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Tower-Mounted Radar Backscatter Measurements in the North Sea

G. P. de Loor

Physics Laboratory TNO, The Hague

Measurements of average normalized backscatter made from a platform in the North Sea 10 km off the Dutch coast are reported here. The measurements provide information on the dependency of *X* band backscatter on grazing angle, wind speed, and look direction. It has been found that for grazing angles under 50° the dependency of backscatter on wind speed is highly sensitive to polarization and look direction. Also an unexplained difference between ground-based and airborne measurements was observed.

Introduction

The results reported here were obtained as part of a study to investigate the use of radar remote sensing as a tool for flood control in the Dutch part of the North Sea. This is done in a program which is composed of ground-based microwave measurements and flights with a real aperture digital SLAR. This program is called Project Noordwijk. In 1979 this program was coordinated with the MARSEN (Maritime Remote Sensing) experiment which took place in the North Sea and the German Bight. We investigate in this paper the average (noncoherent) backscatter of the sea as a function of incidence angle, wind speed, and look direction. Work on the modulation of this backscatter by seawaves will be reported elsewhere.

For these experiments a research platform is available in the North Sea (tower Noordwijk). It offers the opportunity to perform experiments with ground-based reflectometers in the open sea. The tower is permanently instrumented for the measurements of pertinent meteorological and oceanographic data. It lies 10 km offshore. In the direction of the prevailing winds, the fetch is of several hundred kilometers. We shall refer to the wind speed and wind direction as measured at this tower (height 23 m) as the standard since the anemometer was placed there after careful tests in a wind tunnel. Recent measurements have suggested that atmospheric stability may be an important factor in backscatter measurements. This was not initially taken into account; however, preliminary analysis has shown that its influence does not change the conclusions reported here.

Two other institutes participated in the radar backscatter measurements on the Noordwijk tower. They were the Institut Francais du Pétrole in 1978 and 1979, with a four-frequency FM/CW scatterometer (1.5, 3, 4.5, 9 GHz), and the Remote Sensing Laboratory of the University of Kansas in 1979, with an FM/CW system operating in the band from 8 to 18 GHz. This cooperation offered the unique opportunity of intercomparison of the three systems. Our own radar is a short-range *X* band FM/CW system. Its properties are given in Table 1, and a full description of this scatterometer is given by *Smit* [1978].

All radars were mounted at a height of 16 m above mean sea level on a small platform which protruded outside the tower to the northwest, the prevailing wind direction. The radars viewed the undisturbed sea surface—their observations being at least 8 m from the tower legs—when looking vertically downward. A Luneberg reflector with radar cross section of 10 m^2 was used as calibration target. It was mounted at a distance of 16 m on a pole protruding from the helicopter deck in such a way that the radar was pointed above the horizon to avoid interfering sea reflections.

All three radars determined the normalized radar backscatter coefficients σ° as a function of grazing angle θ at upwind, downwind, and crosswind for a wide variety of sea conditions and wind speeds. Below we first give the results of an intercomparison of the data obtained at the tower, and then we describe the method used to compare these data with those obtained elsewhere with airborne/space equipments. This finally leads to a set of parameters which describe the dependency of the normalized radar backscatter on wind speed and wind direction for grazing angles between 20 and 90° (normal incidence).

Tower Measurements

All three radars determined the normalized radar backscatter coefficient from 2 to 6 min recordings of received power. Two common definitions of the radar backscatter will be used. These are σ° and γ. Here, $\sigma^\circ = \sigma/S$ and $\gamma = \sigma/S_i$, where σ is the average backscatter, S the area illuminated by the measuring system, and S_i the area of the cross section of the antenna beam at the position of the target. The relation between σ° and γ is $\sigma^\circ = \gamma \sin \theta$, with θ the depression or grazing angle. Figure 1 gives an example of some of the data sets now available. We include the French data [*Fontanel et al.* 1978] available to us (the crosses). Note the general agreement of our data with the French data. This is encouraging since both systems operated independently, including the calibration procedure. The same applies for the U.S. data, as a first comparison (Figure 2) of the data demonstrates. Here, both equipments were mounted on the same pedestal and was measured simultaneously.

