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One of the most controversial topics in the general area of microwave remote sensing of the sea is the use of backscattered power to infer surface wind speed. The controversy is due in large measure to inadequate detailed knowledge of how the centimeter wavelength components of the ocean surface height spectrum respond to the wind. Although present remote sensing efforts are primarily directed toward the use of large angle microwave scattering to infer surface wind, there is the distinct possibility that near normal incidence scattering may also provide a means for estimating surface winds [Hammond, et al., 1977]. This study represents an initial effort to determine if GEOS-3 $\sigma^\circ(0^\circ)$ data can be used to infer surface wind speed. The "ground truth" for this study were Spaceflight Meteorology Group (SMG) hindcast estimates and ship reports of wind speeds along the ground track of the satellite.

For normal incidence backscattering from a random rough surface, the scattering cross section per unit area $\sigma^\circ(0^\circ)$ is directly proportional to the normal incidence Fresnel power reflection coefficient of the flat surface and inversely proportional to the mean square slope of a low pass filtered replica of the true surface [Brown, 1977b]. The constant of proportionality in the relationship is determined by the probability density function for the slopes of the low pass filtered surface while the cutoff wavenumber of the low pass filter is determined by the electromagnetic wavenumber and the mean square height of the surface wave components corresponding to wavenumbers greater than the em wavenumber [Brown, 1977b]. For 13.9 GHz, the normal incidence Fresnel power reflection coefficient only varies from about -2.08 to -2.37 dB for extreme variations in water temperature and salinity [Matthews, 1975]; thus, it may be considered to be reasonably constant over the open ocean. Also for 13.9 GHz, atmospheric attenuation can usually be ignored for all but a few notable exceptions [Brown, 1977a]. Thus, for the GEOS-3 system, any measured variations in $\sigma^\circ(0^\circ)$ are a direct indication of changes in <u>either</u> the density function for the slopes of the filtered surface <u>or</u> the mean square slope of the filtered surface.

According to the above discussion, $\sigma^\circ(0^\circ)$ may be written in the following form;

$$\sigma^\circ(0^\circ) = \alpha \frac{|R(0^\circ)|^2}{\overline{\zeta^2_{\ell r}}} \tag{1}$$

where α is a constant of proportionality which depends upon the density of the slopes for the filtered surface, $|R(0^\circ)|^2$ is the Fresnel power reflection coefficient for the sea at normal incidence and 13.9 GHz, and $\overline{\zeta^2_{\ell r}}$ is the mean square slope of the filtered surface. Cox and Munk [1954] have obtained measurements of the surface mean square slope in the open ocean with and without filtering, and their results indicate a logarithmic dependence [Wu, 1972] upon wind speed W_{10}, i.e.

$$\overline{\zeta^2_{\ell r}} = a \ln W_{10} + b \tag{2}$$

Combining (1) and (2) and assuming that the density function for the filtered surface slopes does not change appreciably with wind speed, i.e. α independent of W_{10}, then

$$\sigma^\circ(0^\circ) = \frac{|R(0^\circ)|^2}{A \ln W_{10} + B} \tag{3}$$

where $A = a/\alpha$ and $B = b/\alpha$. For $|R(0^\circ)|^2 = -2.1$ dB or 0.617,

$$\sigma^\circ(0^\circ) = \frac{0.617}{A \ln W_{10} + B} \tag{4}$$

Thus, equation (4) represents the expected relationship between $\sigma^\circ(0^\circ)$, as measured by GEOS-3, and the surface wind speed W_{10} at the standard anemometer height of 10 m above mean sea level.

The purpose of this study was to determine if there existed sufficient correlation between $\sigma^\circ(0^\circ)$ inferred estimates of surface wind speed and ground truth data to warrant more detailed investigation. The only "ground truth" data base large enough and readily available for such a comparison were the hindcast wind speed estimates produced by SMG. Although these data do not represent *in situ* measurements, they do provide reasonable estimates of surface wind speed and their density overcomes many of the problems associated with single-point *in situ* measurements. It must be remembered that the purpose of this study was to determine feasibility, not necessarily to establish hard and fast relationships.

Since SMG indicates the presence or absence of swell, this study treated the two cases as separate and distinct. That is, $\sigma°(0°)$ vs. SMG wind estimates were obtained for both no swell and swell present conditions. This was done in view of recent conjecture in the literature on the effect of swell on small scale surface waves [Keller & Wright, 1976; Wu, 1977]. The SMG data base for this study comprised the Parsons and Goodman [1975] report covering the early mission checkout phase for GEOS-3 (April-May, 1975) and the special Newfoundland sea state mission (February, 1976). A plot of $\sigma°(0°)$ versus SMG wind estimates is shown in Figure 1 for swell conditions. Although there is some clustering of the data, there is also significant scatter. In order to try and determine if the scatter was due to a nonunique $\sigma°(0°)$ vs. W_{10} relation or just incorrect SMG wind estimates, the SMG maps were searched for ship reports in the immediate vicinity of the GEOS-3 ground track ($\lesssim 1.5°$ separation). The results are shown in Figure 2 . Although there are certainly less data, there is also significantly less scatter in the data. It is apparent from these data that a double-branched curve would be required to fit the data. That is, for $W_{10} \lesssim 9$ m/s one set of A and B coefficients are required in (4) while a different set are required for $W_{10} \gtrsim 9$ m/s. A general least-squares routine produced the following set of coefficients for $\sigma°(0°)$ vs. W_{10};

$W_{10} \lesssim 9.2$ m/s	$W_{10} \gtrsim 9.2$ m/s
A = 0.02098	A = 0.08289
B = 0.01075	B = -0.12664

The solid curve in Figure 2 indicates the degree of fit of (4) to the ship report data using the above A and B coefficients. Using the curve in Figure 2 , it is possible to translate $\sigma°(0°)$ measurements into wind speed estimates. When this was done for the ship report data and a linear regression was accomplished on the resulting scatter plot, the following equation resulted;

