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Abstract

The satellite SEASAT-A will carry a radar scatterometer in order to measure microwave backscatter from the sea surface. From pairs of radar measurements at angles separated by $90^{0}$ in azimuth the surface wind speed and direction may be inferred, though not uniquely. In this paper the character of the solutions for wind speed and direction is displayed, as well as the nature of the ambiguities of these solutions. An economical procedure for handling such data is described, plus a criterion for the need for conventional (surface) data in order to resolve the ambiguities of solutions.

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# THE NATURE OF MULTIPLE SOLUTIONS FOR SURFACE WIND SPEED OVER THE OCEANS FROM SCATTEROMETER MEASUREMENTS

## I. INTRODUCTION

A knowledge of surface wind speed and direction over the oceans is desireable on a number of counts. The value to shipping and fishing industries and to the military is quite apparent. Predictions of winds and waves are likewise important for many coastal applications, with the case of a hurricane making landfall an obvious example.

In a broader sense surface wind is an ingredient in the understanding of the global circulation. Through surface friction the wind provides the driving force for small and large scale ocean currents: it is thus an essential input to ocean dynamics models. For meteorological applications the knowledge of the spatial distribution of surface winds provides information on the surface pressure distribution, which in turn is a key parameter for global weather forecasting. In all these cases the need beyond currently available data is for global measurements at frequent time intervals.

The radar scatterometer to be flown on SEASAT-A has generated considerable interest because it provides data which may be analyzed to yield the desired winds. Individual measurements, having a footprint of some hundreds of square kilometers, yield estimates of spatially averaged wind values, with the local (point) variability due to gustiness averaged out. These values are the required input for oceanic and atmospheric applications studies.

The purpose of this paper is to describe the interpretation of radar data, and to develop an efficient procedure for obtaining values for surface wind speed and direction from the measurements.

The general features of the measurement system and of the nature of the radar return are described in section II, which draws heavily on work by Pierson, Cardone and Greenwood (1974). Section III describes a lookup table procedure which may be used in "inverting" the model equations for radar backscatter to obtain wind speed and direction, as well as the nature of the solutions. In most cases there are four possible values for the wind angle, which may be expressed as either $\alpha$, $360° - \alpha$ and $180° \pm \beta$, or $\alpha$, $270° - \alpha$, and $90° \pm \beta$, with $\alpha$, $\beta < 90°$. The necessity for conventional data to resolve this ambiguity is discussed in section IV.

## II. SCATTEROMETER MEASUREMENTS

Although the SEASAT is not completely defined at this time, a general description of the scatterometer is possible. From a height of approximately 800 kilometers the instrument will measure radar backscatter at 13.9 GHz ( $\lambda$ = 2.2 cm). Measurements will be taken in a crosstrack pattern, with radar footprints at angles (in azimuth) $45^{\circ}$ to right and left, fore and aft of the subsatellite track. Due to satellite motion the backscatter from a spot on the ocean surface will be measured twice, at nearly coincident times, but with a separation of $90^{\circ}$ in the direction of measurement (see Figure 1). These two measurements of radar cross section $\sigma$, permit estimation of two quantities, surface wind speed V, and direction $\chi$. This geometry appears to be optimum for observation from a satellite, given the level of instrumentation which is currently feasible. Observations at a number of azimuth angles would be desireable, but this would cause greater complexity in the radar scanning mechanism and electronics. The dependence of radar cross section on surface roughness has been estimated theoretically (Beckman and Spizzachino (1963), Stogryn (1967), Wu and Fung (1972)) but experimental results are not completely understood. For present purposes the dependence of cross section on surface wind is assumed, and the problem is that of inverting $\sigma_1$, $(\chi, V)$, $\sigma_2$ $(\chi + 90^{\circ}, V)$ to infer $\chi$ and V.