The similarity in the results obtained by the three different equipments is encouraging, in particular in view of the (yet unexplained) systematic difference we found in these measurements [*de Loor et al.*, 1981; *de Loor and Hoogeboom*, 1982] between the data obtained by the ground-based equipments in comparison with the data reported for airborne/space equipments [*Schroeder et al.*, 1982; *Smith and Dome*, 1979; *Moore et al.*, 1979; *Moore and Fung*, 1979; *Kaupp and Holtzmann*, 1979; *Moore et al.*, 1978; *Young and Moore*, 1977; *Jones et al.*, 1977]. The measurements suggest that the difference between σ° measured with the ground-based equipments and airborne/space equipments is constant (for a fixed grazing angle).

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TABLE 1. The FM/CW X Band Measuring Radar

	Parameters
Frequency	X band, used at 10 GHz
Frequency sweep	variable, used at 400 MHz (1977), 50 MHz (1978), 100 MHz (1979)
Modulation waveform	triangular
Modulation frequency	25–150 Hz; 50 Hz (1977), 150 Hz (1978, 1979)
Power transmitted	1 W
Polarization	VV, HH, VH, HV
Range	up to 100 m
Antenna opening	4.4°
Recording	analog (FM) or digital

This enables us to determine this difference for each grazing angle empirically. The result is given in Figure 3. A preliminary explanation of this phenomenon has been given by *Attema et al.* [1982] and *Levine* [1982], but the effect requires further investigation.

Comparison With Other Data

The systems used on the platform cover a wide frequency range. The same applies for the literature data mentioned. We therefore developed the following method to compare them.

Wright [1968], applying first-order (small roughness amplitude) scattering theory, gave the following relation for the sea clutter in terms of the mean-squared spectrum of the sea [*Valenzuela*, 1978]

$$\sigma^\circ(\theta)_{ij} = 4\pi\kappa^4 \sin^4\theta\, |g_{ij}(\theta)|^2\, S(2k\cos\theta, 0) \qquad (1)$$

where S is the two-dimensional (Cartesian) wave number spectral density of the sea surface roughness, $k = 2\pi/\lambda$ with λ the radar wavelength used, θ the grazing angle, and $g_{ij}(\theta)$ are the first-order scattering coefficients; the indices i and j denote the polarization of the incident and backscattered radiation, respectively. Through (1) it is possible to infer the wave number

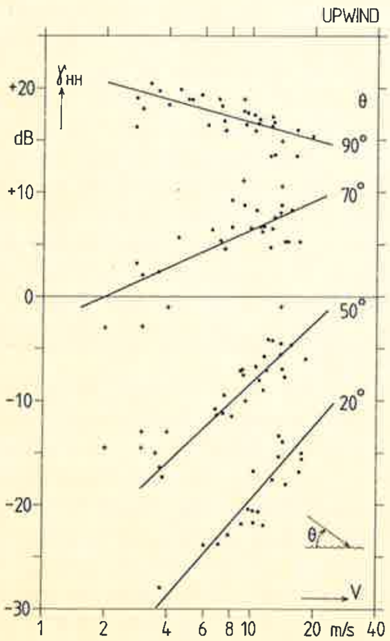

Fig. 1. Example of radar cross section measurements as a function of wind speed v, as made at platform Noordwijk. Dots, Physics Laboratory TNO; pluses, French data.

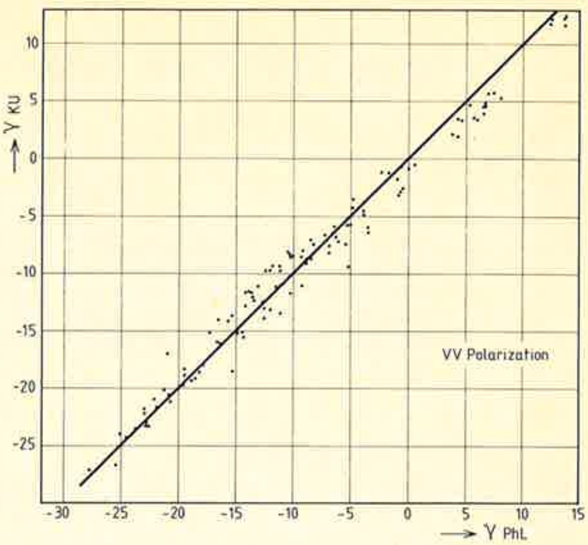

Fig. 2. Comparison of data of the Physics Laboratory TNO with those of University of Kansas. Data were taken simultaneously.

spectrum $S(K)$ from σ° data ($K = 2k\cos\theta$), and Wright suggested the relation $S(K) = AK^{-4}$. He showed that the relation with the measurements available to him was good.