$$(W_{10})_{ALT} = 0.91(W_{10})_{SR} + 0.84 \qquad (5)$$

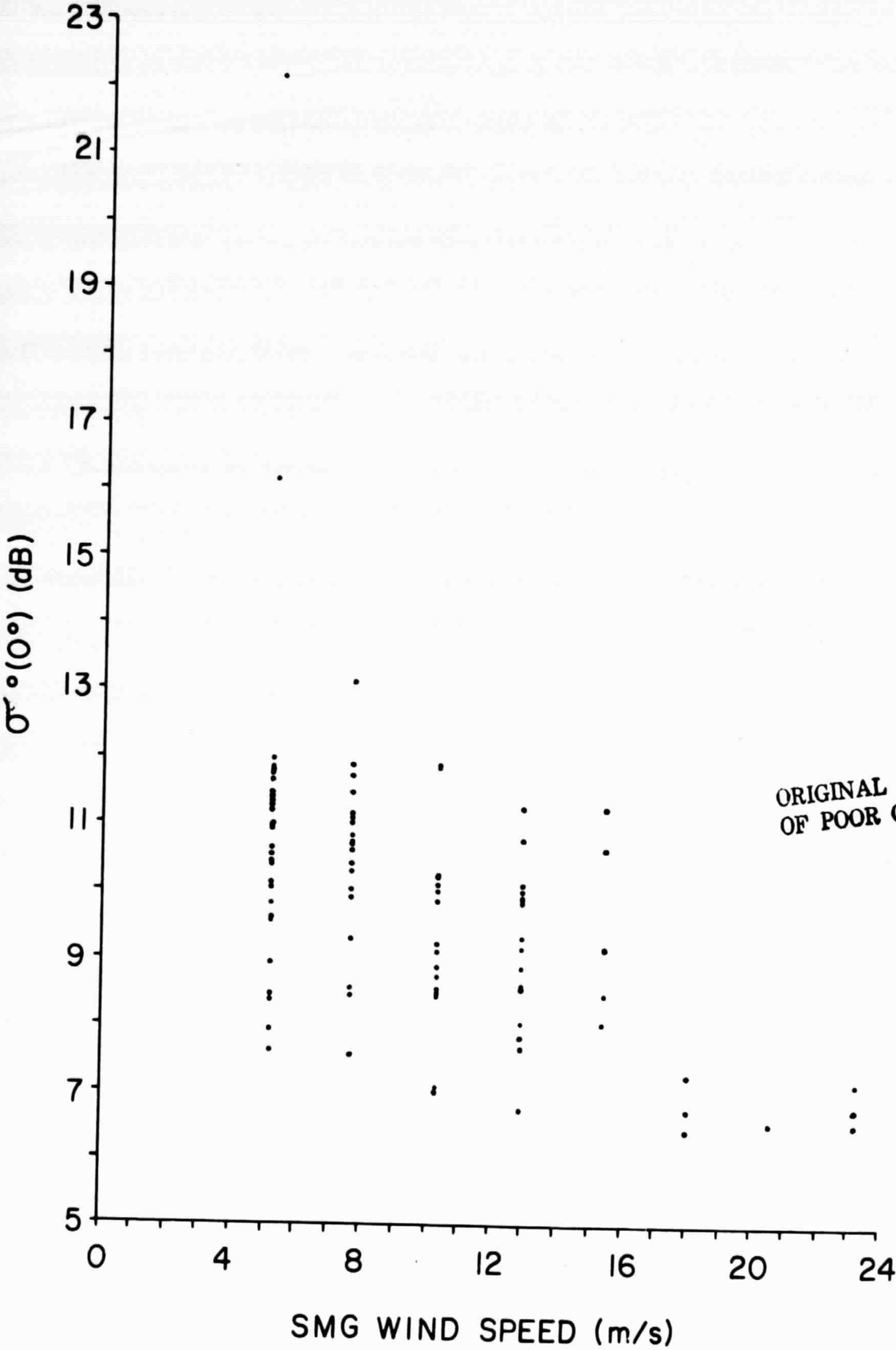

Figure 1. σ°(0°) vs. SMG estimates of wind speed for swell conditions.

where $(W_{10})_{ALT}$ was the $\sigma°(0°)$ inferred wind speed and $(W_{10})_{SR}$ was the ship reported wind speed. The correlation coefficient for this fit was 0.84, and the error about a unity slope line, i.e. error = $(W_{10})_{SR} - (W_{10})_{ALT}$, had a mean value of -0.64 m/s and a standard deviation of 2.6 m/s. A histogram of the error appeared to be nearly uniform with a slight tail in the negative direction.

When the above procedure was applied to the SMG data in Figure 1, the slope of the regression fit decreased to 0.74 while the intercept increased to 3.1 m/s. The correlation coefficient only reduced to 0.64 while the mean error, i.e. error = $(W_{10})_{SMG} - (W_{10})_{ALT}$, decreased to -0.55 m/s but the standard deviation increased to 4.14 m/s. Hence, for the case of swell, there is very good correlation of $\sigma°(0°)$ inferred wind speed estimates with ship report data and the correlation is not as good with the SMG wind speed estimates.

For the case of no swell, the data base was significantly smaller with the majority of the SMG estimates occurring at 5.2 m/s. The ship report data base was so small as not to warrant separate consideration; the complete data set (SMG and ship reports) is shown in Figure 3. The coefficients resulting from a least-squares fit of (4) to the data in Figure 3 are as follows; A = 0.03731 and B = -0.01324. Because of the preponderance of data at 5.2 m/s, a regression fit to the scatter-plot data is not meaningful. However, the mean error was -0.8 m/s while the standard deviation was 2.8 m/s.

For the transformation of $\sigma°(0°)$ data into wind speed estimates, the results of Figures 2 and 3 have been combined to produce the composite curves shown in Figure 4. In region I ($W_{10} \leq 4$ m/s) the no swell curve is used for both swell and no swell data because there was virtually no reliable swell-present data in this region. In region II, there are two separate curves for conditions of swell and no swell; however, one should be cautious of drawing any conclusions from this separation since the curves were derived from mean square fits to data of questionable accuracy. In region III, the swell curve is used since it is doubtful that winds exceeding 12 m/s could be instantaneously generated. One other point that should be made is that all the $\sigma°(0°)$ data derived from the GEOS-3 altimeter were corrected for pointing angle errors according to the scheme given in [Brown & Curry, 1977]. This was found to be absolutely essential in view of the slope of the curve (in Figure 4) in region III and the fact that the pointing angle was found

