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Reflection of radar waves by soils, crops and forest: A review of some recent Dutch work

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Summary

The use of radar reflection as a classifier for agricultural purposes is discussed and demonstrated. The results of some series of measurements being performed by a Dutch working group in collaboration with the Agricultural University is mentioned. An indicating treatise is given on the problems of data handling.

Reflection of radar waves by soils, crops and forest

Like light and heat waves radar waves are electromagnetic vibrations. They have wavelengths varying from 1 cm to 1 m. Radar means *ra*dio *d*etection *a*nd *r*anging. For detecting purposes use is made of the properties of these waves which are reflected by many natural objects, and by metallic reflectors adapted to the wavelength chosen.

In principle radar waves can be characterized by wavelength, amplitude, phase and polarization. Their physical behaviour, however, differs from that of visual light. For instance, they have characteristics enabling the nature of materials to be defined. The information on the materials, obtained by the attenuation and reflection of radar waves, can help in the characterization of natural materials, such as soils, plants and crops.

Principles

For the present purpose, it is deemed unnecessary to deal exhaustively with the theoretical features and possibilities of the measuring equipment. It seems logical that short wavelengths and a small powerful beam are to be preferred, since under these circumstances a higher amount of energy can be reflected. A narrower beam will be found at shorter wavelengths with equal geometry of the antenna. For instance, a beam width 0.3° with $\lambda = 8$ mm or 1.0 – 1.25° with $\lambda = 3$ cm is frequently used for horizontally directed beams.

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As a general rule it may be stated that an aperture of N wavelengths corresponds to a beam width of 1/N radians, which means that so with values of 100 cm and $\lambda = 1$ cm, respectively, an aperture of 0.6° will be an adequate value. This includes that at a distance of e.g. 5 km an object can be discerned from a neighbouring object, when the distance between the two objects exceeds 30 m; therefore large antennes are needed.

In the last few years many types of radar systems have been developed. One subdivision can be made in that real 'synthetic' aperture systems can be distinguished. In the latter case variations in the phase are registered with variations in amplitude. In this article some results of monostatic and bistatic systems are presented. In these systems the antenna is used to transmit and receive. In the latter case, the receiver has its own antenna.

In fact during measurement short-lasting trains of electromagnetic energy are transmitted. The amplitude corresponds with the transmitting power. The antenna directs a part of the energy (P_u) in the beam discussed. This means that the radiated energy is not equially distributed over a sphere, but concentrated on one side. After each transmitting period the reflected wave is awaited of which the spectrum of amplitudes will be registered in an analogous way. Sometimes this occurs after filtering. The natural surface that reflects the incoming wave will scatter and attenuate the incoming energy. Consequently the almost equal amplitudes of the incoming waves will be deformed to a series of waves of different amplitudes. The signal that is received after reflection (P_r) is far lower in energy level, and is expressed in a decibel scale, i.e. in tenths of the logarithm of the power ratio of incoming and transmitted energy (e.g. $P_r = -60$ dB).

Changing the length of time between transmission and receiving, the so-called sweep or scan length, permits measurement at different distances from the antenna.

A very useful expansion of the possibilities of discerning is given by the polarization of the transmitted and the received signal. This includes more degrees of freedom, which means that, for example, horizontally polarized waves (H) are transmitted and horizontally (HH) or vertically polarized waves (HV) are received. In this way some important additional information can be collected on the experimental fields.

In practice a reflector is used in the field to adapt and correct for the environmental conditions. Such a reference can be, for example, a metallic sheet with a diamond shape. It can be directed in positions perpendicular to the transmitted wave.

The whole arrangement of the measuring equipment can thus be tested during the measuring period. Calibration takes place at least two times a day. The reflection of this reference (called the radar cross section (RCS) and to be described later) is expressed in square meters. There can exist a large difference between the actual physical size of a reference and its RCS. This is due to the special reflection mechanisms involved. During the experiments to be described the RCS was 1000 m^2 where the actual dimensions of the reference were in the order of 1 m^2 The description and data in Table 1 give the parameters of the measuring equipment used. However, corrections are required, for instance for the form of the beam

Table 1. Properties of the X-band measurement radar (λ = 3.2 cm) of the Physics Laboratory TNO.