Later measurements by the Naval Research Laboratory [e.g., *Daley et al.*, 1971], which covered a large frequency range, gave a further support to the theory. *Valenzuela et al.* [1971] analyzing these data showed that the wave number spectra inferred from these radar cross-section data could be written for vertical polarization as $S(K) = AK^{-\alpha}$.

We repeated their calculations, using the JOSS-I and Puerto Rico data as reported by *Daley et al.* [1971]. Figure 4 gives an example. Where *Wright* [1968] gives for $\alpha = 4$, with possible deviations for low and high values of K, the figure suggests a dependency on wind speed with α ranging from 3.65 at high wind speed to 4.35 at low wind speed. Figure 5 shows the high frequency part of Figure 4 in more detail. We now inserted the $S(K)$ values as derived from the data as measured by us on platform Noordwijk for the appropriate grazing angles. We see here also a clustering of the data obtained at high wind speeds at the top of the graph and of the data for the lower wind speeds near the underside. As remarked before, these tower data are high when compared to aircraft/space measurements and must be corrected for altitude. This correction is dependent on grazing angle (see Figure 3). We also made a comparison with the available French data [*Fontanel*

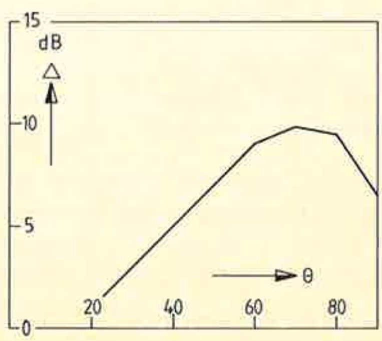

Fig. 3. Discrepancy between our groundbased data and those taken by airborne/space equipments.