By scanning in nadir angle the scatterometer will provide wind field estimates in swaths on both sides of the subsatellite track. (At near nadir viewing the pairs of measurements are not independent and no information is available on wind direction). Questions of instrument calibration, noise, etc. are not addressed here as these have no direct bearing on the development of an efficient procedure for converting measured radar cross sections into surface winds.

A starting point is the equation for radar backscatter derived by Pierson et al from experimental data from the Langley AAFE (Advanced Applications Flight

Experiment) Program. For vertically polarized transmitted and received radiation this equation is

$$\sigma_{VV}(\chi, V) = EV^{N} + (EV^{N} - K_2V^{Q}) \cos 2\chi + 1/4\,(K_1V^{m} + K_2V^{q} - 2EV^{n}) \times (3 \cos \chi + \cos 3\chi) \qquad (1)$$

where ($E$, $K_1$, $K_2$, $N$, $M$, $Q$) are constants depending only on the nadir angle, $V$ is the wind speed, and $\chi$ is the angle measured clockwise from the meteorological wind to the measurement angle. (The meteorological wind direction is that from which the wind blows). Pierson et al give values for E -- Q based on AAFE Radscat data and Skylab data, both at 13.9 GHz. Preliminary values for a nadir angle of 30° are:

| | |
|---|---|
| $E = 2.24 \times 10^{-3}$ | $M = 1.83$ |
| $K_1 = 2.27 \times 10^{-3}$ | $N = 1.69$ |
| $K_2 = 2.21 \times 10^{-3}$ | $Q = 1.55$ |

These values were used in this study in order to model the radar backscatter. Revised values, or even a different functional form (e.g., including terms in $\cos 4\chi$) may be necessary as more and better data are analyzed. Such changes will not affect conclusions drawn here as long as the general behavior of the radar cross section is not changed. Figure 2 illustrates the dependence of $\sigma$ on $\chi$ and $V$, with values given in decibels due to the great dynamic range involved. Henceforth $\sigma$ will be referred to in db.

## III. SOLUTIONS FOR WIND SPEED AND ANGLE

The proposed satellite instrument will obtain nearly simultaneous measurements of cross section $\sigma$ at angles separated in azimuth by $90^{\circ}$, i.e., $\sigma_1$, $(\chi, V)$, $\sigma_2 (\chi + 90^{\circ}, V)$. Although the solution for $\chi$, $V$ of the equations

$$\sigma_1 (\chi, V) = \sigma_1^{\text{ measured}}$$

$$\sigma_2 (\chi + 90^{\circ}, V) = \sigma_2^{\text{ measured}}$$

is reasonably straightforward, for large scale data reduction or for operational purposes a lookup table is preferable. From this table questions of the ambiguities of solutions may be worked out systematically, and computer savings are possible once the lookup table is generated.

In this study it was found that the quantities $\sigma_1$ and $\sigma_2 - \sigma_1$ may be used to label a storage array with a minimal number of entries which includes the full range of values of $\sigma_1$, $\sigma_2$ to be expected. The first of these, $\sigma_1$, provides a reasonable first estimate of the wind speed, while the difference, $\sigma_2 - \sigma_1$, provides information principally about the wind angle. Because the radar backscatter tends to increase faster with windspeed at $\chi = 0^{\circ}$, $\chi = 180^{\circ}$ than at $\chi = 90^{\circ}$, $\chi = 270^{\circ}$ (see Figure 2) the magnitude of $\sigma_2 - \sigma_1$ increases with surface windspeed, and thus with $\sigma_1$. For this reason it is best to scale $\sigma_2 - \sigma_1$ by dividing by

$$D = 4.50 + 0.084 (\sigma_1 + \sigma_2),$$

which is to good approximation the maximum value of $\sigma_2 - \sigma_1$, for a given value of $\sigma_1$. It follows that the ratio $\delta = (\sigma_2 - \sigma_1)/D$ varies between −1 and 1, and tables of V ($\sigma_1$, $\delta$), $\chi$ ($\sigma_1$, $\delta$) represent all physically possible combinations of $\sigma_1$, $\sigma_2$ in a compact fashion, granted the hypothesis that equation 1 adequately describes the measurements.

