INSTITUTE OF HYDROLOGY

ANALYSIS OF DIGITAL RADAR DATA FROM SAR-580 IN RELATION TO SOIL/VEGETATION MOISTURE AND ROUGHNESS

by

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ABSTRACT

A comprehensive survey of soil and vegetation characteristics was undertaken in two test areas in southern England to evaluate the capabilities of digitally processed X and L band radar for detecting spatial and temporal variations in soil moisture. One test area (GB8) lay on homogeneous clay soils and here test sites were chosen to sample vegetation densities on a range of slopes and aspects relative to the radar look direction. The other area (GB12) was of mixed soils and varying subsurface permeability. Where possible, flat, bare-earth sites were selected to reduce the factors affecting radar backscatter. Surface soil and vegetation roughnesses were sampled at 17 test sites along with soil and vegetation moisture and soil texture. Both X and L band HH digital data were recorded during a single pass over each test site on 29 June 1981. On 13 July 1981, one pass at XHH was recorded over GB8 and two passes at XHH lying at 90° to one another over GB12. This report describes field sampling methodology, digital data extraction techniques, radiometric balancing of digital data and the effects of soil and vegetation moisture and roughness on radar relative backscatter.

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CONTENTS

BACKGROUND

[illegible] the [illegible] in the European (SAR-580) Experiment [illegible] variations in soil moisture of both vegetated and unvegetated [illegible] could [illegible] be identified and secondly be quantified using the available synthetic aperture radar configurations.

The theoretical basis explaining the possible relationship between radar backscattering coefficient σ° and soil moisture is well documented (eg. Dobson and Ulaby, 1981) and several excellent field scatterometer programmes [illegible] in the USA (eg. Ulaby et al., 1978) and Europe (eg. [illegible], 1980) to identify the optimum radar configuration for soil moisture monitoring [illegible]. A detailed description of the results of these experiments [illegible] consensus of opinion exists on the most useful starting points for radar studies of soil moisture in terms of radar frequency, polarisation and angle of incidence.

Figures 1 and 2 show that an increase in moisture content of either soil or vegetation causes an increase in the electrical conduction properties of the medium (permittivity) which in turn influences the degree of internal back-scattering [illegible]

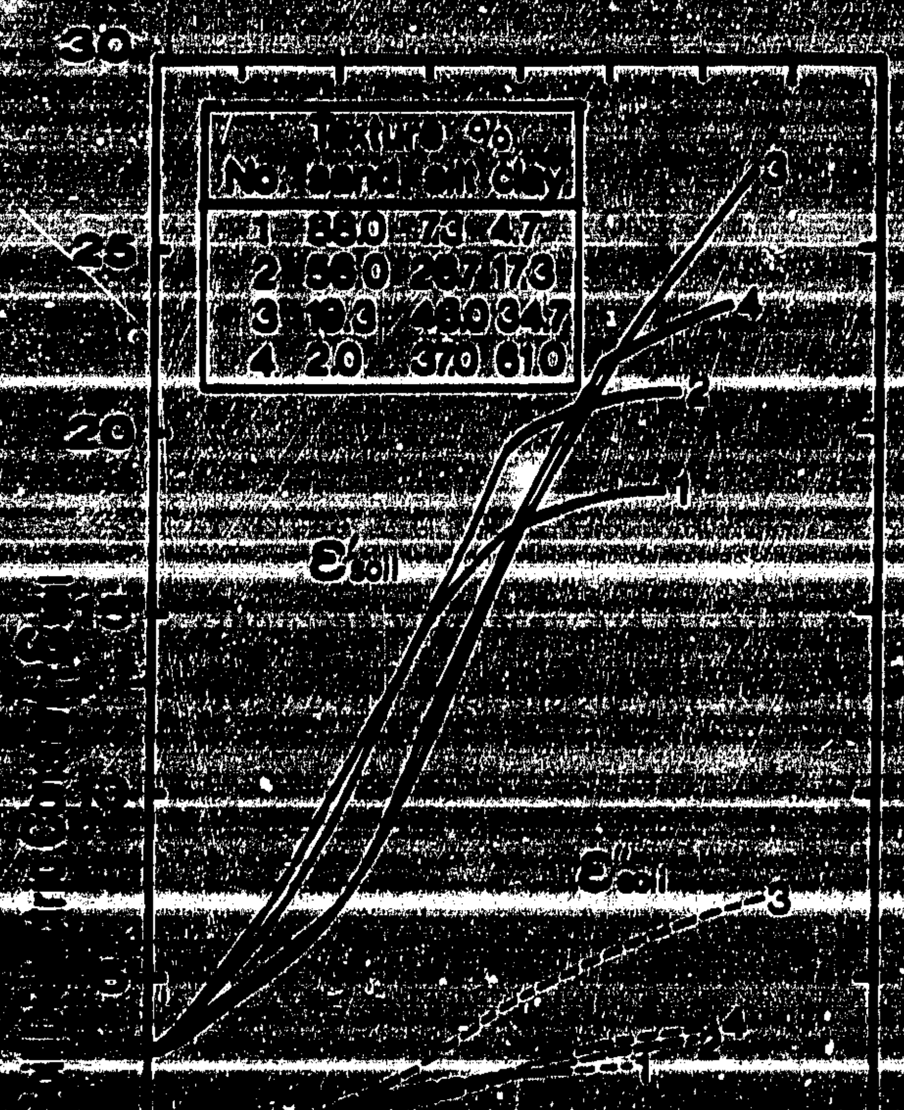
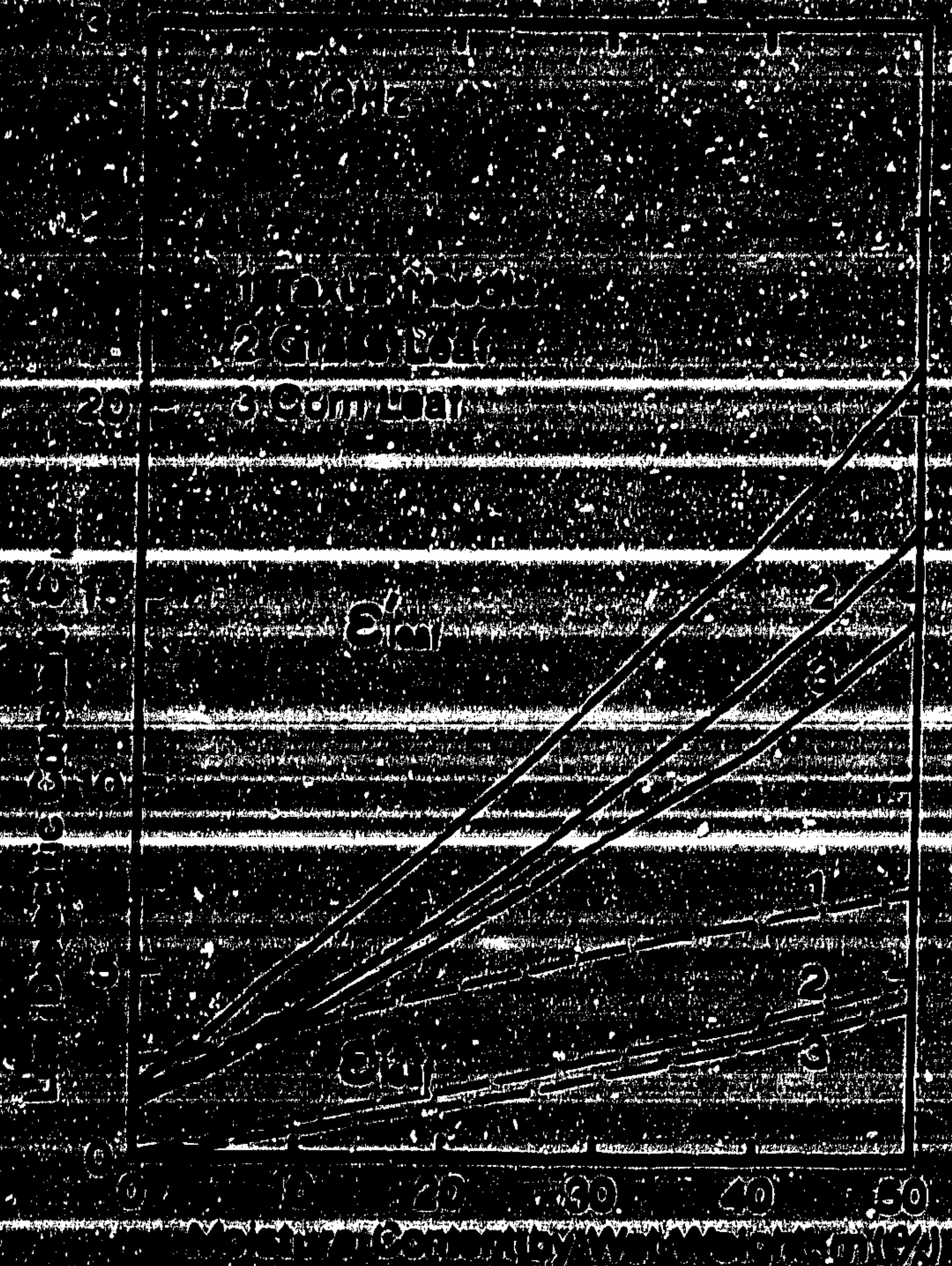


FIGURE 1

The relative dielectric constants versus volumetric water content for four soils measured at [illegible] (from Wang, [illegible], 1980).



