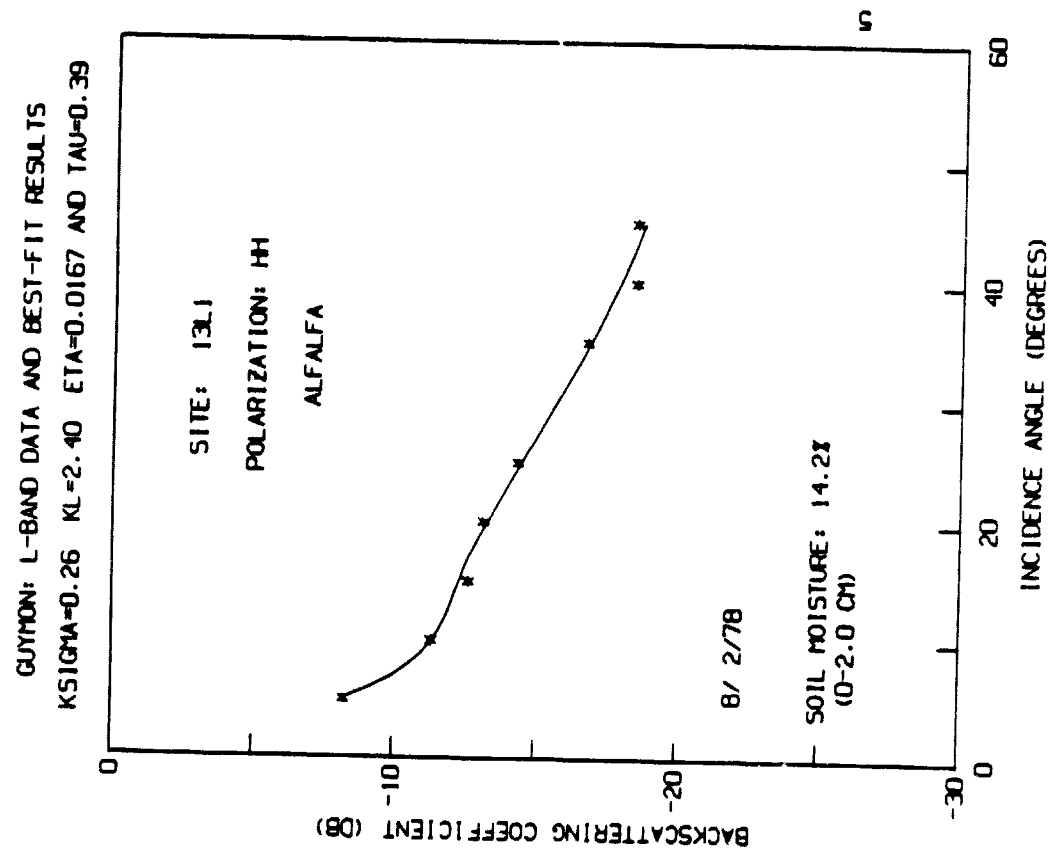

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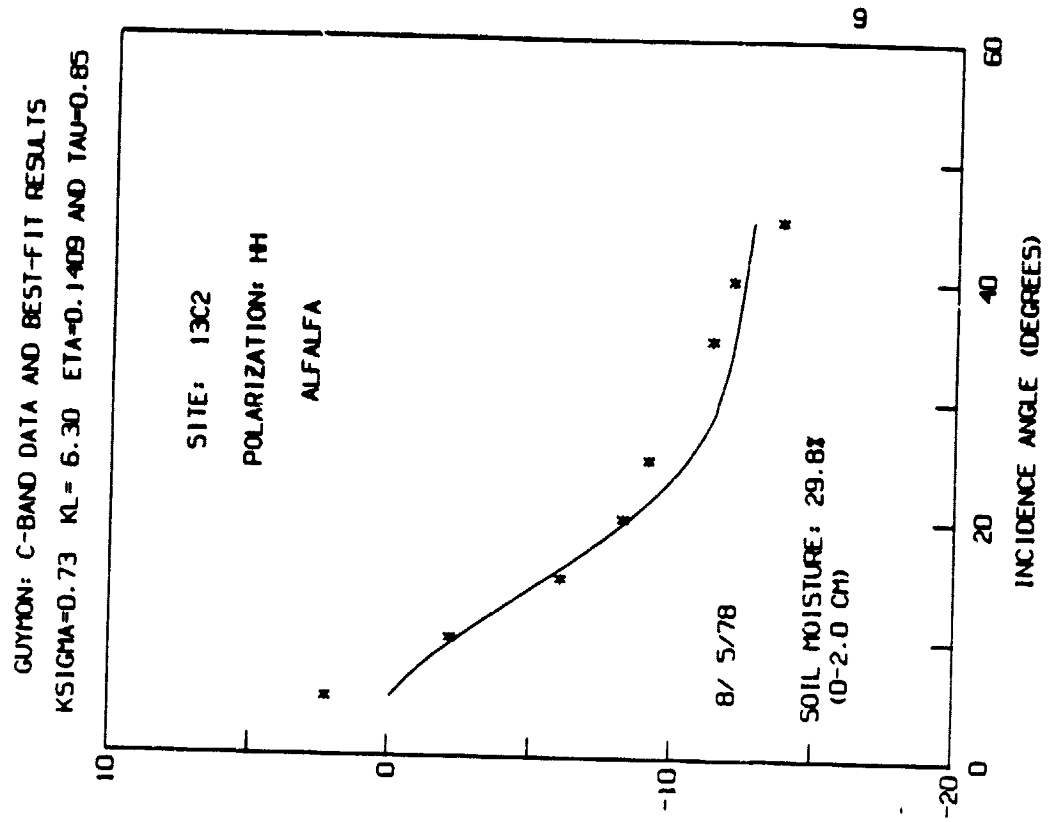

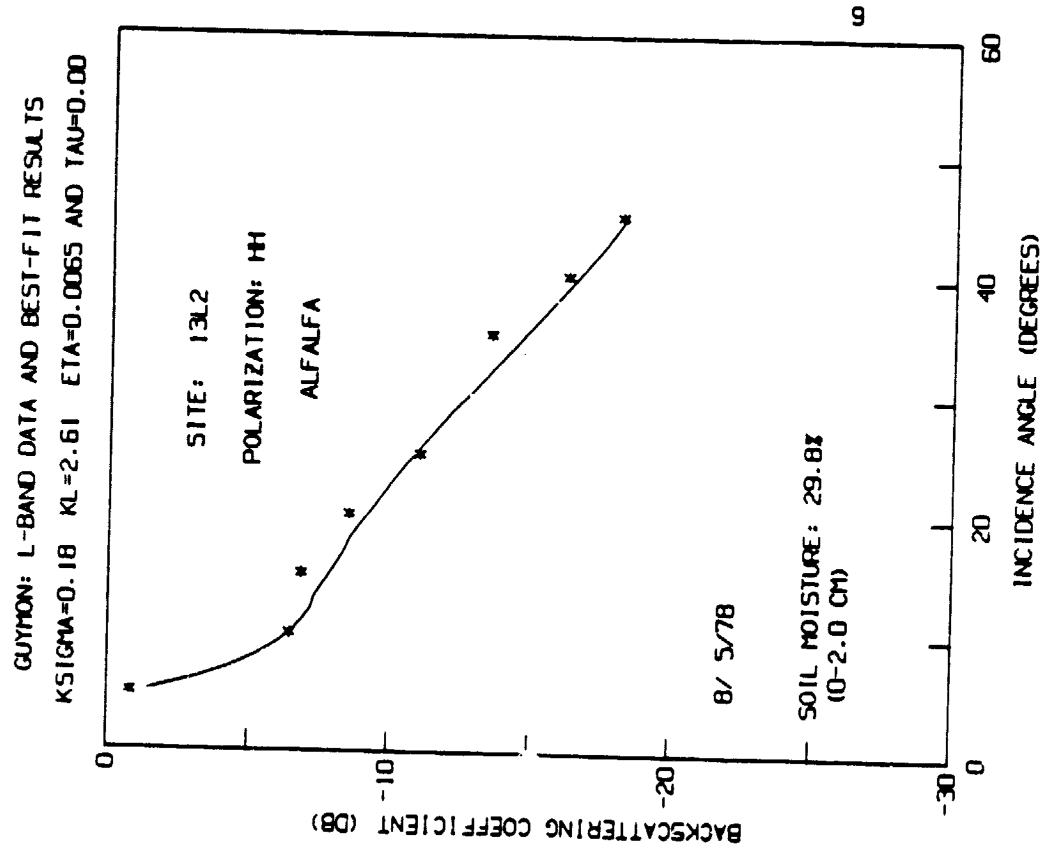

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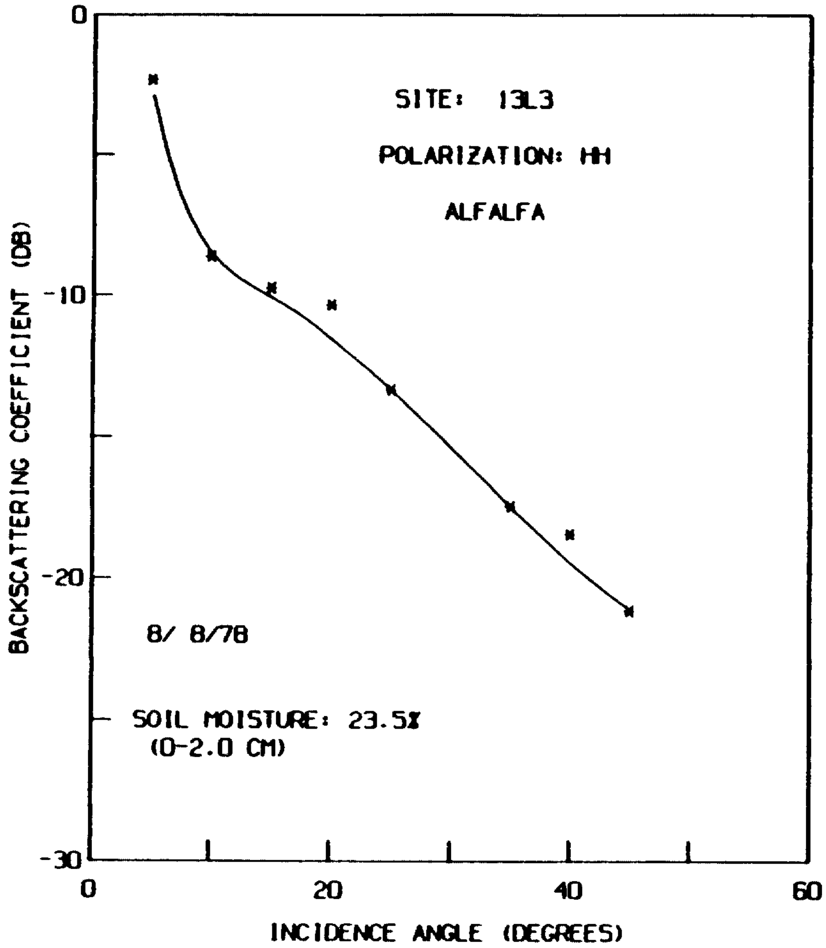

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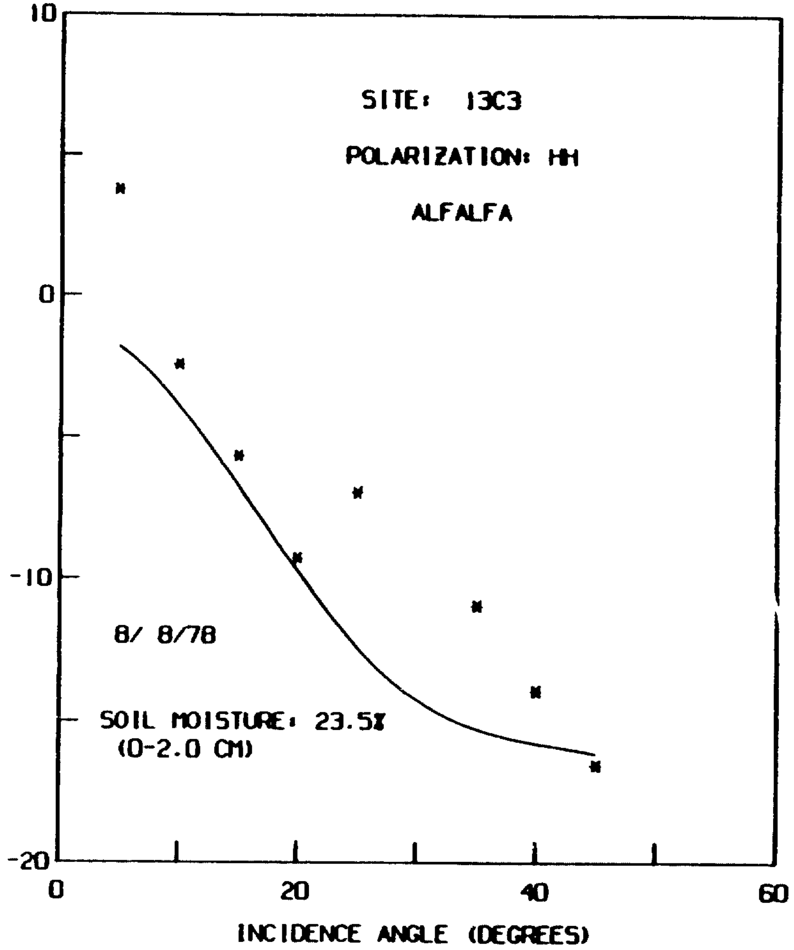

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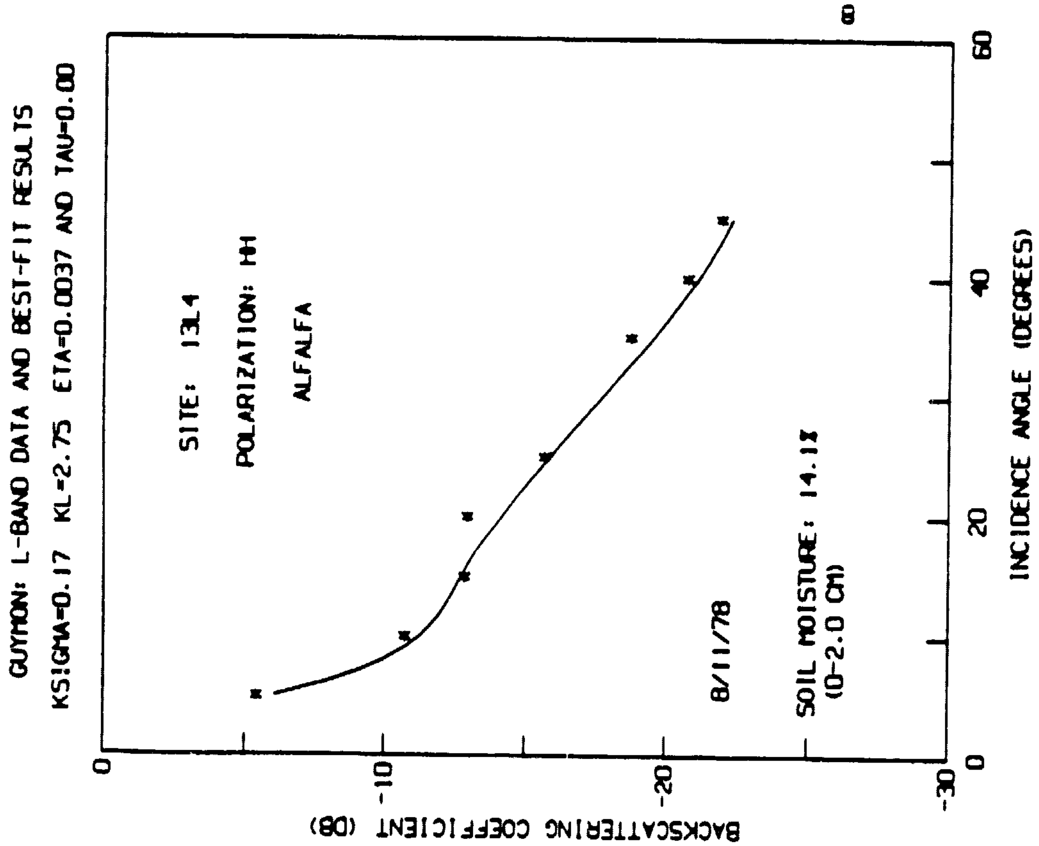

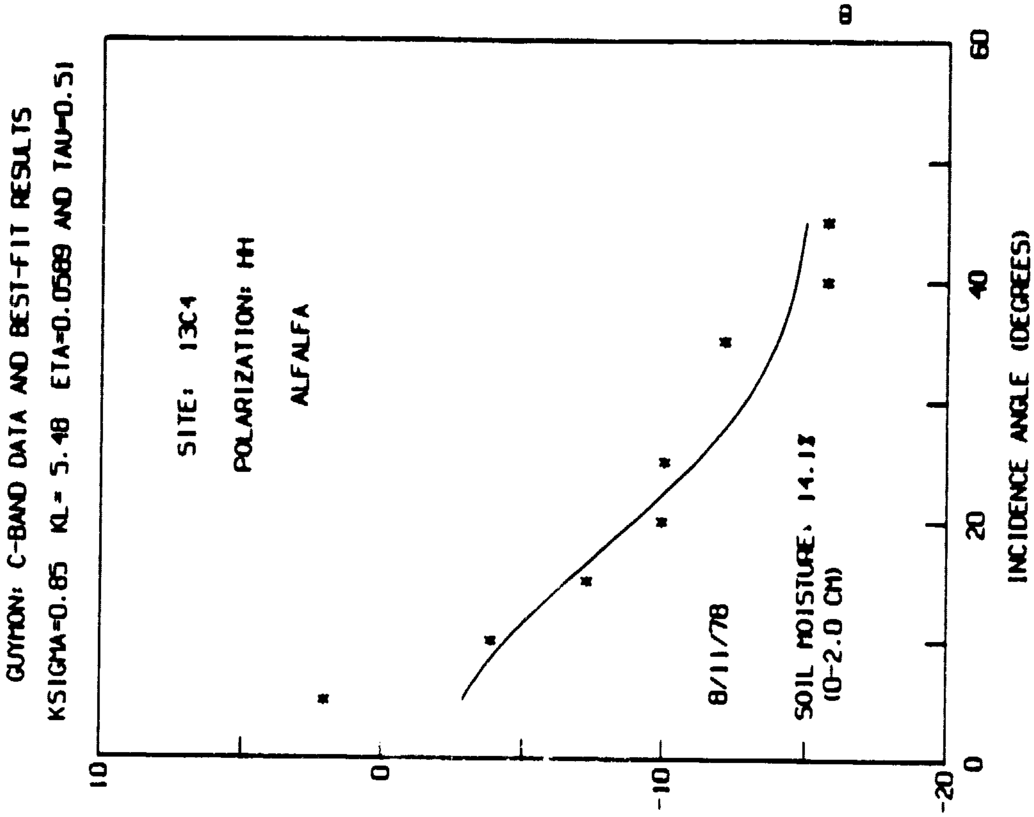

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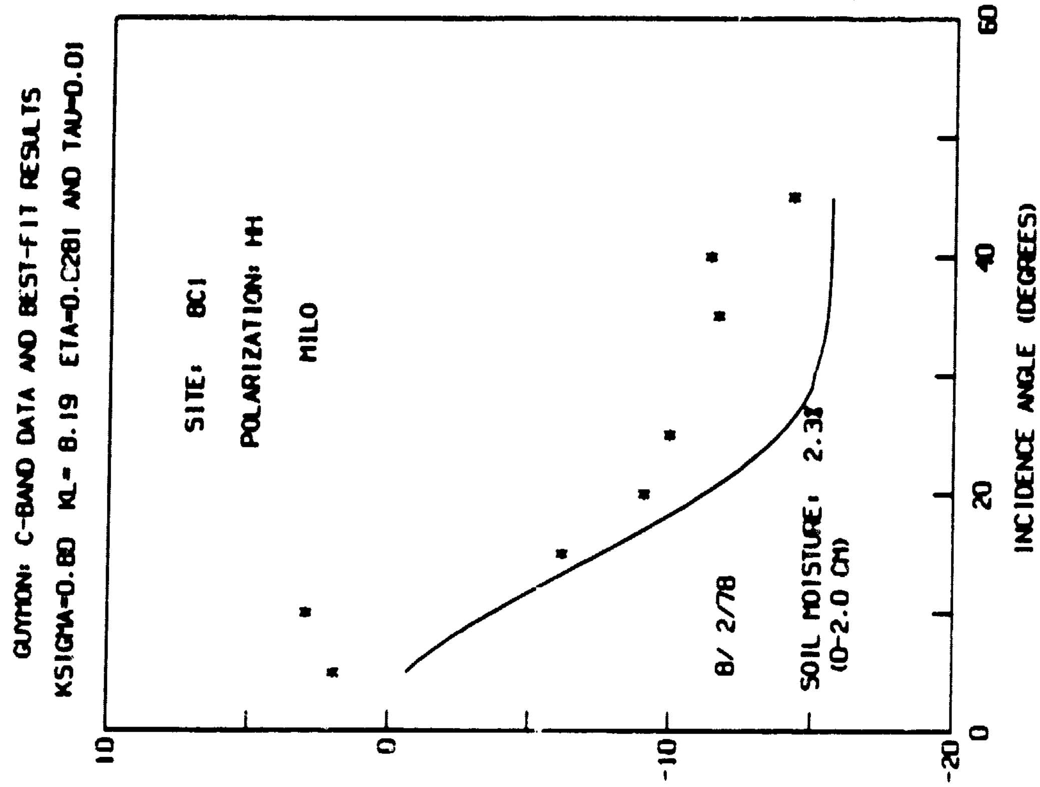