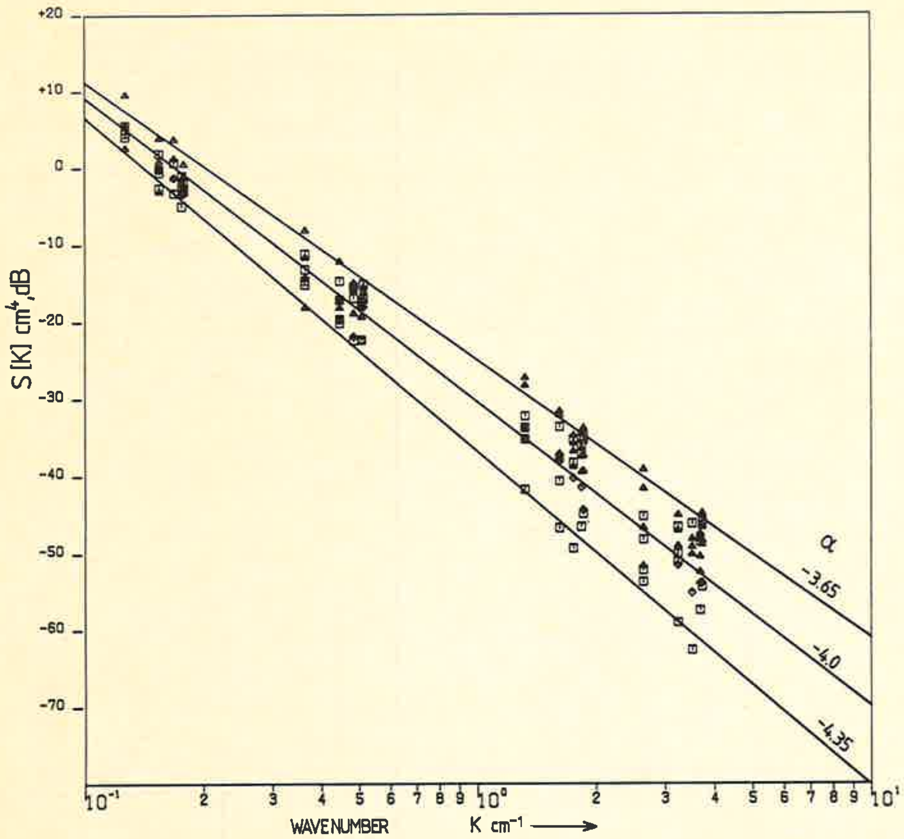

Fig. 4. Ocean wave number spectra inferred from vertically polarized radar backscatter data obtained in JOSS-1 [*Daley et al.*, 1971] at *P*, *L*, *C*, and *X* band for various wind speeds. After *Valenzuela* [1978]. Triangle, 7.5–12.5 m/s; square, 4.5–7.5 m/s; diamond, 2–4.5 m/s.

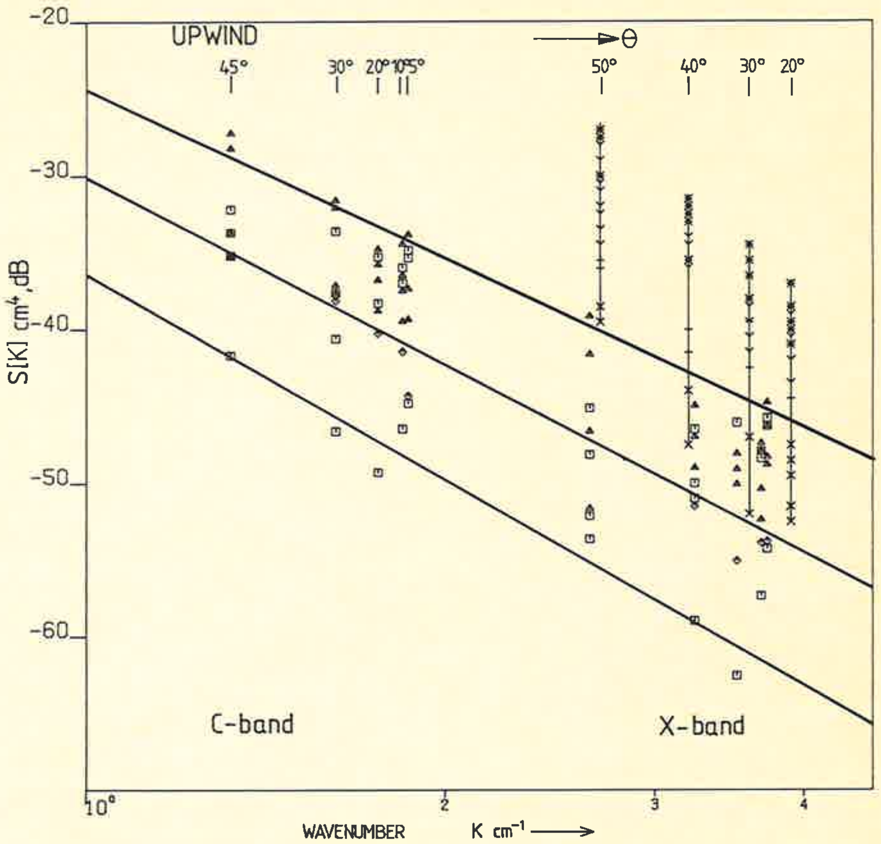

Fig. 5. Enlargement of Figure 4 for *K* between 1 and 4 cm^{-1}, with the data taken at platform Noordwijk. Cross, 2–4.5 m/s; plus, 4.5–7.5 m/s; arrow, 7.5–12.5 m/s; asterisk, >12.5 m/s.