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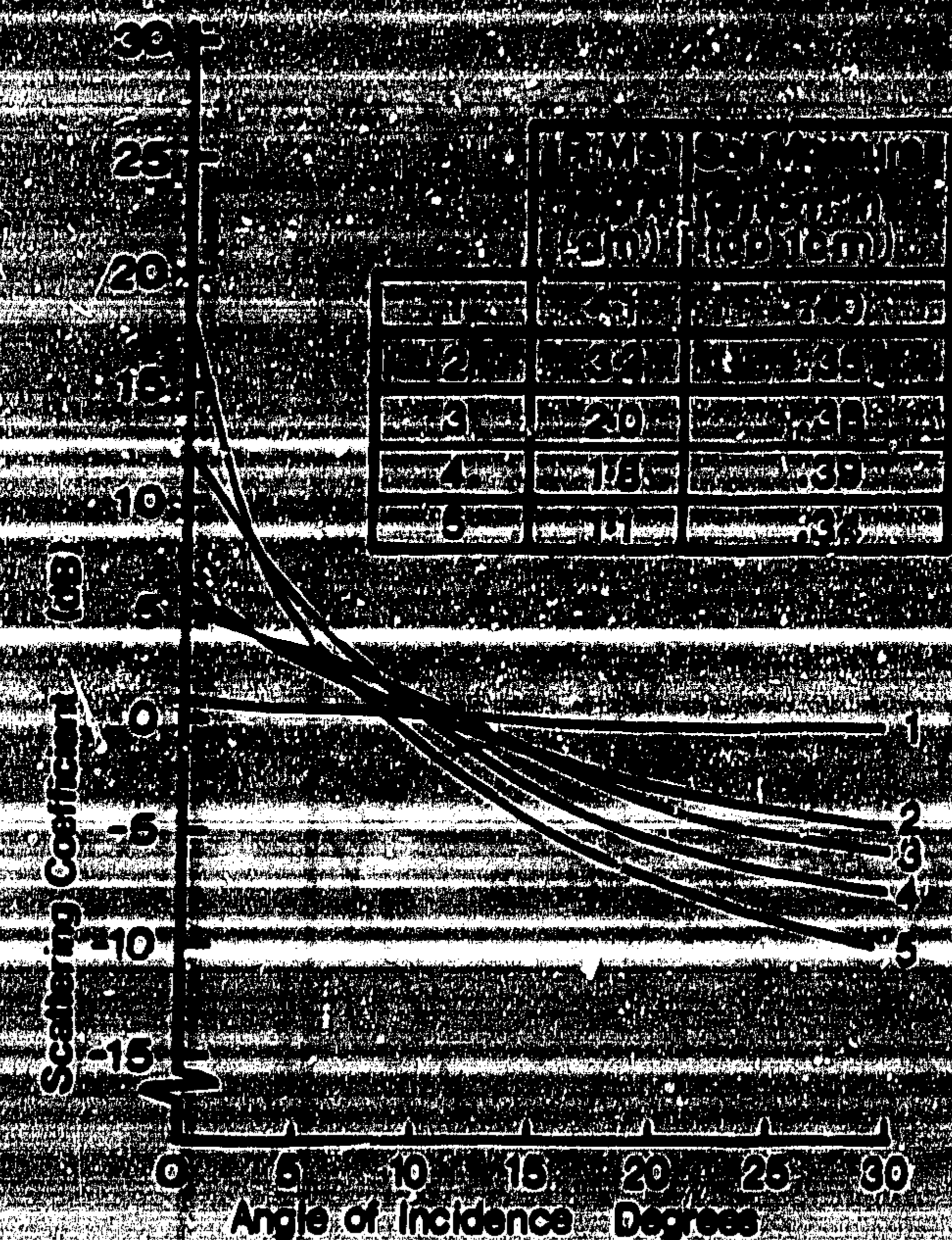

[illegible]

... Unfortunately, these effects are generally secondary to the [illegible] of surface slope and [illegible] which must be considered in relation [illegible] of the [illegible] to the ground surface. However, results [illegible] have confirmed earlier findings of ground-based [illegible] frequencies provided that the [illegible]

2 TEST SITES AND THEIR INSTRUMENTATION

The SAR-580 Experiment provided the first opportunity to compare radar data with measured ground conditions within our test areas, selected primarily to study the relationship of soil moisture with radar backscatter. Figures 4 and 5 show the location of the test area GB8 at Grendon Underwood in Buckinghamshire and GB12 in the Thames Valley near Wallingford, Oxfordshire. GB8 (approx. 50 km²) is an area of homogeneous clay soils where local variations in soil moisture would be minimised. Seven test sites were chosen here to sample a variety of vegetation densities on various slopes and aspects relative to the look direction of the radar. GB12 (approx. 75 km²) is an area of mixed soils with underlying geology of varying permeability where local variations in soil moisture would [illegible] possible, the 10 test sites were located on flat, bare [illegible] affecting radar backscatter. However, as a delay of four weeks was encountered on the first aircraft pass, many of the sites had some vegetation cover. For both GB8 and GB12, test sites were located within the planned radar swaths to sample

[illegible] test sites within the Grendon Underwood (GB8) test area

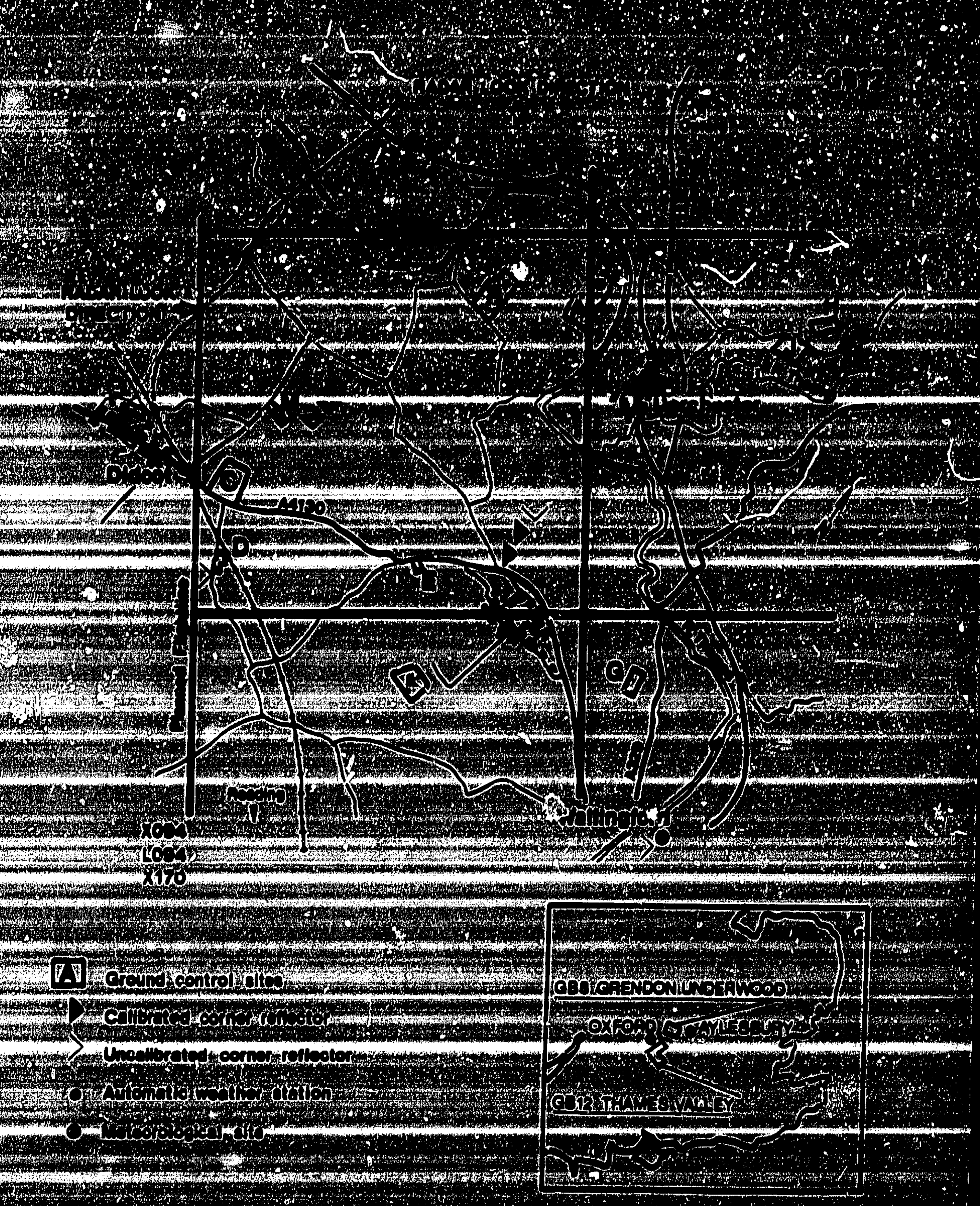

FIGURE 5. Location of test sites within the Thames Valley (GB12) test area

the full range of available incidence angles (θ) with a concentration on the 0 - 5°-20° region. Unfortunately, drift in the aircraft inertial navigation system caused it to fly a path which was consistently too far away from the test areas, with the result that for all five passes, no near nadir data was acquired, the steepest angle being 25°. Table 1 summarises the ground conditions at each site which in most cases comprised a single field unit.

TABLE 1 GROUND CONDITIONS AT EACH FIELD SITE

FIELD NO	SOIL TYPE	LAND USE 29.6.81	13.7.81	ACTUAL θ XAL X	X		SOIL MOISTURE
(a) CB12				094	170	171	
A	Sandy/Alluvium	Early potatoes	Early potatoes	60	55	35	Spray irrig.
B	" "	Late potatoes	Late potatoes	55	50	35	" "
C	Gault clay	Long hay	Mown hay	35	25	50	Wet
D	" "	Bare earth-smooth	Bare earth-smooth	35	25	55	Dry
E	Alluvium	Bare earth-mixed	Bare with rough grass	50	45	55	Medium
F	Limestone gravel	Young maize	Young maize	50	45	*	Dry
G	" "	V. young maize/ cabbage	Young maize/	*	60	*	Dry
H	River gravel	Bare earth-smooth	Bare/young veg.	*	*	40	Spray irrig.
J	" "	Bare earth-smooth	Bare/young veg.	*	*	40	" "
K	Gault clay	Bare - v. rough	Bare - v. rough	40	30	45	Dry surface
(b) CB8				093	172		
N	Oxford clay	Sheep pasture - steep	Sheep pasture	*	*		Medium
O	" "	Dry hay stubble	Stubble + regrowth	55	60		Dry
Q	" "	" "	" "	50	55		Dry
R	" "	Cattle pasture	Cattle pasture	50	55		Dry
S	" "	Long hay	Sheep grazed hay	25	35		Medium
T	" "	Barley	Barley	35	45		Medium
U	" "	Cattle pasture	Long hay	40	50		Dry

* Test sites not recorded by radar.

2.1 Corner Reflectors

In order to successfully relate σ° to soil and vegetation conditions, both within a single scene but especially between different scenes, accurately calibrated data is required. To aid this calibration, two pairs of calibrated corner reflectors were installed by the Royal Aircraft Establishment in both test areas (Figure 6). Sites were chosen near to Ordnance Survey triangulation points which were used to locate the height and position of the reflectors. Azimuth and inclination angles were carefully set in relation to the planned aircraft flightpath and altitude. In addition, six non-calibrated reflectors were installed in CB8 and five in CB12 to aid geometric rectification of the radar data (see Figures 4 and 5).

FIGURE 6 [illegible]

2.2 Automatic Instrumentation

Didcot Automatic Weather Station [illegible] at five minute intervals the following [illegible] direction, solar radiation, net radiation, air temperature and humidity [illegible]. At site A, soil temperature was measured at four depths [illegible] soil along with windspeed and direction and short-wave albedo [illegible] intervals. Similar instrumentation was also installed at site [illegible] meteorological stations were also operational within a few kilometres of both test areas.