The non uniqueness of $\chi$ and V is illustrated in Figures 3 through 6. Values of $\sigma_1$ have been chosen in order to represent regimes of high wind speed ($\sigma_1$ = −2.5 db) and low wind speed ($\sigma_1$ = −10.0 db). The degree of ambiguity of a solution is given by the number of times a vertical line ($\delta$ = constant) intersects the solution curves. The solution regimes are most easily described in terms of the angle $\chi$ between the first measured value and the meteorological wind.

1. Values of $\delta$ from −1.0 to approximately −0.7 represent a "first look upwind" solution in which the first measurement is taken nearly upwind, the second nearly cross wind. The results illustrate the inability to distinguish left-right values of angle, i.e., $\alpha$, $360^{\circ} - \alpha$, with $0 < \alpha < 45^{\circ}$.

2. Values of $\delta$ from 1.0 to approximately 0.7 represent a "second look upwind" solution in which the first measurement is approximately cross wind, the second is nearly upwind. The resultant ambiguity with respect to left-right of upwind corresponds to $270^{\circ}$

$\pm \alpha$ as defined by the angle of the first radar measurement with respect to the wind.

3. For all intermediate values of $\delta$ (-.7 to + .7) there exist, in addition to "upwind" solutions at larger angles relative to the wind direction, the "downwind" solutions which begin at approximately -.7 - "first look downwind," and + 0.7 - "second look downwind." These values of $\delta$ correspond to angles from $45^{0}$ to $225^{0}$.

The results of ambiguity in wind speed determination are easier to describe. Basically the solutions fall into pairs representing upwind and downwind. As illustrated in Figures 5 and 6 the upwind solutions fall on the lower, larger wing of the butterfly shape, and the upwind solutions fall on the upper, smaller wing.

It should be emphasized at this point that the parameter $\delta$ involves the difference in the logarithms of the measured radar returns, and is thus sensitive to small values due to the derivative $d(\log x) = dx/x$. Small values occur when either measurement is crosswind. Such cases are particularly bad, because such values also represent turning points of the solution for wind angle $(\frac{d\,(\text{angle})}{d\,\delta} = \infty)$ in Figures 3 and 4. In such a case some form of data averaging or smoothing is absolutely required. The next section recommends such a procedure.

## IV. RECOMMENDATIONS FOR DATA ANALYSIS

The previous section illustrates the fact that scatterometer data, by itself, does not yield satisfactory (unique) results for surface winds over the oceans. Additional input data will be required, such as surface wind observations, or results from a global scale meteorological analysis, which relies on observations of surface wind and barometric pressure. In either case the spatial density of actual surface measurements will be much lower than the density of scatterometer measurements. For physically reasonable results it will be necessary to assume spatial continuity of wind fields on the scale of 20-50 kilometers, and to average or smooth the scatterometer results. The assumption of spatial smoothness is not a strong one, as synoptic scale wind variations are generally significant only over distances of many hundreds of kilometers.

In principle one may smooth either the measurements $\sigma_1$, $\sigma_2$ of the scatterometer, or the resultant values of derived wind. However the sensitivity of results for wind angle at $0^o$, $90^o$, $180^o$, $270^o$ to variations in measured cross section argues strongly in favor of smoothing the scatterometer data itself. The degree of such smoothing will represent a trade off between effects, instrument noise errors and the amount of spatial smoothing which is acceptable. Undoubtedly experimentation on the amount of smoothing or averaging will have to be carried out after the launch of the satellite. It is possible that different averaging routines will be needed for different purposes.