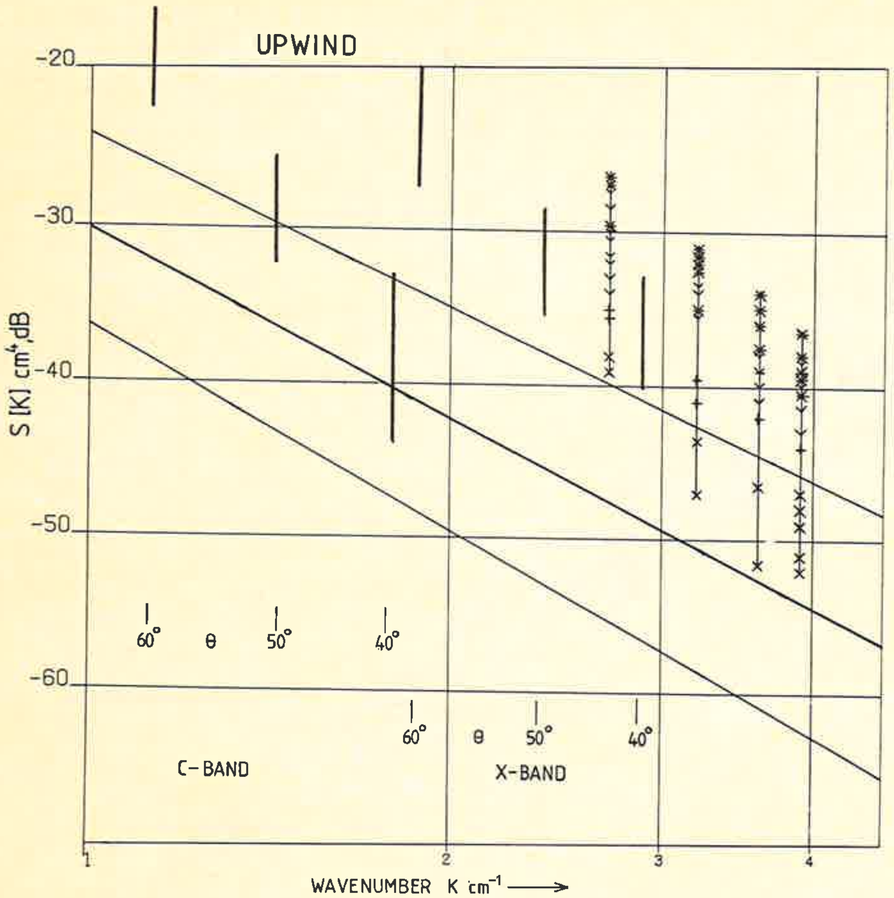

Fig. 6. Comparison of our data with the French data [after *Fontanel*, 1978] and those of NRL (lines of Figures 4 and 5) for K between 1 and 4 cm^{-1}.

