

Selection of optimum frequency of a wind scatterometer

ABHIJIT SARKAR, RAJ KUMAR and MANNIL MOHAN

Meteorology and Oceanography Division, Space Applications Centre,
Ahmedabad 380 053, India

MS received 19 June 1987.

Abstract. The problem of selecting the optimum operating frequency of a scatterometer, used for remote sensing of sea surface wind speed has been addressed by applying the criteria of maximum sensitivity of backscattering coefficient to wind speed as well as its correlation with wind speed. The backscattering coefficient values for sea surface were computed by the two-scale scattering theory. To compute the atmospheric transmittance, 753 clear sky atmospheres over Indian Ocean were used. While the correlation coefficient was uniform (0.94) throughout the frequency range of 1 to 30 GHz, only frequencies above 5 GHz were found sensitive enough to yield a wind speed accuracy of $\pm 2 \text{ msec}^{-1}$ and better, the accuracy improving with frequency.

Keywords. Scatterometer; sea surface wind speed; optimum frequency; atmospheric transmittance.

1. Introduction

In order to achieve maximum accuracy and resolution of the remotely-sensed parameter, it is desirable to have remote sensing sensors with optimum operating characteristics. A number of studies on optimum system parameters of remote sensing instruments have been reported (Macdonald and Waite 1971; Ulaby and Bativala 1976; Kondratyev and Pokrovsky 1979; Matzler *et al* 1982; Pandey and Kakar 1983; Peckham *et al* 1983). However, remote sensing instruments appear to have been developed by and large through the evolution of a new technology or the retrieval technique.

The present work evolves an optimum frequency of a wind scatterometer and it is hoped the results would be useful for defining a scatterometer system for remote sensing of oceanic winds in tropical regions like the Indian waters.

Satellite-borne radar scatterometer operating in microwave frequency band is emerging as a prime sensor for mapping global ocean wind. The earlier satellite-borne scatterometer SASS (Seasat A scatterometer system) provided surface wind speed to $\pm 2 \text{ msec}^{-1}$ and direction $\pm 20^\circ$ accuracy (Jones *et al* 1982). A number of satellite-borne scatterometer systems are being planned in the next few years e.g. ERS-1, NROSS, RADARSAT etc. Scatterometer systems are also being considered for future Indian remote sensing satellites.

To select an optimum frequency of a wind scatterometer, the sensitivity spectrum (sensitivity of backscattering coefficient to surfacial oceanic wind) and the correlation coefficient (correlation between the surface wind speed and the backscattering coefficient) were studied. The sensitivity spectrum was used to

identify the range of frequencies for which the backscattered signal has higher wind detectability. The backscattered signal however gets attenuated as it passes through the atmospheric column before it is sensed by the sensor onboard the satellite. As the attenuation is different for different frequencies, the value of correlation coefficient for any frequency is an indicator of the accuracy of the retrieved wind speed.

2. Sensitivity of backscattering coefficient to wind

To study the sensitivity of the backscattering coefficient (σ°) to ocean surface wind W over a range of frequencies (1 to 30GHz), σ° was simulated through the well-known two-scale scattering model (Moore and Fung 1979; Fung and Lee 1982, 1983). Utilizing the common procedures of curve fitting and the above mentioned scattering theory, the sensitivity of σ° to W was derived for four specific values of frequency viz 1, 5, 9 and 13 GHz (representing L-, C-, X-, and Ku-bands) for the incidence angles ranging from 30 to 60° (Sarkar and Kumar 1985). The angle of incidence of 45° which was found to be optimum from the sensitivity point of view was chosen for this study while the frequency was varied from 1 to 30 GHz. A linear representation of backscattering coefficient in decibels is

$$\sigma^\circ(\text{dB}) = A + B \log(W).$$

The coefficient B indicates the sensitivity of scattering coefficient to wind speed. Figure 1 represents the variation of B over the frequency range from 1 to 30 GHz. As is seen from the figure, the value of B almost doubles when the frequency is changed from 5 to 25 GHz. The curve steadily rises with increasing frequency. Hence, from the sensitivity point of view, higher the frequency, greater will be the wind detectability. For most of the present-day meteorological and oceanographic