3 DATA COLLECTION ON EACH OVERFLIGHT DAY

In each of the 17 fields, at least 20 volumetric soil samples were taken of the top 50 mm of soil and, where possible, 150 mm cores were extracted [illegible] were sliced into 20 mm sections. When vegetation was present in significant amounts, five bulk samples were taken [illegible] for the estimation of vegetation biomass and moisture content. [illegible] and soil temperature measurements [illegible] were recorded.

3.1 Soil and Vegetation Roughness

Within a maximum period of three days, measurements of surface roughness [illegible] at all sites. Alloy plates of [illegible] 1000 mm [illegible] pattern were used to make a photographic record [illegible] ness, generally at the four corners and centre [illegible] sampling network, as shown in Figure 13. To record soil roughness, the plates had first to be hammered into the soil; initially this process was found to be very

FIGURE 7

Soil roughness reference plate [illegible]

FIGURE 8

Rough soil surface in relation to 20mm grid marked on 1000mm long plate

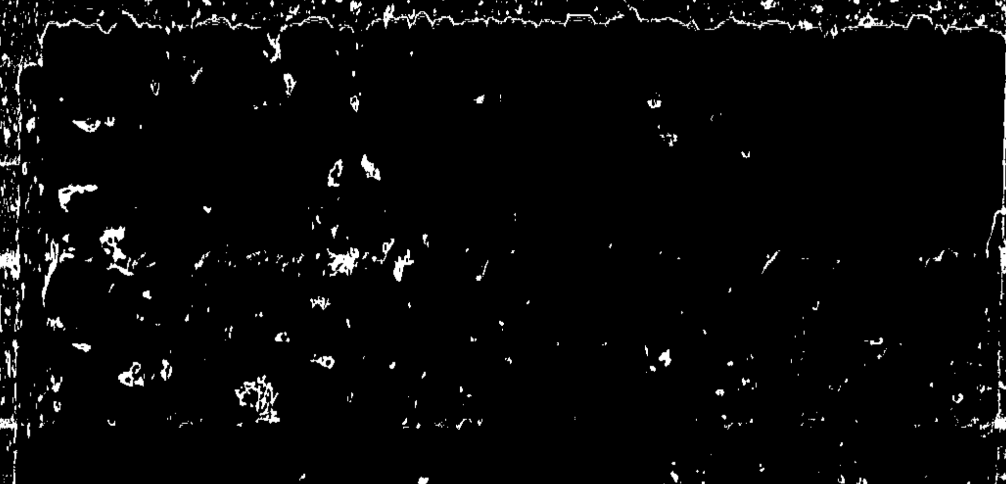

FIGURE 9

Tall barley seen against 20mm reference grid

difficult in all but the lightest of soils. The process was made easier by welding spikes to the bottom rear edge of the plate to provide some initial support in the soil and then by attaching a cutting edge of hardened steel along the bottom edge of the plate. Finally a grooved striking block was positioned over the top edge of the plate to prevent damage during hammering (Figures 7 and 8). This plate was also used to record details of crops up to 300 mm high. For taller crops, a plate of similar dimensions and markings was held above ground level on two vertical tubes hammered into the ground (Figure 9). The plate was adjustable for height and level via thumbscrews locating the plate to the vertical tubes and, before photographing the vegetation canopy, the distance from the top of the plate to local ground level was measured to enable mean crop height to be determined. At each sample point, the plates were aligned by prismatic compass to lie both parallel and at 90° to the aircraft flightline.

At the same five sites per field as the above measurements, vertical photographs taken from a height of three metres and oblique photographs taken from the planned look direction and incidence angle of the radar provided a record of surface conditions and crop cover in relation to calibrated reference poles (Figures 11 and 12). Wide angle, oblique photographs of each field were taken from a height of four metres. This extensive photographic record was invaluable for determining surface changes which had occurred during the two weeks separating the radar overpasses. Due to the large number of similar photographs acquired, the use of a data back on the camera was found to be an essential aid as it provided a unique reference number on each image. [illegible]

FIGURE 10

Vertical photograph of field to determine crop cover.

FIGURE 11

Oblique photograph [illegible] angle of viewing [illegible]

3.[illegible] [illegible] Survey

[illegible] provide a detailed land use survey, but major categories and [illegible] noted within the visibility of metalled roads. On [illegible] July, midway [illegible] colour and panchromatic aerial photo- [illegible] both test sites using a light aircraft. The data was subse- [illegible] to be of great value for extending the limited land use survey and [illegible] in-field information on crop cover and other anomalies which were [illegible] radar data.

4. DATA [illegible]

4.1 Soil [illegible]

[illegible] samples were oven-dried to determine their free water content. [illegible] these were volumetric samples taken from the top 50 mm of soil and [illegible] at least one 150 mm deep sample per field, the core of which [illegible] information on the [illegible] soil moisture profile between 0-20 mm, 20-[illegible] mm, 60-150 mm. In some fields of very rough bare earth, the surface [illegible] surface layers were taken for subsequent gravimetric analysis. [illegible] values are [illegible] in Table [illegible]. A single bulk sample of around [illegible] taken for each of the [illegible] sites to determine soil texture in terms of [illegible] fractions by weight of sand (2.0 to 0.05 mm), silt (0.05 to 0.002 mm) and clay (< 0.002 mm).

[illegible] soil moisture [illegible] reasonable estimates of the field capacity of any soil [illegible] proportions of sand, silt and clay using the [illegible]

[illegible] 1977 [illegible]

[illegible] and the proportions of sand and clay are [illegible]

[illegible] experiment were calculated using

TABLE 3 : SUMMARY OF [illegible] MOISTURE

SITE NO		MEAN SOIL MOISTURE % BY WEIGHT	STANDARD DEVIATION	% BY VOLUME	% FIELD CAPACITY	MEAN VEGETATION MOISTURE % BY WEIGHT	[illegible]
29 June 1981							
CB12	A	10	1.8	12	80	?	5500
	B	8	2.0	9	58	96.9	3544
	C	89	1.0	51	415	41.4	999
	D	14	5.5	11	147	–	–
	E	41	8.7	31	194	51.1	85
	F	11	2.3	14	76	95.4	20
	H surface	5	0.7	6	19	–	–
	subsurface	15	5.9	13	55	–	–
CB8	O	39	6.8	34	109	67.2	333
	Q	63	14.6	60	175	?	minimal
	R	38	3.8	42	165	?	minimal
	S	53	6.5	21	147	80.0	1837
	S'	50	1.6	33	139	76.7	374
	T	22	3.0	22	60	69.7	1669
	U	71	8.8	50	196	75.0	1261
13 July 1981							
CB11	A	10	2.1	13	75	90.2	5120
	B	11	2.4	14	83	–	–
	C	85	20.9	51	397	67.2	5707
	D	12	3.6	10	40	–	–
	E	34	6.0	36	150	76.6	343
	F	9	2.9	14	38	94.2	250
	G	7	1.4	8	49	?	?
	H	9	3.2	12	44	–	minimal
	J	8	1.3	10	54	–	minimal
	M surface	13	1.1	7	20	–	–
	subsurface	19	6.0	20	71	–	–
CB8	O	30	1.0	25	82	64.5	[illegible]
	Q	44	0.7	44	122	50.1	520
	R	32	3.8	38	90	80.3	223
	S	38	14.4	43	106	72.2	1567
	S'	28	14.7	28	87	[illegible]	[illegible]
	T	20	2.7	24	55	71.1	[illegible]

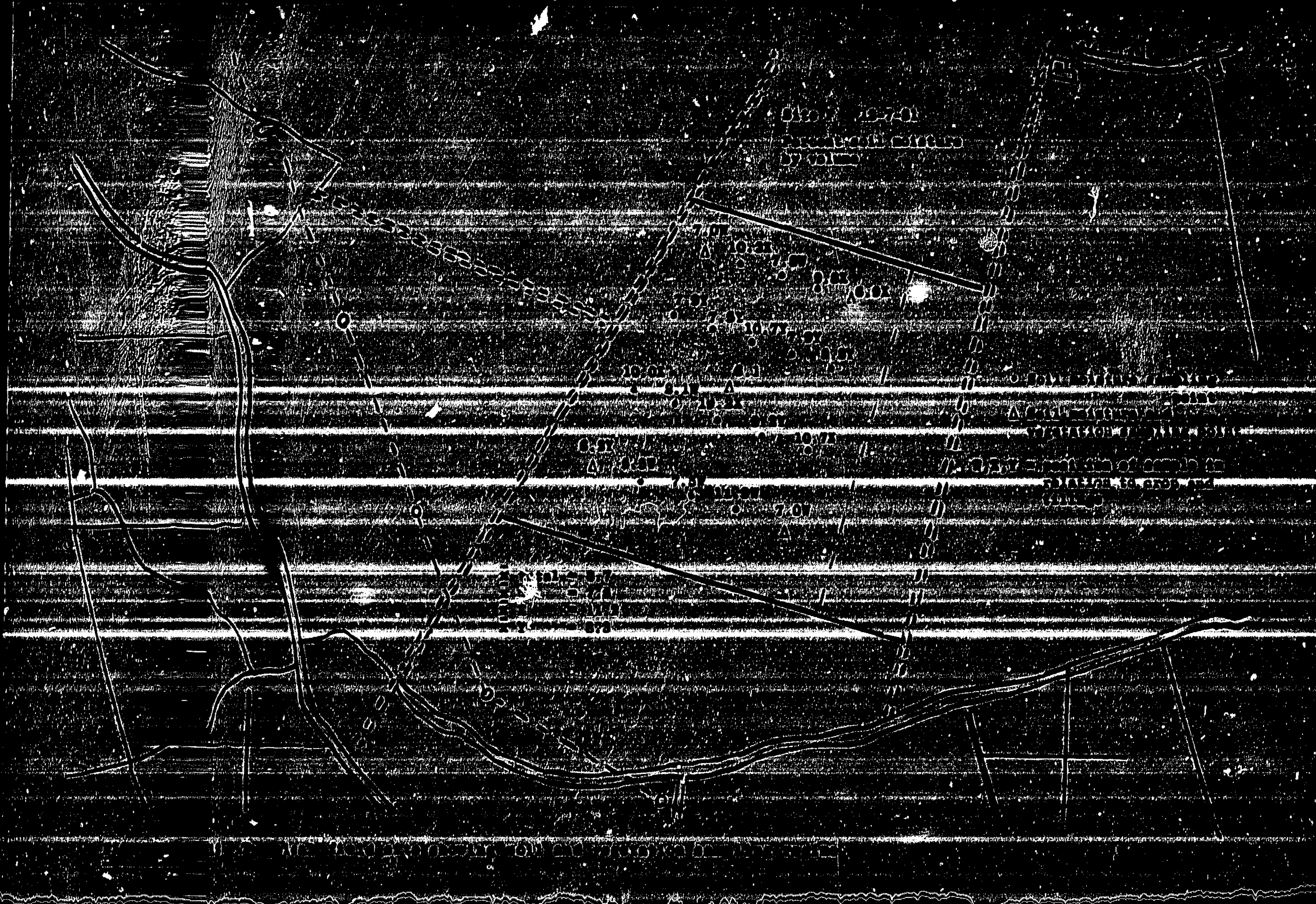

TABLE 3 - ESTIMATES OF SOIL FIELD CAPACITY DERIVED FROM MEASUREMENTS OF SOIL TEXTURE

SITE	SAND (2.0-0.05mm) % by weight	SILT (0.05-0.002mm) % by weight	CLAY (<0.002mm) % by weight	FIELD CAPACITY % by weight
GB12				
A	62.17	37.83	-	12.0
B	57.67	42.33	-	13.0
C	28.46	60.81	10.73	21.5
D	17.36	43.80	38.84	30.0
E	24.67	69.91	5.42	21.1
F	56.51	36.62	6.87	14.7
G	62.09	30.98	6.93	13.6
H	61.54	30.39	8.07	14.0
J	57.44	32.43	10.13	15.3
M	15.78	60.89	23.33	26.9
GB8				
N - U (all on Oxford clay)	$\bar{x}$ = 2.5	45.0	52.5	[illegible]