From the analysis it is possible to specify the volume of ground truth required in order to specify unique wind fields from the scatterometer results. In an approximate sense the solution for wind angle is given by $\chi = -\cos^{-1}(2\delta)$. From the spatial continuity of surface winds it follows that an ambiguity must be resolved only in the vicinity of possible movement from one branch of the arc cos function to another, i.e., at $0^{\circ}$, $90^{\circ}$, $180^{\circ}$ and $270^{\circ}$. In terms of an automated analysis of scatterometer data, only these branch points must be flagged. After such identification all intermediate data may be specified by comparison with surface truth data in the same region. As little as one surface measurement may be used to fill in uniquely the wind values from one branch point to the next.

Such a procedure is considerably simpler than that advocated by Pierson, Cardone and Greenwood, which involves comparison with all available high quality ship reports, with appropriate interpolation to points midway between ship reports. Such a procedure is excessively conservative, provided only that the scatterometer data is of adequate quality to permit reasonable smoothing. Of course the analysis described here of comparison with ship reports once per solution branch does not preclude further comparison with all available surface observations. Hopefully such comparisons will soon establish the validity of the satellite derived values, and the resultant global wind field over the oceans. At this point a compact lookup table plus occasional reference to surface truth will permit rapid and efficient application of the SEASAT results.

## ACKNOWLEDGEMENT

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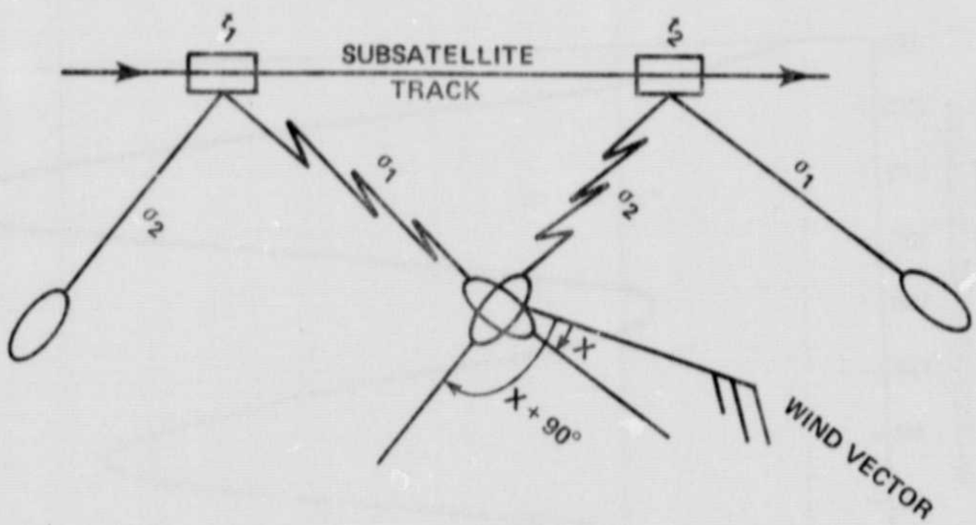


Figure 1. View From Above of Scatterometer Measurement Geometry. The Instrument is Planned to View Left as Well as Right (Shown), and to Scan in Nadir Angle from 25° to 45°, Providing Parallel Swaths Along the Subsatellite Track