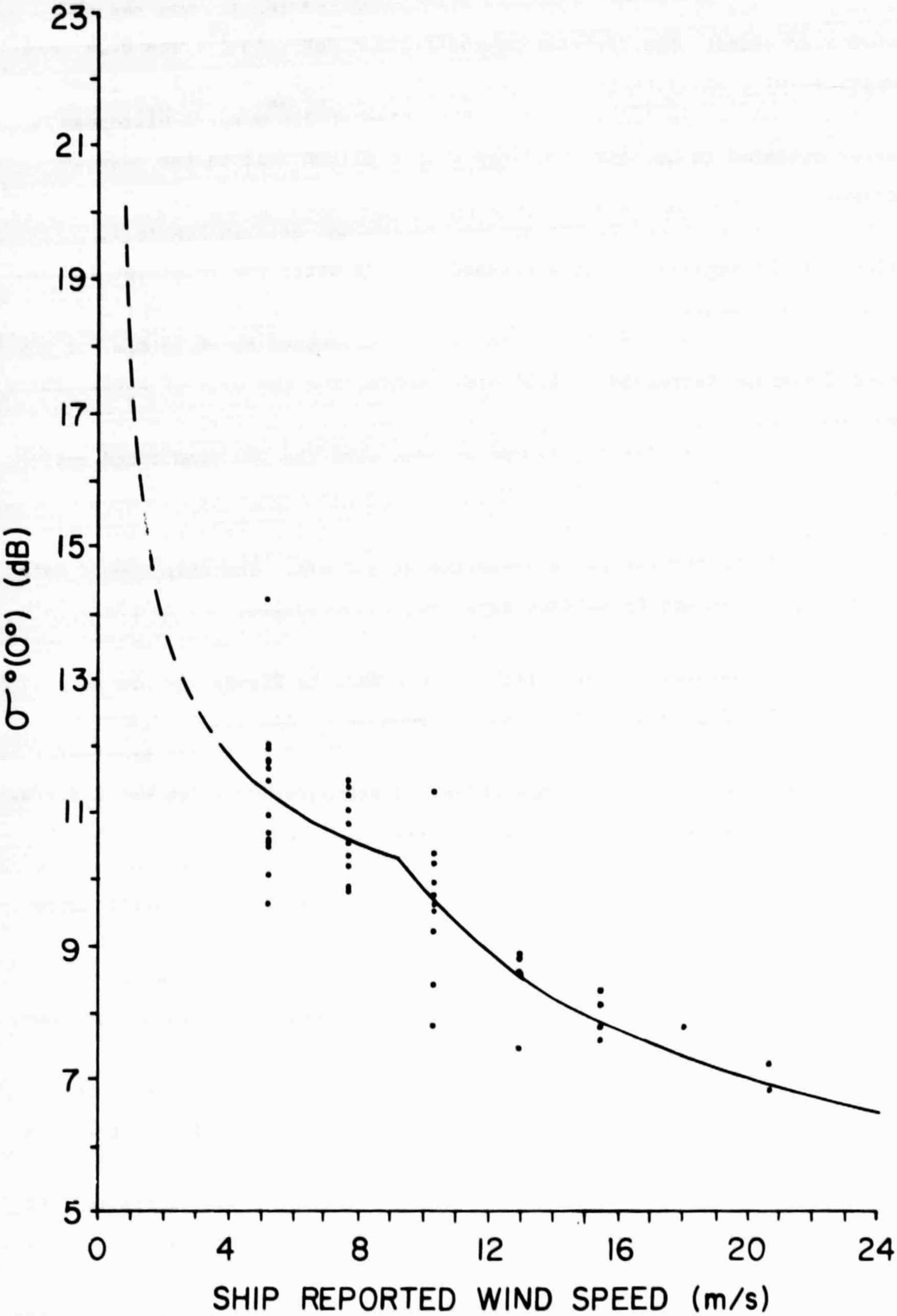

Figure 2. σ°(0°) vs. ship reported wind speed for swell conditions. The curve is a double-branched mean square fit to the data.

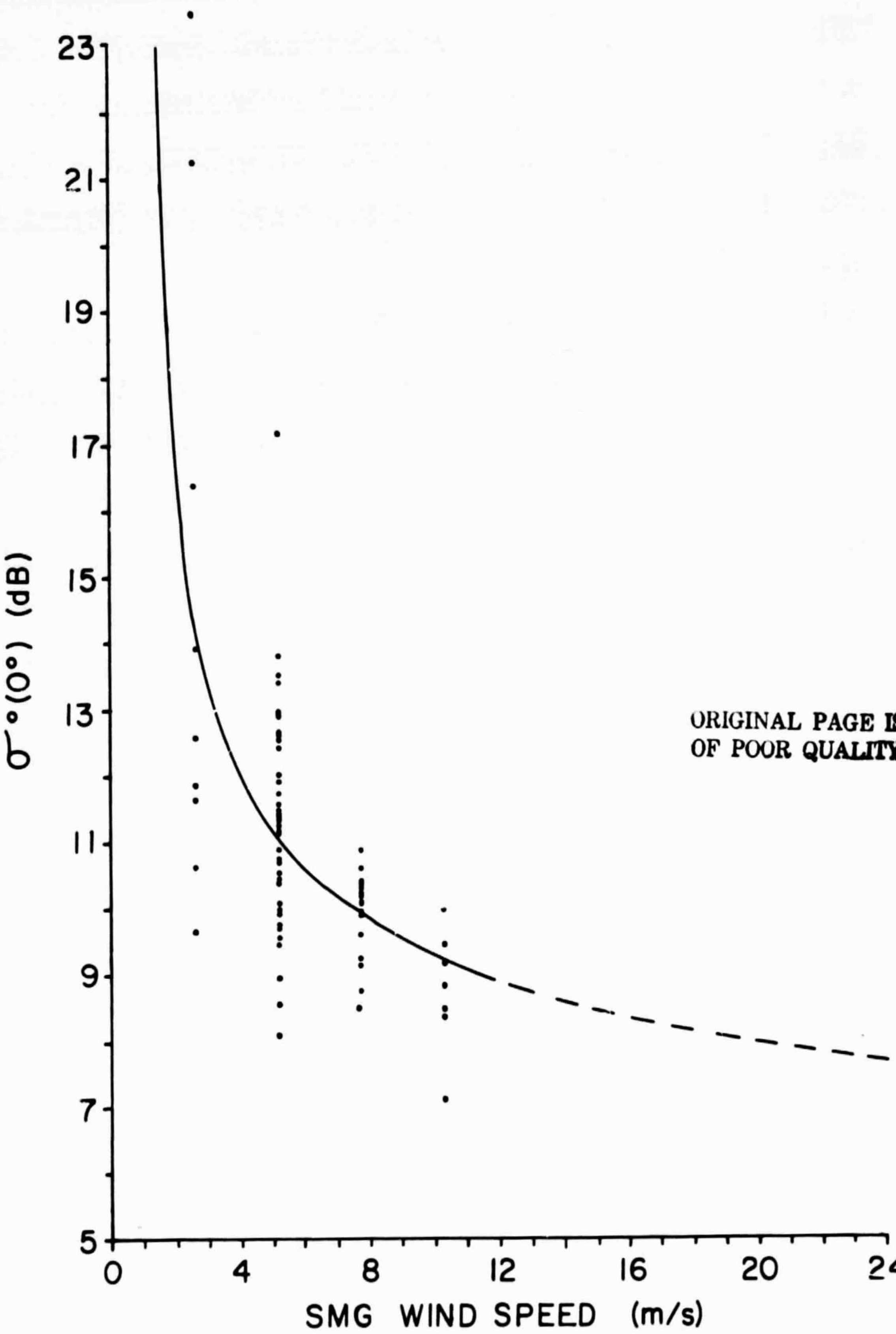

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Figure. 3. σ°(0°) vs. SMG estimates and ship reports of wind speed for no swell conditions. The curve is a mean square fit to the data.