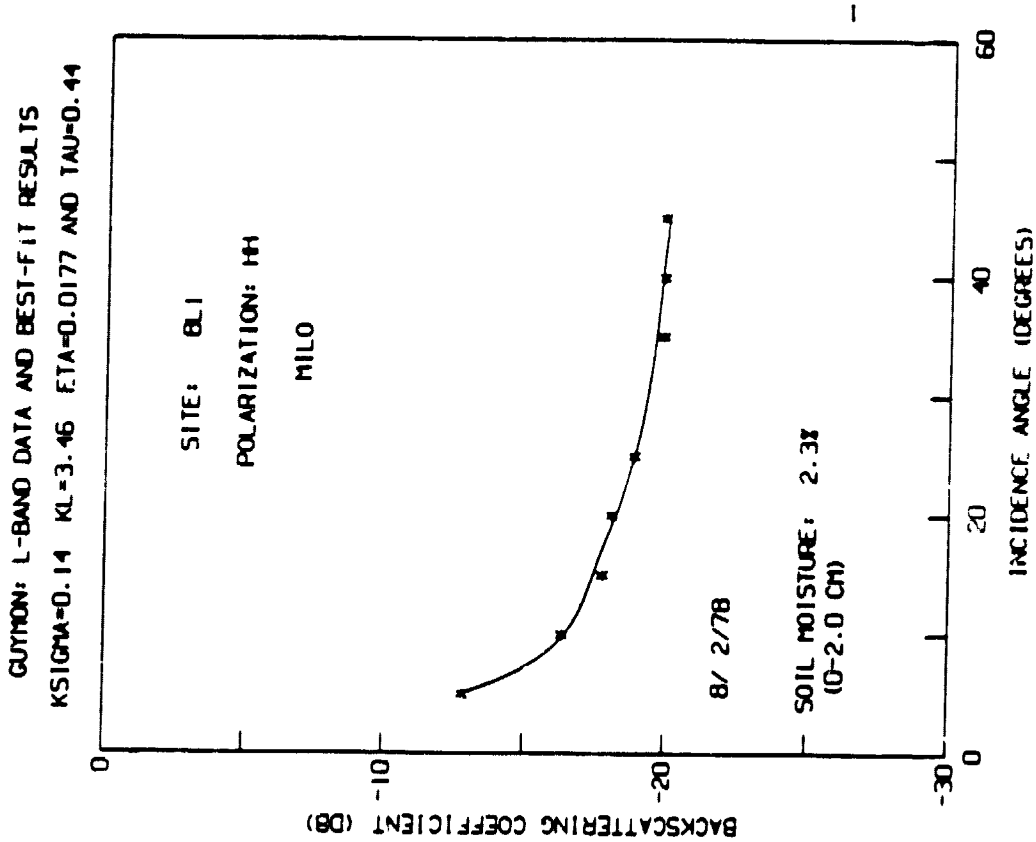

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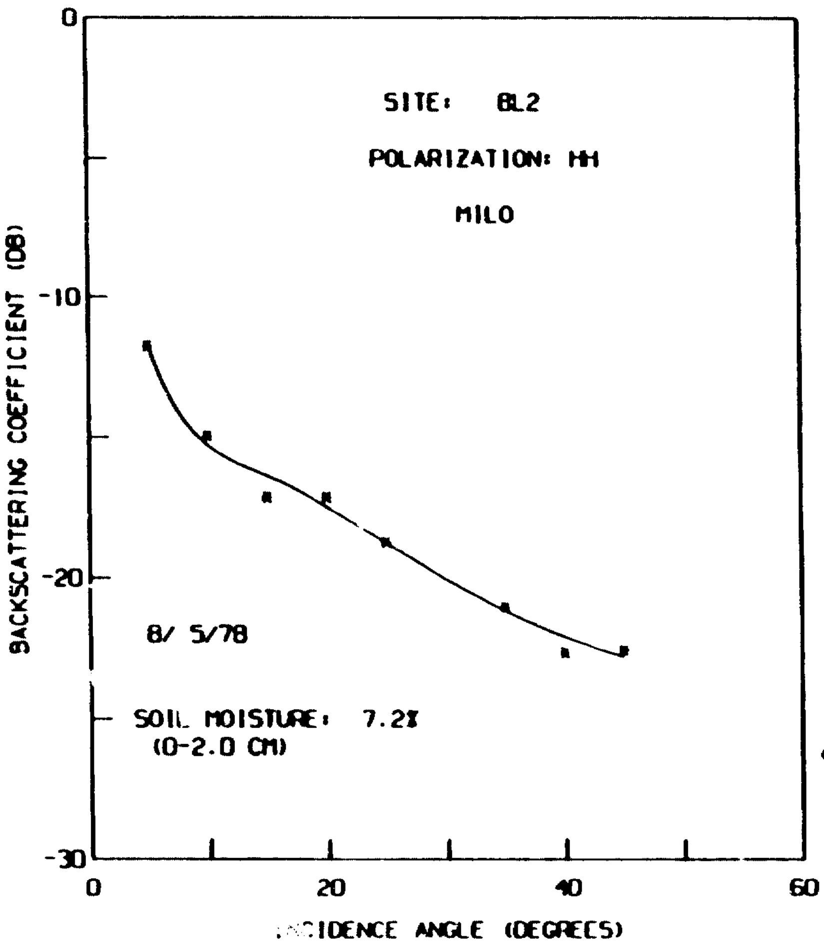

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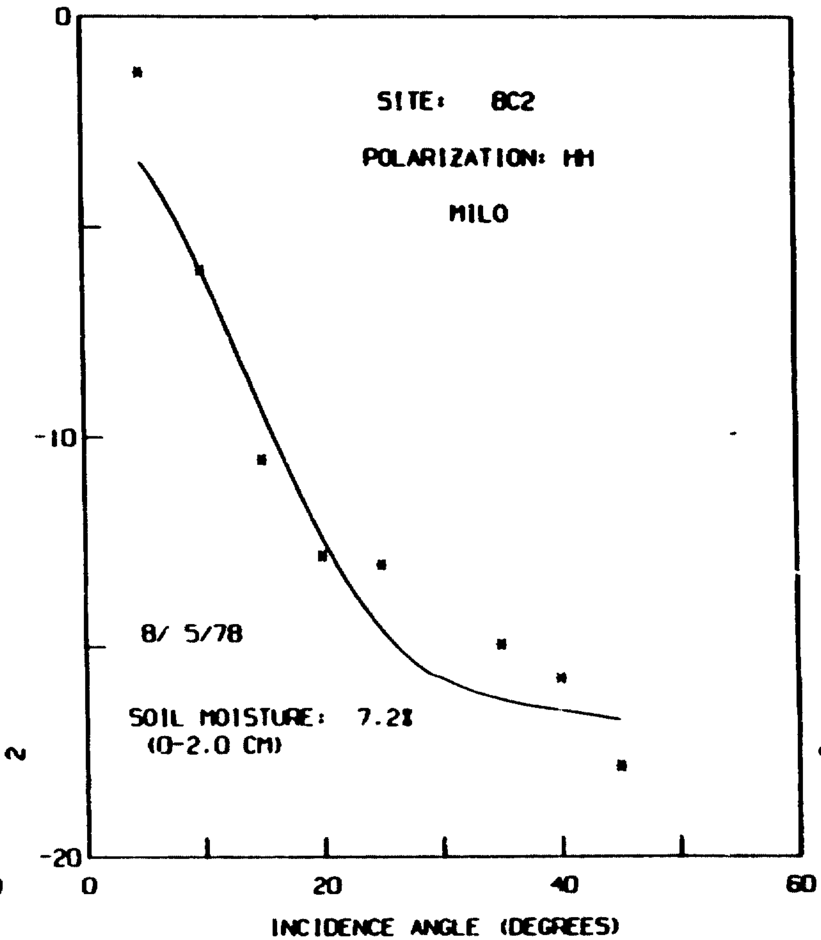

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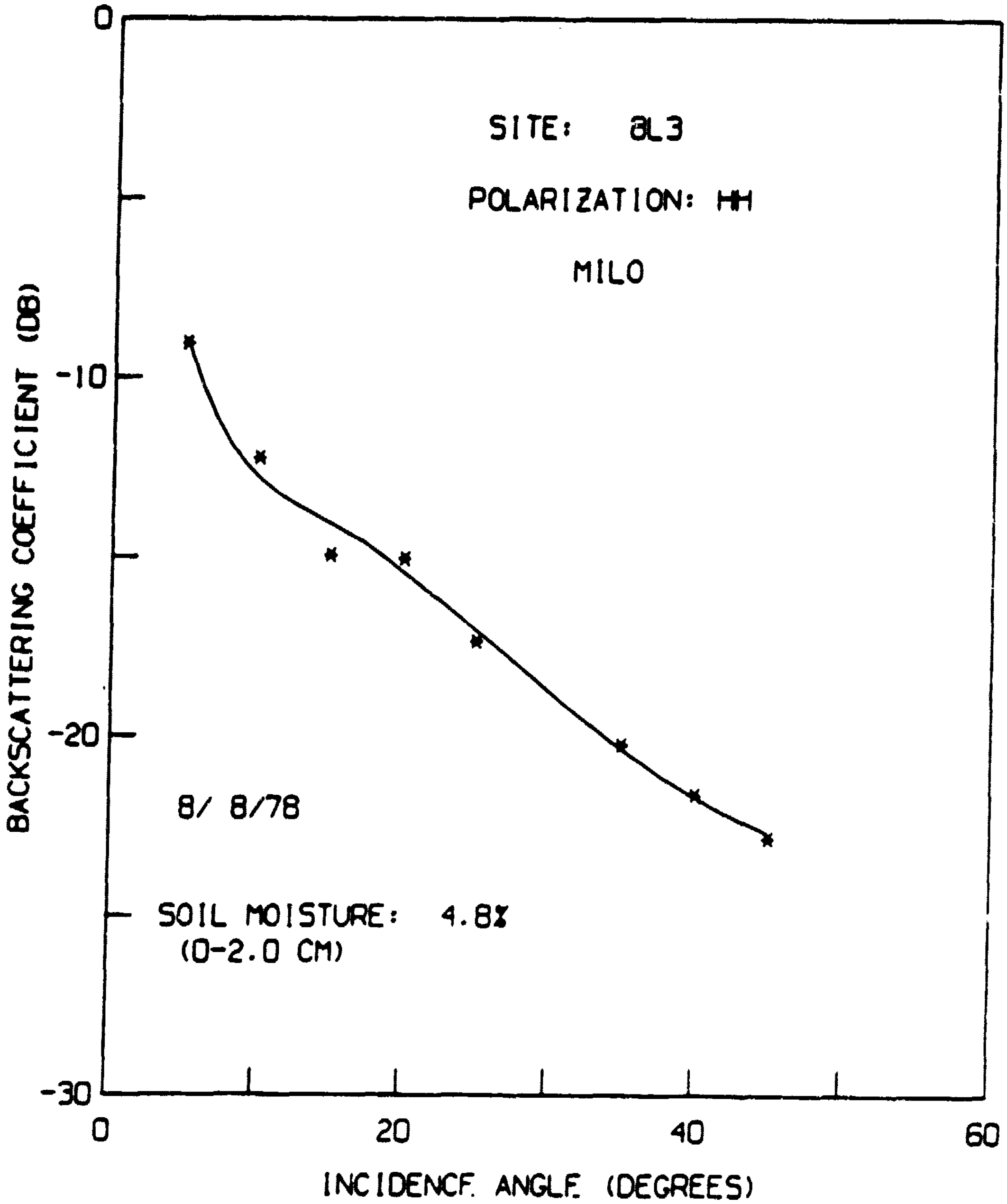

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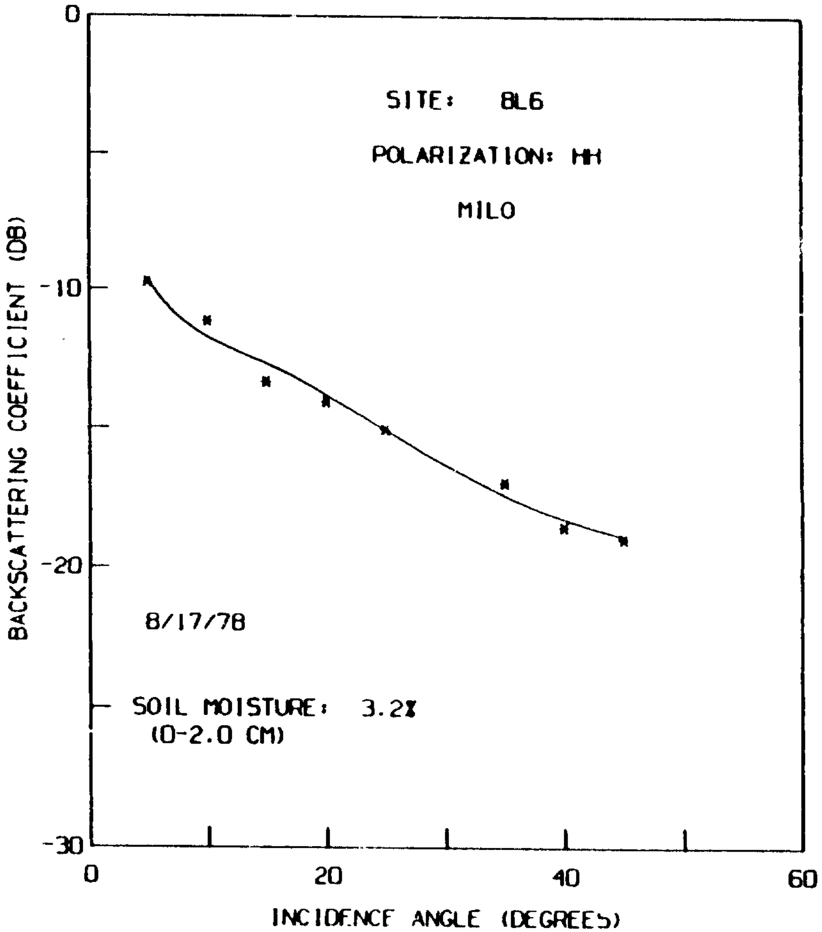

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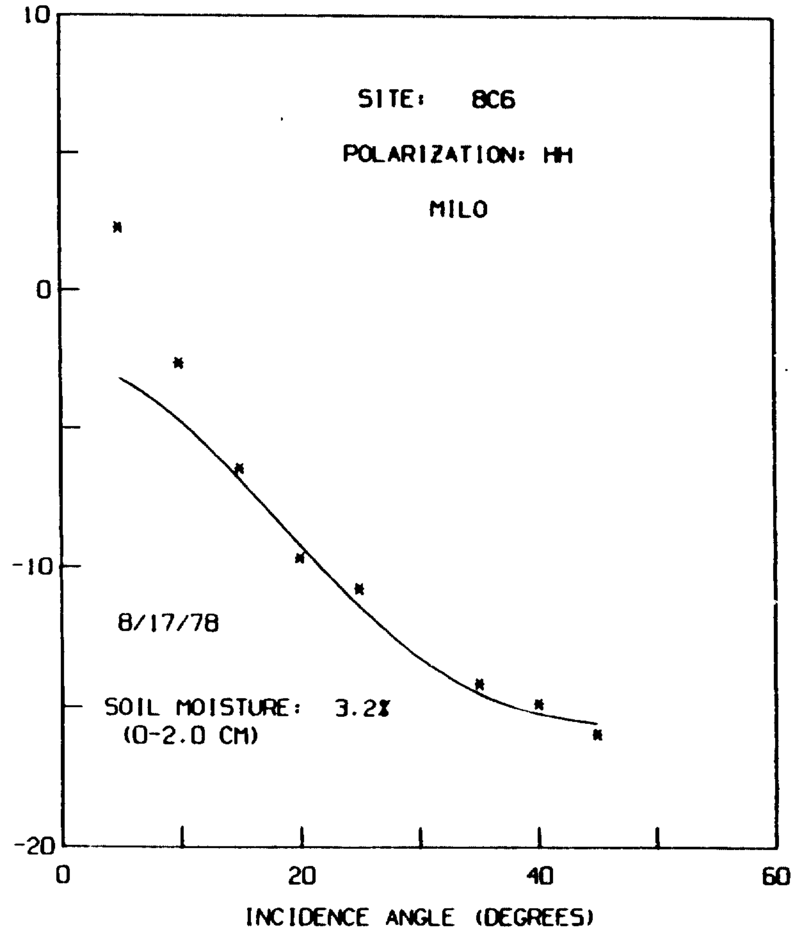

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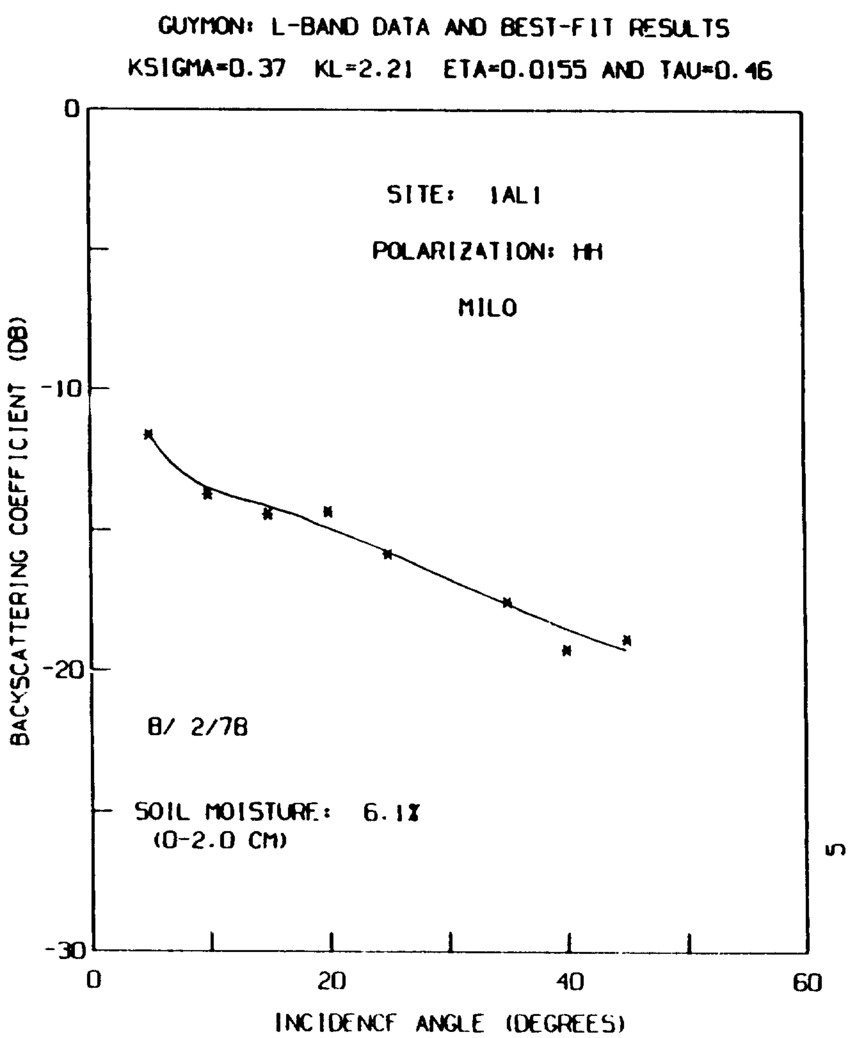