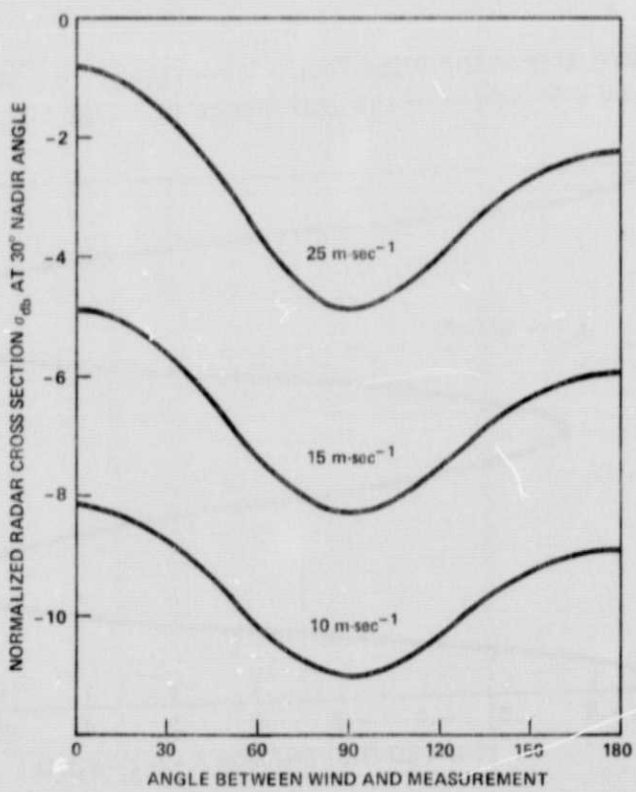


Figure 2. Variation of Radar Cross Section Versus Look Angle for Representative Values of Wind Speed. The Curves are Symmetric About 0°

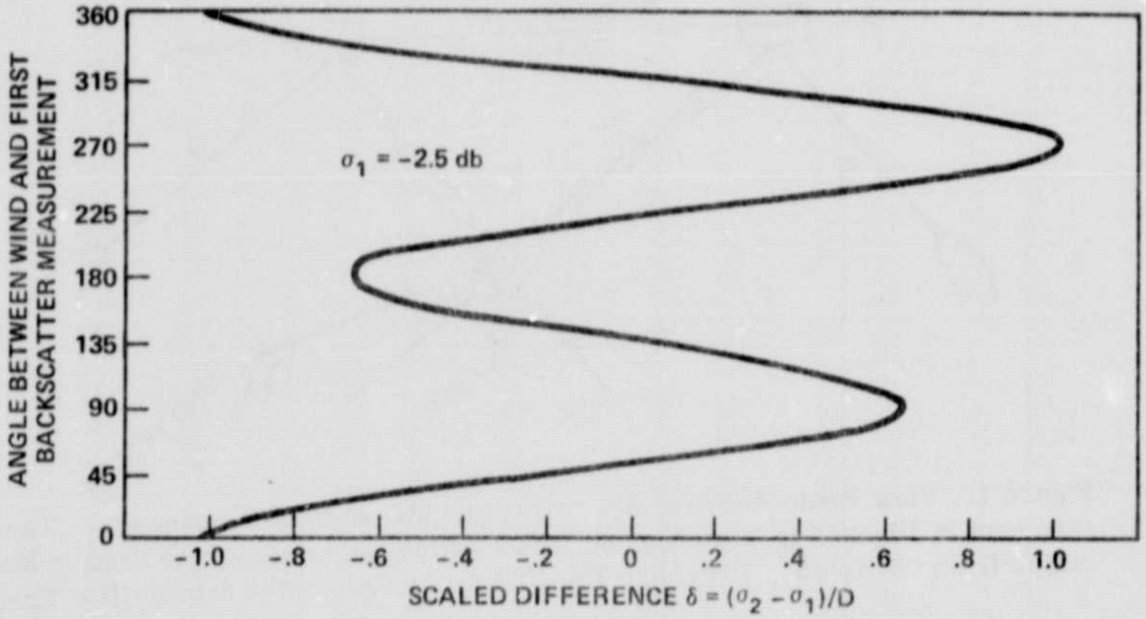


Figure 3. Solution Curve for Wind Angle Moderately High Winds ( $\sigma_1$, = -2. 5) as a Function of the Difference in Radar Cross Sections