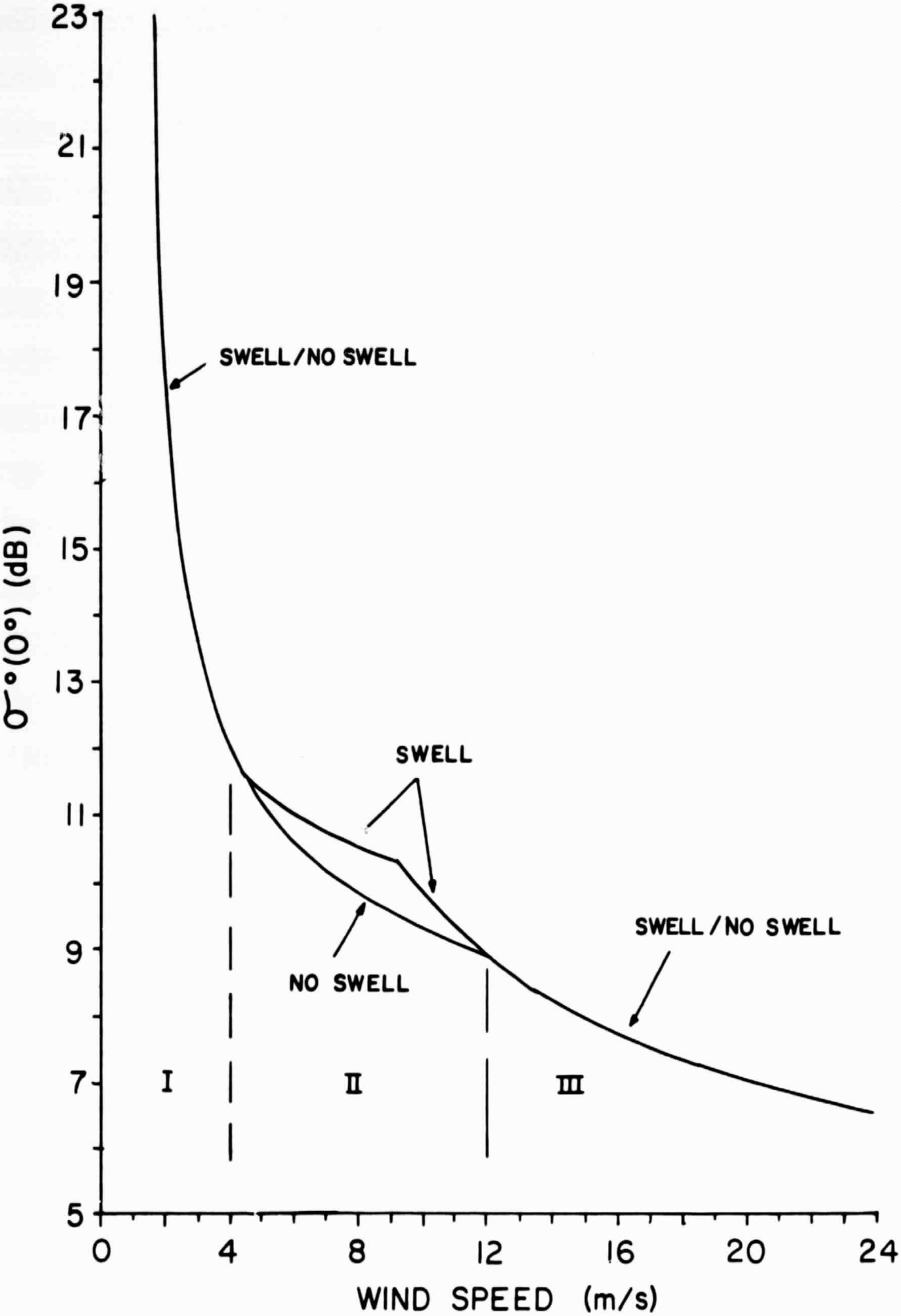

Figure 4. Composite curves used tc infer surface wind speed from $\sigma°(0°)$ measurements.

to be as large as 0.8°.

Using the curves in Figure 4 and SMG estimates of the existing swell conditions, it is possible to produce along track estimates of the surface wind speed from $\sigma°(0°)$ measurements. Comparisons of these estimates with SMG wind speed estimates are illuminating because they show some of the reasons behind the scatter in Figures 1 and 3. Figures 5 through 8 are data from a group of passes occurring, in sequence, on the 23 rd through the 25 th of April, 1975, along the east coast of the U.S. For Rev 183, there is reasonably good agreement between SMG and altimeter estimates. The calm wind estimate by SMG at an elapsed distance of 2520 km results from a nearly 180° reversal in the SMG estimate of wind direction. It has been noted in other data sets that whenever SMG indicates a nearly 180° change in wind direction, they also estimate calm winds at the point of direction change. The altimeter, i.e. $\sigma°(0°)$, seldom indicates calm conditions at the same point. Not indicated in Figure 5 is the fact that the SMG estimates were supported by a large number of ship reports. Figures 6 through 8 show progressively less agreement between the SMG and altimeter inferred estimates of wind speed; however, it is interesting to note that the difference appears to be in the form of a bias rather than a random error. It also should be noted that the SMG estimates for the data in Figures 6 through 8 based upon significantly <u>less</u> ship reports than the data in Figure 5. In addition, it is worth noting that if the aircraft wind speed measurement at 300 m altitude for rev 217 (Figure 8) is translated down to 10 m using a logarithmic wind profile, the resulting value of W_{10} is about 19 m/s which is in much better agreement with the altimeter estimate than the SMG estimate. Rev 217 (Figure 8) represents about the most significant disagreement between the altimeter and the SMG wind speed estimates that has been encountered to date. From the above discussion and the relatively good agreement between the altimeter wind estimates and the limited ship reports in Figures 6 through 8, it appears that the accuracy of the SMG estimates degrades in the absence of ship reports in a cumulative fashion. This hypothesis may be a significant contributor to the scatter in Figures 1 and 3.