Frequency	9375 Hz
Pulse recurrency frequency	1000 Hz
Antenna (opening)	1.8°
Polarization	HH and VV
Pulse length	0.5 μs
Gate length	40 ns, resp. 1 μs
Output	50 kW
Receiver	logarithmic, dynamic range 50 dB
Receiver sensitivity	— 103 dB m
Recorder	Ampex FR 1600

of transmitting and reflecting antenna (not being coaxial, etc.). Thus a value for γ, the radar return parameter (Cosgriff et al., 1960), can be found, but more considerations should be taken into account. The signal received fluctuates ('fading spectrum'). This spectrum can reflect specific, hence identifying properties of the detected surface and is related to movements of scatterers in the area under consideration ('Doppler') (Moore, 1970; de Loor et al., 1974).

There are some important reasons for our interst in the physical behaviour of longer waves (λ varying from 0.8 to 70 cm), aside from the interesting properties of visible light. Firstly, longer waves penetrate the atmosphere much better, even when a large number of water molecules is present. For the different radar wave bands, Fig. 1 indicates this property together with an indication of the internationally accepted band designation.

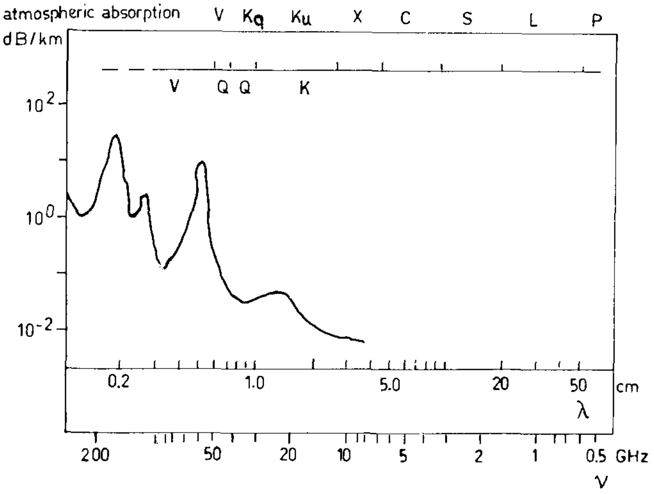

Fig. 1. Indication of radar waves of different wavelength by characters and the attenuation of radar waves by the atmosphere (in dB/km).

The measurement of the radar cross-section

Taking the effective opening of the antenna to be Θ and the effective distance to a reflective surface to be R, the irradiated surface, perpendicular to the axis of the beam will equal

$$A = (\pi/4)\, R^2 \operatorname{tg}^2 \Theta$$

The general radar equation is (Moore, 1970):

$$P_{\mathrm{r}} = P_{\mathrm{u}} \frac{\sigma\, G_1\, G_2\, \lambda^2}{(4\pi)^3\, R^4} = \sigma \frac{Q}{R^4},$$

where G_1 and G_2 are the so-called antenna gain of the transmitting and receiving antenna, respectively, λ is the wavelength used, P_{u} is the transmitted microwave power, P_{r} the power received back and σ is the so-called radar cross-section. For a surface searched the following equation applies:

$$\sigma_{\mathrm{m}} = P_{\mathrm{r,m}}\, R_{\mathrm{m}}^4/Q.$$

For a reference surface, such as a metallic surface or a corner reflector, applies analogously

$$\sigma_{\mathrm{h}} = P_{\mathrm{r,h}}\, R_{\mathrm{h}}^4/Q.$$

The characteristic parameter γ is defined as

$$\gamma = \sigma_{\mathrm{m}}/A,$$

corresponding to

$$\gamma = \frac{4\, P_{\mathrm{r,m}}\, R_{\mathrm{m}}^2\, \sigma_{\mathrm{h}}}{\pi\, P_{\mathrm{r,h}}\, R_{\mathrm{h}}^4 \operatorname{tg}^2 \Theta}.$$

The large decrease in power level of the reflected signal requires logarithmic notation (in dB), which can be written in the following form

$$\log \gamma = \log\, [4\sigma_{\mathrm{h}}/(\pi\, R_{\mathrm{h}}^4 \operatorname{tg}^2 \Theta)] - \log P_{\mathrm{r,h}} + \log P_{\mathrm{r,m}} + \log R_{\mathrm{m}}^2.$$

Expressing σ_{h} in square meters, γ (in dB) can be obtained in $\mathrm{m}^2/\mathrm{m}^2$, in a dimensionless form.