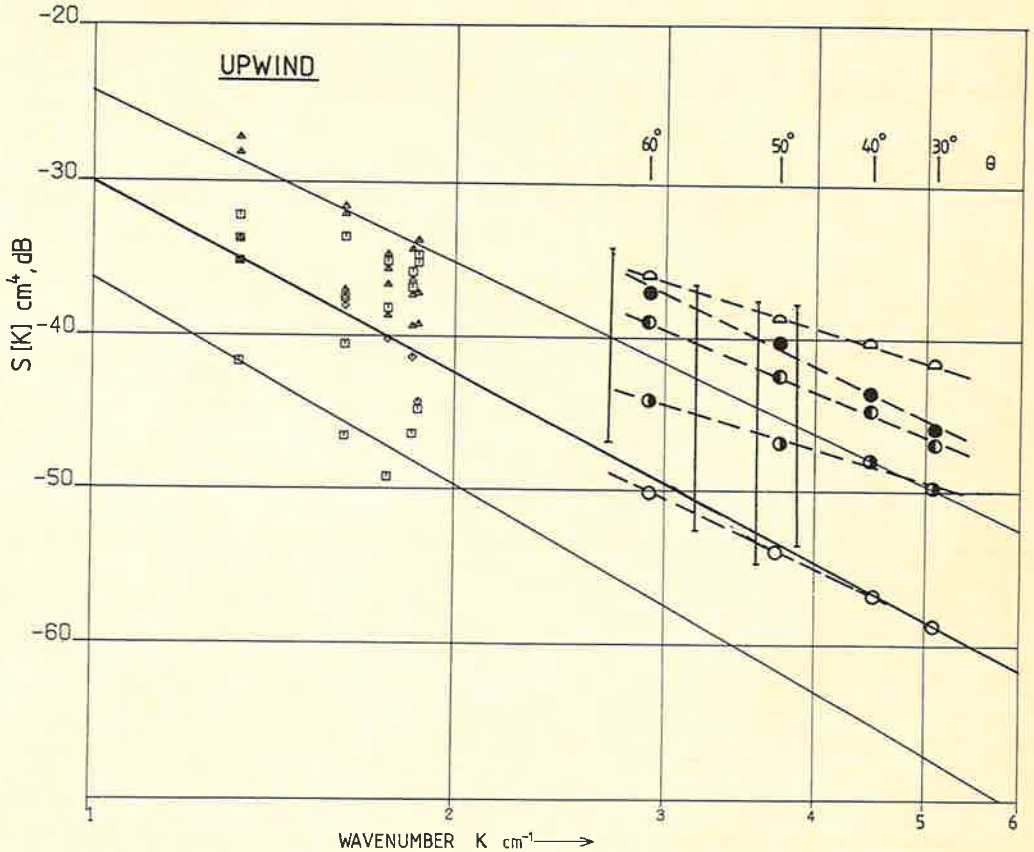

Fig. 7. As Figure 5. Vertical lines: our data for all wind speeds as taken at platform Noordwijk but corrected for height with the aid of Figure 3. Circles: airborne data as obtained by *Jones et al.* [1977]: open circle, 3 m/s; half-filled circle (right), 6.5 m/s; half-filled circle (left), 13.5 m/s; solid circle, 15 m/s; half circle, 23.6 m/s.

et al., 1978]. The results are reported in Figure 6. Again we see the deviation to higher values and also that this correction for altitude is dependent on grazing angle. This deviation is also observed in the other frequency bands used by the French (Figure 6 gives *X* and *C* band only). For the *X* band the French data fall in the same range as our data.

Using Figure 3 we corrected our data. The corrected curves are shown in Figure 7 (which cover the total wind speed range over which we measured per grazing angle). In this figure we also inserted the data of *Jones et al.* [1977] taken at 13.9 GHz. We left out the JOSS-I data for the *X* band but kept the $S(K)$ functions as obtained from this experiment. We now see that after correction the tower data are consistent with other measurements. We show the data of *Jones et al.* [1977] as an example, since they also fit well with the literature for this frequency range as obtained with airborne/space instruments [*Schroeder et al.*, 1982; *Smith and Dome*, 1979; *Moore and Fung*, 1979; *Kaupp and Holtzmann*, 1979; *Moore et al.*, 1979, 1978; *Young and Moore*, 1977].

Having established the correction (Figure 3) it now becomes possible to reduce the tower data to values as measured by airborne/space scatterometers and so give average curves for γ as a function of grazing angle for different wind speeds. An example is given in Figure 8 for upwind and wind speeds of 5, 10, 15, and 20 m/s. This also enables us to investigate the dependency of $\gamma(\sigma°)$ on wind speed in more detail (wind scatterometer applications).

THE DEPENDENCY OF γ ON WIND SPEED

A considerable number of measurements of γ $(=\sigma°/\sin\theta)$ as a function of wind speed v is now available. A relation of the form

$$\gamma \sim v^c \tag{2}$$

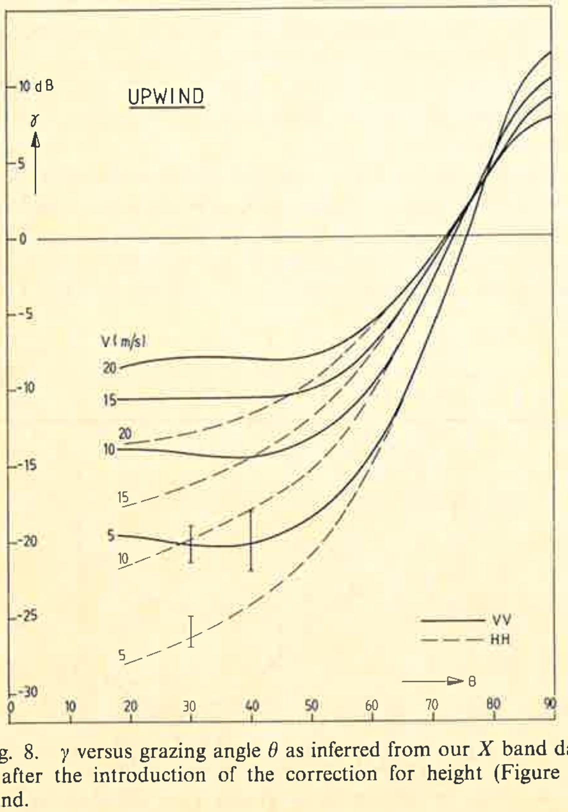

Fig. 8. γ versus grazing angle θ as inferred from our *X* band data and after the introduction of the correction for height (Figure 3); upwind.