Figures 9 through 12 show results for which there is significantly better agreement between SMG and $\sigma°(0°)$ inferred wind speed estimates. Of particular note in these figures is the fact that they all represent very

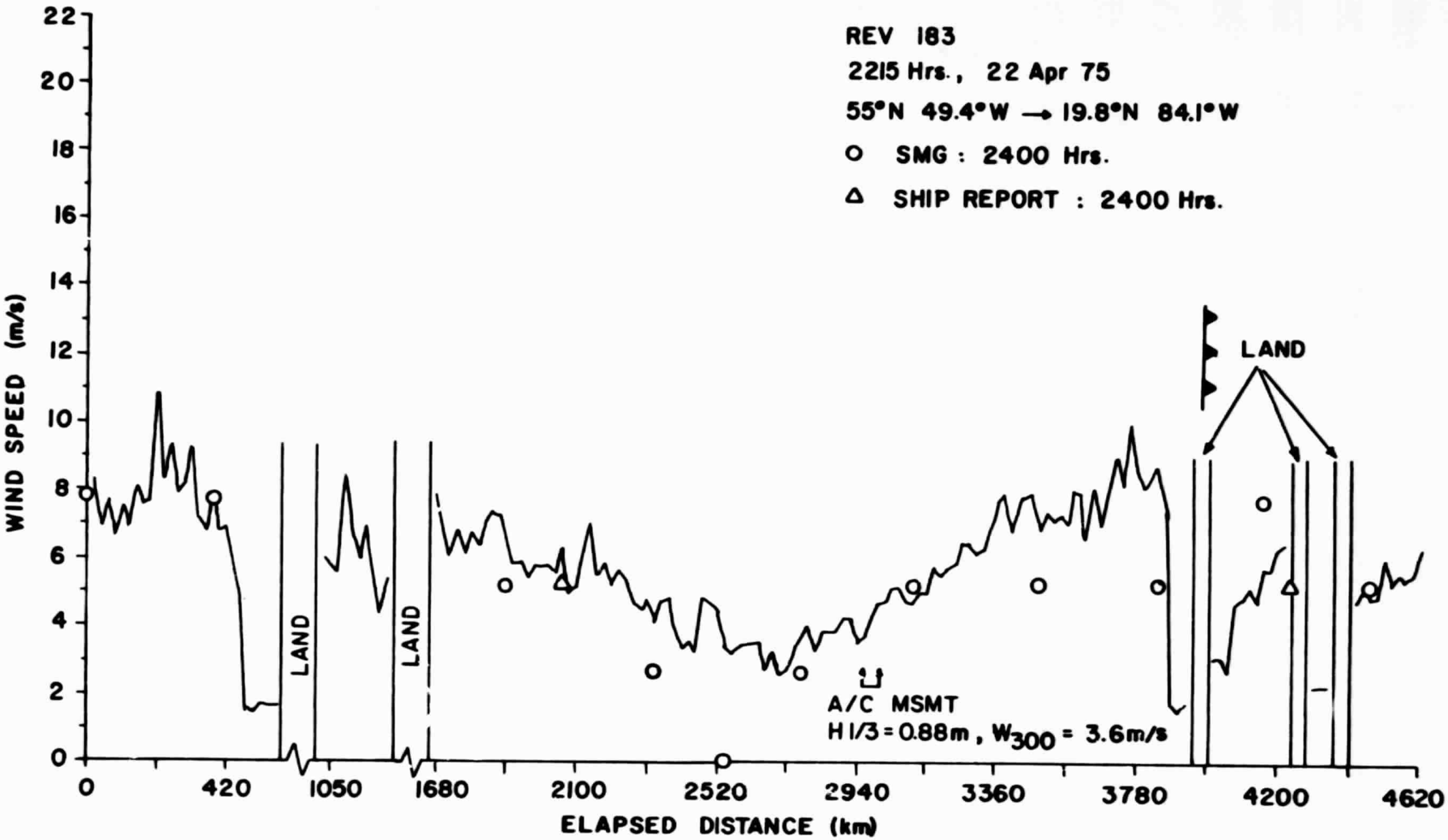

Figure 5. Altimeter, ship report, and SMG wind speed estimates for rev 183 and no swell surface conditions.

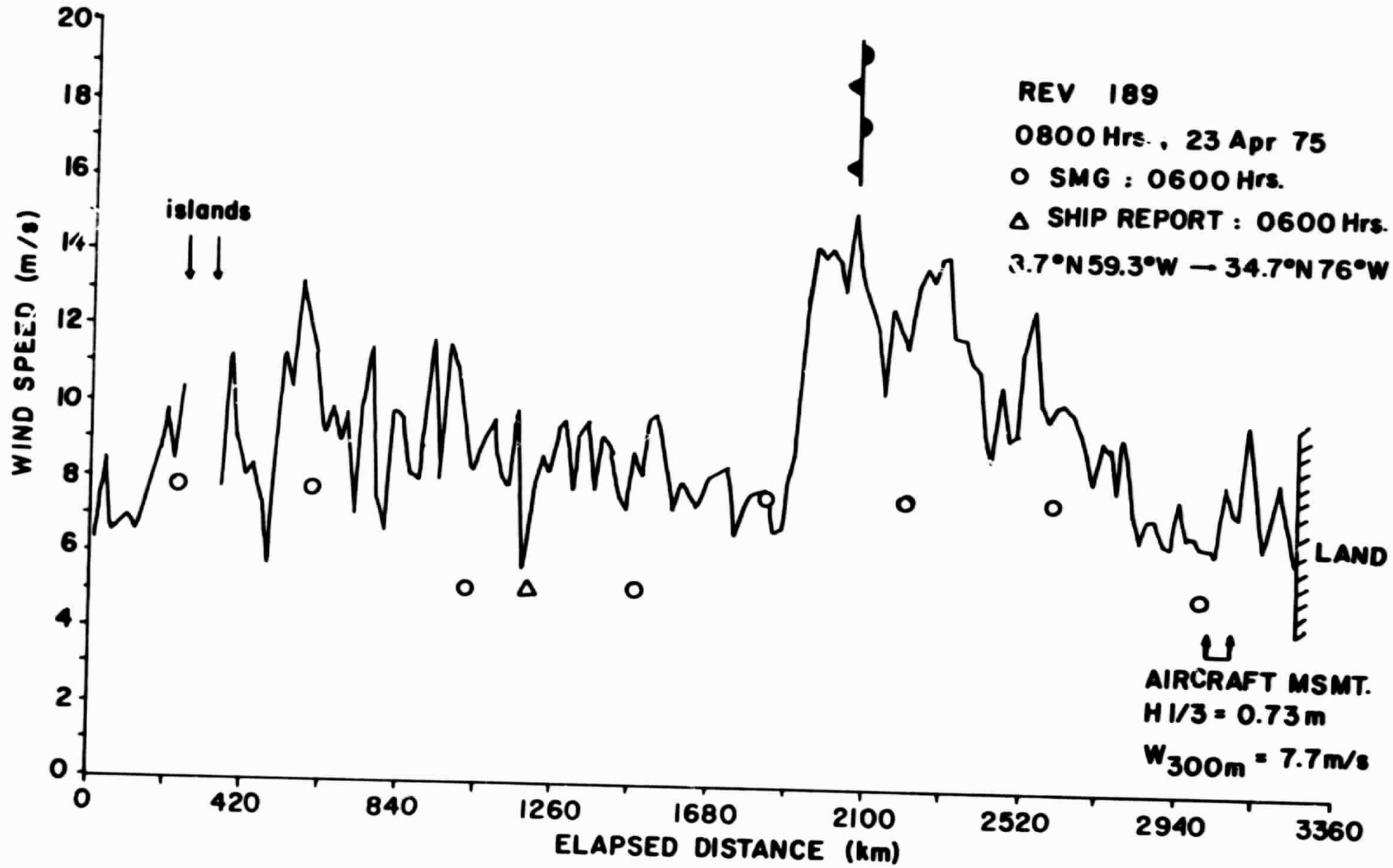

Figure 6. Altimeter, ship report, and SMG estimates of wind speed for rev 189 and no swell surface conditions.