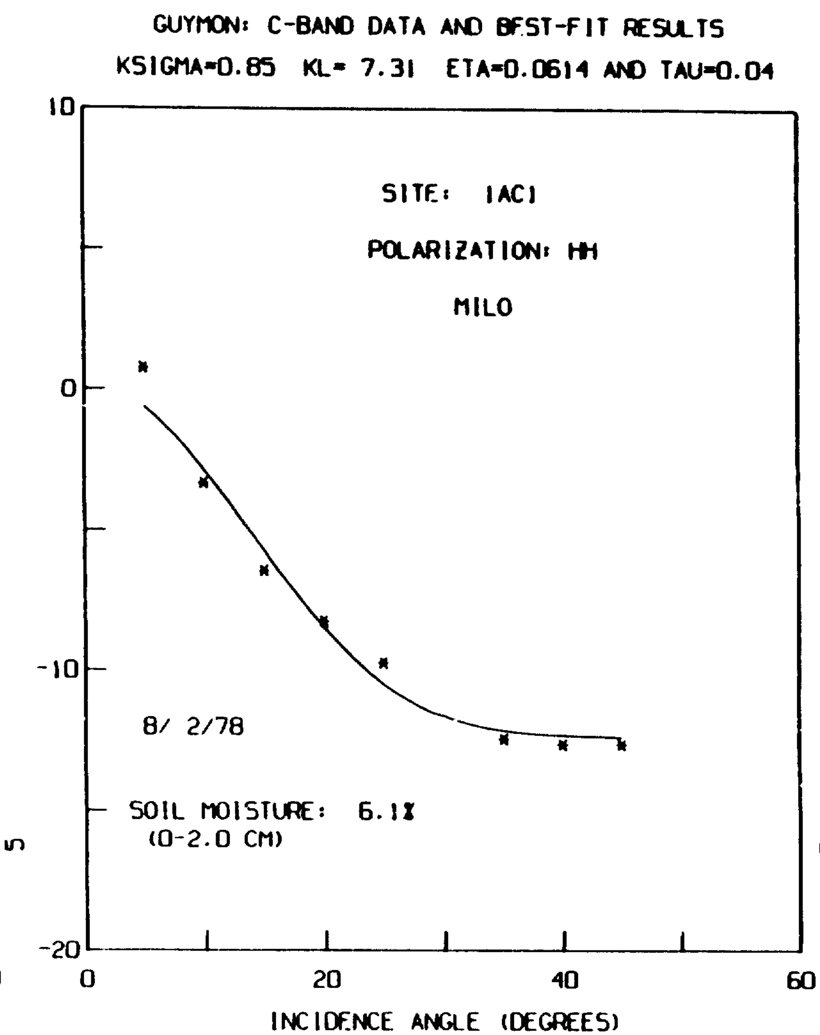

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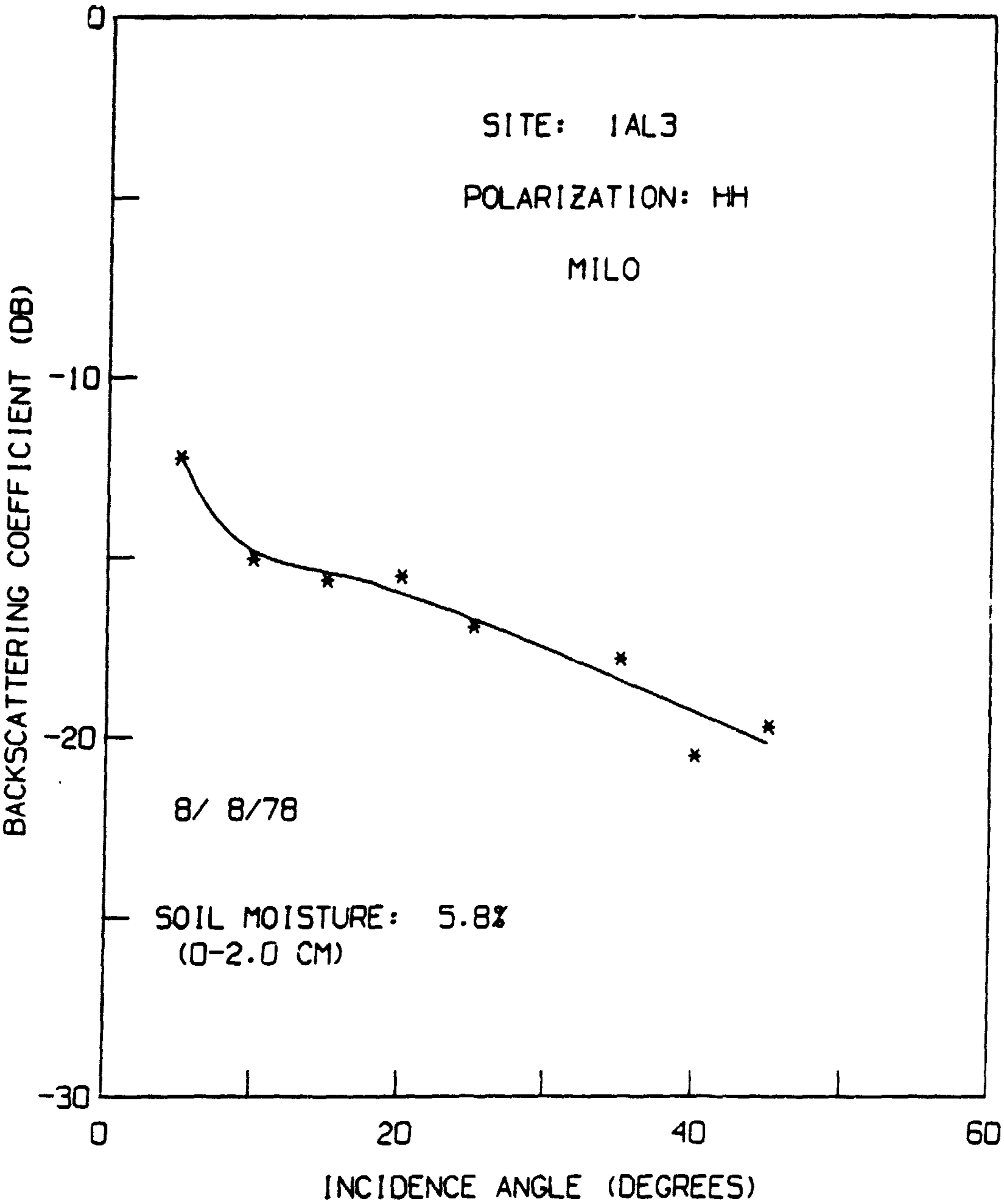

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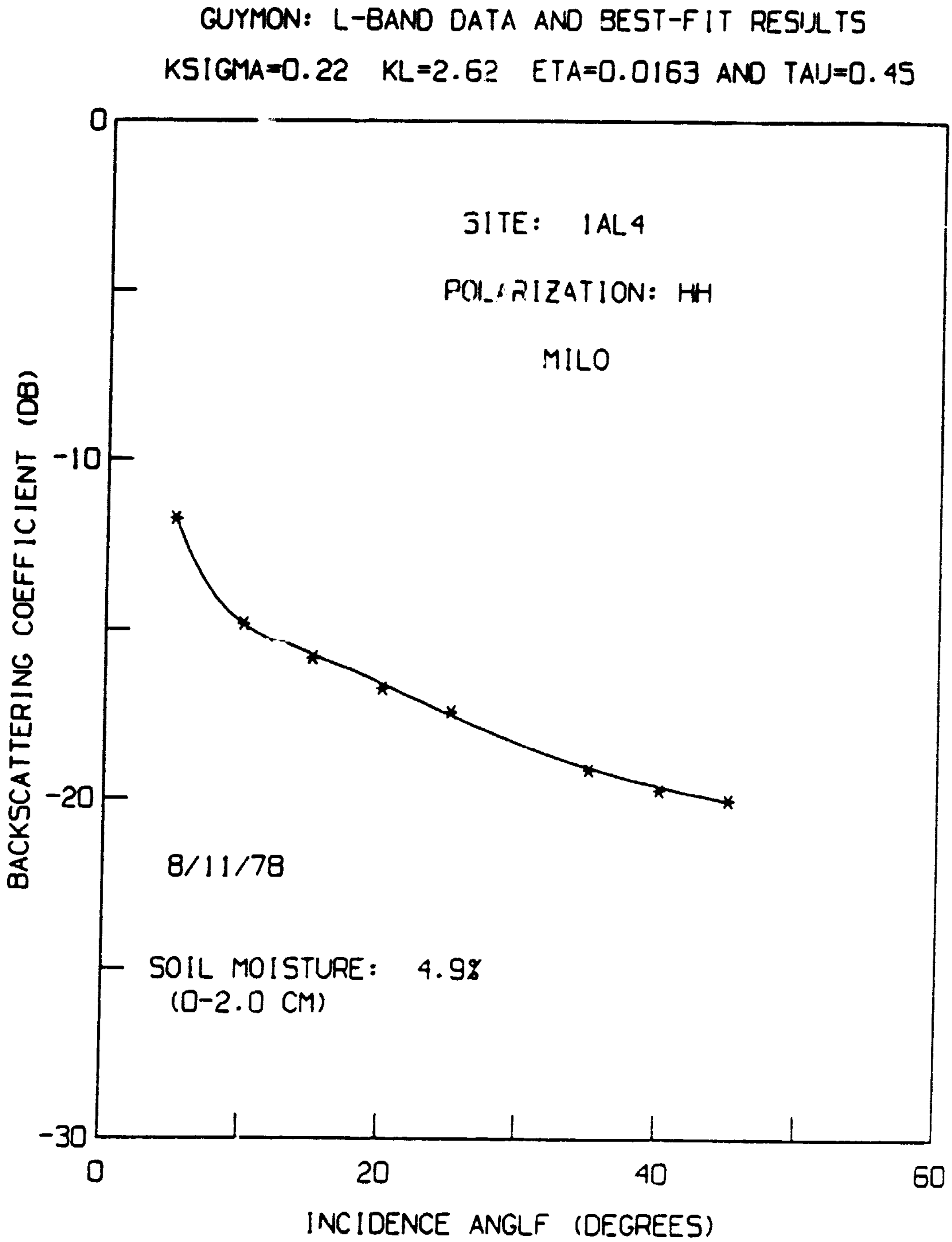

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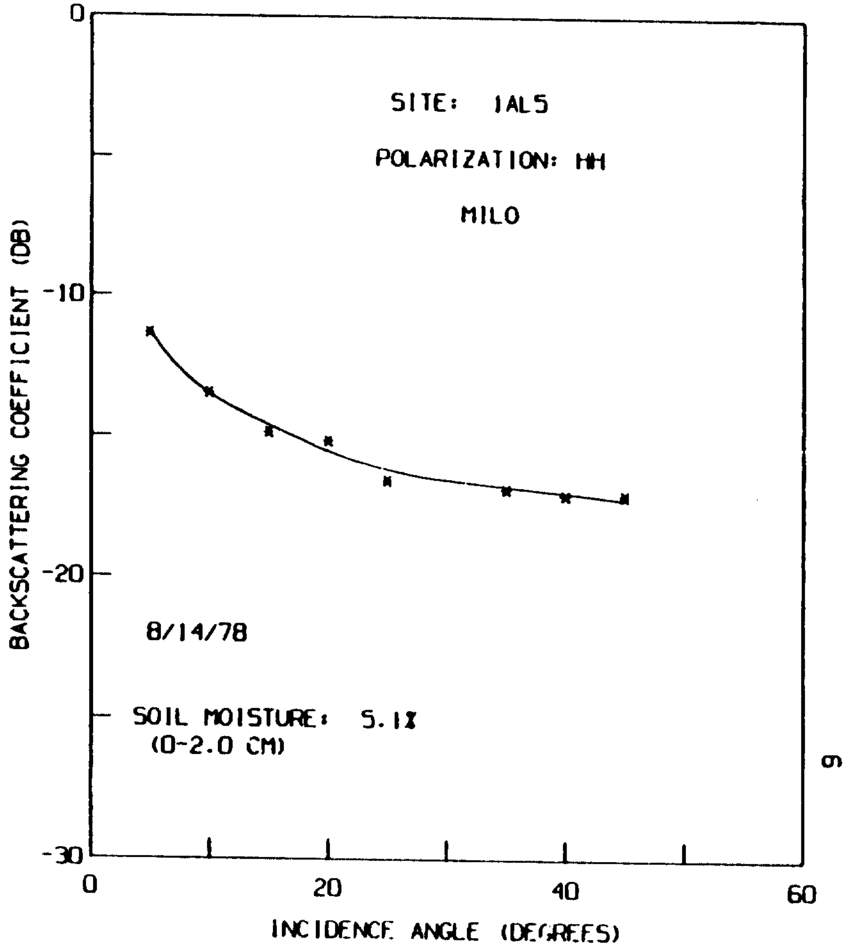

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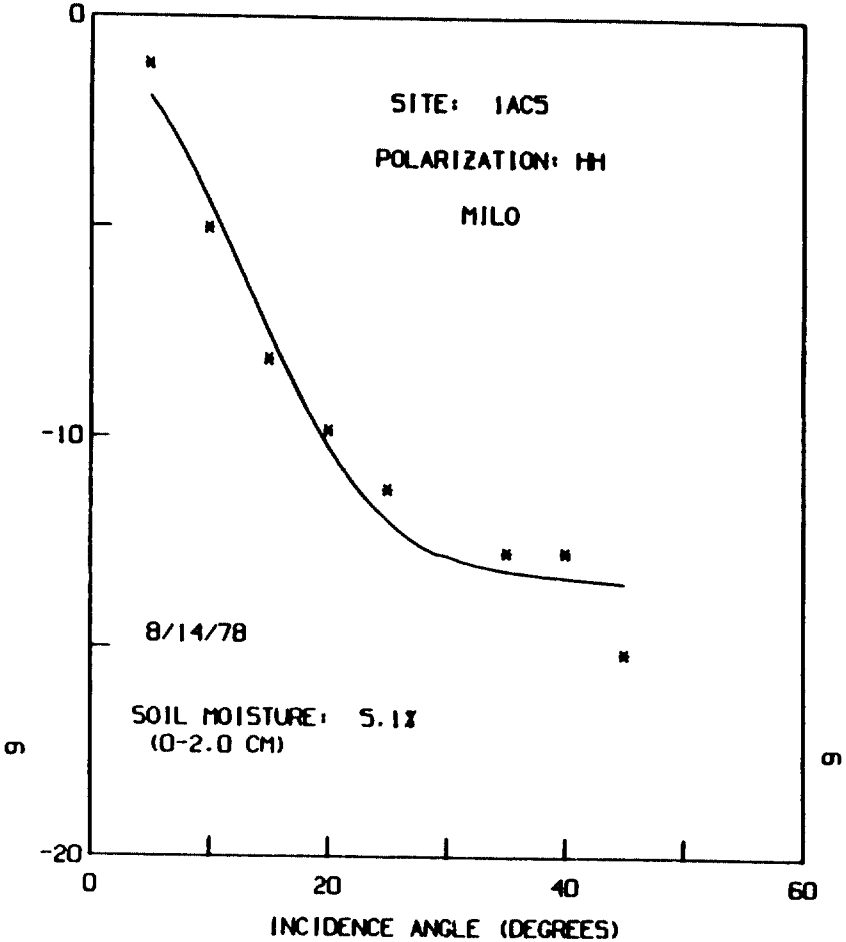

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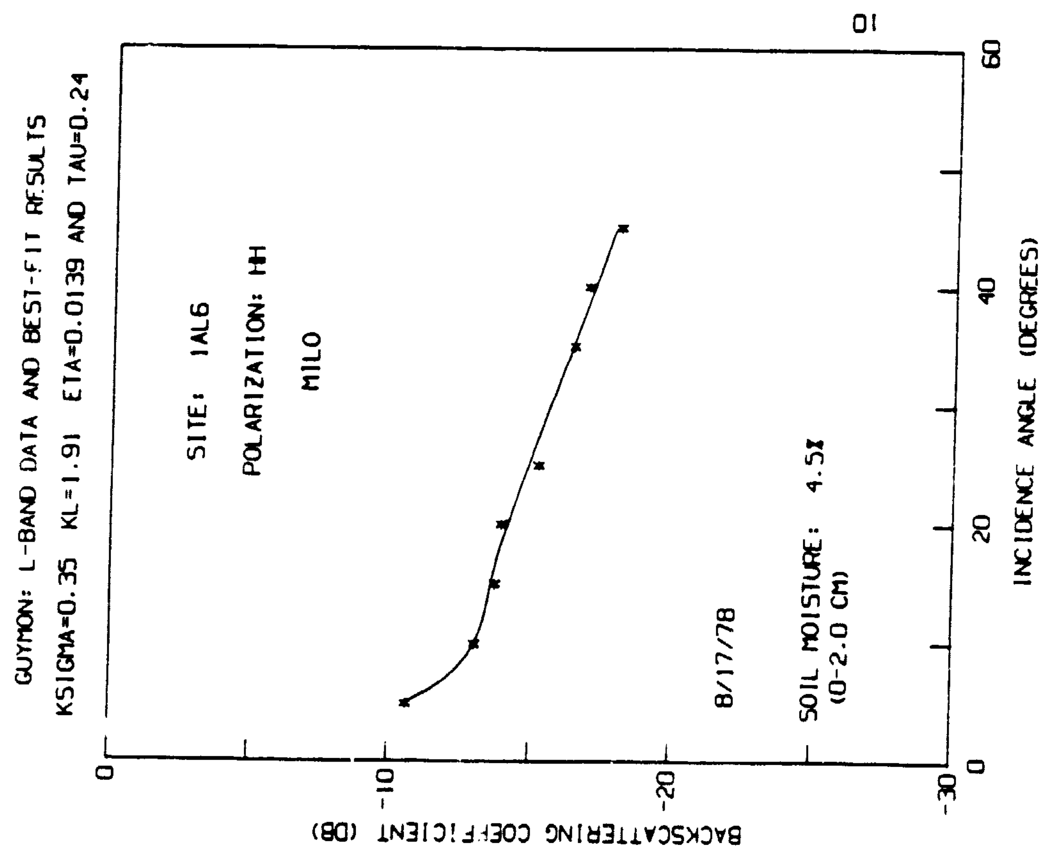

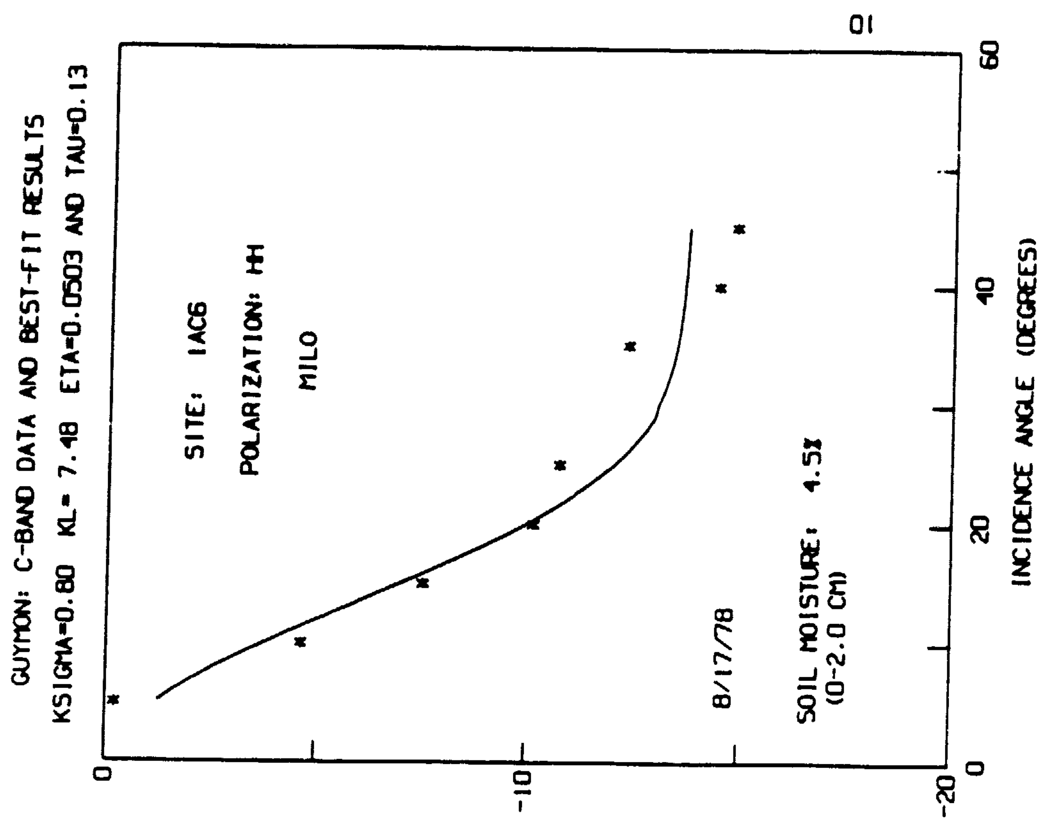

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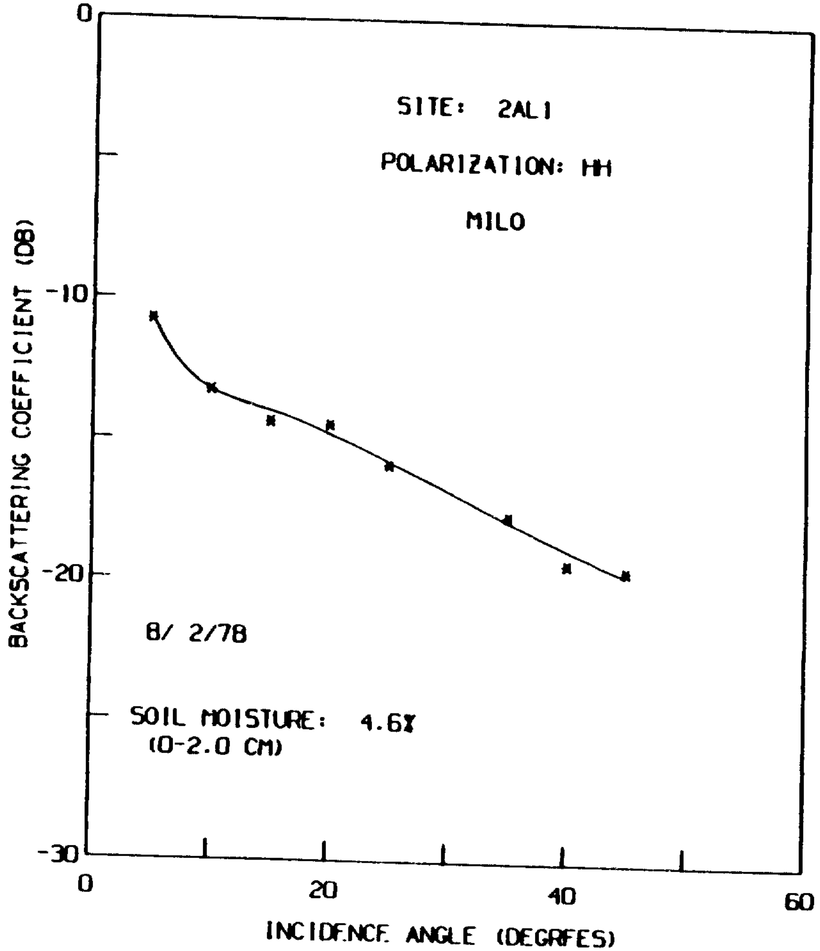