The first term at the right hand side of the equation (for a given Θ) is a constant; the momentary value of the two other terms can usually be read directly on a recorder.

Occasionally the results are presented in $\sigma_0 = \gamma \sin \alpha$, where α corresponds to the incidence angle of the radar beam, with the surface being studied.

The characterization of the materials

The specific material properties in these wave bands are related to a number of electric field parameters. The beam touching the natural surface causes a change of the electromagnetic field. Aside from the parameters of the incoming waves, such as wavelength, angle of incidence, direction of polarization, a geometric definition of the surface itself has to be dealt with.

Without a further introduction into the theoretical aspects, the results can be expressed in a parameter varying with the height of the object and one related to the angle of incidence, thus leading to the introduction of a so-called characteristic length and an effective variance. For practical application, two values are of importance; the roughness of the surface and the influence of the specific electrical properties of the materials.

These last ones are related to the complex dielectric constant:

$$\varepsilon = \varepsilon' - j\varepsilon''$$

where the last term at the righthand side varies with the frequency and is related to the conductivity c[1] of the material. The permittivity ε' and the loss ε'' may vary from layer to layer in a soil or crop, but in the reverse sence they contain important information of the fields studied. For homogeneous materials, based on the values for ε' and ε'', the so-called skin depth of damping depth can be calculated beforehand. This value correspond to the length, or layer thickness, at which 37 % of the energy received at the surface has been lost by absorption, in effect heat loss. As a general rule this usually corresponds to roughly the wavelength or less. Due to no identical geometries possessing distinct permittivities occurring in nature, treatment of the data is very difficult. For the roughness some assumptions have been introduced, based on the distribution functions of the lengths in the three space axes, which are related in a relatively simple way to each other: an autocorrelative function. In Table 2 the dielectric properties of some natural materials are given, with water serving as a dominant (Deane & Domville, 1972; Lundien, 1966). Roughly speaking, most of the data gathered from field research are related

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[1] $\varepsilon'' = \varepsilon''_c + \varepsilon''_{dip.}$; $\varepsilon''_c = 4\pi c/\omega$ (in c.g.s. units) where c = the conductivity; $\varepsilon''_{dip.}$ = the dipolar loss

Table 2. Dielectric properties of some soils and some materials (at λ = 30 mm) (after Moore, 1970; Deane & Domville, 1972; Lundien, 1966).

	Moisture content % (w/w)	Real part of dielectric constant, ε'	Conductivity c* (mho/m)
Dry sand	0.5 – 3	2 – 4	10^{-2} – 10^{-3}
Wet silt loam	6 – 18	5 – 10	10^{-1} – 10^{-2}
Very wet soil	> 20	14 – 24	7 – 0.1
Quartz	–	3.8	$2 \cdot 10^{-4}$
Marl	–	6.7	10^{-4} – 10^{-8}
Concrete	–	6.5	0.83
Seawater	100	67	16
Ice	100	3.17	10^{-3}

* $\varepsilon'' = 4\pi c/\omega$ (in c.g.s. units) or: 60 $\lambda\sigma$ (λ in cm, c in mho/cm). At microwave frequencies (here under consideration) the conductivity due to dipolar losses must be added.

to the geometrical arrangement of the water molecules. This finding may also be related to the presence of water in the crop or in the soil. It is related to the amount of biomass, and to the percentage of soil surface covered by the crop.