4.2 Vegetation Samples

Depending on the density of vegetation at each site, bulks samples were collected within quadrats of either 0.25 m^2 or 1.00 m^2 to obtain samples of a manageable size. These were weighed wet and after oven drying to determine water content per square metre of vegetation and also the vegetation dry biomass per square metre. The former is of major importance in determining the effect of vegetation on radar backscattering. Soil and vegetation moisture data are summarised in Table 2.

The backscattering coefficient σ^0 of vegetation-covered soils viewed from an incidence angle of θ can be expressed as:

$$\sigma^0(\theta) = \sigma^0_v(\theta) + \sigma^0_s(\theta)e^{-2\tau/\cos\theta}$$ (after Tsang et al., 1982)

where $\sigma^0_v(\theta)$ is the vegetation backscattering coefficient, $\sigma^0_s(\theta)$ is the soil back-scattering coefficient and τ is the radar path length through the vegetation which varies with incidence angle.

The vegetation component $\sigma^0_v(\theta)$ can be approximated by

$$\sigma^0_v(\theta) = \frac{\eta\cos\theta}{2\tau}\left(1 - e^{-2\tau/\cos\theta}\right)$$

where η, which depends on the canopy water content per unit area (Attema and Ulaby, 1978) is a vegetation volume scattering factor. Ho *et al.* (1984) have recently tested a two part model based on the above relationships describing the combined radar scattering from a vegetation covered soil and have found it to perform well.

against observed values of σ°. They confirmed that coherent scattering from the soil surface is most important at angles approaching nadir (where vegetation effects are reduced) while vegetation volume scattering is dominant at larger incident angles (> 30°).

(b) Surface Roughness Measurements

When recording soil and vegetation roughness against the calibrated alloy plates, the scale and angle of photographs varied from image to image. In order to compile a comparable record of surface data from which statistically acceptable estimates of surface roughness could be made, it was first necessary to rectify the images. This was achieved with the aid of a Zeiss Sketchmaster, a desktop instrument with a split-image viewfinder with which the operator superimposes a hard copy photographic image held in the vertical plane over a sheet of graph paper held in the horizontal plane. Scale differences and image distortions were removed by instrument adjustment until the calibration lines seen on the alloy plates were in agreement with those on the graph paper. The outlines of both soil surface and vegetation were then traced onto the graph paper to provide a permanent and directly comparable record of surface roughness at each site. Figures 13 and 14 show outlines of typical smooth and rough fields of bare earth, Figure 15 is a typical of a typical maize crop where both soil and vegetation details are recorded, and Figure 16 shows the profile of a tall barley crop with mean height about 1 metre above ground level.