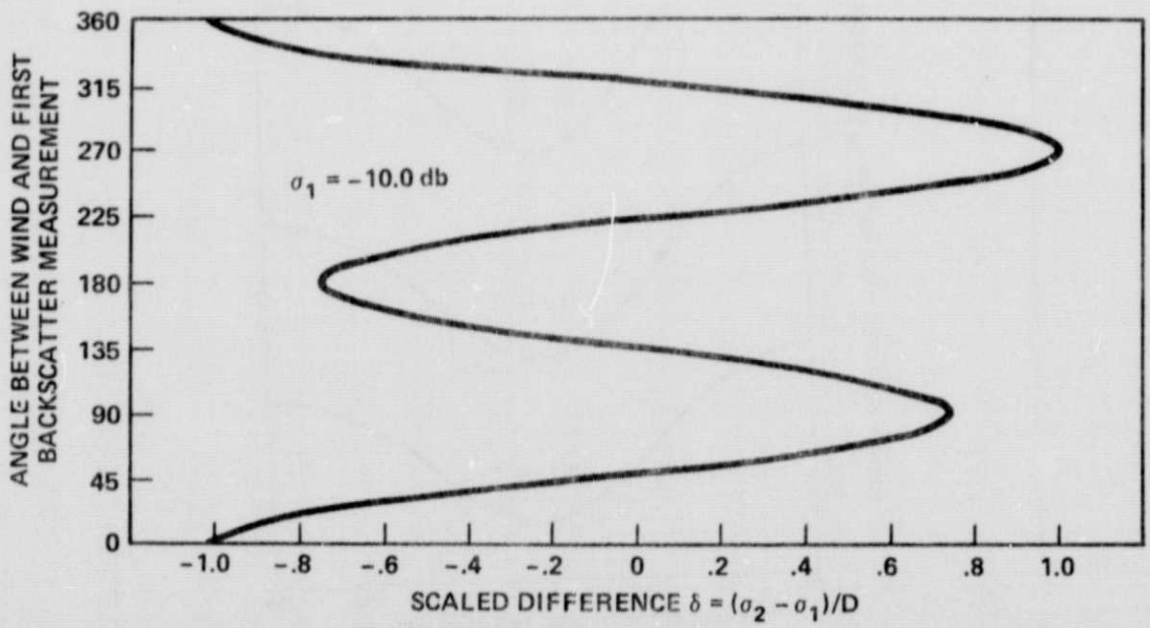


Figure 4. Solution Curve for Wind Angle for Low Wind Speed ($\sigma_1$ = -10. 0) as a Function of the Difference in Radar Cross Sections