Measurements on soils

In the literature referring to radar properties of soils some data can be found. References to possible agricultural uses of the data are available only to a limited extent. Some modelling has even taken place in an attempt to classify the data (Ruck et al., 1970), but not in view of agricultural application. An interesting graph (Fig. 2) found in the literature (Deane & Domville, 1972) demonstrated the relation between skin depth and wavelength. So changes in phreatic level in dry sands can be followed. For normal agricultural fields, Fig. 3 is interesting (Moore, 1970; Lundien, 1966). This figure is corrected for with data obtained by Lundien (1966) in the GHz range and some results of recent experiments of the Physics Laboratory TNO. Proceeding from this basis a large series of measurements were undertaken by this Laboratory for several years (de Loor et al., 1974; de Loor, 1974a) in the southwestern part of the Netherlands, north of Goes. In Tables 3 and 4 a summarizing survey is given of the winter 1972/73 series undertaken in collaboration with NIWARS (Eradus & de Loor, 1974). The measurements took place with the monostatic system of which the parameters are given in Table 1 and with an antenna placed at a height of 70 m, in the tower of a television station (Fig. 4 and 5). A systematic treatment based on some model theories is in study.

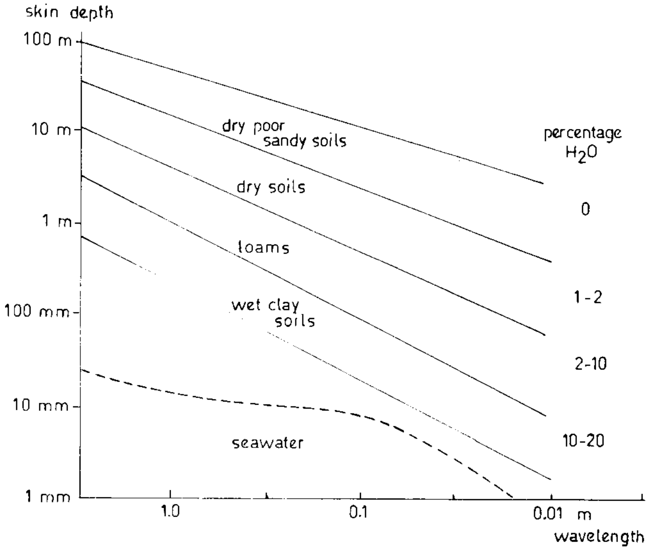

Fig. 2. Skin depth of radar waves in soils, calculated from the dielectric properties (after Deane & Domville, 1972).

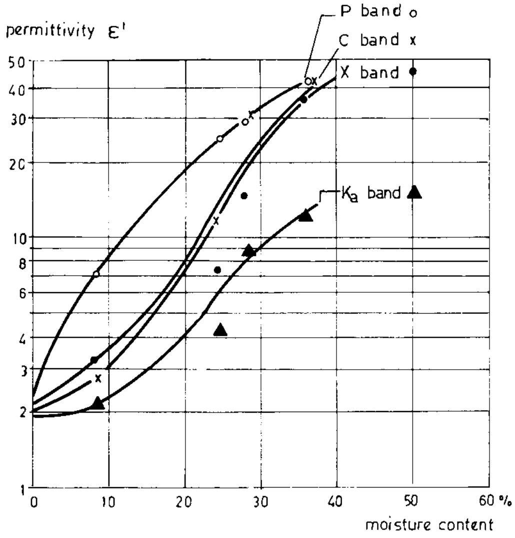

Fig. 3. Relationship between dielectric permittivity ε' and changing moisture constant, for a silt loam, and for different wavelengths (after Lundien as reported by Moore, 1970).

Measurements on crops

Fig. 6 is instructive in giving a qualitative insight into the interaction between crops and radar waves. It denotes the values of ε' and ε'' of a number of maize leaves (Carlson, 1967). In the reverse sense one may conclude that growth phase hydra-

Table 3. Radar reflection of some bare soils, with distinct moisture contents and roughness of the top layer (after Eradus & de Loor, 1974).