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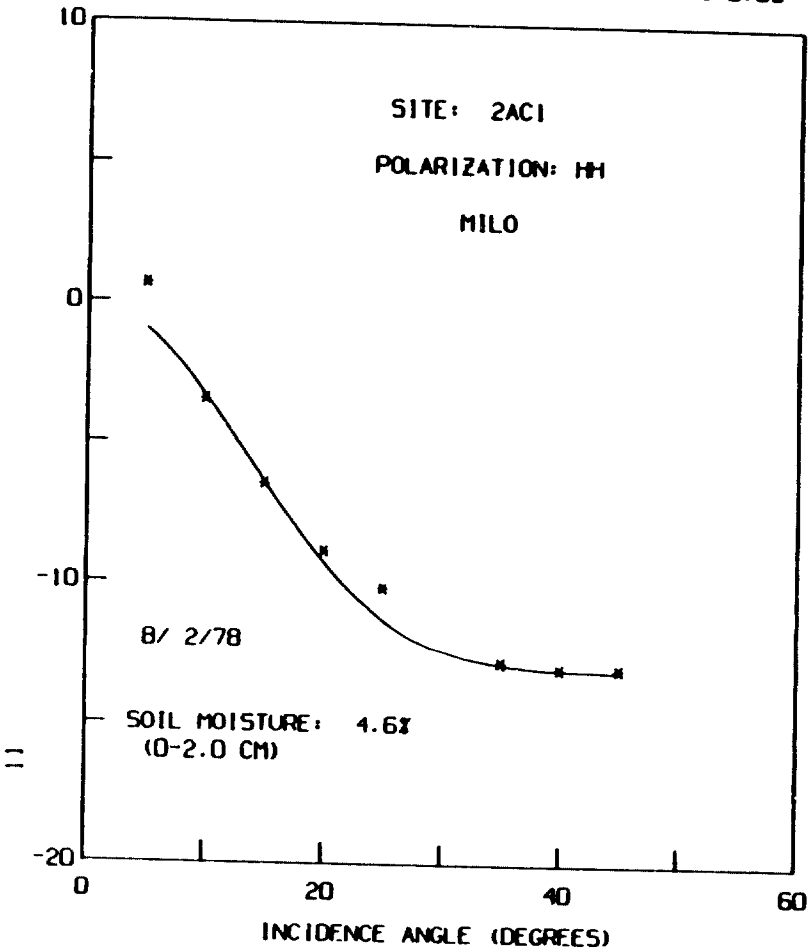

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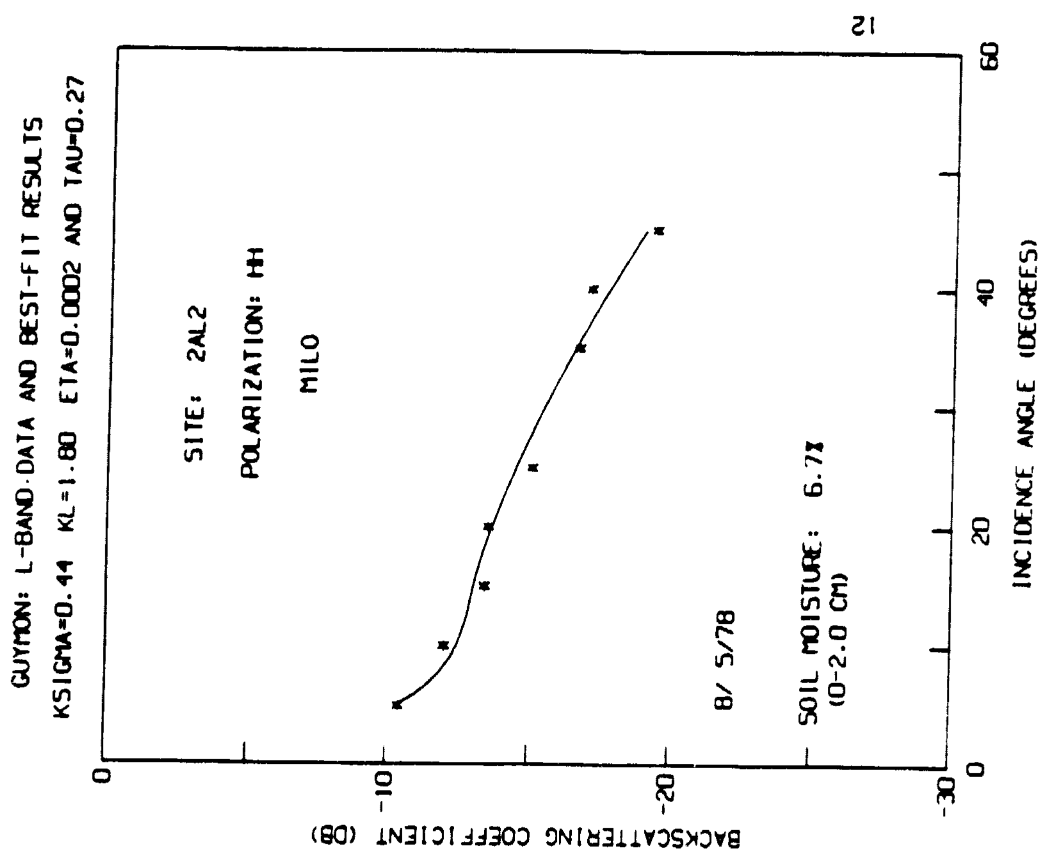

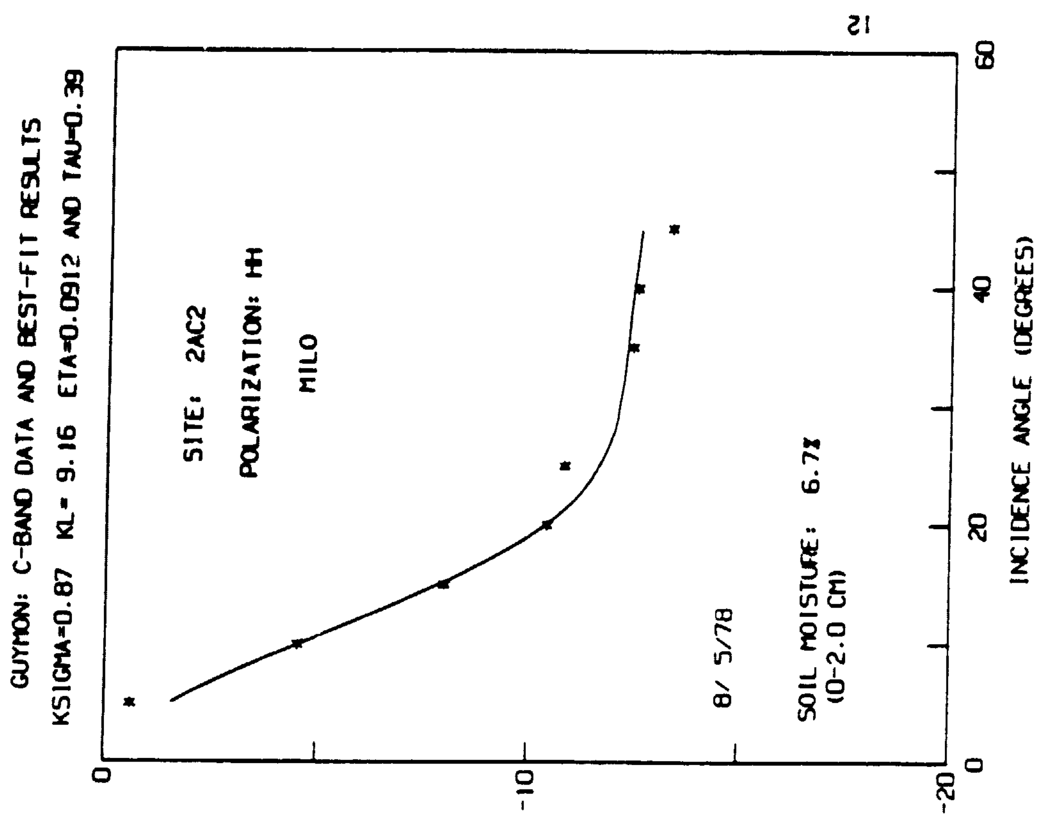

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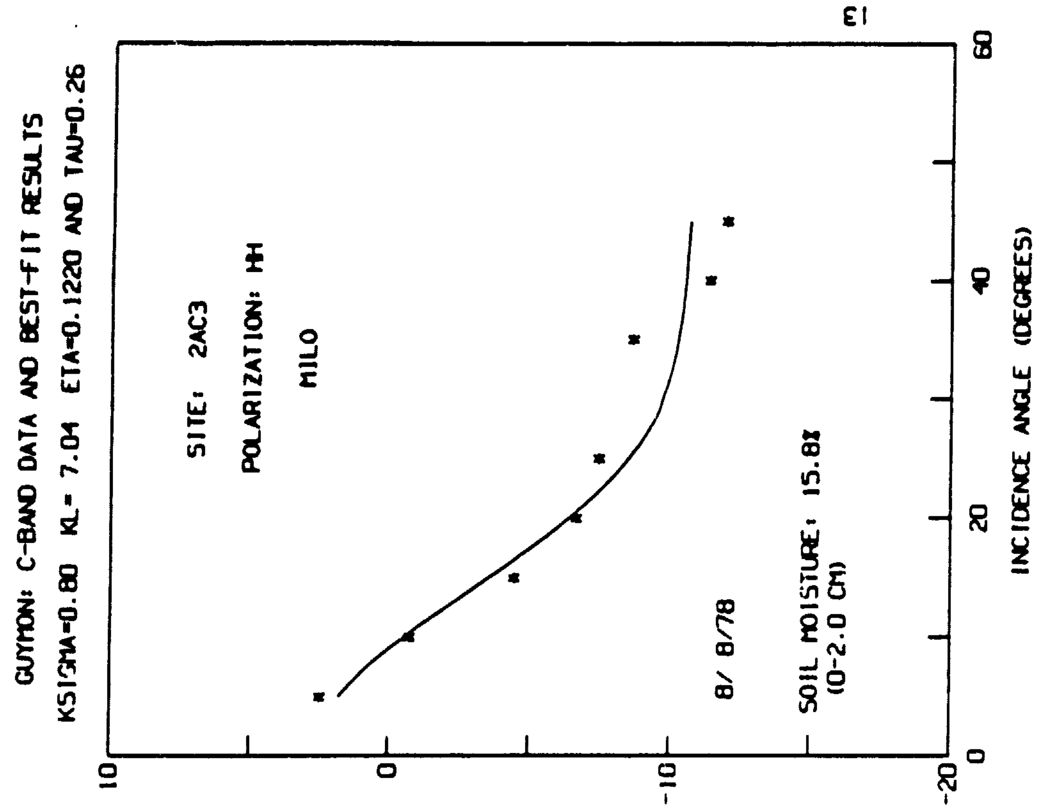

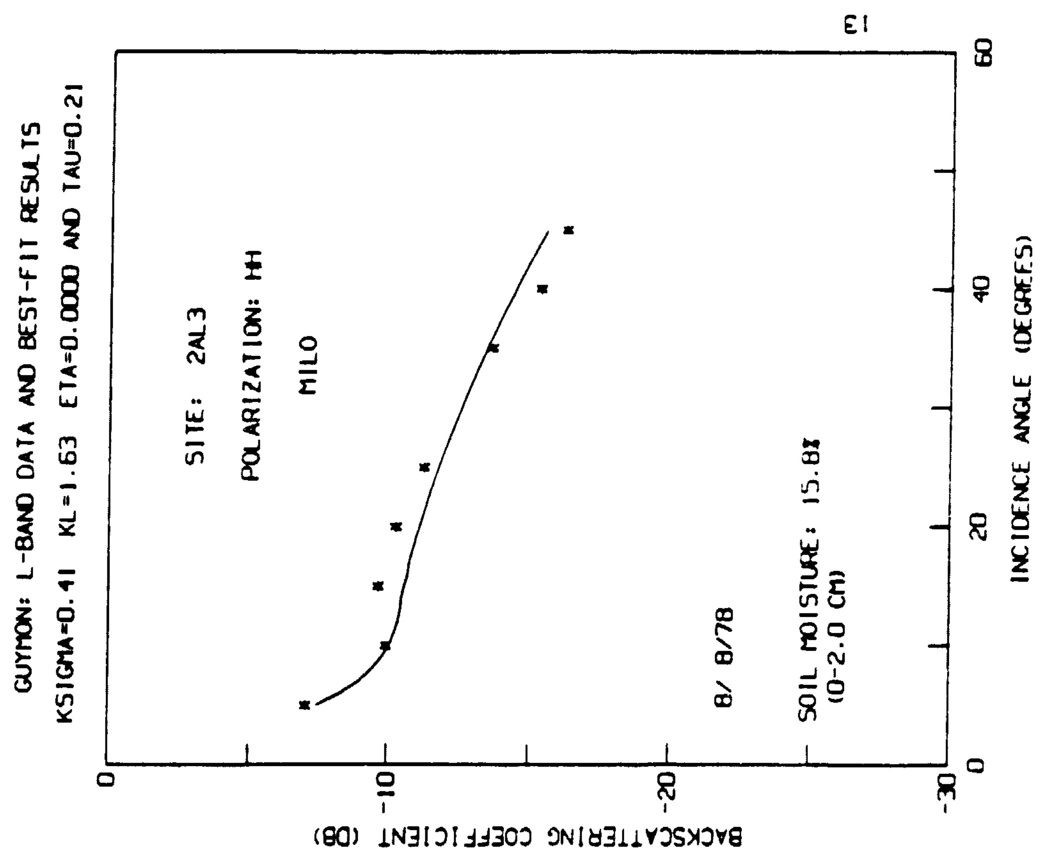

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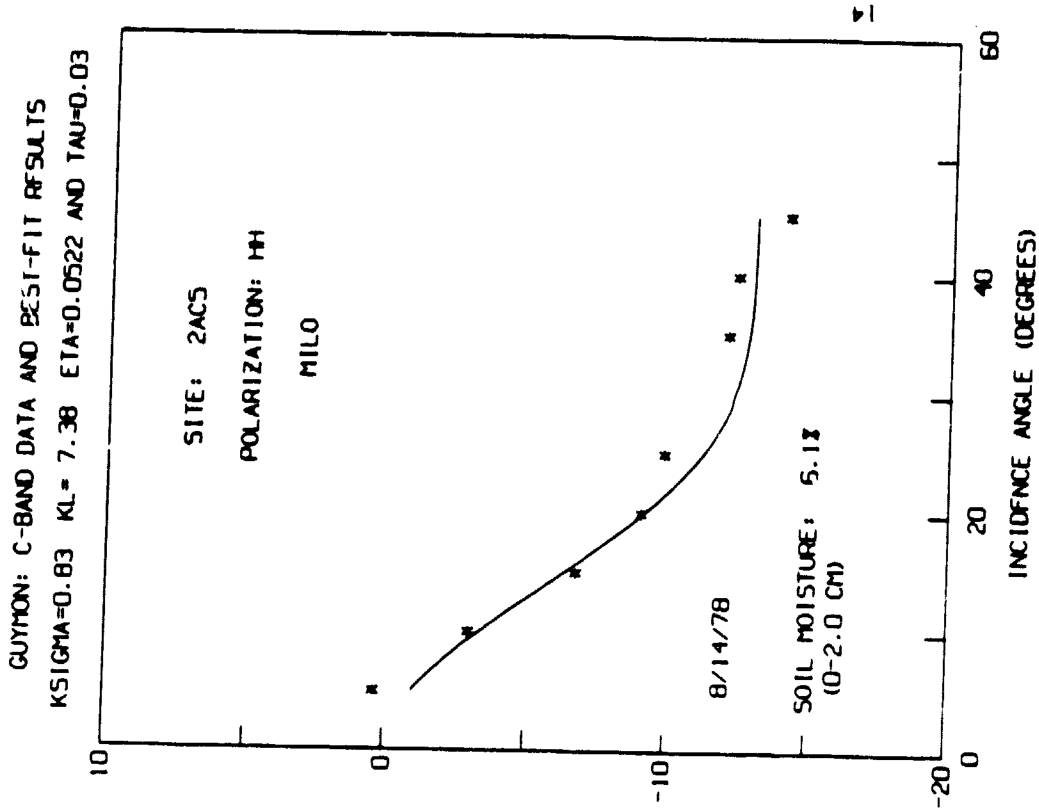