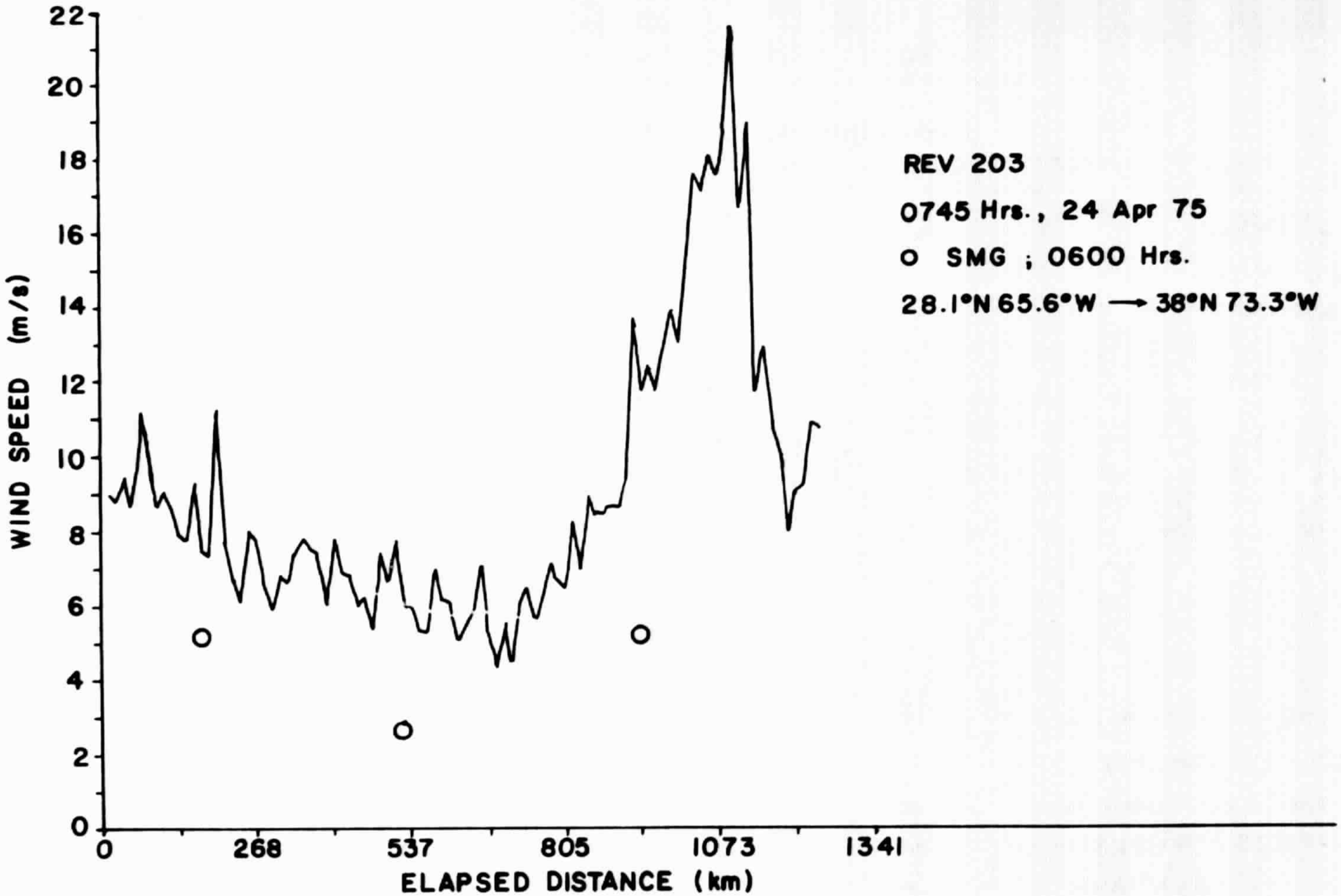

Figure 7. Altimeter and SMG estimates of wind speed for rev 203 and no swell surface conditions.