Clay content (% > 16 μm)	Direction of tillage	Moisture content top layer (% w/w)	Roughness	$-\gamma_{HH}$ (dB)	$-\gamma_{VV}$ (dB)
15 – 18	E – W 82.5°	17.2	170**	29.1	31.8
	N – S 7.5°	21.1	118	32.6	35.5
	N – S 7.5°	34.5	402	26.9	30.7
25 – 35	N – S 7.5°	29.3	21	27.3	20.9
	N – S 17.2°	26.4	68	36.7	32.2
	N – S 27.5°	27.5	109	37.2	34.3
35 – 45	N – S 17.2°	21.4	217	32.1	27.5
	N – S 27.5°	24.1	73	31.8	34.6
	N – S 27.5°	25.1	37	35.9	34.5
	E – W 78.5°	26.8	59	21.2	21.0
> 45	N – S 7.5°	23.9	178	39.4	33.4
	N – S	28.0	992	29.1	31.3

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* The point of observation is at about 1.5 km south of the experimental fields.

** The variance of distances to a horizontal reference level.

Table 4. Relationship between the radar reflection and moisture condition in the top layer (after de Loor, 1974b).

Clay content (% < 16 μm)	Structural condition of the surface	Moisture condition of the top layer	Damping (γ in dB)	
15 – 18	slaked	saturated	H-30	V-31
		field cap.	H-31	V-36
35 – 38	slaked	saturated	H-21	V-24
		field cap.	H-16	V-22
45 – 50	ploughed	saturated	H-39	V-37
		field cap.	H-42	V-40

ture and stage of maturity of the crop may be inferred from the specific results of measurements. However, the geometry and distribution of water in the crop dominates under all these conditions. By lowering a reflector in the cropped fields and measuring the attenuation (Eradus & de Loor, 1974) the effective skin depth can be determined. For this purpose special radar equipment has been constructed for the remote sensing team in the Netherlands (Attema & van Kuilenburg, 1974). For maize, an attenuation of 50 %, thus 3 dB, corresponded just before ripening to 25 cm; for sugar-beets to nearly 10 cm, etc. (Table 5).

Some recent papers deal with the possibilities to describe a vegetative canopy with a model theory. Peake (as referred to in Ruck et al., 1970), for instance, has compared plants with wet cylinders, but this is only a start. For grasses and some other young crops it appeared that this array of water needless in vertical position

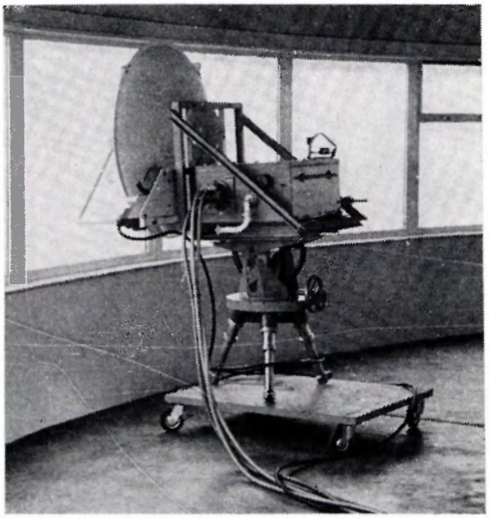

Fig. 4. The antenna of the X-band measuring radar of the Physics Laboratory TNO on the top floor of the television tower at Goes (in south-west Netherlands).

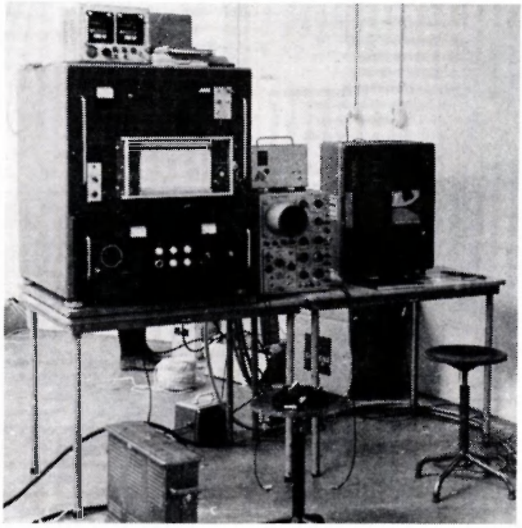

Fig. 5. The registering equipment. On the right the Ampex tape recorder, on the left the direct registration for calibration and the mean value of the radar cross section. The place of the gate along the sweep can be seen on the screen of the scope.