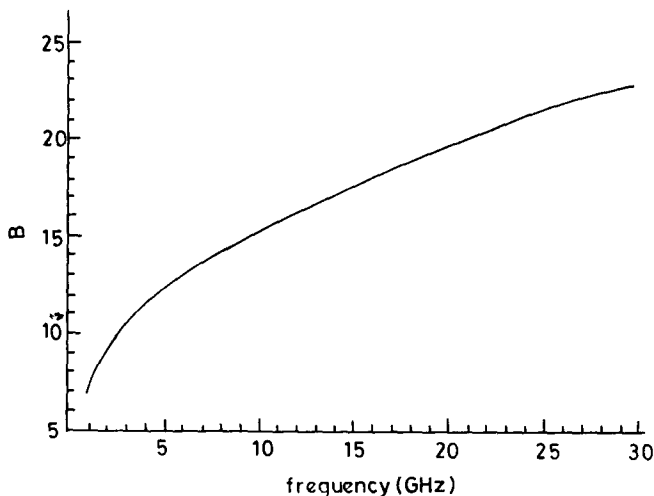


Figure 1. Variation of B with frequency.

applications, an accuracy of $\pm 2 \text{ msec}^{-1}$ in wind speed is acceptable. For low wind speed conditions this is achievable over the entire frequency range considered in this paper; but for higher wind speed conditions (i.e. more than 10 msec^{-1}), it may not be possible to achieve the wind accuracy of $\pm 2 \text{ msec}^{-1}$ by scatterometers operating at 5 GHz or lower (this can be verified in figure 1, assuming a 1 dB measurement precision).

3. Correlation between scattering coefficient and wind speed

In order to derive the realistic values of correlation coefficient, level III b data as generated by ECMWF over the selected test site (-13.125 to $+5.625^\circ$ latitude; 60°E to 90°E longitude) were used. The temperature, relative humidity and geopotential height values corresponding to the pressure levels of 1000, 850, 700, 600, 500, 400, 300, 200, 150 and 100 mb were utilized to compute the atmospheric transmittance τ . The equations used to obtain τ are given in Appendix I and the variation of τ for a typical cloudless atmosphere over the frequency range of 1 to 30 GHz is shown in figure 2. A rather big dip in τ occurs around 22 GHz, the water vapour resonance absorption frequency.

The values thus calculated were used to simulate the scattering coefficient that a spaceborne scatterometer placed above the atmospheric column would measure

$$\sigma_m^\circ = \sigma_s^\circ \tau^2,$$

where σ_m° is the measured scattering coefficient, and σ_s° the surface scattering coefficient (Moore and Fung 1979; Fung and Lee 1982, 1983; Sarkar and Kumar 1985). The surface (1000 mb) wind speed values as given in level III b data set, corresponding to the τ values for which σ_m° was computed were used for deriving the correlation coefficient. Figures 3–6 represent the scatter plots of simulated values of measured scattering coefficient vs surface wind speed for frequencies

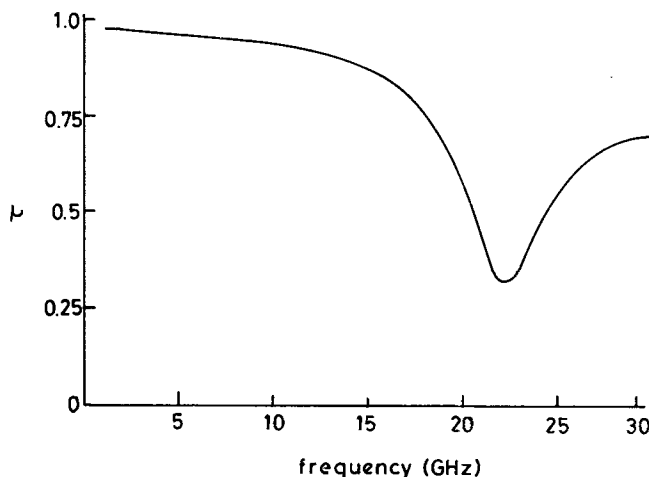


Figure 2. Variation of τ with frequency.