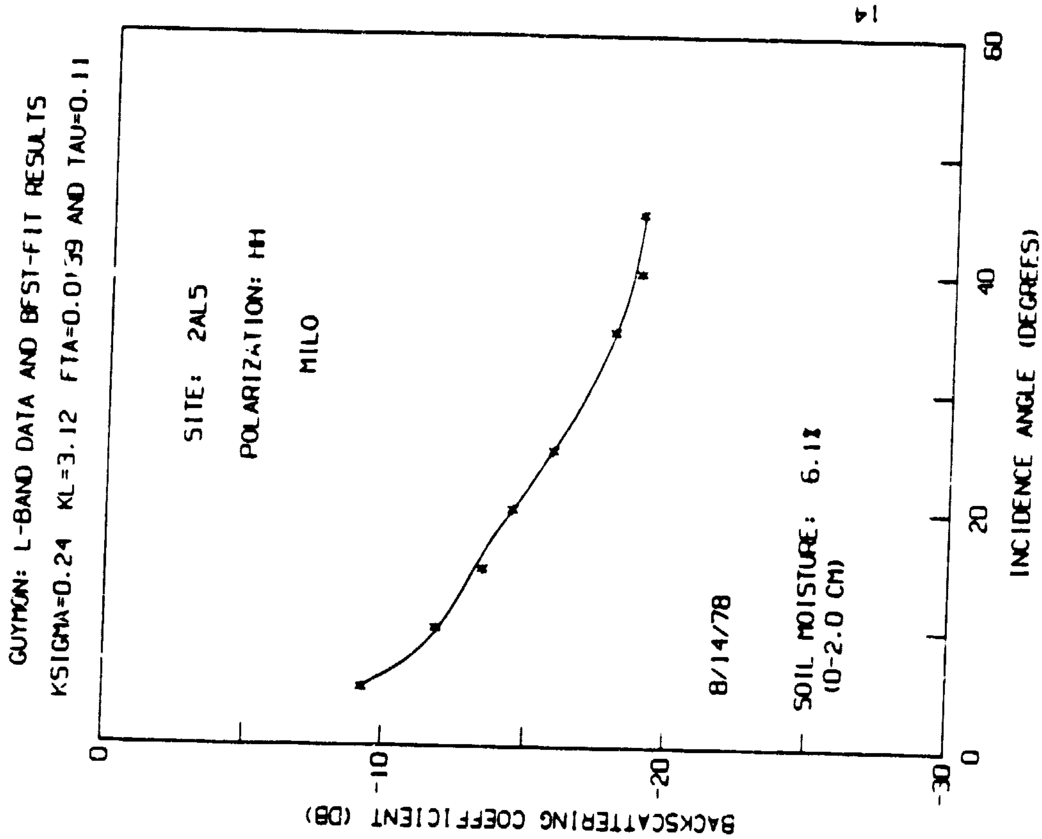

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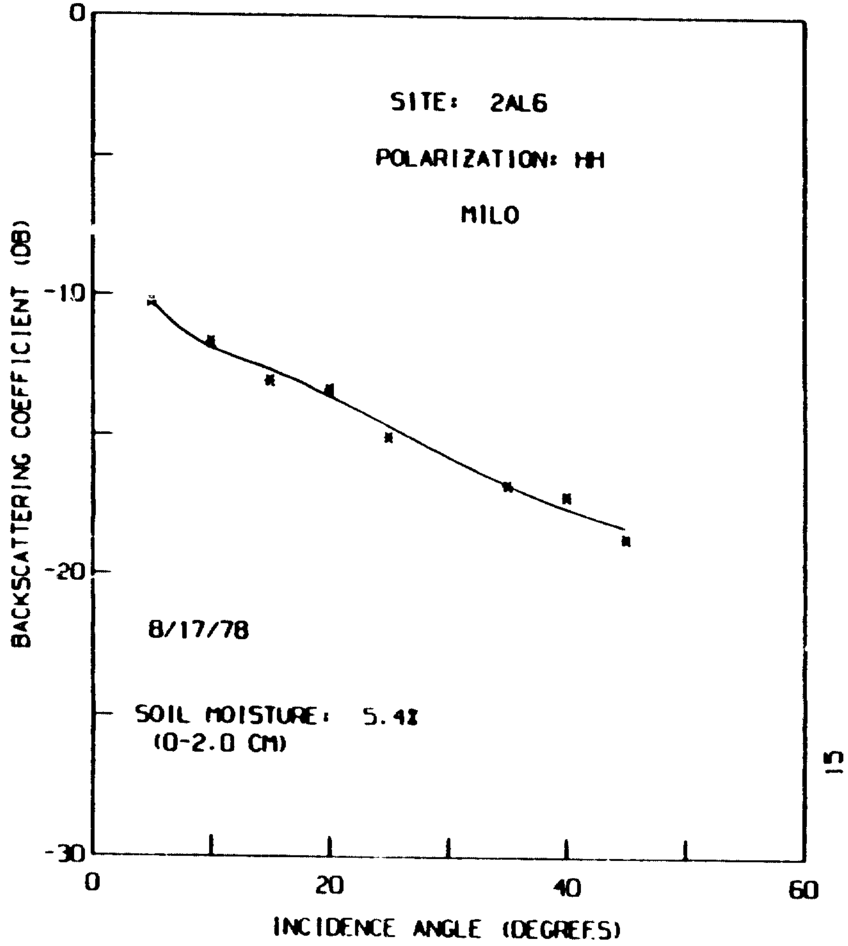

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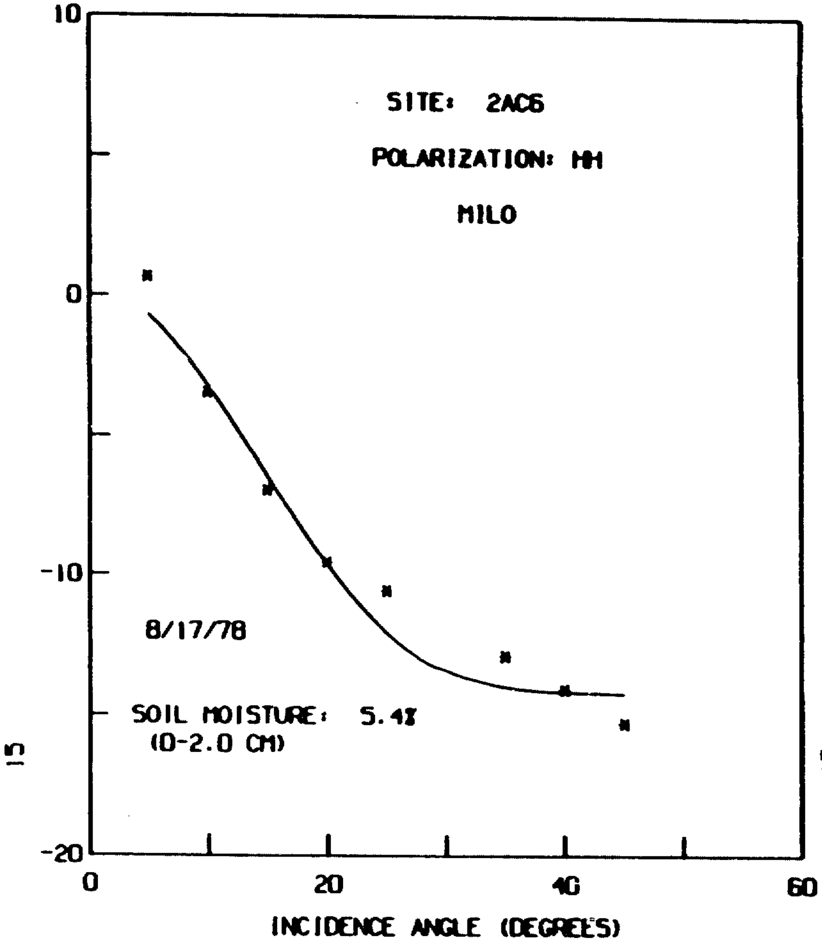

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DALHART: L-BAND DATA AND BEST-FIT RESULTS

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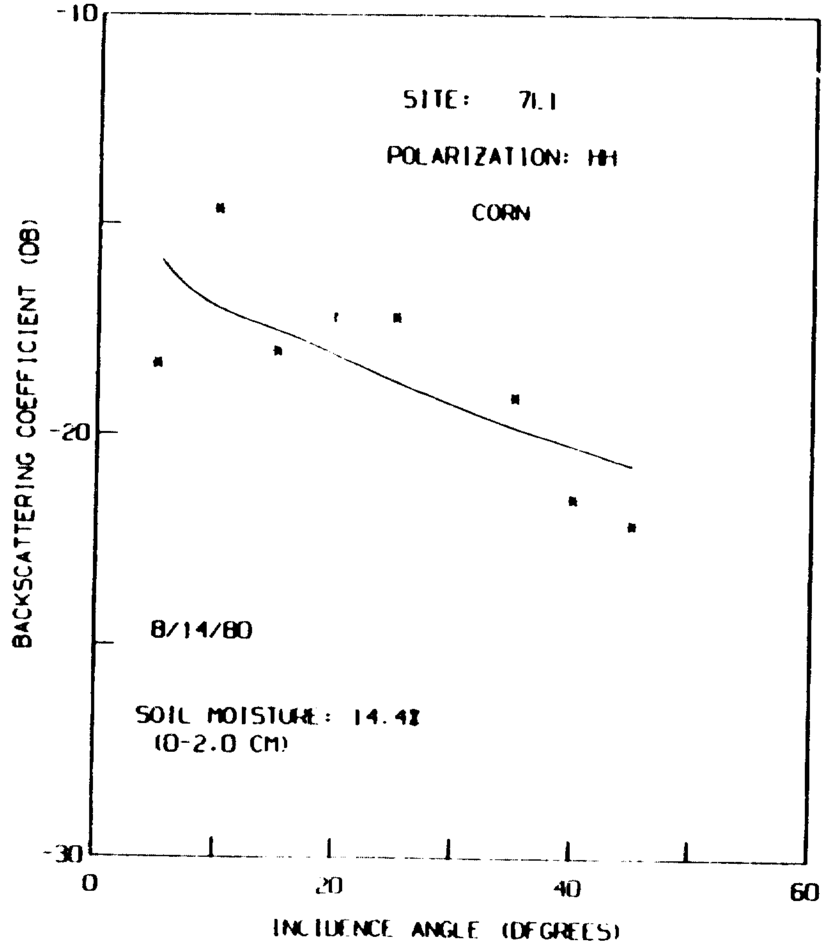

DALHART: C-BAND DATA AND BEST-FIT RESULTS

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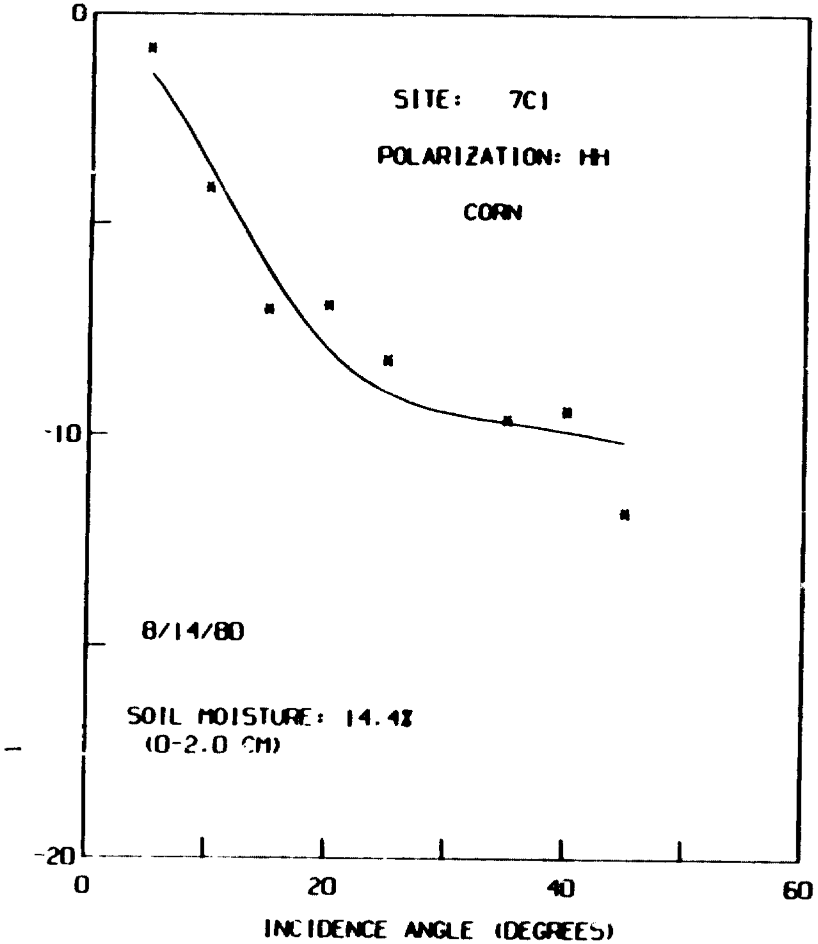

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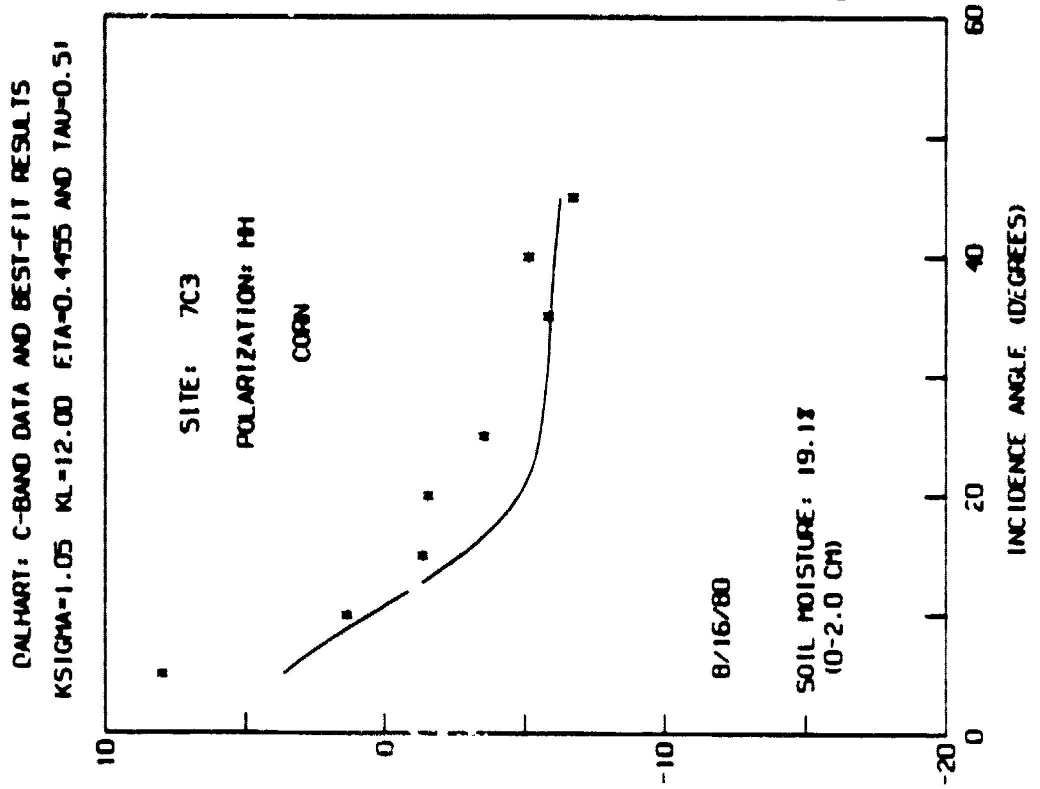

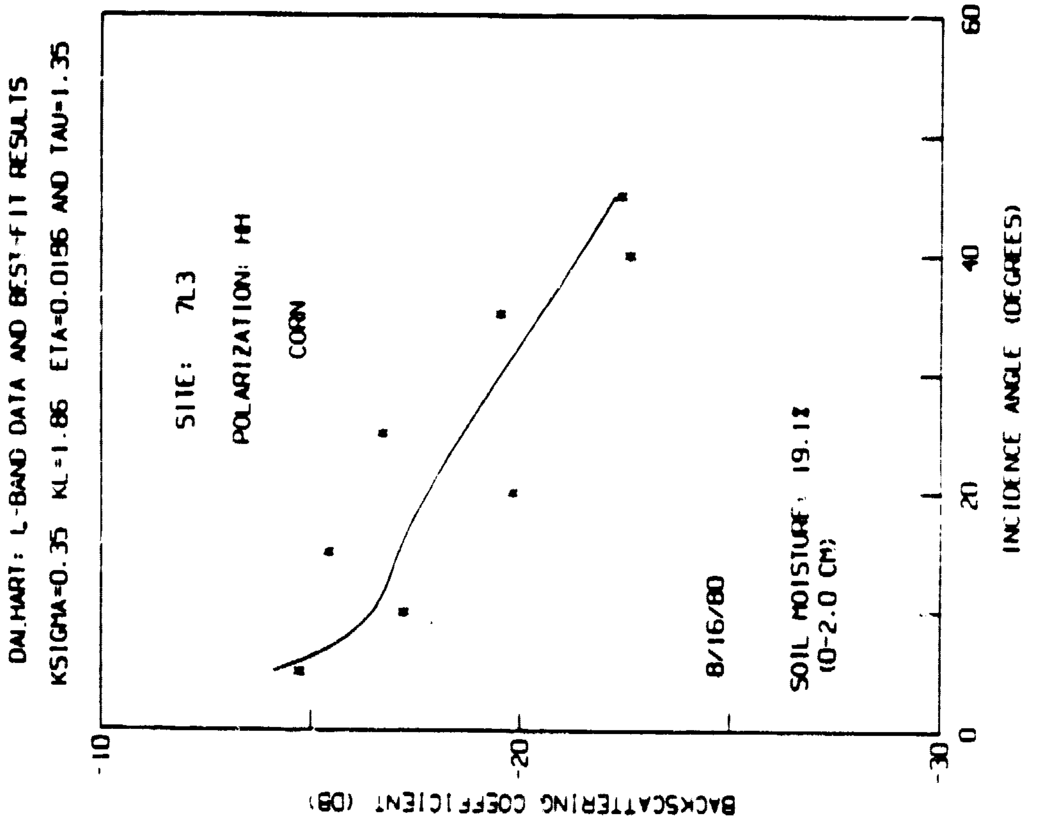

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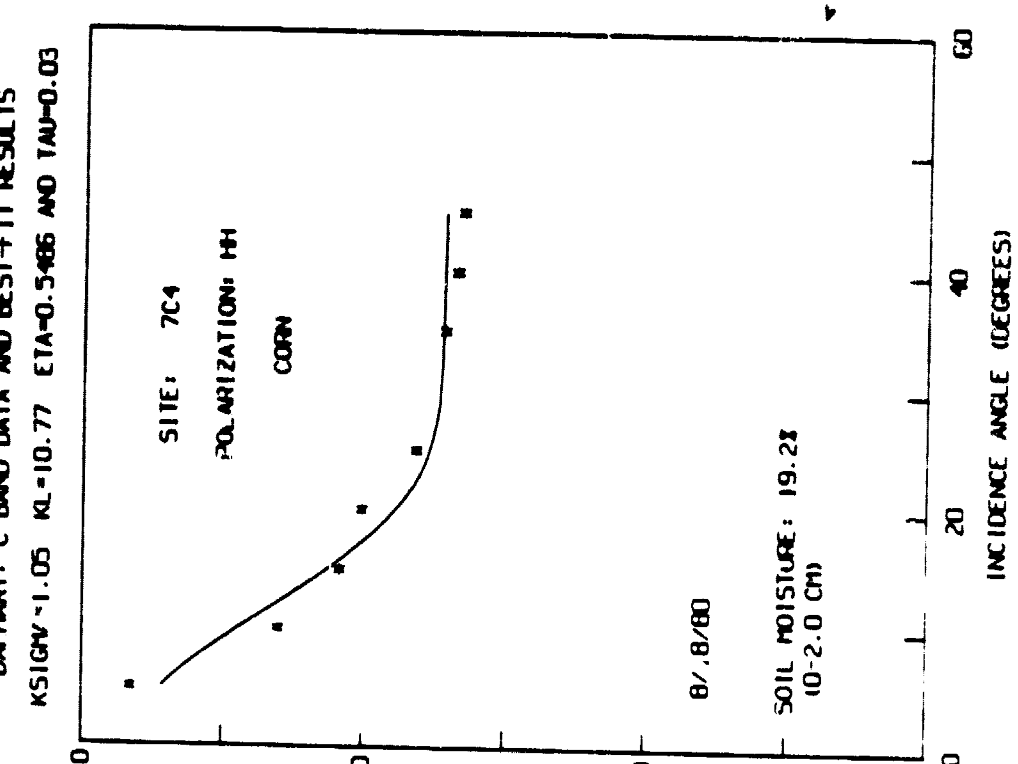