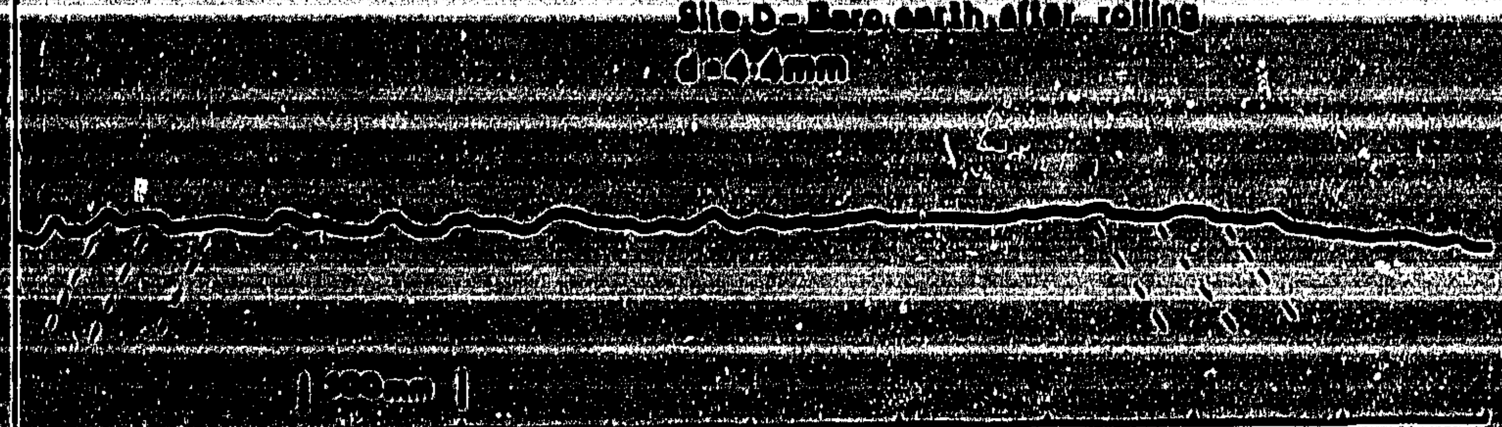

FIGURE 13 Rectified record of a smooth soil surface

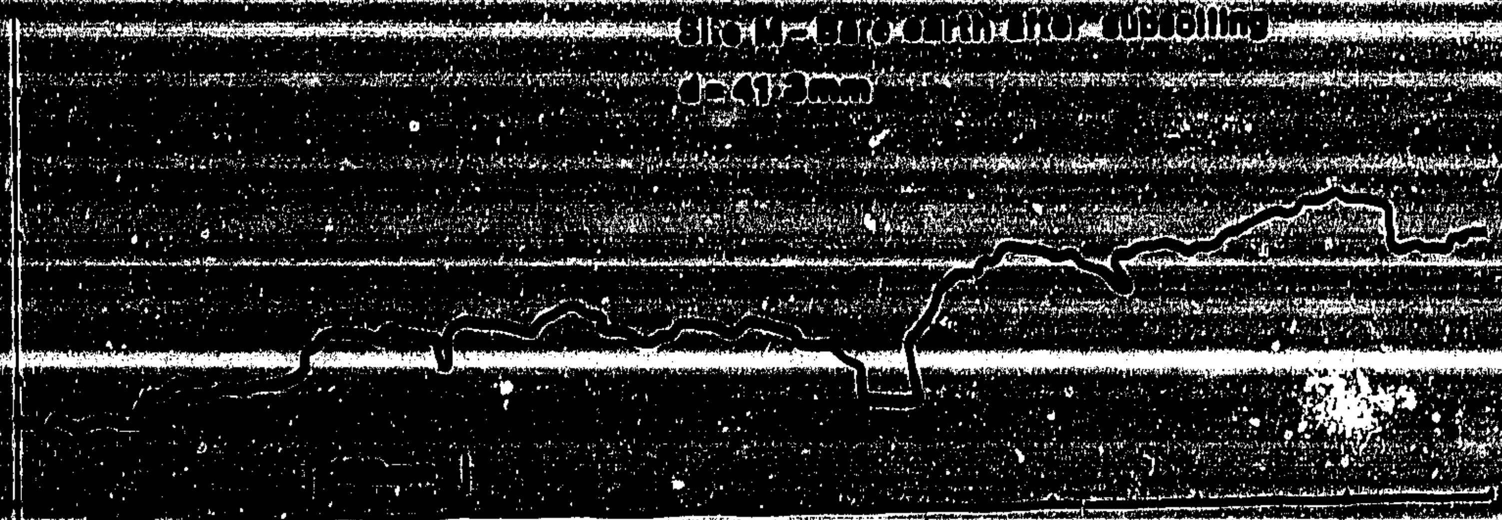

FIGURE 14 Rectified record of a rough soil surface

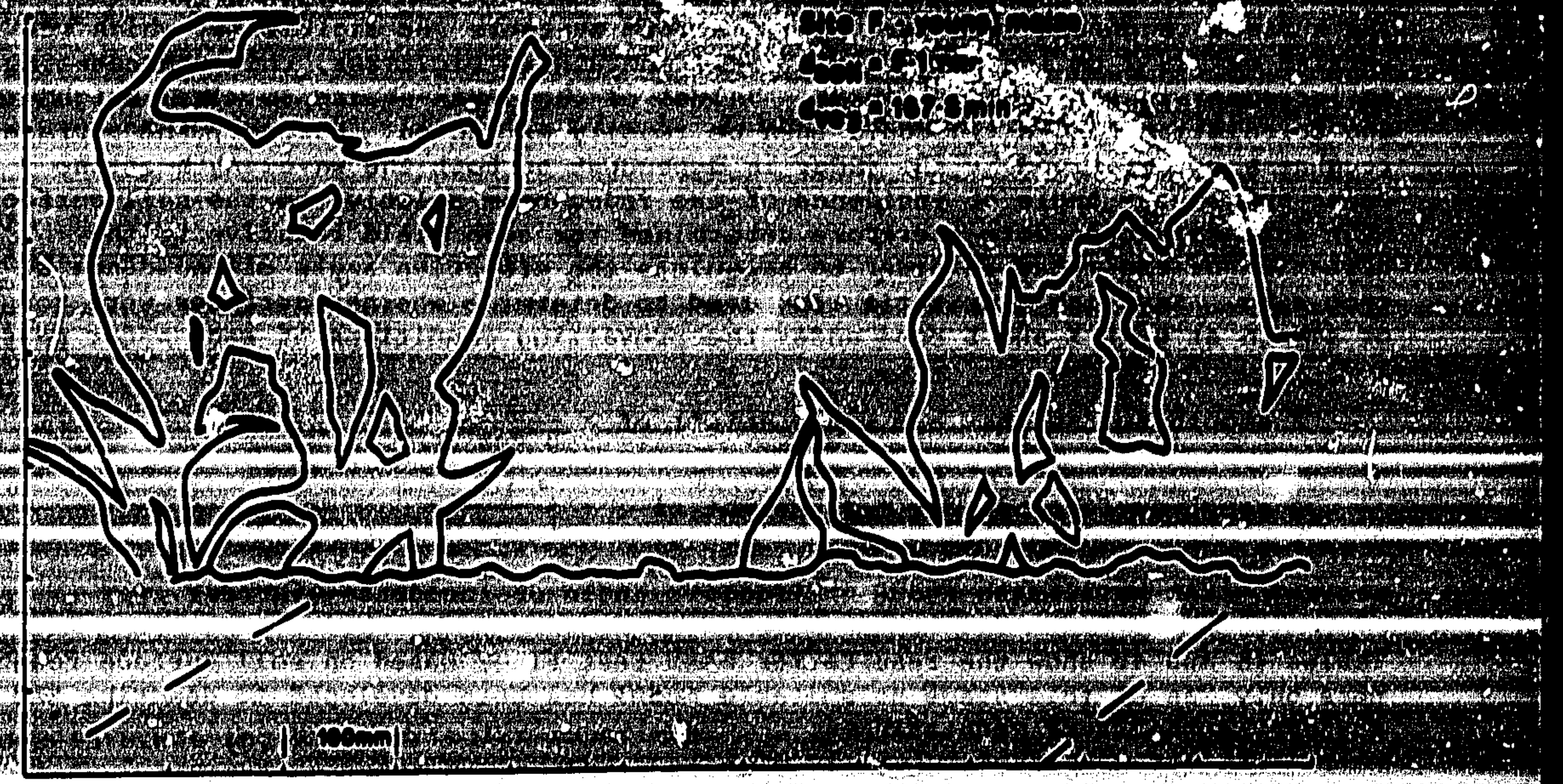

FIGURE 15 Rectified record of soil partially covered by vegetation

FIGURE 16 Rectified record of upper layers of tall vegetation

The surface roughness data were now in a form suitable for digitising, which was carried out at 2 mm increments on a D-Mac Coordinate Digitizer, this representing an increment in the field of 10 mm. Values of root mean square (r.m.s.) height (d) and correlation length (ℓ) could then be readily extracted. However, the surface roughness as perceived by the radar is dependent on both the wavelength of the radar and on the angle of incidence of the radar beam relative to the soil surface. Mean surface slopes were therefore determined for each field relative to the direction of the radar in order to calculate the effective angle of incidence at each site. Rayleigh's criteria were used to determine whether surfaces were rough or smooth at both X and L band under the prevailing conditions of each radar pass:

a smooth surface has a r.m.s. height of $< \frac{\lambda}{8 \cos \theta}$

a rough surface has a r.m.s. height of $< \frac{\lambda}{4 \cos \theta}$

where λ = SAR wavelength and θ = effective angle of incidence of radar.

Tables 4a and 4b show the results for each test site, based on soil surface roughness only, as at this stage no suitable model has been developed to describe the surface roughness of vegetation.

TABLE 4a ROUGHNESS ESTIMATES FOR CB12, THAMES VALLEY

SITE	APPROX r.m.s. ROUGHNESS (d) in mm	PASS 094 X band	PASS 094 L band	PASS 170 X band	PASS 171 X band
A	100	*	*	R	R
B	100	*	*	R	R
B'	10	*	*	I	R
C	25	R	S	R	*
D	4.5	S	S	I	*
E	35	R	S	R	R
F	7.5	I	S	I	*
G	10	*	*	I	*
H	6.5	*	*	*	I
J	10-5.5	*	*	*	I
M	45 then 25	R	I	R	*

Based on Rayleigh's criteria: S = smooth $S = < \frac{\lambda}{8 \cos \theta}$
I = intermediate
R = rough $R = > \frac{\lambda}{4 \cos \theta}$

* denotes site not imaged by radar

TABLE 4b SOIL ROUGHNESS ESTIMATES FOR C98, GRENDON UNDERWOOD

SITE	APPROX r.m.s. ROUGHNESS (d) in mm	PASS 093 X band	PASS 093 L band	PASS 172 X band
O	10	R	S	R
Q	17.5	R	S	R
R	15	R	S	R
S	18	R	S	R
T	10	R	S	R
U	20	R	S	R

5 DATA ANALYSIS

Our interest in this particular experiment was restricted to the study of soil moisture effects on radar backscatter, so only digital radar data was used. As previously mentioned the most significant correlations of soil moisture to σ^0 have been obtained at C band at incidence angles of 5°-20°. However, it appeared at the start of the experiment that there were problems with the calibration of C-band, so X and L band data were requested in preference. At the outset of our experiment, it was intended that with the aid of the field installed corner reflectors, geometric and radiometric rectification of the digital data would be carried out to a relatively high precision to enable the position of data extracts to be controlled relative to survey measurements taken in the field. Unfortunately the deviation of the final aircraft flightlines from the planned flightlines was so great that in many cases the corner reflectors could not [be] detected. As there appeared to be no means of calibrating the data over the test areas, a less rigorous approach was chosen in the extraction of digital values.

5.1 Extraction of Pixel Values

Extraction of digital values from the CCT monitors was carried out interactively using both the NERC I²S System 101 and the NRSC GEMS image processing facilities. Polygons were defined in relation to the position of soil samples within each field site as shown typically in Figure 17. Care was taken to position the polygons well within the field boundaries to avoid edge effects. In general four or five polygons per site were selected to detect major in-field variations. In general, little difficulty was experienced in locating the field sites but this varied from image to image and within each image. Probably the most difficult sites to manipulate were H and J which were located on a market garden where individual plots were rather small for the radar to depict adequately, but even here a minimum of 600 pixels were used to determine the test site statistics.

5.2 Radiometric Rectification of Digital Data

On first receiving the digital data the above extraction of information was started to determine whether there was any obvious in-field variability which could be related to changes in soil moisture. As each field was small in relation to the full radar swath, the effects of antenna variation across any given field should not have greatly affected the data. In addition, [illegible] the four or six [illegible] per

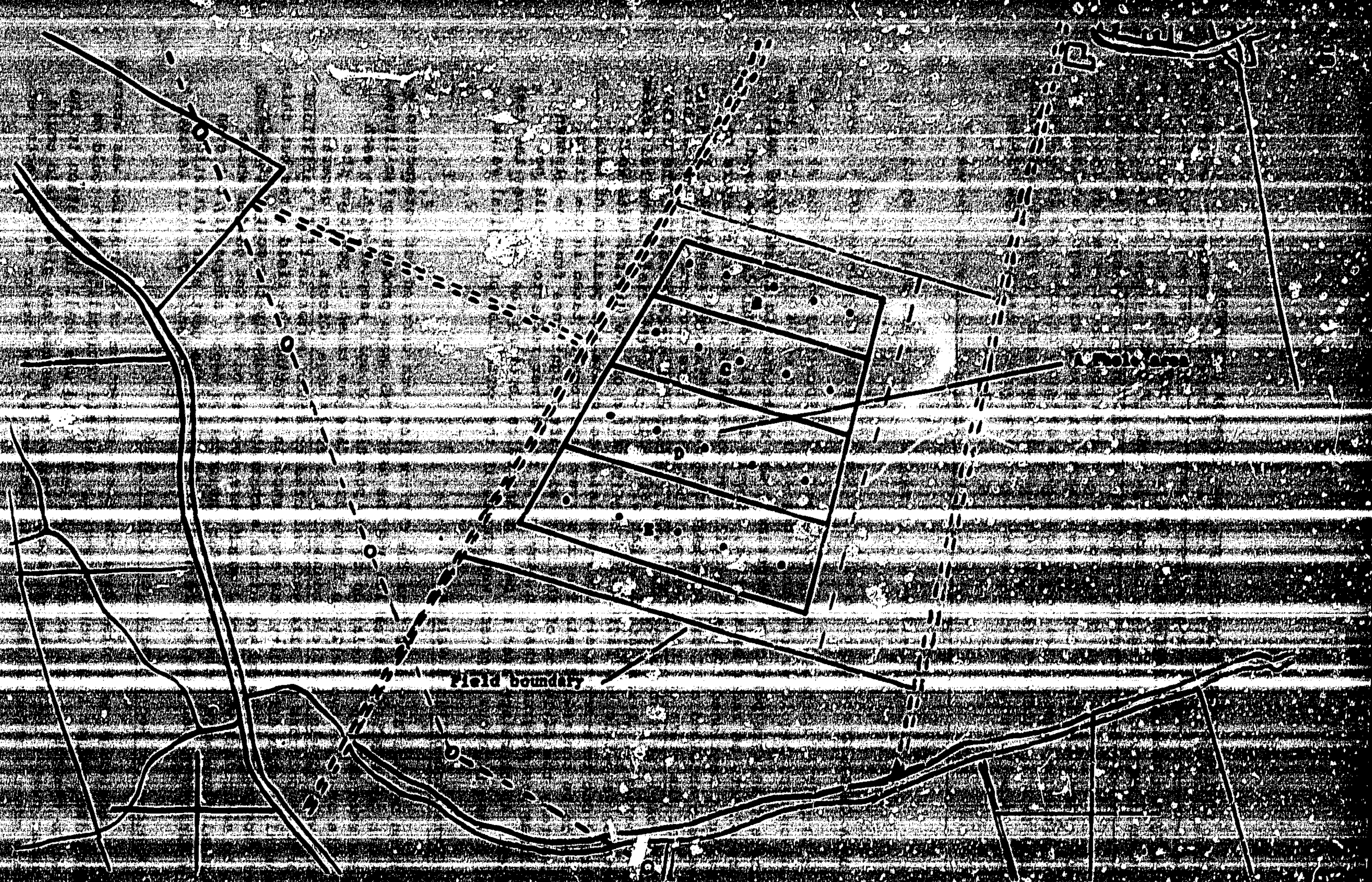

FIGURE 17 - Typical polygon data extracts relative to soil moisture sample positions

field site, additional extracts were performed on surrounding fields to try and build up a picture of factors affecting the radar returns. By the time a procedure had been developed for reducing the effect of antenna variation to allow comparisons to be made from field to field, most of the data extracts had been completed on uncorrected data. It was decided that the quickest method of obtaining partially corrected data would be to apply a correction ratio to each extract of the raw data rather than by correcting a whole image file and then having to go through the process of interactive polygon extraction on the image processing system once again.