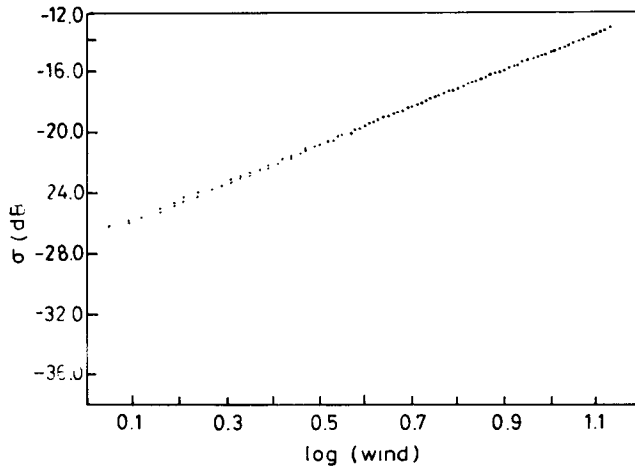


Figure 3. Scatter plot of σ^0 (dB) vs $\log W$ for 5 GHz.

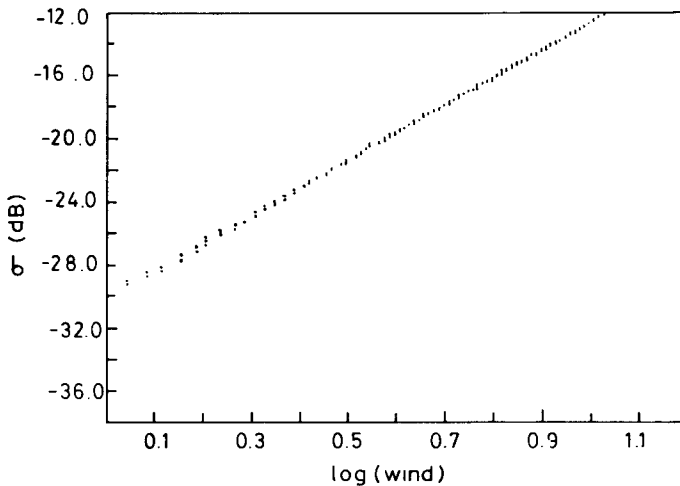


Figure 4. Scatter plot of σ^0 (dB) vs $\log W$ for 15 GHz.

5 GHz, 15 GHz, 22 GHz and 30 GHz representing C, Ku and K_u bands respectively. The angle of incidence was fixed at 45° as this angle lies well within the peak portion of the wind sensitivity curve (Sarkar and Kumar 1985). Only the upwind case ($\phi = 0^\circ$) is studied in this paper. Any other value of wind azimuth angle ϕ does not alter the trend in the results and hence has not been reproduced here. Since polarization also has been found inconsequential, only HH polarization is considered here. Although τ changes substantially around 22 GHz, the spread of points is not significant. As a result, there is no significant variation in correlation coefficient for the frequencies considered here. For the 753 data sets considered here, the coefficient of determination (square of coefficient of correlation) was 0.89.

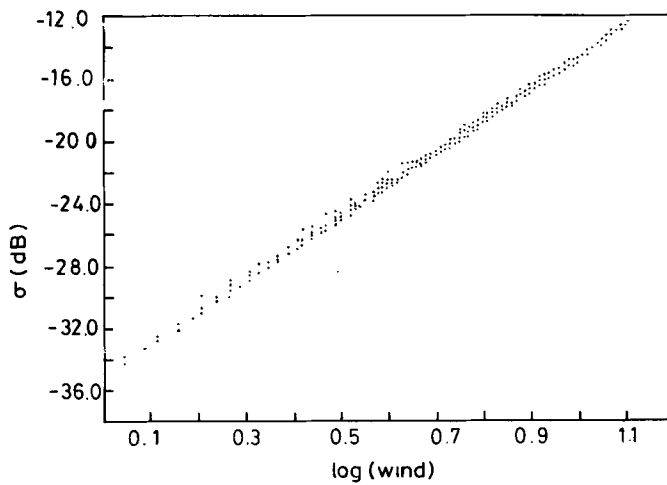


Figure 5. Scatter plot of σ^0 (dB) vs $\log W$ for 22 GHz.