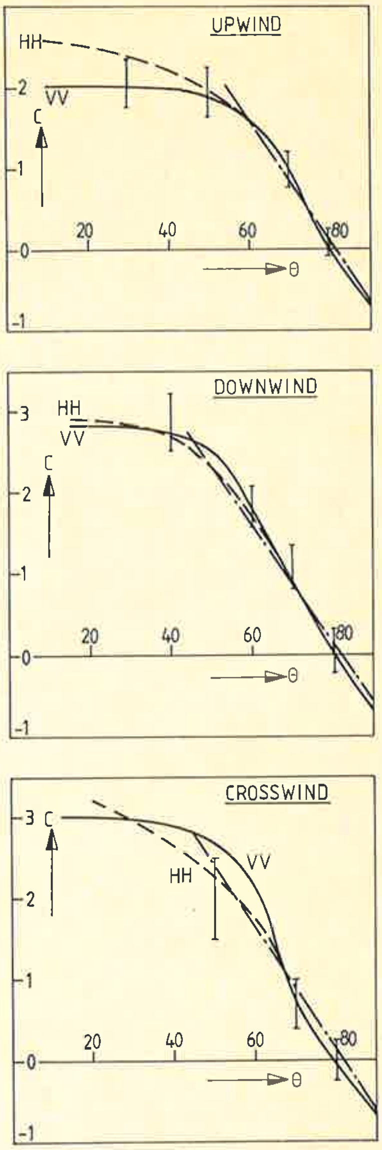

Fig. 9. The exponent c as a function of grazing angle θ (see text).

provides a good fit to the data. Assuming this relation to be true for all grazing angles we made a regression analysis on all our data. Since both γ and v are subject to experimental error we regressed γ versus wind speed (giving c_a) and wind speed versus γ (giving c_b) and finally plotted $(c_a + c_b)/2$ as a function of grazing angle θ in Figure 9. For grazing angles below $\theta = 70°$ and for vertical incidence the correlation coefficient is higher than 0.8. For $\theta = 70°$ and 80° we obtain large variations; c is small for these two angles. At all angles the standard error of estimate is for γ between 1 and 3 dB and for log v between 0.1 and 0.2.

The measurements suggest [*de Loor et al.*, 1981; *de Loor and Hoogeboom*, 1982] that the difference between γ measured with ground-based systems and airborne/space systems is constant (per grazing angle). In that case the slope c will be the same in both cases. Thus we also used the literature data [*Schroeder et al.*, 1982; *Smith and Dome*, 1979; *Moore et al.*, 1979; *Moore and Fung*, 1979; *Kaupp and Holtzmann*, 1979; *Moore et al.*, 1978; *Young and Moore*, 1977; *Jones et al.*, 1977] to produce Figure 9. This figure shows the slope c as a func-

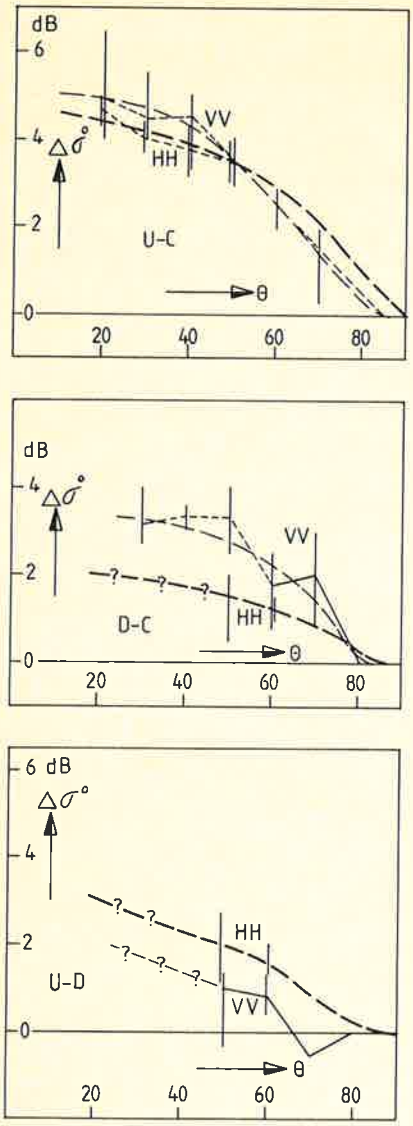

Fig. 10. Differences in σ° (and γ) due to look direction.