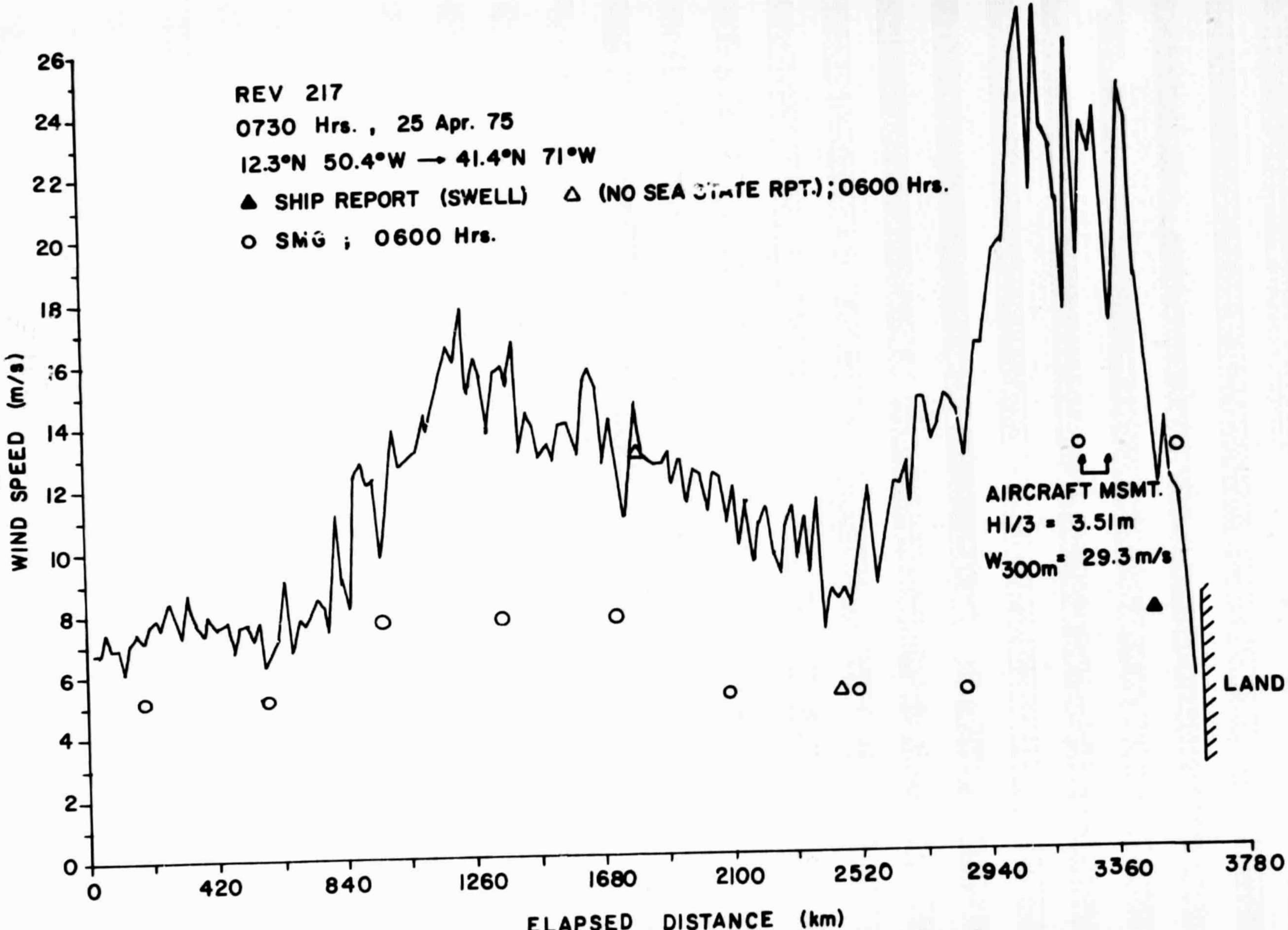

Figure 8. Altimeter, ship report, and SMG estimates of wind speed for rev 217 and mixed swell conditions.

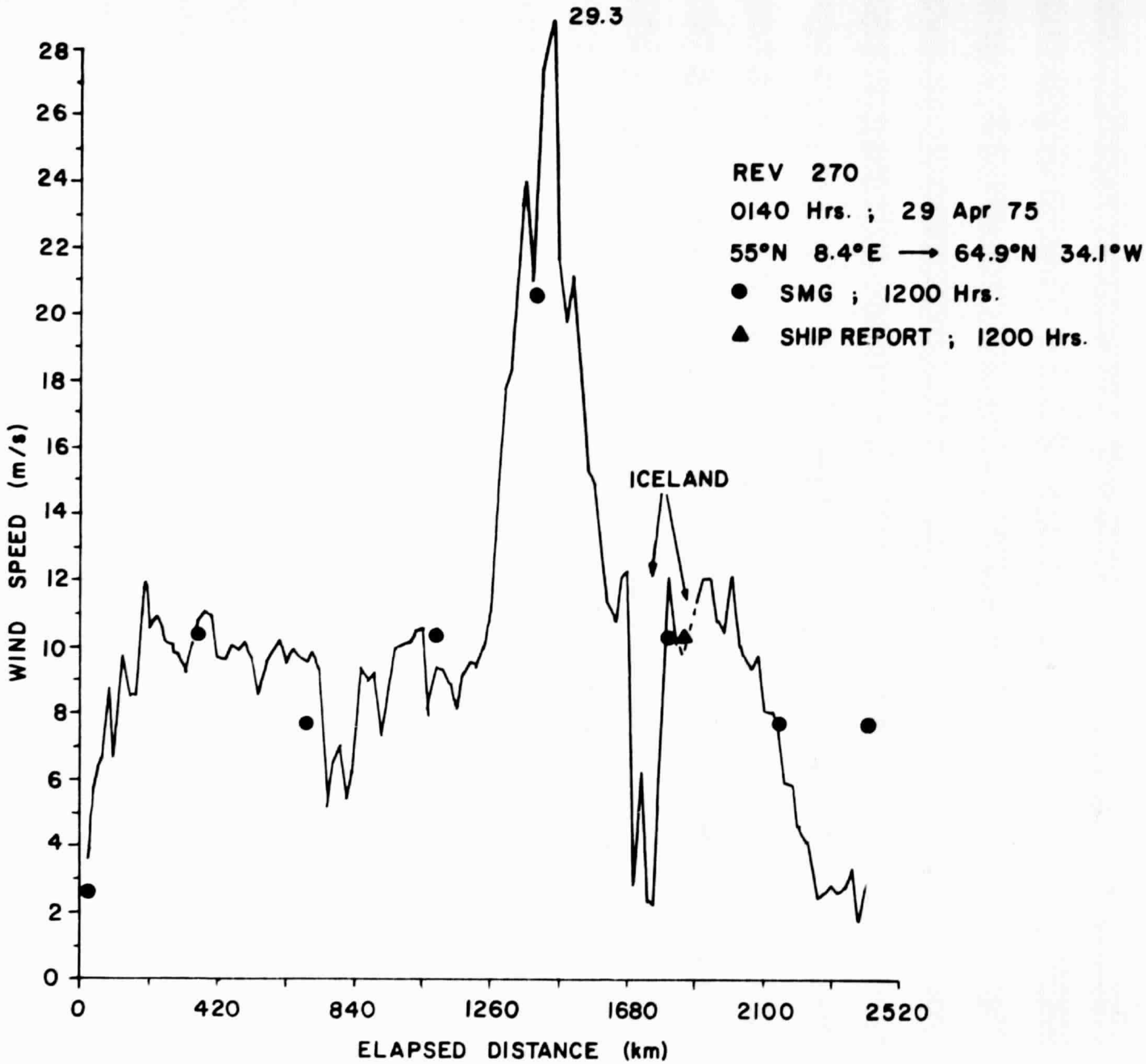

Figure 9. Altimeter, ship report, and SMG estimates of wind speed for rev 270 for swell surface conditions.