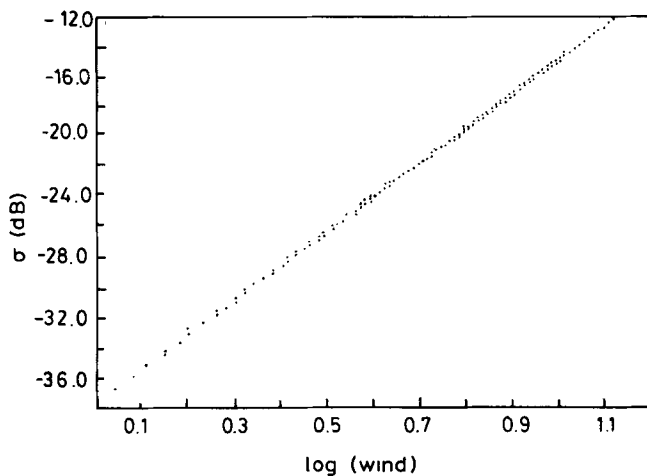


Figure 6. Scatter plot of σ^0 (dB) vs $\log W$ for 30 GHz.

4. Results and discussions

The 753 data sets used in this study represent cloud-free atmosphere in May, June and July 1979. The cloudy data were separated by discarding the data having relative humidity values higher than 80% at any level other than 1000 mb. The total water vapour content in the data varied between 1.5 g cm^{-2} and 4.7 g cm^{-2} and the surface wind speed varied from calm to 13.4 msec^{-1} . It is seen that the transmittance for these atmosphere makes only a small difference to the scattering coefficient values and hence the scatter of points for any frequency band is not large (the largest among them being 22 GHz). This results in an almost uniform correlation coefficient (correlation between the scattering coefficient and the

surface wind speed). Since the variation in correlation coefficient for the data set used in the study is almost absent, the only consideration for selecting the optimum frequency is sensitivity. The relative sensitivity between C- and Ku-bands as seen from figure 1 agrees with the results of ESA's airborne scatterometer campaign 'PROMESS' (Freeman *et al* 1986).

The values of transmittance and the resultant scattering coefficient for cloudy atmosphere for the microwave frequency range are expected to vary considerably. This study is in progress and will be reported separately. As far as cloud-free atmospheres are concerned, frequencies higher than 5 GHz yield the required windspeed accuracy, the accuracy improving with frequency.

Acknowledgements

The authors are grateful to Dr P S Desai and Mr B Simon for explaining their work on evaporation estimates. Thanks are due to Dr M S Narayanan, who suggested the use of ECMWF data for this study and to Dr P C Joshi for assistance in data retrieval. The authors also thank Dr M M Ali and other colleagues for helpful discussions.

Appendix 1. Computation of atmospheric transmittance

$$\tau = \int K(Z) dZ, \text{ (dB)} \quad (\text{A.1})$$

where

$$K(Z), \text{ the total absorption coefficient} = K_{\text{H}_2\text{O}}(Z) + K_{\text{O}_2}(Z) \quad (\text{A.2})$$

$$\begin{aligned} K_{\text{H}_2\text{O}} &= 2f^2 \rho (300/T)^{3/2} \gamma_1 \\ &\times \left(\frac{300}{T} \right) \exp(-644/T) \frac{1}{(494.4 - f^2)^2 + 4f^2 \gamma_1} \\ &+ 1.2 \times 10^{-6}, \text{ dB km}^{-1} \end{aligned} \quad (\text{A.3})$$

where f is the frequency (GHz), ρ is the water vapour density (gm^{-3}), P is the pressure (mb) and T is the average temperature of the layer (K). γ_1 and K_{O_2} are given as

$$\gamma_1 = 2.85 \left(\frac{P}{1013} \right) \left(\frac{300}{T} \right)^{0.626} \left[1 + 0.018 \frac{\rho T}{P} \right] \text{ GHz}, \quad (\text{A.4})$$

$$\begin{aligned} K_{\text{O}_2} &= 1.1 \times 10^{-2} f^2 \left(\frac{P}{1013} \right) \left(\frac{300}{T} \right)^2 \gamma \\ &\times \left[\frac{1}{(f-f_0)^2 + \gamma^2} + \frac{1}{f^2 + \gamma^2} \right] \text{ dBkm}^{-1} \end{aligned} \quad (\text{A.5})$$

where

$$f_0 = 60 \text{ GHz,}$$

γ = linewidth parameter

$$= \gamma_0 \left(\frac{P}{1013} \right) \left(\frac{300}{T} \right)^{0.85} \text{ GHz, with}$$

$$\gamma_0 = \begin{cases} 0.59 & P \geq 333 \text{ mb,} \\ 0.59 [1 + 3.1 \times 10^{-3} (333 - P)], & 25 \leq P \leq 333 \text{ mb,} \\ 1.18 & P \leq 25 \text{ mb.} \end{cases} \quad (\text{A.6})$$