tion of grazing angle for the three major look directions. Some error bars, showing maximum deviations in c, are included. The data suggest that c increases linearly from -0.6 to $+2$ for grazing angles going from 90° (normal incidence) to 55° (broken line in Figure 9) and is equal to 2 or larger for angles under 55°, dependent on polarization and look direction.

Differences in γ Due to Polarization and Look Direction

Although the spread in the values obtained for c is large, the data reported in Figure 9 suggest different values for c (and thus a different dependency of γ on wind speed) for the different look directions for grazing angles under 55°. This would mean that the ratios of γ for upwind and crosswind, respectively, downwind and crosswind, and upwind and downwind, are dependent on wind speed for grazing angles under 55°. This would complicate the algorithms for a wind scatterometer working at these lower grazing angles. And indeed, when we try to determine $\Delta\gamma$ (in dB) due to look direction by using the average curves (slope c) for each grazing angle as found in the regression analysis we find such a dependency.

Another approach was used also. We compared the measurements in different look directions taken on the same day, under the assumption that values for γ taken close to each other in time go better together. Then a wind dependency is not found for the ratios of γ for upwind and crosswind, respectively, downwind/crosswind and upwind/downwind, for grazing angles under 60° and in the wind speed range of 5–18 m/s. The spread in the results, however, is large and may screen such a wind dependency. We also determined said ratios for the measurements of *Jones et al.* [1977] and for our own measurements in a wave tank [*Van Kuilenburg*, 1975].

Taking all these data together we obtain the results given in Figure 10. This figure suggests that $\Delta\gamma$ ($=\Delta\sigma^\circ$ in dB, the ratios) are small and less than 1 dB for grazing angles above 70°.

The same procedure as described above was used for the determination of $\gamma_{VV}/\gamma_{HH}(=\sigma^\circ{}_{VV}/\sigma^\circ{}_{HH})$. Here the different approaches lead to very similar results, giving these ratios fairly accurately. See Figure 11. This figure shows that γ_{VV}/γ_{HH} is less than 1 dB for grazing angles between 60° and nadir. Under 60° it increases to a 6–7 dB at $\theta = 35°$, under which angle downwind strongly deviates from upwind and crosswind.

Conclusions

A fair amount of data for γ versus wind speed v is now available. These data cover a large incidence angle range and are useful for application in wind scatterometer designs. The exponent c, describing this dependency through the relation $\log \gamma \sim c \log v$ can now also be given with a reasonable accuracy. It is practically independent of polarization and look direction for the higher grazing angles between 50° and 90°. Under 50° it varies considerably with polarization and look direction.

Similar variations for these two regions are found for the ratios of γ for upwind/downwind, respectively, upwind/crosswind and downwind/crosswind and also for γ_{VV}/γ_{HH}.

The observed variations for grazing angles under 50° will make it difficult to use these low grazing angles for wind scatterometers.

A discrepancy has been observed between the values for the average backscatter obtained with airborne and ground-based equipments. Ground-based equipments give higher values for γ. Only preliminary explanations are available and the effect requires more in-depth investigations and measurements.

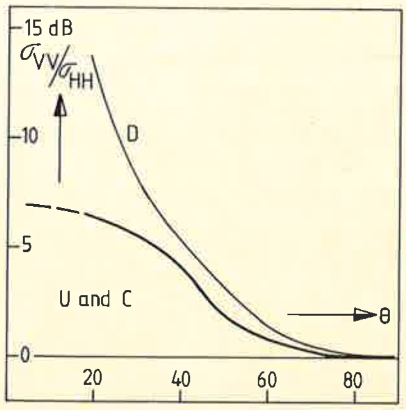

Fig. 11. Differences in σ° (and γ) due to polarization.

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G. P. de Loor, Physics Laboratory TNO, The Hague, The Netherlands.

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