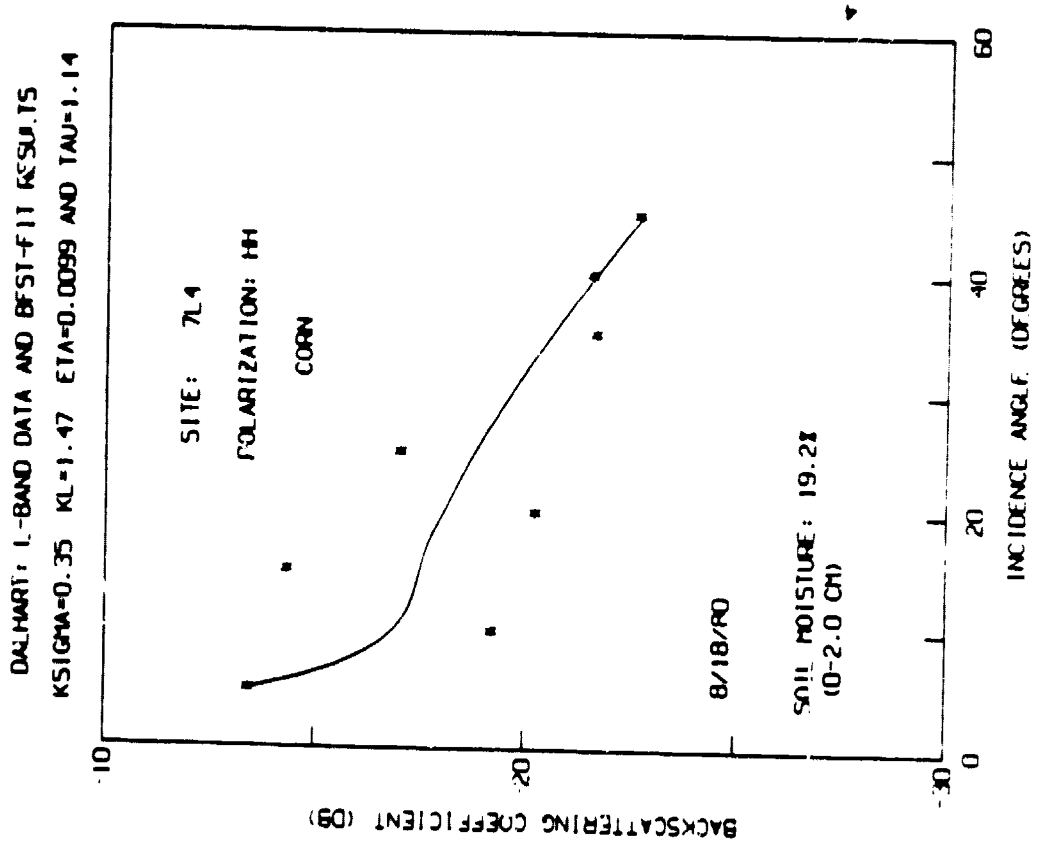

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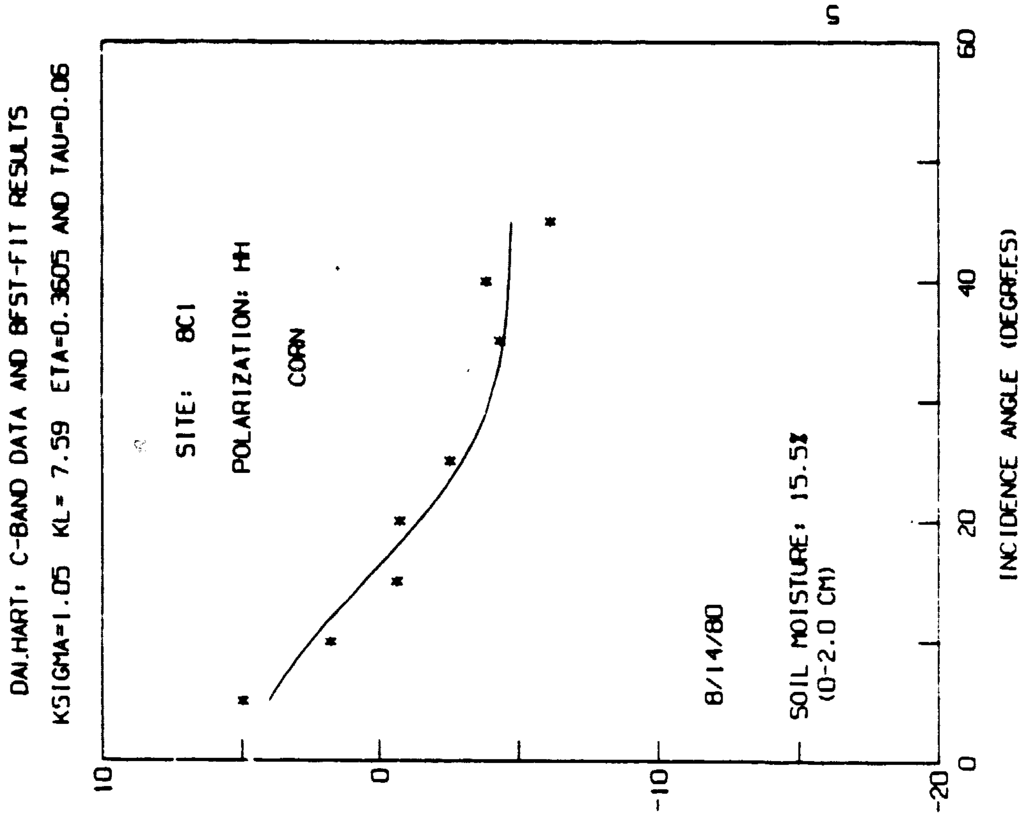

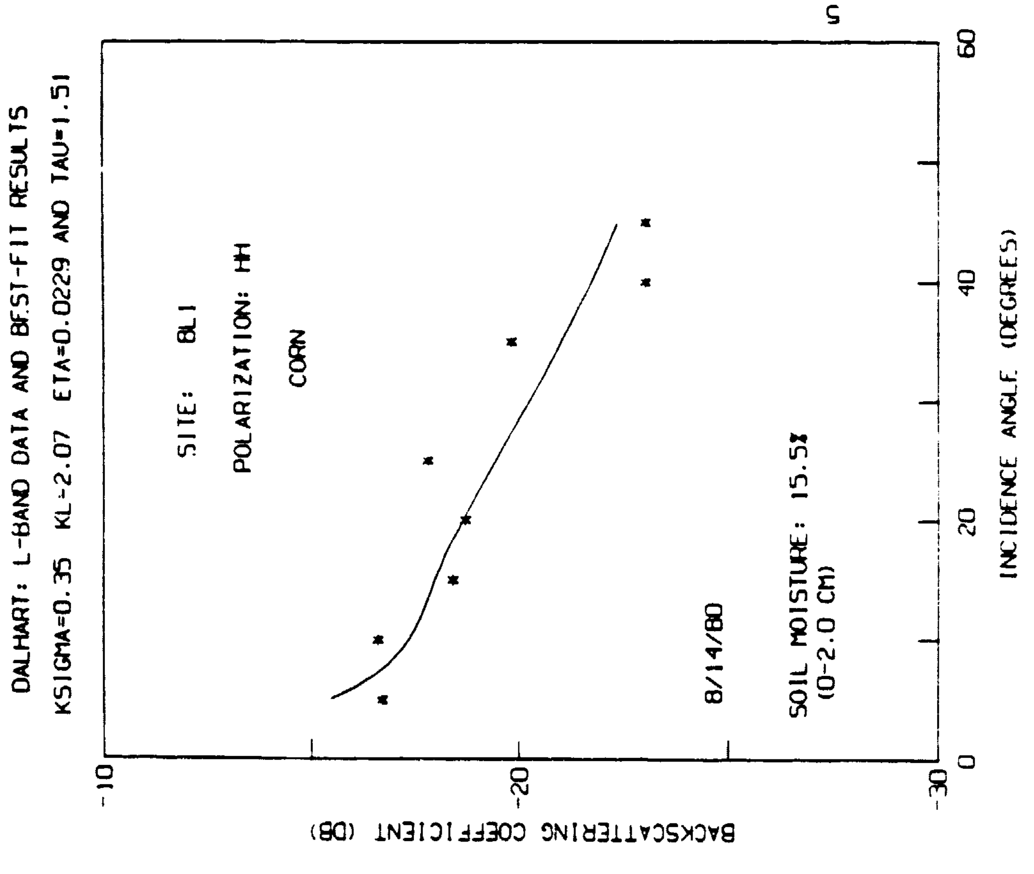

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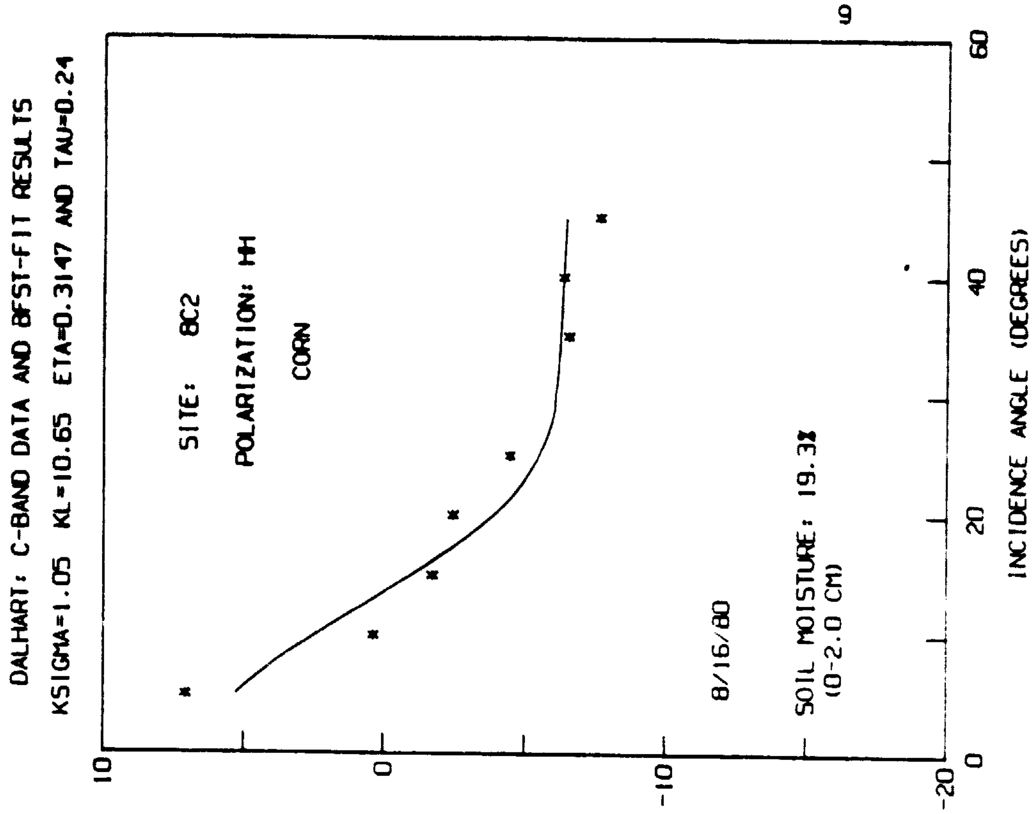

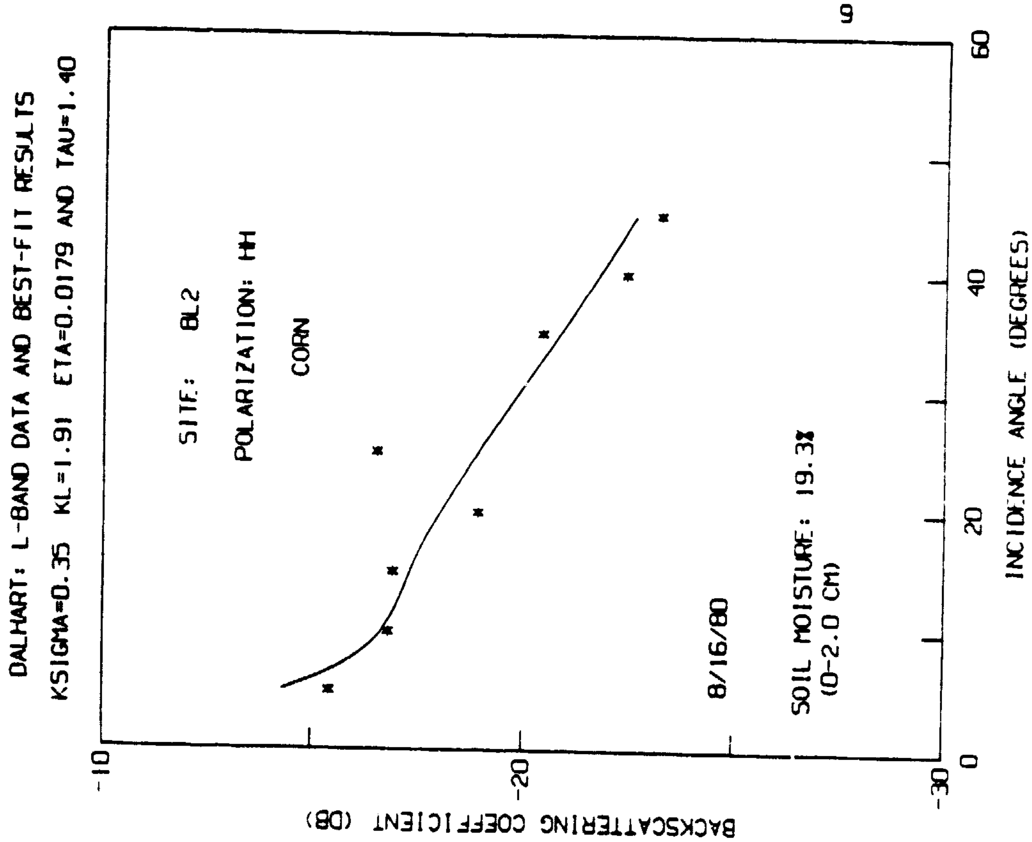

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DALHART: L-BAND DATA AND BEST-FIT RESULTS

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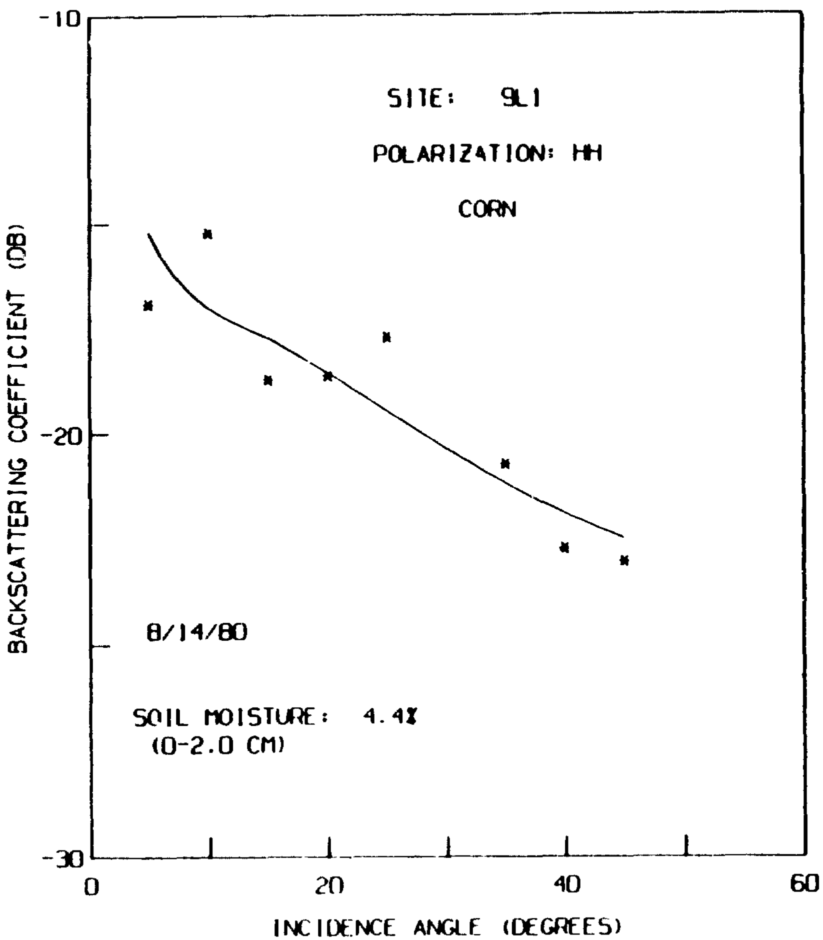

DALHART: C-BAND DATA AND BEST-FIT RESULTS

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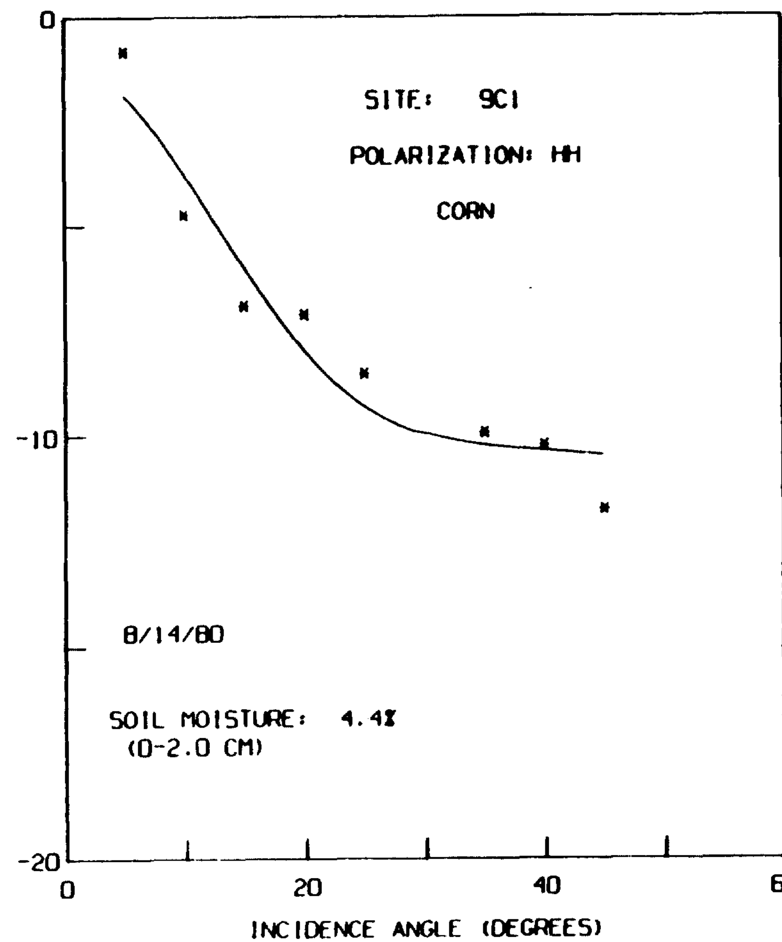

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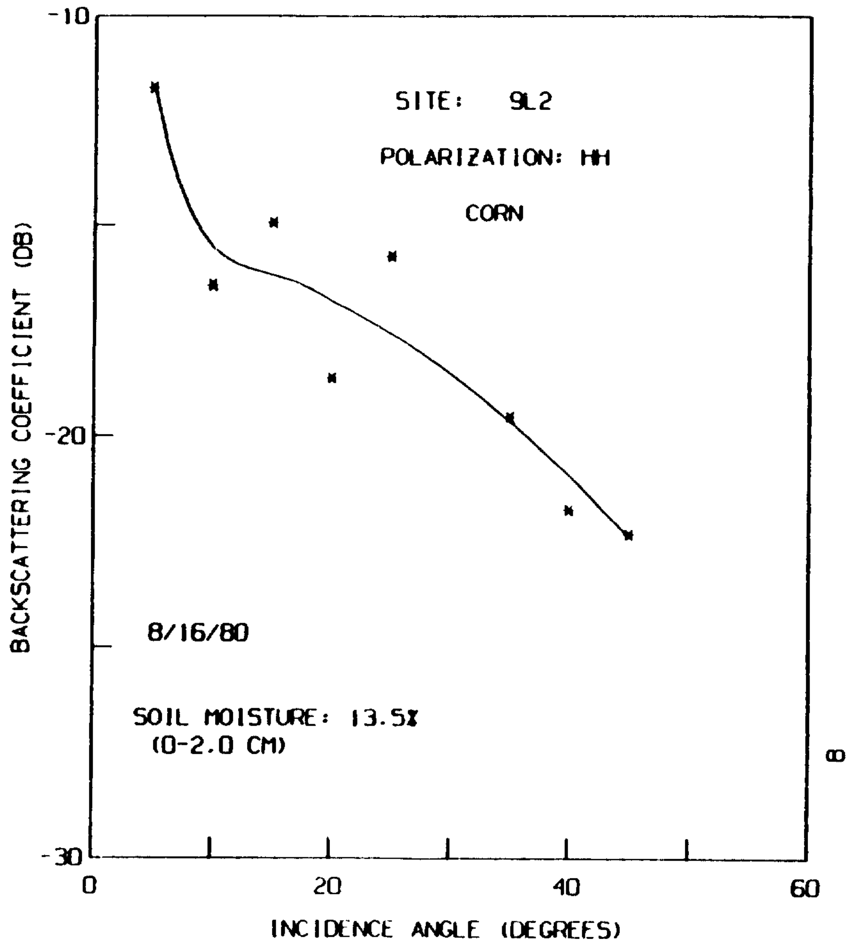
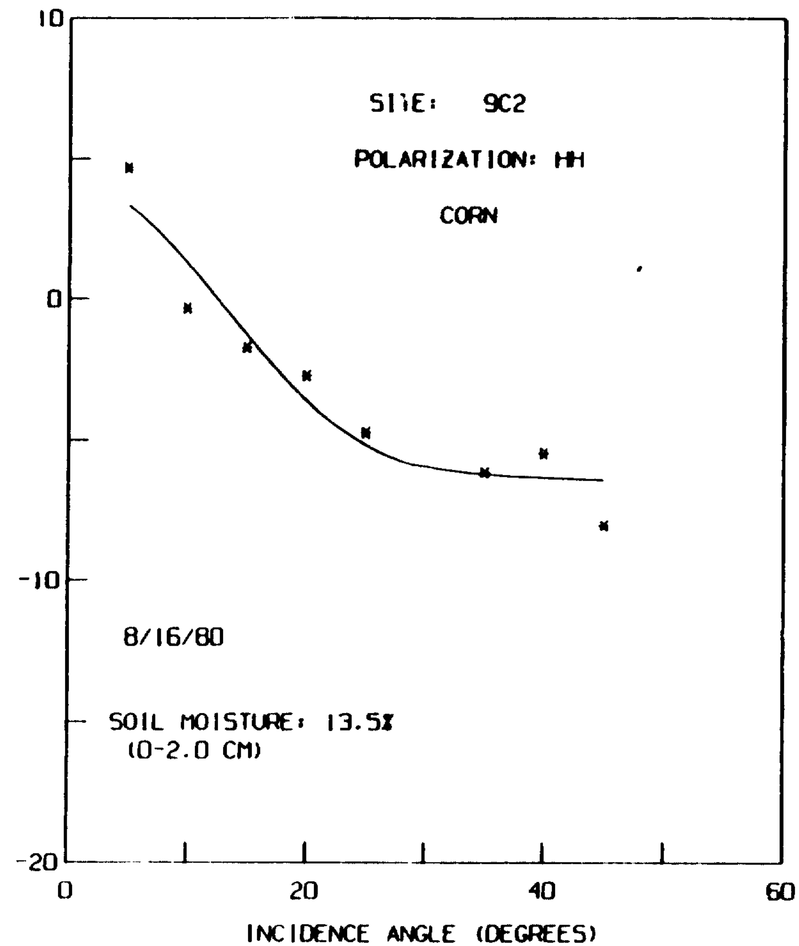
DALHART: L-BAND DATA AND BEST-FIT RESULTS