Equations (1) to (6) are from Ulaby *et al* (1981). The water vapour density ρ was computed as follows:

$$\rho = eM/RT,$$

where the vapour pressure is

$$e = R_h e_s / 100, \quad (\text{A.7})$$

M is the molecular weight of water vapour, R the universal gas constant, R_h the Relative humidity in % and the saturated vapour pressure (mb) is

$$e_s = T^A \times 10^{(B+C/T)}, \quad (\text{A.8})$$

where $A = 4.928$, $B = 23.55$ and $C = -2937.0$. The empirical equation (8) was first introduced into a radiative convective model by Manabe and Wetherald (1967). The above formulation was also used by Simon and Desai (1986) to obtain ocean evaporation estimates from satellite data.

References

- Freeman N G, Gray A L, Hawkins R K and Livingstone C E 1986 CCRS convair 580 results relevant to ERS-1 wind and wave calibration; *Proc. ESA workshop, Schliersee, ESA SP-262*, (ed) J J Hunt (Noordwijk, Netherlands: ESA Pub.)
- Fung A K and Lee K K 1982 A semi empirical sea spectrum model for scattering coefficient estimation; *IEEE J. Oceanic Eng.* **OE-7** 166-176
- Fung A K and Lee K K 1983 Variation of sea wave spectrum with wind speed. In: *Digest of international geoscience and remote sensing Sym.* (ed.) M Buettner (New York: IEEE Pub.) Vol. II TP-2
- Jones W L, Schroeder L C, Boggs D H, Bracalente E M, Brown R A, Dome G J, Pierson W J and Wentz F J 1982 The Seasat-A satellite scatterometer: Geophysical evaluation of remotely-sensed wind vector over the ocean; *J. Geophys. Res.* **87** 3297-3317
- Kondratyev K Y and Pokrovsky O M 1979 A factor analysis approach to optimal selection of spectral intervals for multipurpose experiments in remote sensing of the environment and earth resources; *Remote Sensing Environ.* **8** 3-10
- Macdonald H C and Waite W P 1971 Optimum radar depression angles for geological analysis; *Mod. Geol.* **2** 179-193
- Manabe S and Wetherald R T 1967 Thermal equilibrium of the atmosphere with a given distribution of relative humidity; *J. Atmos. Sci.* **24** 241-259
- Matzler C, Schanda E and Good W 1982 Towards the definition of optimum sensor specifications for microwave remote sensing of snow; *IEEE Trans. Geosci. Electron.* **GE-20** 57-66
- Moore R K and Fung A K 1979 Radar determination of winds at sea; *Proc. IEEE* **67** 1504-1521

- Pandey P C and Kakar R K 1983 Selection of optimum frequencies for atmospheric electric path length measurements by satellite borne microwave radiometers; *IEEE Trans. Antennas Propag.* **AP-31** 136–140
- Peckham G E, Gatley C and Flower D A 1983 Optimizing a remote sensing instrument to measure atmospheric surface pressure; *Int. J. Remote Sensing* **4** 465–478
- Sarkar A and Kumar R 1985 A study on the sensitivity of the radar scattering coefficient to oceanic winds; *Proc. Indian Acad. Sci. (Earth Planet Sci.)* **94** 249–259
- Simon B and Desai P S 1986 Equatorial Indian Ocean evaporation estimates from operational meteorological satellites and some inferences in the context of monsoon and activity; *Boundary-Layer Meteorol.* **37** 37–52
- Ulaby F T and Battivala P P 1976 Optimum radar parameters for mapping soil moisture; *IEEE Trans. Geosci. Electron.* **GE-14** 81–93