The method of normalising the antenna variations followed the procedure suggested by Sieber (1982). Adequate land-use information was not available to use the procedure based on a single crop type, although this would have undoubtedly produced a more accurate correction. The method adopted was to calculate the r.m.s. pixel value of each line of a whole image as supplied on CCT. The assumption is made that each line passes over an area of average or typical land use and that no large areas producing unusually high or low pixel values are present in the image such as large urban areas, factories, etc. or other large water bodies. On the assumption that there is no major change in land-use across the radar swath, the line by line r.m.s. values should replicate the gain pattern of the antenna. An example showing the results of this procedure for the Thames Valley test area is given in Figure 18 and it can be seen that the main lobe and side lobes of the antenna are clearly defined in the X band HH image. In contrast, Figure 19 is the result of the same procedure carried out on an L band HH image, also of the Thames Valley area, which shows much more variability and skewed antenna pattern.

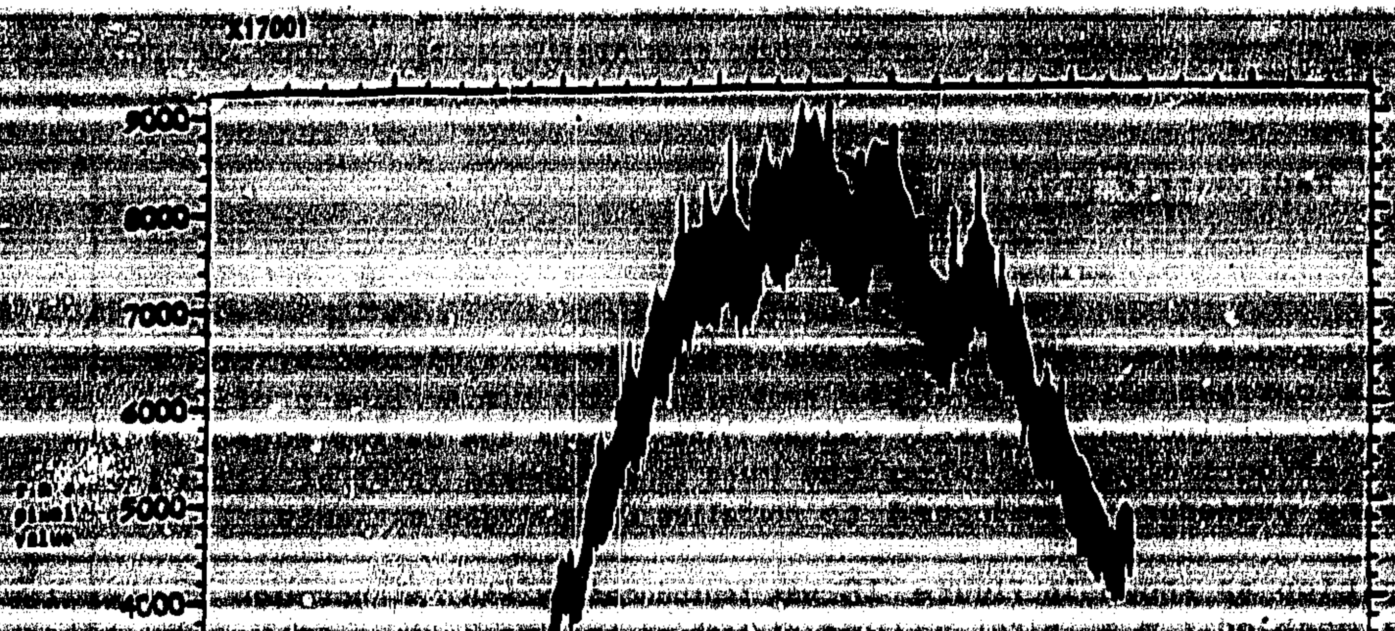

FIGURE 18 Radiometric profile of XHH image

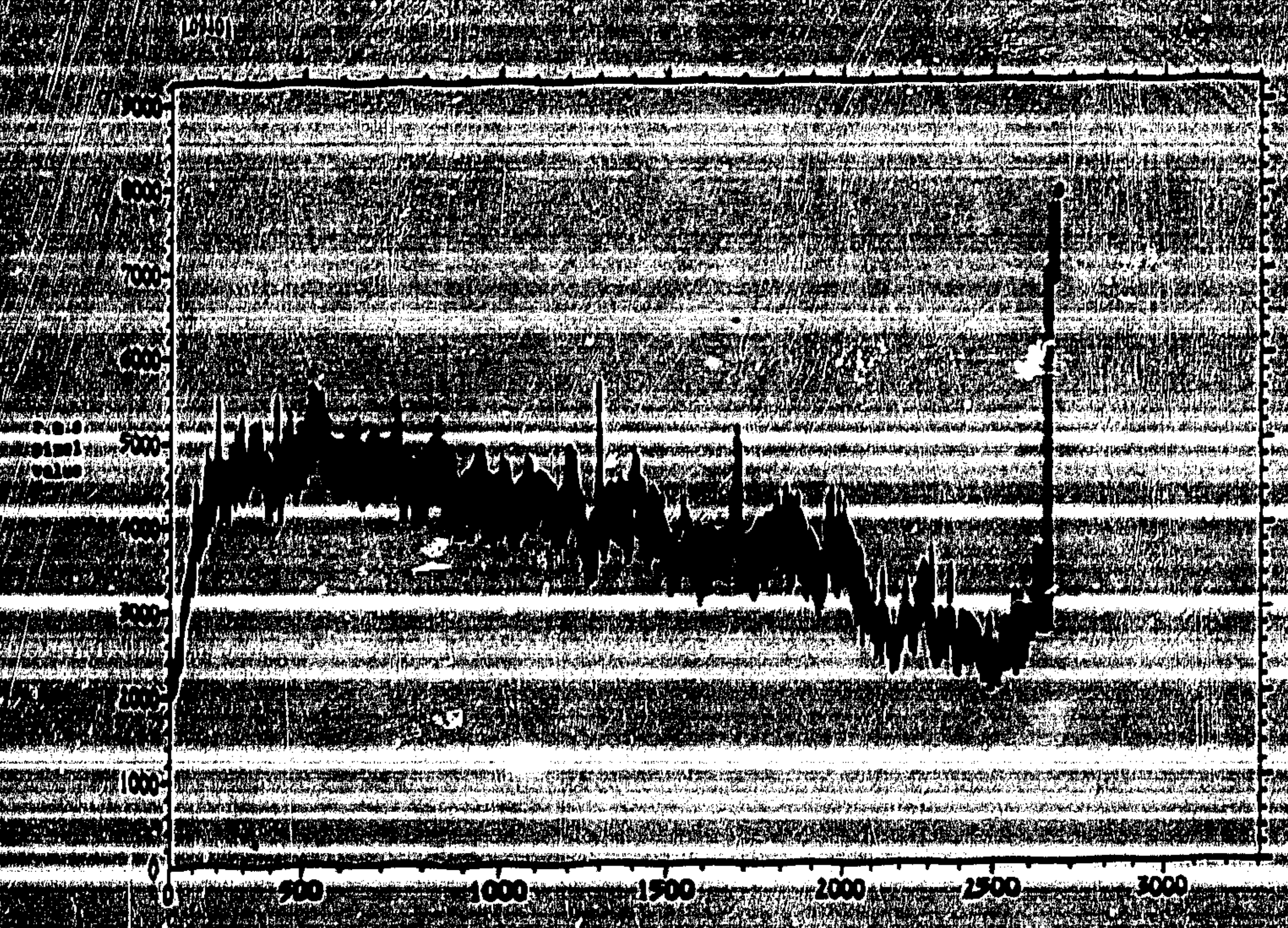

FIGURE 19 [illegible] profile of L[illegible] image

Under normal procedure, each line of the original image is divided by the r.m.s. value of its corresponding line after smoothing of the r.m.s. line profile. This has the effect of increasing pixel values lying towards the darker edges of the image, thus effectively normalising the image to a standard level of illumination. The following procedure was adopted to normalise our polygon extracts.

The information as shown in Figure 18 was reproduced by RAE Farnborough in tabular form which enabled [illegible] pixel values of each of the image lines to be obtained. The line number corresponding to the centre of each test site (ℓc) was obtained on the [illegible] image processor. This line was found on the output of r.m.s. pixel values and the mean [illegible] pixel value for 21 lines centred around this identified line was calculated. The maximum r.m.s. value for the image was found and the [illegible] of 21 lines centred on this point was calculated. The correction [illegible] for the test site was simply r.m.s. max/r.m.s. ℓc. Correction ratios were applied to the digital data statistics extracted for each polygon of interest and a measure of power (P) for each area was obtained using P = (mean)^2 + (standard deviation)^2. Values of backscatter coefficient σ° were generally calculated in dB relative to max for our areas of interest, but not always so for reasons which will be given later.

[illegible] of the line by line r.m.s. pixel value graphs for all of the passes [illegible] our two test sites showed some marked variations such as poor dynamic [illegible] band image of Figure 19) and other anomalies which are not fully understood. The majority of results given here are from passes which produced 'antenna diagrams' of shape similar to that shown in Figure 18, i.e. exhibiting full use of the available dynamic range and of conventional shape with no marked anomalies.

6 RESULTS

Based on the above criteria, five images were identified as being suitable for comparison in that their 'antenna diagrams' could be overlaid with only very minor adjustment required to obtain superimposition. Over GB8 at Grendon Underwood pass X09301 of 19.6.81 was compared with pass X17202 of 13.7.81. Similarly pass X09401 was obtained over GB12, the Thames Valley site, on 29.6.81 and passes X17001 and X17101 were flown over the same area on 13.7.81 along flightlines lying 90° to one another.