KSIGMA=0.35 KL=1.49 ETA=0.0000 AND TAU=0.71



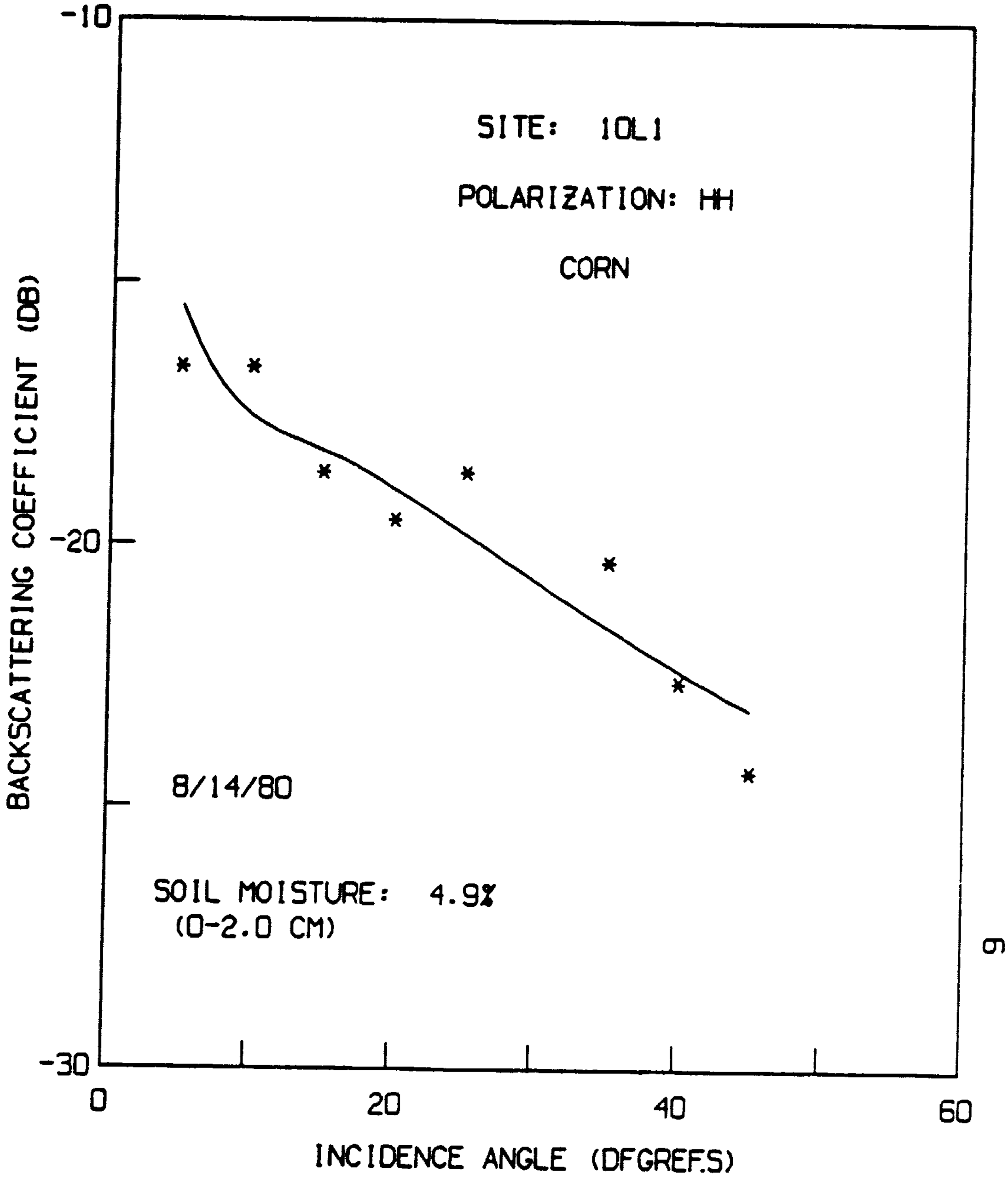
DALHART: C-BAND DATA AND BEST-FIT RESULTS

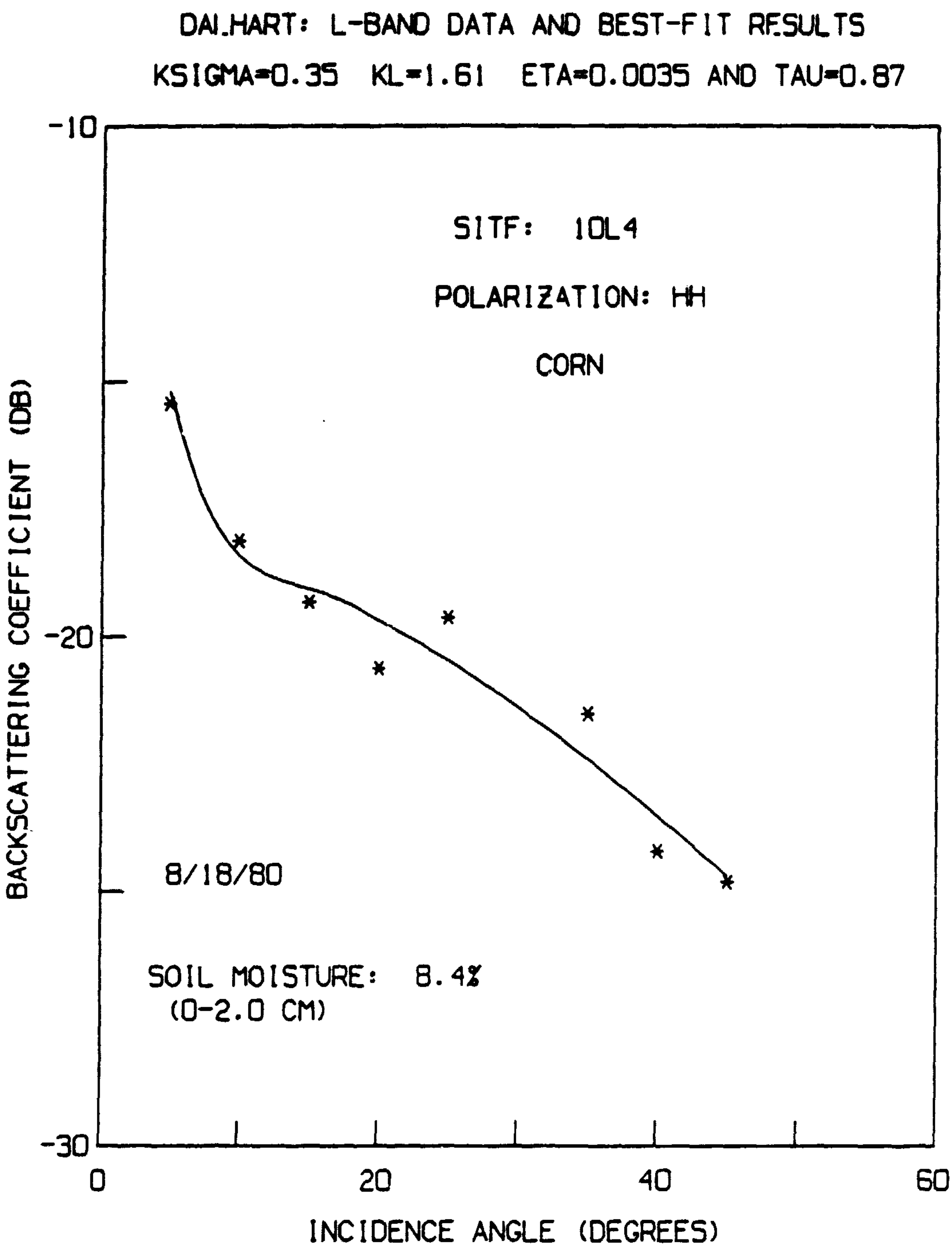
KSIGMA=1.05 KL= 9.00 ETA=0.2838 AND TAU=0.16



DALHART: L-BAND DATA AND BEST-FIT RESULTS

KSIGMA=0.35 KL=2.10 ETA=0.0108 AND TAU=0.90




DALHART: L-BAND DATA AND BEST-FIT RESULTS
KSIGMA=0.35 KL=1.61 ETA=0.0035 AND TAU=0.87
SITE: 10L4
POLARIZATION: HH
CORN
8/18/80
SOIL MOISTURE: 8.4%
(0-2.0 CM)
BACKSCATTERING COEFFICIENT (DB)
-10
-20
-30
0
20
40
60
INCIDENCE ANGLE (DEGREES)

10

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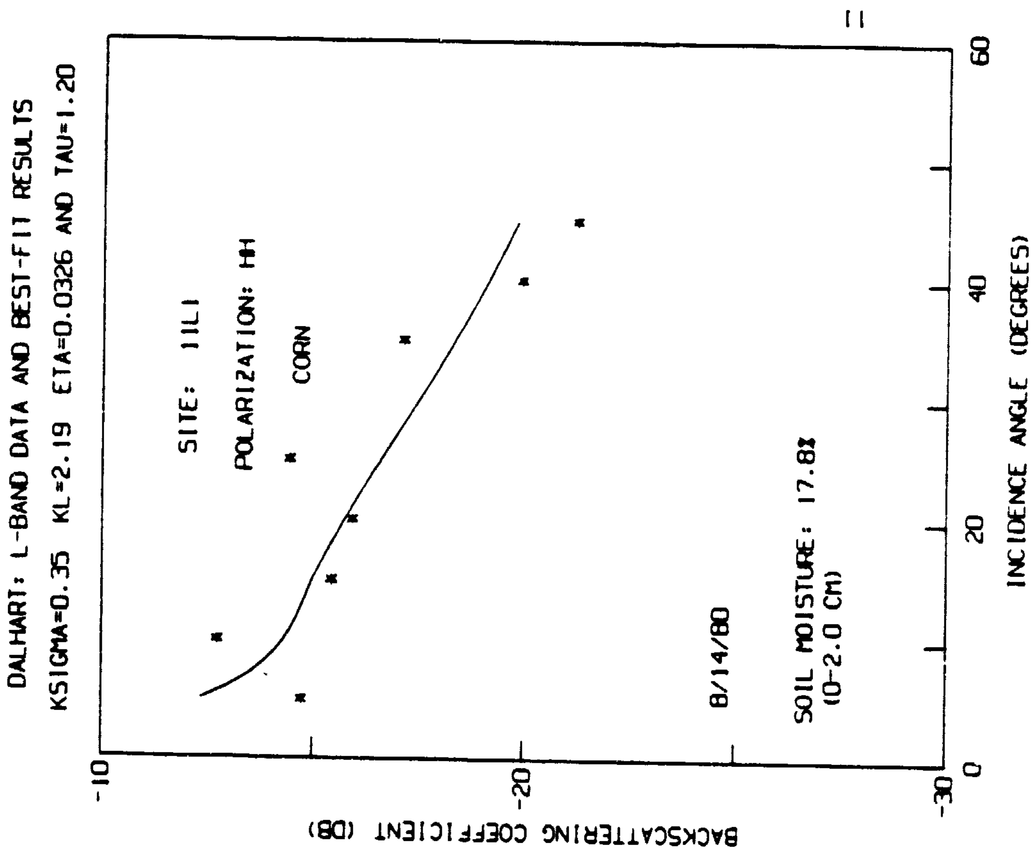

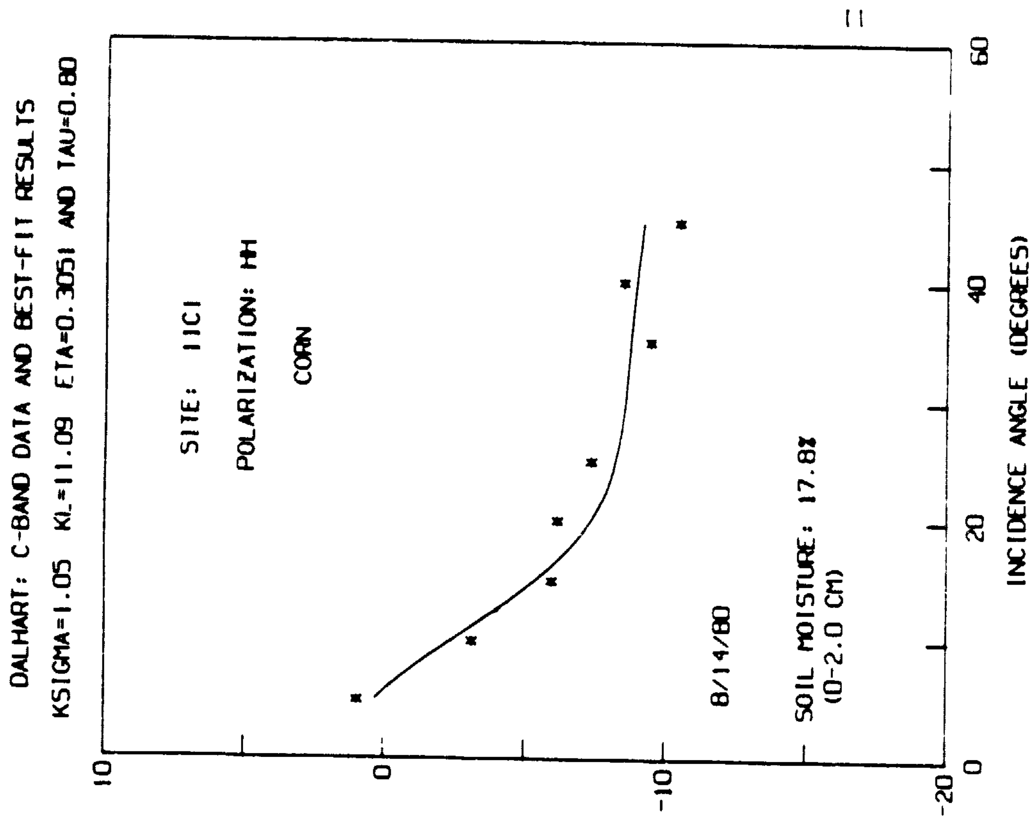

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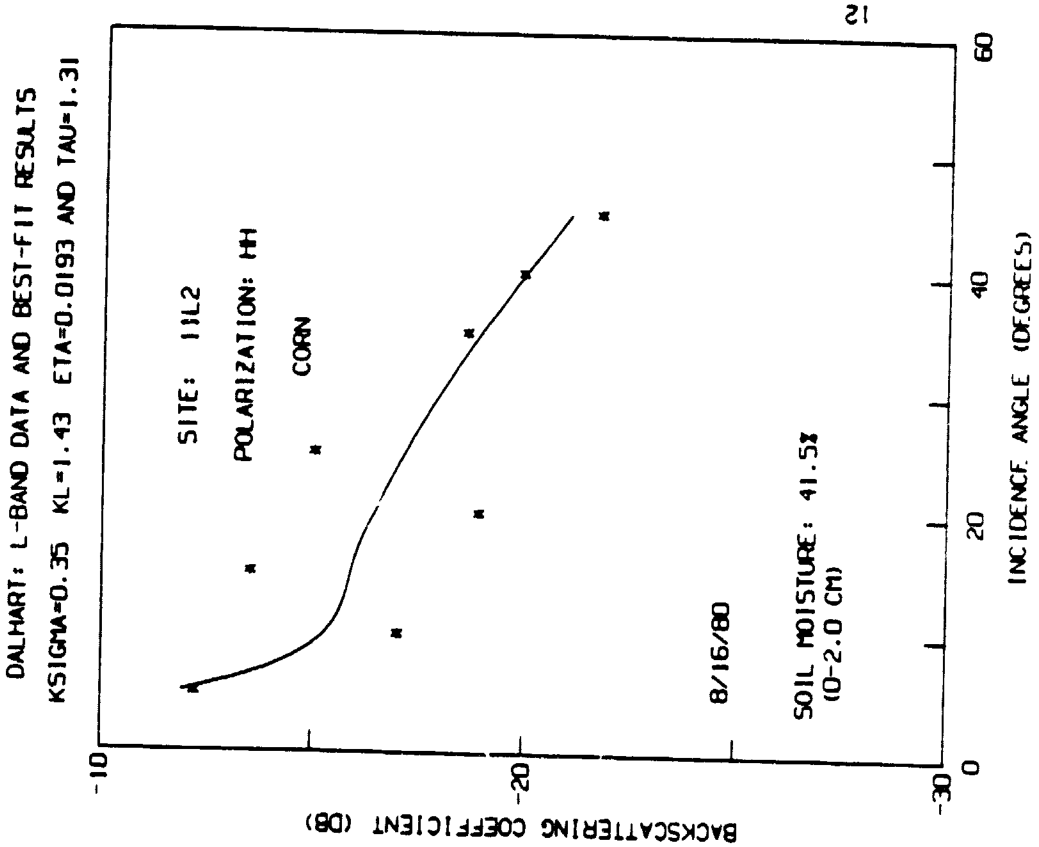