was quite acceptable. The results show that the coverage of only a few percentages of soil surface with crops suppressed the effects of soil itself. It was shown that partly due to regularity the attenuation of grasses is much larger than of trees and beets. Beans, however, due to their large variation in moisture content, show a marked change in behaviour during the growing season. At a lower moisture content the attenuation increases but never reaches the level of that of ripening oats

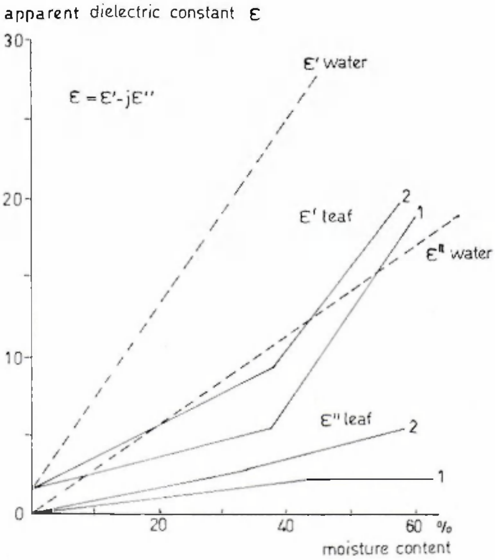

Fig. 6. Apparent dielectric constant of maize leaves in dependence of their moisture content (after Carlson as reported by Moore, 1970).

Table 5. Skin depth of radar waves in crops (after Eradus & de Loor, 1974).

Crop	Height (cm)	Skin depth (cm)
Oats	100	15
Beets	50	15
Potatoes	80	15
Barley	60	25
Wheat	90	38

(Fig. 7 and 8). This figure should be considered as tentative information, the spread of the results being quite substantial. The attenuation is probably influenced by rain and dew, and seems to be related to the angle of incidence. Further experiments are needed to prove this.

Measurements on forests

To study the reflective behavior or crops, measurements on forests are very useful. Usually the extension is large; the objects are more rigid and in many cases the electric field strength can be measured at different heights and distances. The tops of the trees are mostly very good scatterers with practically ideal performances. This can be shown especially when the soil surface is wet and acts as a perfect

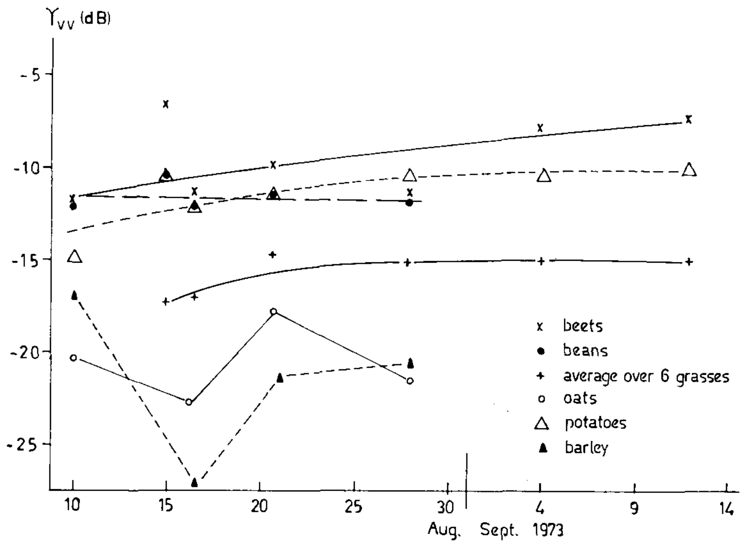

Fig. 7. Change of the radar return parameter γ for different crops with time (after Eradus & de Loor, 1974).