GB12 Thames Valley

As a result of poor reproduction of flightline position, only one test site appears in all three images - Site E. On examination of the field data it was found that neither the soil moisture, surface roughness nor sparse vegetation had varied appreciably over the two week period between flights. It is therefore decided to use this site as a reference between the three passes rather than relate conventionally to maximum power within each band. Site E therefore appears as 0dB in Figure 20 which shows backscatter in dBs relative to Site E, against soil moisture

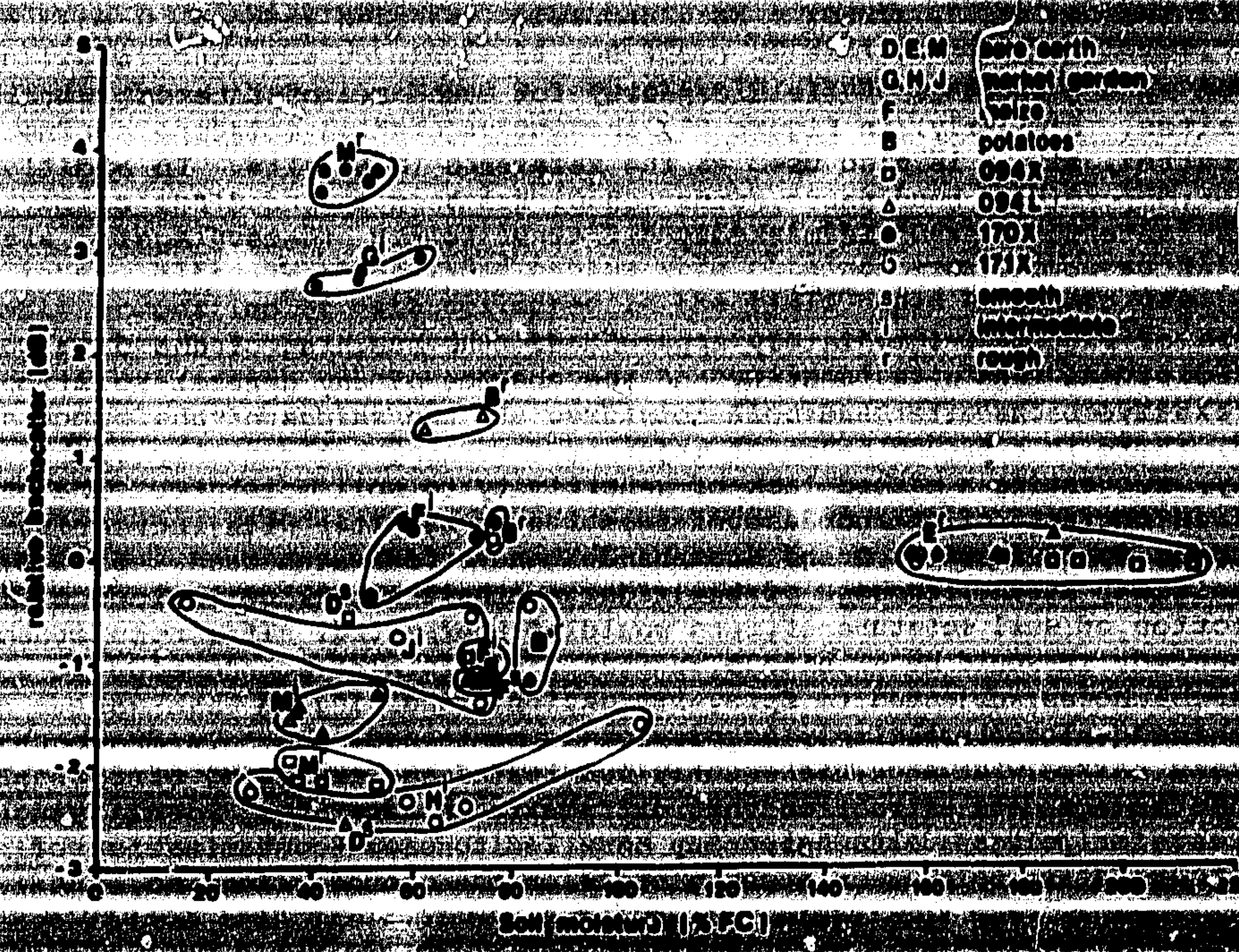

FIGURE 20 Effects of soil moisture on relative backscatter for Thames Valley sites

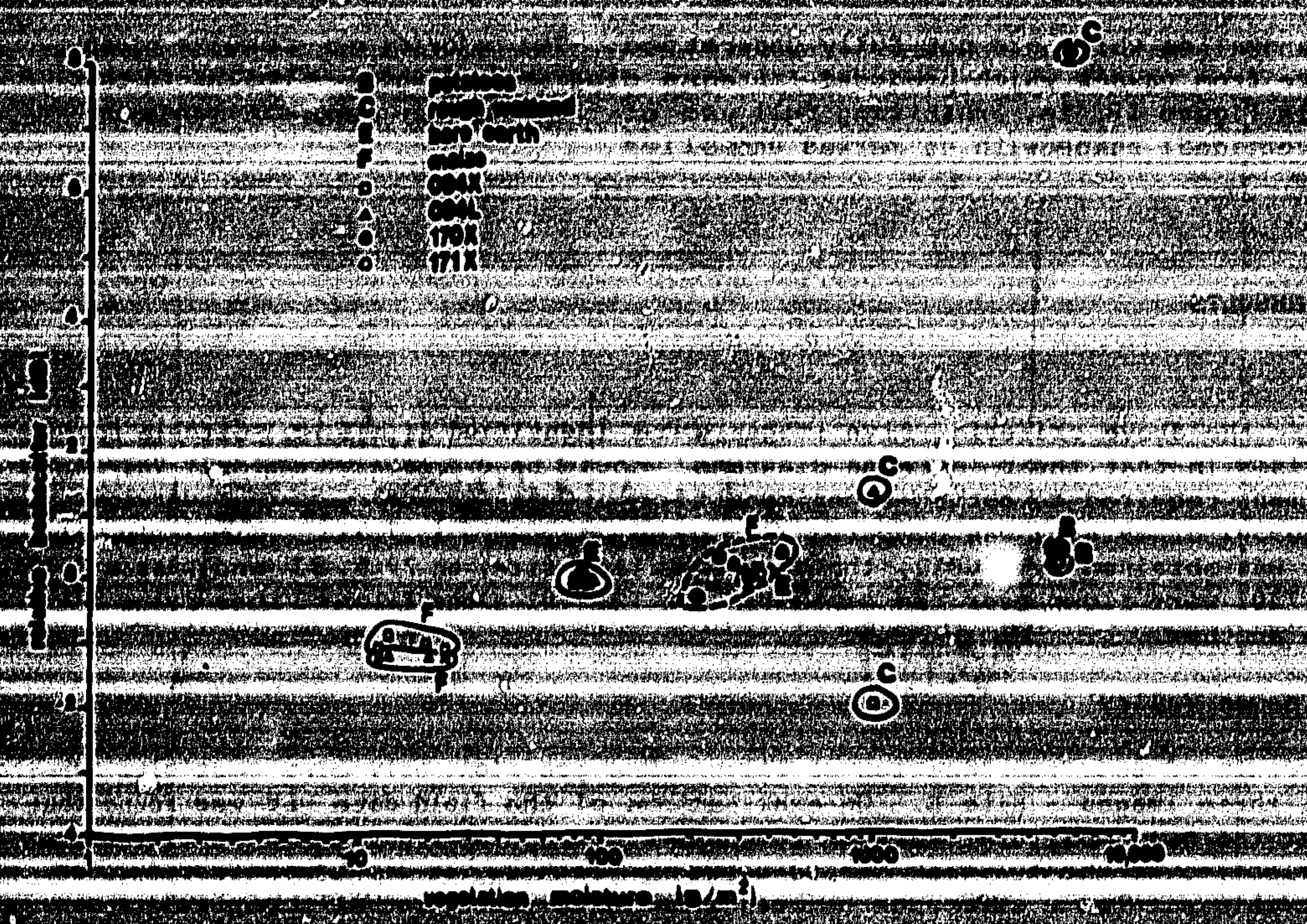

FIGURE 21 Effects of vegetation moisture on relative backscatter for Thames Valley sites

values expressed as a percentage of field capacity for each area of interest within the nine test sites. Similarly, in Figure 21, showing vegetation moisture against relative backscatter, site E is also used as the reference (OdB) site. In addition to the three corresponding X band passes, pass L09401 has been included for comparison even though its 'antenna diagram' is markedly different to the others. Again, site E appears as OdB after normalisation.

The two features of Figure 20 immediately apparent are the bunching of the data which retain individual test site identity and the absence of any general relationship between relative backscatter and soil moisture. If the shapes of the bunches are considered, there is a predominance of major axes running horizontally rather than vertically, suggesting a marked lack of sensitivity to soil moisture. The only suggestions of an [illegible] of an increase of relative backscatter with increasing soil moisture are to be found at sites G and H at band X and site B at L band. Site G is [illegible] at the far edge of the radar swath at a shallow incidence angle where the detection of soil moisture effects would be unexpected. If a relationship were to be expected, it would be at site H, a flat floodplain of homogeneous alluvial soils which was subjected to spray irrigation, resulting in what was expected to be an ideal control site. As previously mentioned, the only drawback lay in the relatively narrow widths of differently cultivated and irrigated strips. It was felt at the time of data extraction that difficulty in accurately identifying the areas of interest for polygon delineation may have led to cross-contamination of digital extracts relative to the wet and dry areas on the ground. Even so, the [illegible] of only 1dB relative to a 40% FC increase in soil moisture can [illegible] poor. Site B was a potato field which again had been subjected to local spray irrigation but which had an almost complete canopy of dense vegetation.

On examination of both the L band and X band data, no obvious difference could be detected between the sprayed and unsprayed areas, even after smoothing and contrast stretching of the digital data, unlike site H where variations over this predominantly bare earth site could be seen.

Site F provides the opportunity to look at the effect of change over the two week period between flights. During this period moisture levels fell from about 75% FC, but an increase in relative backscatter was experienced. This could have been due to the fact that the young maize crop on this site increased its mean moisture content during this period from 19.5 g/m^2 to 208 g/m^2 - more than a 10-fold increase. Again, however, this only corresponds to an increase in relative backscatter of 1dB.

Site M experiences a remarkable increase in relative backscatter over the two week period of about +6dB even though no change in soil moisture occurred. Although the field is classified as rough by Rayleigh criteria on both occasions, the change is undoubtedly associated with its change in surface roughness. For pass O94X site M had a r.m.s. roughness factor (d) of 45 mm as a result of subsoiling which threw up large clods of earth in a random fashion over the surface as recorded in Figures 7 and 14. By the time of pass 170X the field had been disced to break up the clods resulting in a r.m.s. roughness of around 25 mm. Thus although the absolute roughness of the field had been reduced, its backscattering efficiency at the X band wavelength of 32 mm had increased; this factor could not have been predicted readily. L band data was only available for the first series of flights because of a failure in the system shortly before the second flight. Although the L band data is limited, the results appear to be somewhat more predictable than X band in that a smooth surface with a relatively high soil moisture such as site F produces a brighter backscatter than site D which is also smooth but at a lower moisture level. Site M, although of similar soil moisture to site D, appears brighter, presumably as a result of its rougher classification, whilst site B, the potato field and again of similar moisture level, is 3 and 4dB brighter than site M and D respectively, thus carrying on the progression from smooth, to intermediate, to rough.

It is unlikely that any more than general observations such as the above can be made from Figure 20, primarily as a result of the small number of comparable data points. Although three radar passes were obtained over this test site, only a small proportion of data collected in the field could be put to use. If all ten test sites had been imaged on three occasions, the data set would probably have been large enough to draw more concrete conclusions. Nevertheless, the results from GB12 have highlighted the problems associated with soil moisture sampling of bare earth fields.