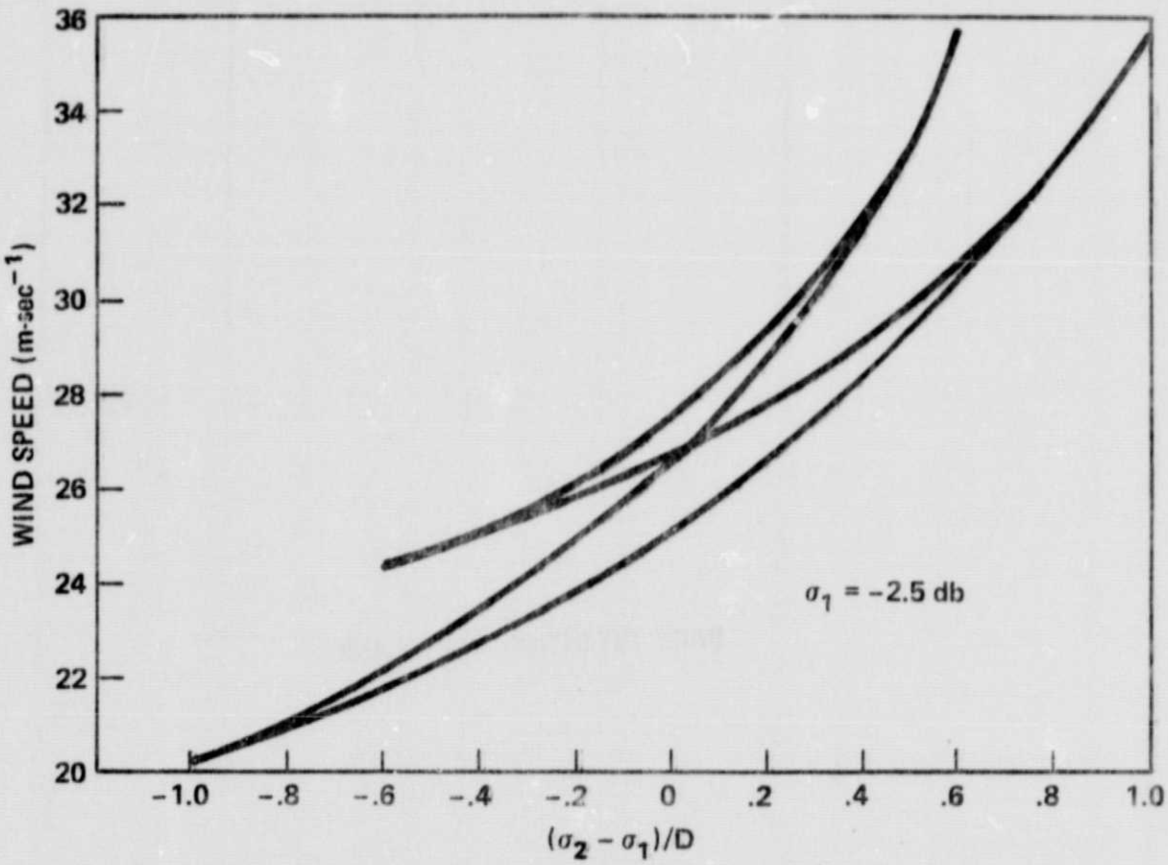


Figure 5. Solution Curve for Wind Speed for High Winds as a Function of the Difference in Radar Cross Sections

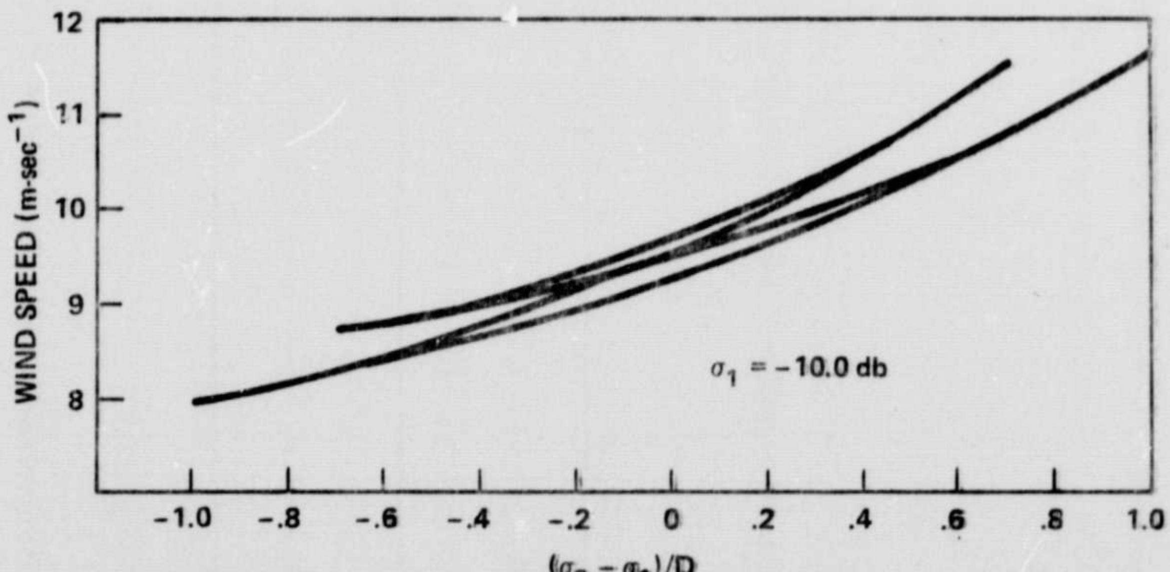


Figure 6. Solution Curve for Wind Speed at Low Winds ($\sigma_1$ = −10.0 db)