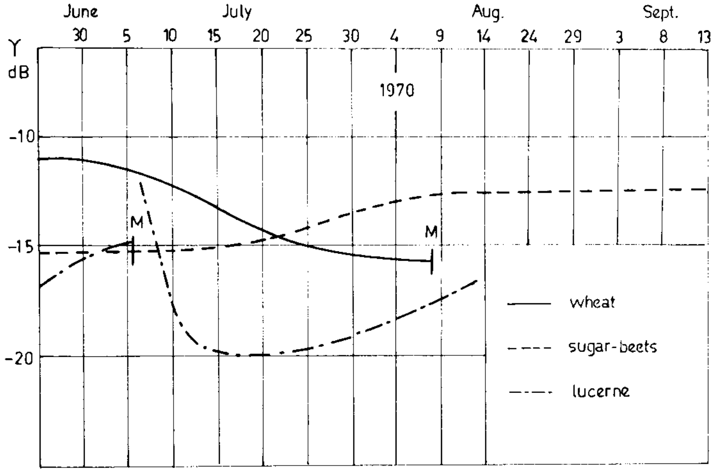

Fig. 8. Variation of the radar return parameter γ (X-band) during the growing season for wheat, sugar-beets and lucerne (M = mowing or cropping) (after de Loor et al., 1974).

reflector. Since the effect of the angle of incidence is also interesting, a TV tower was chosen near Eindhoven which is situated at the border of a large area with different types of forest. A difficulty is that at greater distances the higher trees act as a shadowing screen preventing further measurements. On the other hand, from the literature it is known that with large angles of incidence the influence of the soil under the trees can no longer be neglected (Davies, 1969). During the measuring campaign in the winter 1972/73 (de Loor, 1974b) an extensive ground truth was performed. Many data with respect to the type of tree, number of trees per unit area, size classified, distribution of branches, thickness of the stems, wet and dry weight of the needless, etc. were collected (Table 6).

Table 6. Radar reflections of forests with different types of trees (winter 1972/73) (after de Loor, 1974b).

Type	Height (m)	Diameter of stem (cm)	Number of trees per 100 m^2	$-\gamma_{HH}$ (dB)	$-\gamma_{VV}$ (dB)
Fir	12	20 – 24	16	14.4	14.4
Fir	8	12 – 15	25	13.5	14.4
Fir	10	15 – 20	20	19.4	15.1
Fir	9	8 – 14	60	12.7	13.3
Larch	15	12	35	14.5	15.2
Fir	15	20	16		
Dutch oak[1]	28	25	4	13.8	13.2
American oak[1]	6	8 – 12	14	16.5	14.9

[1] Without leaves.

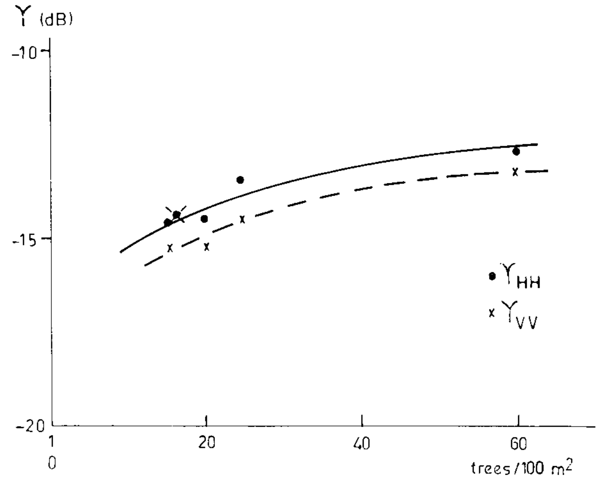

Fig. 9. Relationship between the radar return parameter γ and number of trees per 100 m² of a fir forest (after de Loor, 1974b).

Many replications were made, just before and after rain, and with increasing wind speed. These data were combined with the collection of meterological data.

From the many detailed calculations it appeared that the upper part of the trees dominates (amount of water in the needles of the canopy), as is shown in Fig. 9, where the relationship between the number of trees per unit area and the γ-value is plotted. Effects of thickness of the stems or height of the trees were not significant.

A relationship between the adhering water on leaves and needles could not be proved under the given conditions.

Some conclusions

Any new method that provides significant and reproducible results is challenge for interpretative studies. The fact, that there are possibilities to classify, is of practical use to the field worker. Much fundamental work has still to be done.

These measuring techniques, being one of a large number of techniques in teledetection offer possibilities to delineate specific properties and boundaries in field research. Without doubt their importance to ecologic purposes seems high. One advantage is related to their physical soundness, i.e. the results can be expressed in physically well defined parameters. The interpretative models lack at the moment sufficient validity.

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