Bell et al. (1980) laid down recommendations for sampling soil moisture over large fields and it is generally accepted that at least 20 samples are required per field to define within-field variabilities. Volumetric soil sampling is time consuming both in the field and in the analysis of soil samples. It is therefore not practicable to sample a large number of fields at such an intensive level. In the case of SAR.580 the local surface soil moisture variation appears to be greater than the variation recorded in the digital data after speckle reduction. There would therefore appear to be little point in describing the soil moisture variability through intensive sampling if the radar is not capable of resolving this variability. Jackson (1981) has suggested that the problem of surface soil moisture variability can be partially overcome by sampling in the 0-150 mm depth range rather than the 0-5 mm range, beyond which radar wavelengths will not penetrate. His assumption is that there will be some correlation between surface and subsurface soil moisture. Certainly for SAR.580, a more meaningful data set may have been produced by taking two or three 150 mm core samples over 40 or 50 fields rather [illegible] 20-25 samples in ten fields. This procedure would be recommended for future [illegible] studies provided that the whole soil surface profile was relatively damp. Problems [illegible] still likely to arise when a dry surface crust forms over damp subsoil.

Prior to this [illegible] experiment it was thought that a bare soil surface would be simpler to deal with [illegible] one covered with vegetation as the number of parameters to be modelled would [illegible] fewer. This may not necessarily be the case as a vegetation cover such as [illegible] grass will not greatly influence surface roughness as perceived by the radar, [illegible] it will prevent drying of the surface soil so as to retain a good correlation [illegible] between surface and subsurface soil moisture levels.

GB8 Grendon Underwood

Figures 22 and 23 show the results of two X band passes over the Grendon Underwood test area where [illegible] soils were of an homogeneous clay and various types of vegetation were present [illegible] all cases. The indications are once again that X band at relatively shallow incidence angles is poorly correlated with soil or vegetation moisture. During the 14 [illegible] between passes, drying of the test area occurred and this is reflected in [illegible] reduction of soil moisture values over this period.

Sites O and Q [illegible] where interference from the vegetation would be minimal, as indicated [illegible] low moisture content (Figure 22). A wide spread of surface soil moisture is evident within these fields, ranging from about 65% to 230% field capacity but this is recorded within a range of only 1.5dB of the radar digital [illegible]. A reduction in soil moisture is evident in both fields over the two week period. Sites R and U are of grazed pasture where the vegetation ranged from [illegible] cropped grass to short grass plus fine grass seed heads.

FIGURE 22 [illegible] of soil moisture on relative backscatter for Grendon Underwood sites

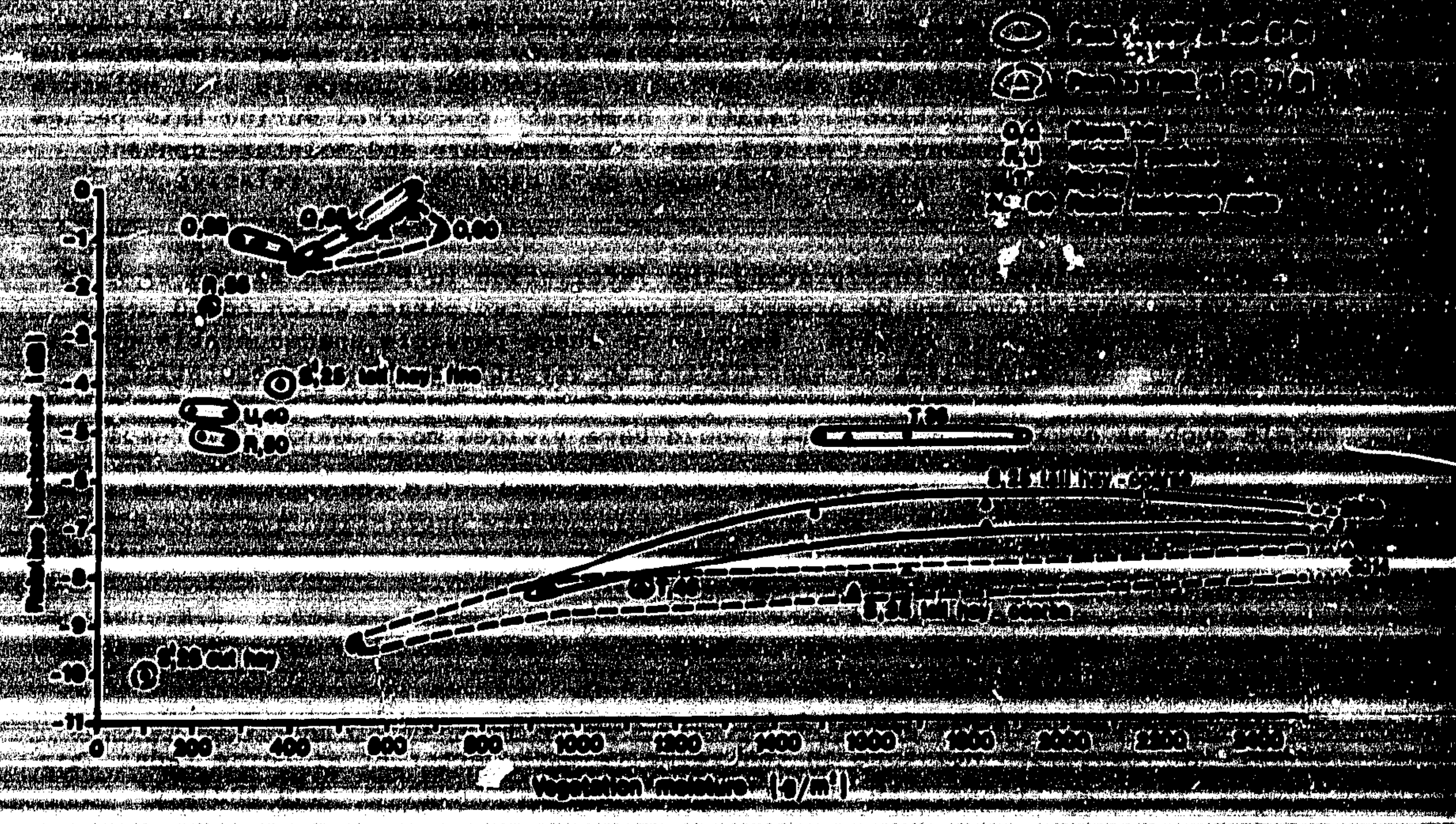

FIGURE 23 Effects of vegetation moisture on relative backscatter for Grendon Underwood sites

For pass X17202 on 13 July, a considerable soil moisture variation existed between these fields (Figure 23) and low vegetation moisture levels were evident but no significant difference in relative backscatter was observed. Conversely, taking site R alone, although both vegetation and soil moisture levels are almost identical for both passes, the backscatter (relative to Q max) for site R on 13 July is 2.5dB higher than for 29 June. The reason for this is unclear. Only two factors are known to have changed; (1) the mixed pasture, being subjected to cattle grazing, was slightly shorter for the second pass and the number of tall seed heads had been reduced, and (2) the angle of incidence of the radar had changed from 50° to 55°. Neither of these changes would normally be associated with an increase in radar backscatter and it can be seen that most of the other sites exhibited a reduction in relative backscatter from 29 June to 13 July. It must be assumed therefore that the above two changes have combined to produce an increase in perceived surface roughness resulting in increased relative backscatter.

Site S was a field of hay. One half, having been established for several years, comprised a [illegible] mixture of grasses, nettles and other weeds. The other half (S') had been [illegible] newly seeded and was therefore of a single uniform fine grass species. Figure 22 indicates that little difference exists between the two [illegible] in terms of soil moisture, but the fine hay produced a 3-4dB brighter [illegible] than the coarse hay, even though the former has a much lower vegetation moisture content, as shown in Figure 23. Again, this suggests that the perceived surface roughness at X band is probably of greater influence to radar backscatter than either soil or vegetation moisture. The fine hay was cut and left to dry some days prior to the second overflight and a reduction of relative backscatter of about [illegible] was the result, demonstrating that in this case, the X band response [illegible] from the vegetation itself than from the underlying soil.

Site 7 was a field of tall barley which ripened progressively during the 14 days between passes. This is illustrated in Figure 23 by a fall in vegetation moisture of around 30% whilst during the same period no appreciable change in soil moisture was recorded. A 4dB reduction in relative backscatter occurred during this period, thus supporting the findings at site 5 that the structure and moisture content of tall vegetation has significant influence on X band values of relative backscatter.

It must be appreciated in interpreting the information in Figures 22 and 23 that large system variations may be present between the two passes which could make some of the observations invalid. Because of these possible unaccountable errors, coupled with the marked lack of sensitivity to variations in soil vegetation moisture, there was no suggestion that proceeding with more complex soil/vegetation models such as outlined by Mo (1984) would have yielded more meaningful results.

7 CONCLUSIONS AND RECOMMENDATIONS

It was known prior to the planning of this experiment that any possible effects of soil or vegetation moisture on the relative backscatter of airborne radar data would be small in relation to the effects of surface roughness and angle of incidence, and that in order to detect such variations a well calibrated radar system would be required. On paper, SAR 580 could not provide the ideal instrument set up for such a purpose. Nevertheless it provided us with the first opportunity to work with radar over our own test areas, so efforts were made to make as much use as possible of the data through indirect calibration via a network of ground-based corner reflectors. It was unfortunate that these corner reflectors could not be used to obtain a reasonable intercalibration of the various passes, as from a soil moisture point of view, the lack of calibration was disastrous. Although attempts at radiometric balancing were made via image line smoothing in the azimuth direction to try and reproduce an antenna diagram, these were inadequate for our purposes and evidence of major errors exists.

No evidence of a consistent relationship between either surface soil moisture or vegetation moisture against radar backscatter could be seen in the data which was reduced in volume by the non-imaging of a number of test sites. The lack of such evidence is not unexpected as no data were available at incidence angles of 5-15° where the effects of surface roughness would have been minimised.

Whilst the result of our experiment was inconclusive for this particular radar configuration, the experience gained during the course of the experiment in the use of radar for hydrological purposes has been enormous, especially in ground [illegible] radar calibration and digital data handling. The experiment has greatly increased our knowledge of methods of field survey and ground control in relation to radar remote sensing programmes and has indicated that (a) soil and vegetation sampling over many fields at less frequent spatial intervals may be more fruitful than intensive ground sampling within a few fields, and (b) that bare earth sites may not be the best places to build up our understanding of soil moisture/radar interaction; short grassland sites could be simpler to model [illegible] required in the modelling of surface roughness or tall vegetation [illegible] of different frequencies as this is very difficult to quantify. [illegible] future work in soil/vegetation moisture estimation should centre [illegible] the 5-20° range of incidence angles, with a future eye on multifrequency systems which may provide the opportunity of estimating surface roughness directly.

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