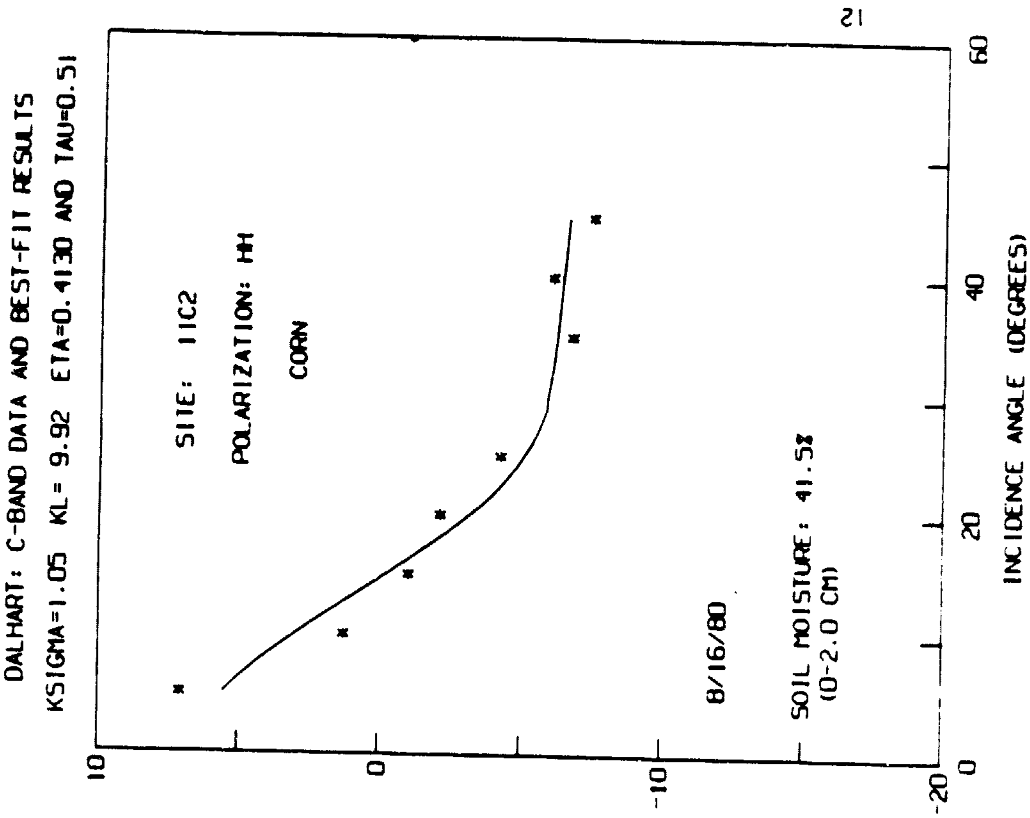

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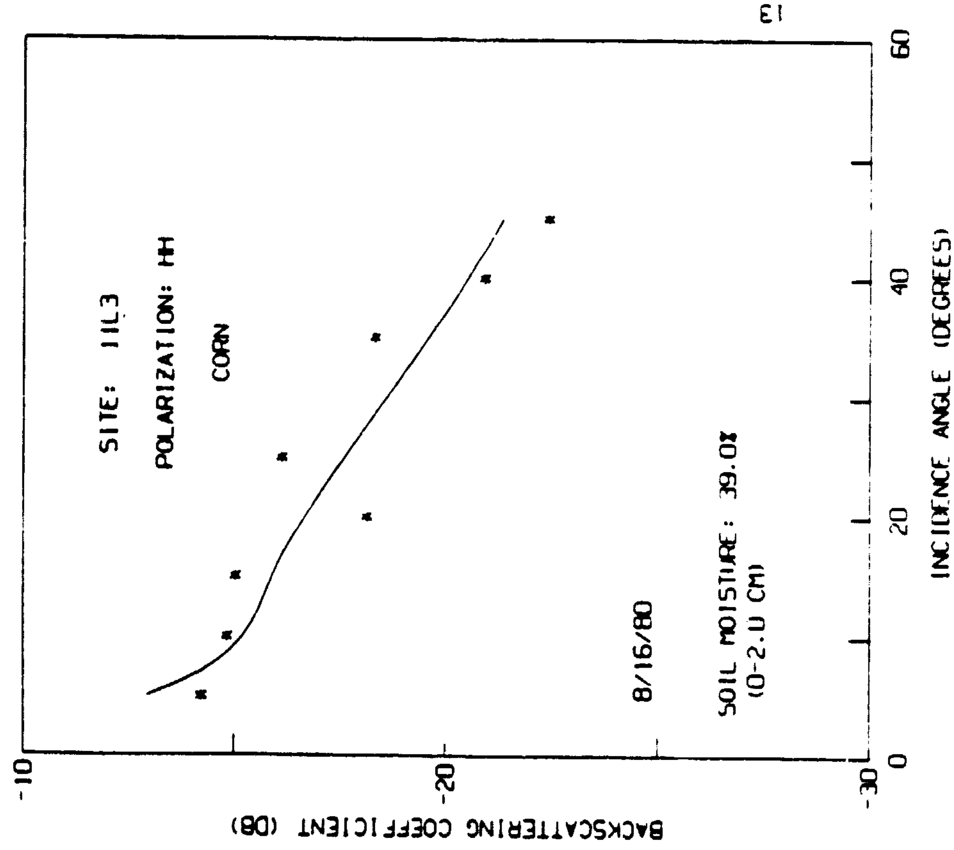
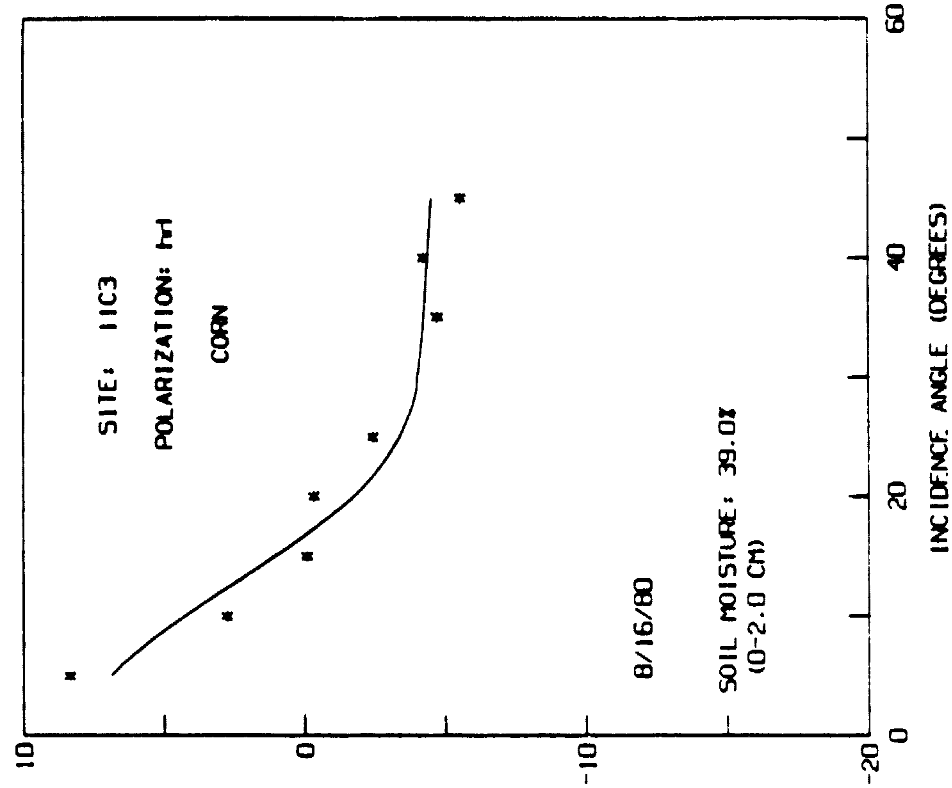
DALHART: L-BAND DATA AND BEST-FIT RESULTS

KSIGMA=0.35 KL=1.98 ETA=0.0286 AND TAU=1.59



DALHART: C-BAND DATA AND BEST-FIT RESULTS

KSIGMA=1.05 KL=10.23 ETA=0.5582 AND TAU=0.36



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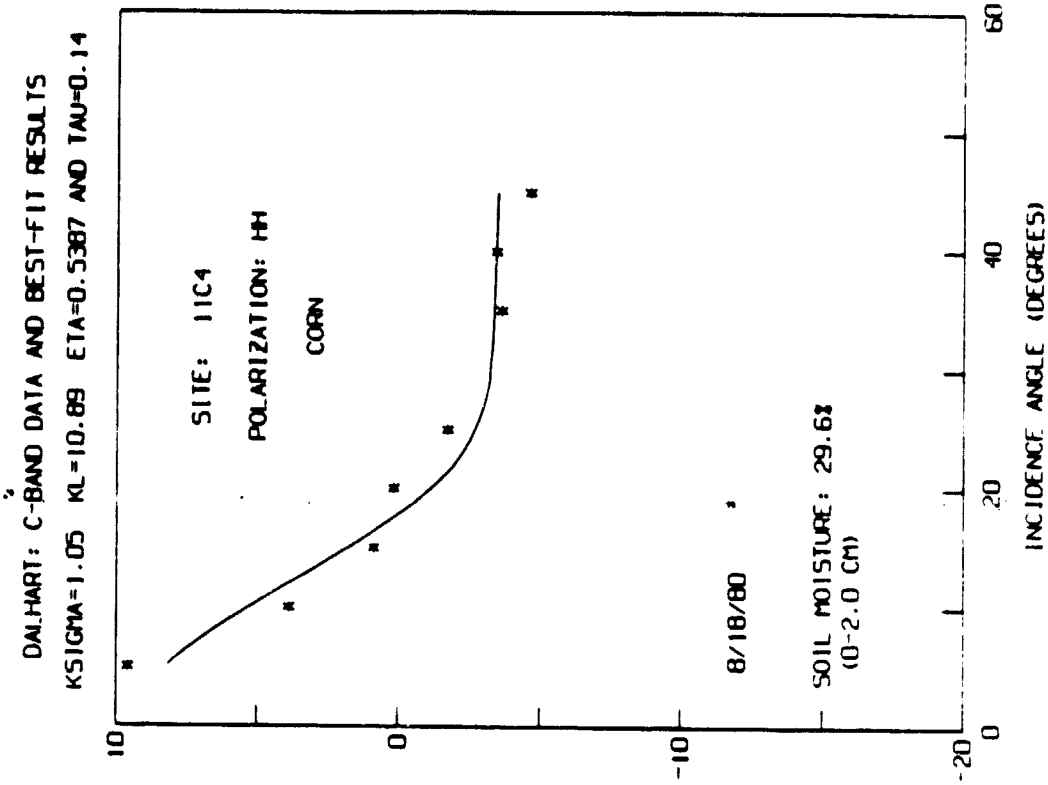
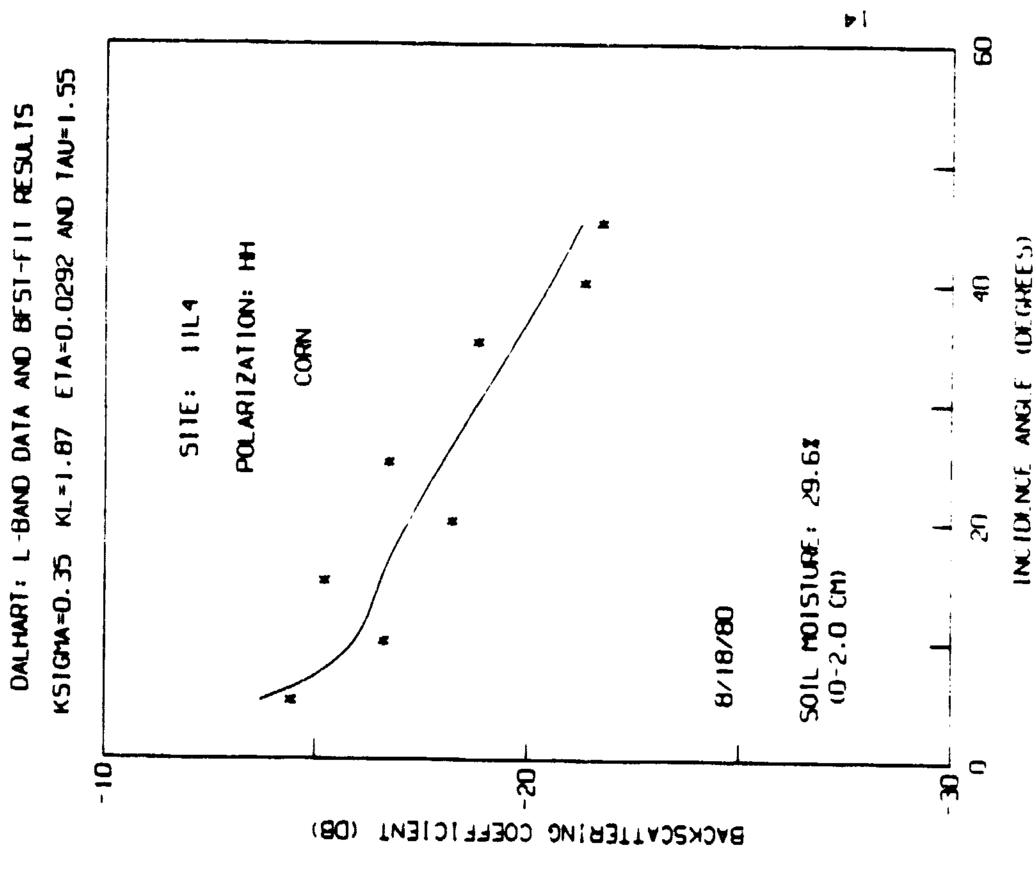
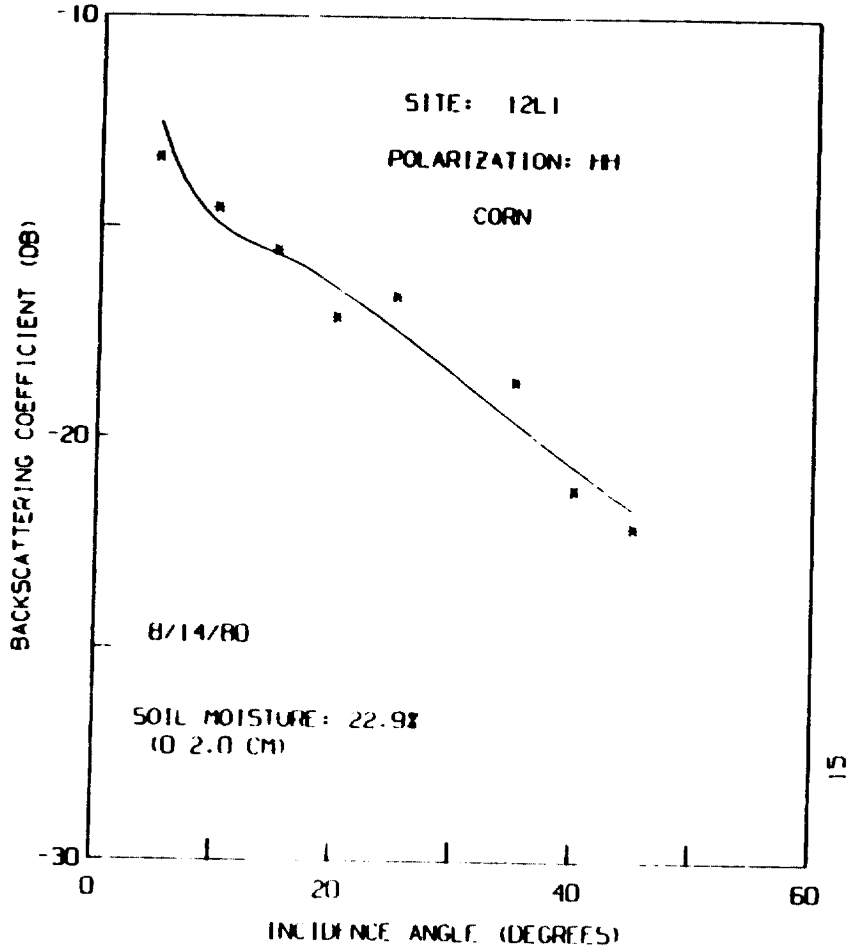
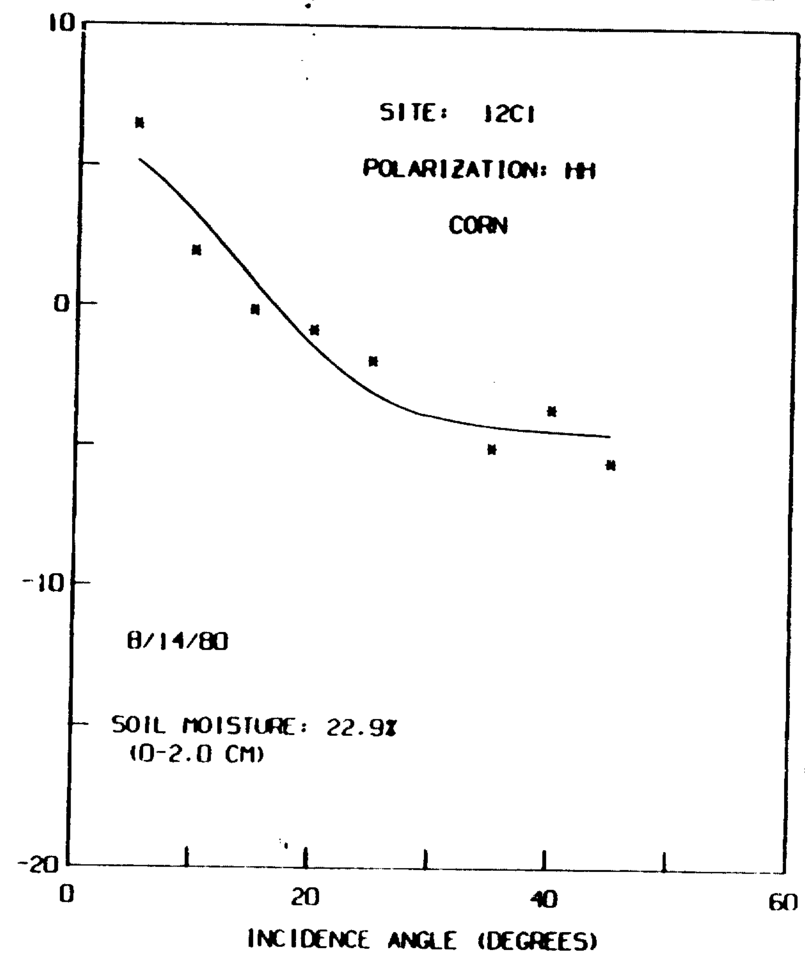




DALHART: L-BAND DATA AND BEST-FIT RESULTS
KSIGMA=0.35 KL=1.98 ETA=0.0192 AND TAU=1.27



DALHART: C-BAND DATA AND BEST-FIT RESULTS
KSIGMA=1.05 KL= 8.63 ETA=0.4728 AND TAU=0.22



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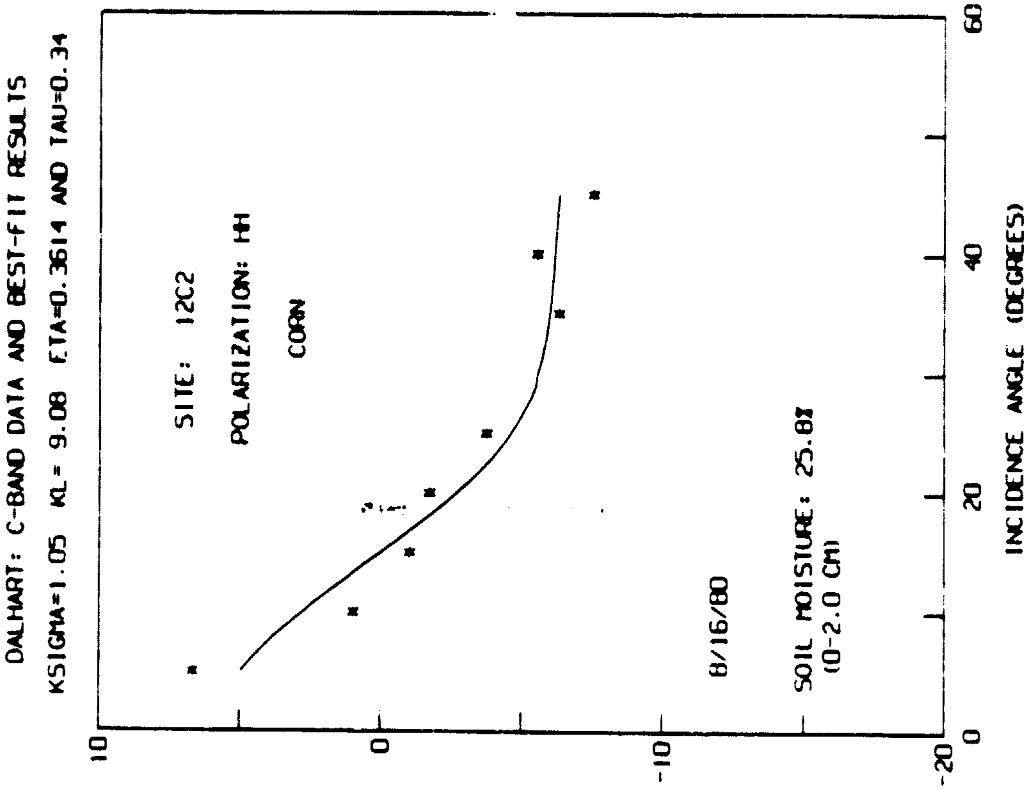

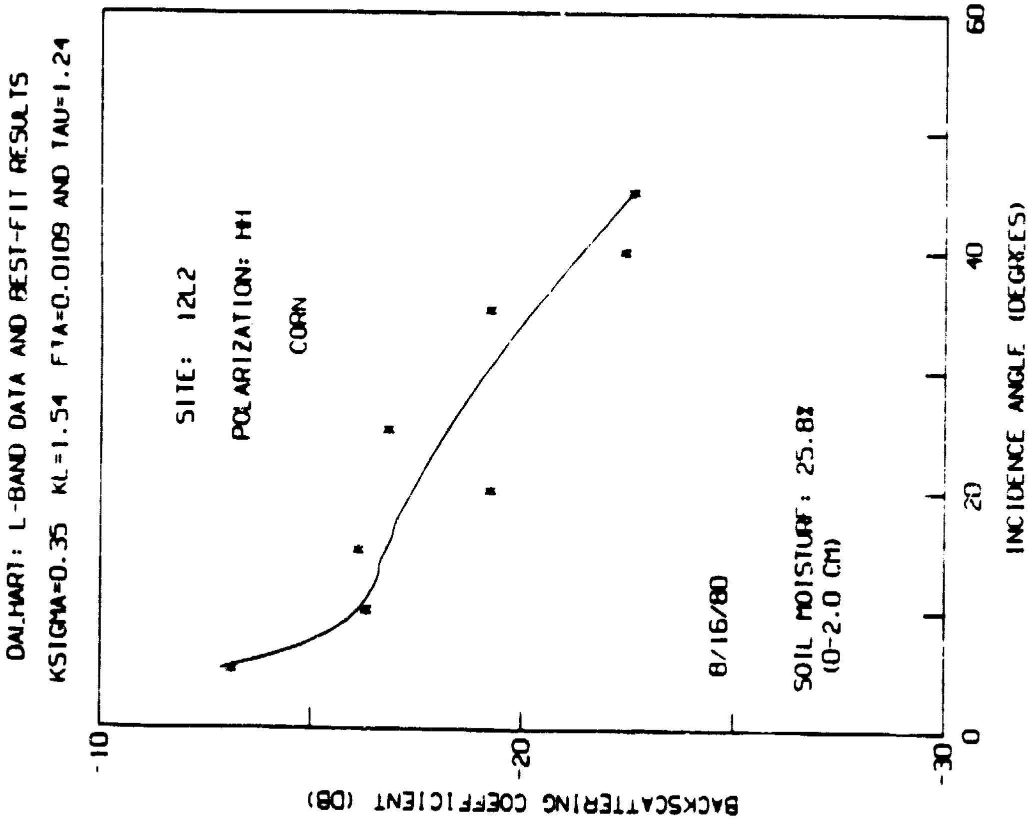

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