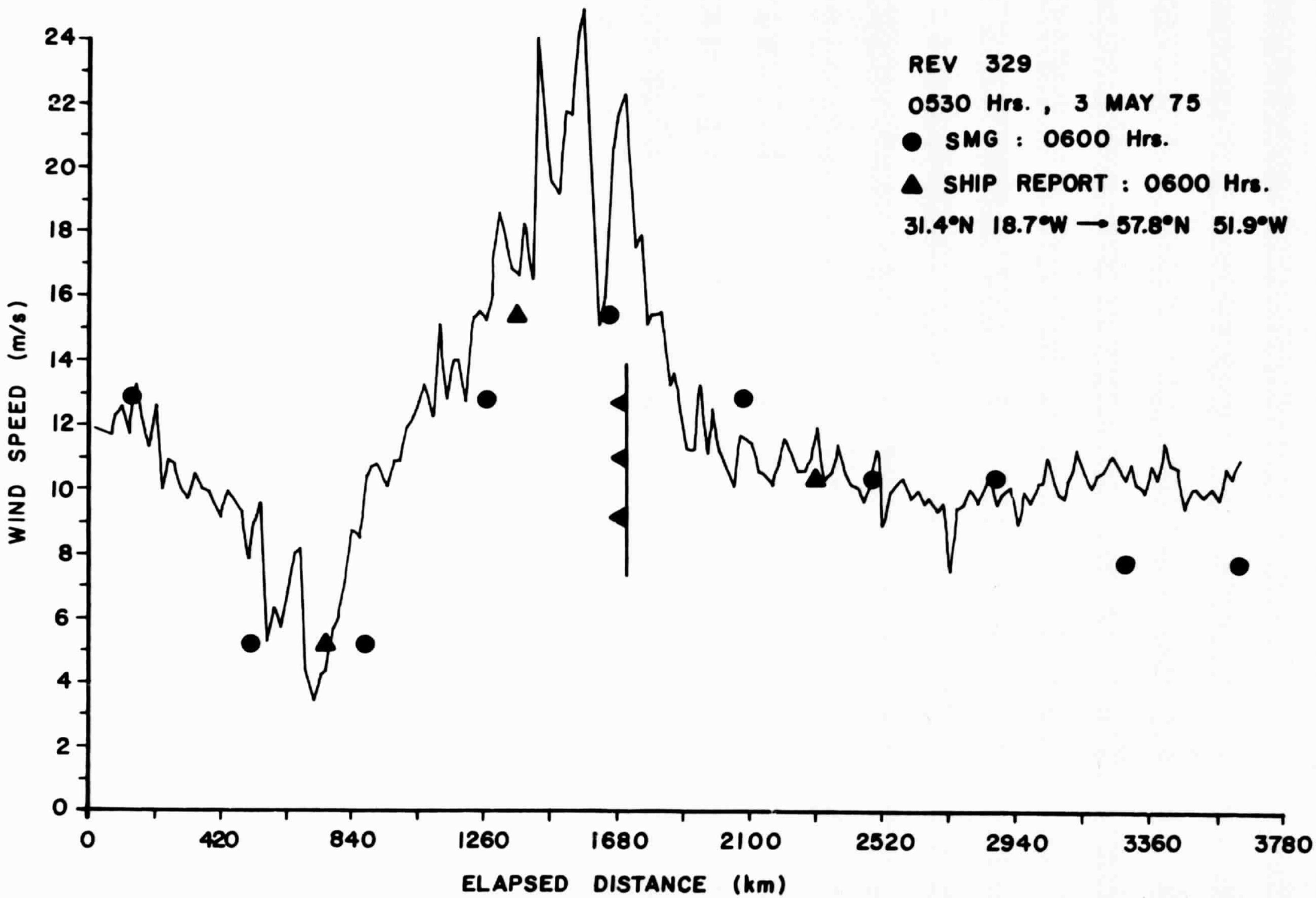

Figure 10. Altimeter, ship report, and SMG estimates of wind speed for rev 329 for swell surface conditions.

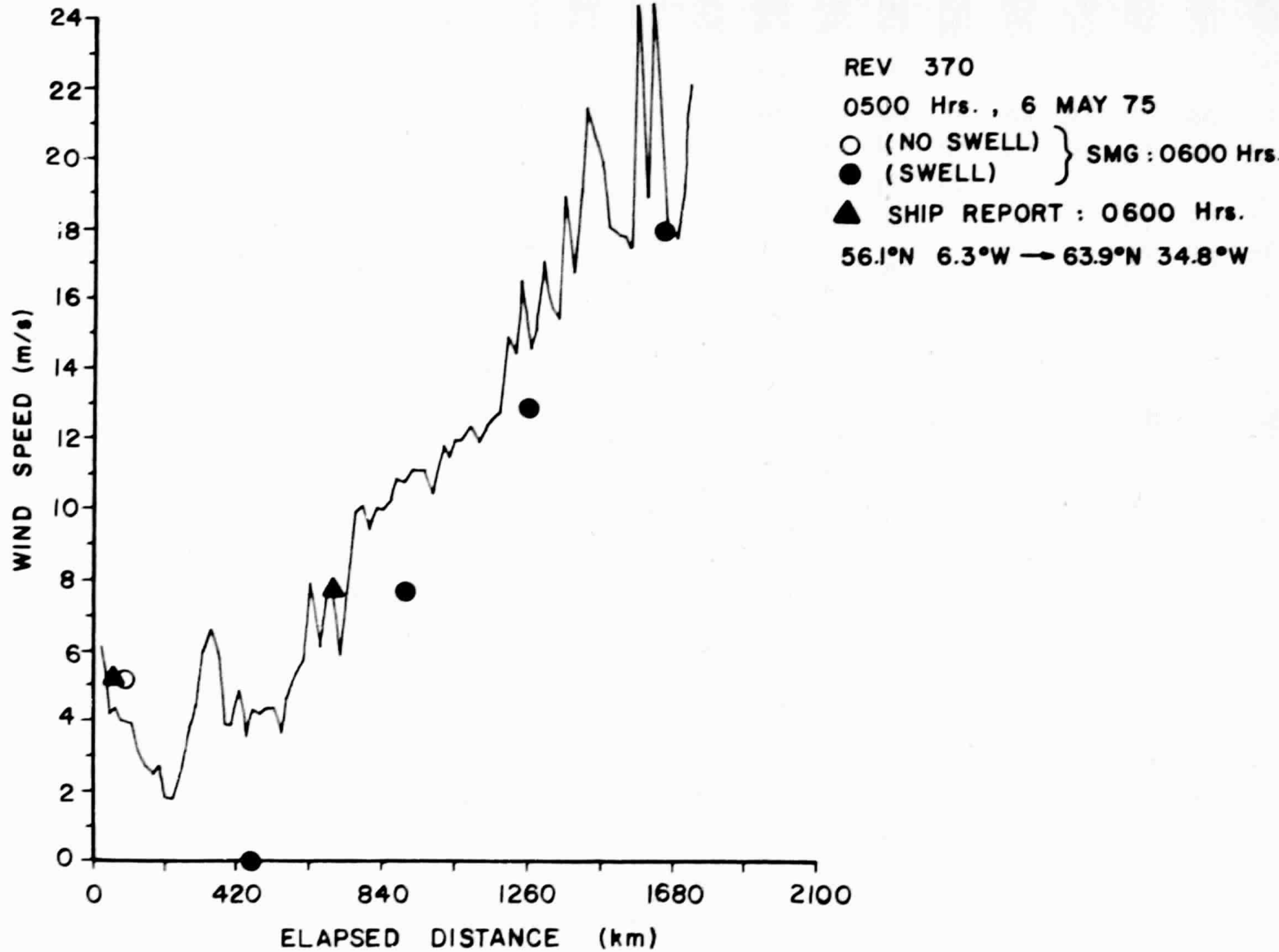

Figure 11. Altimeter, ship report, and SMG estimates of wind speed for rev 370 for mixed swell conditions.

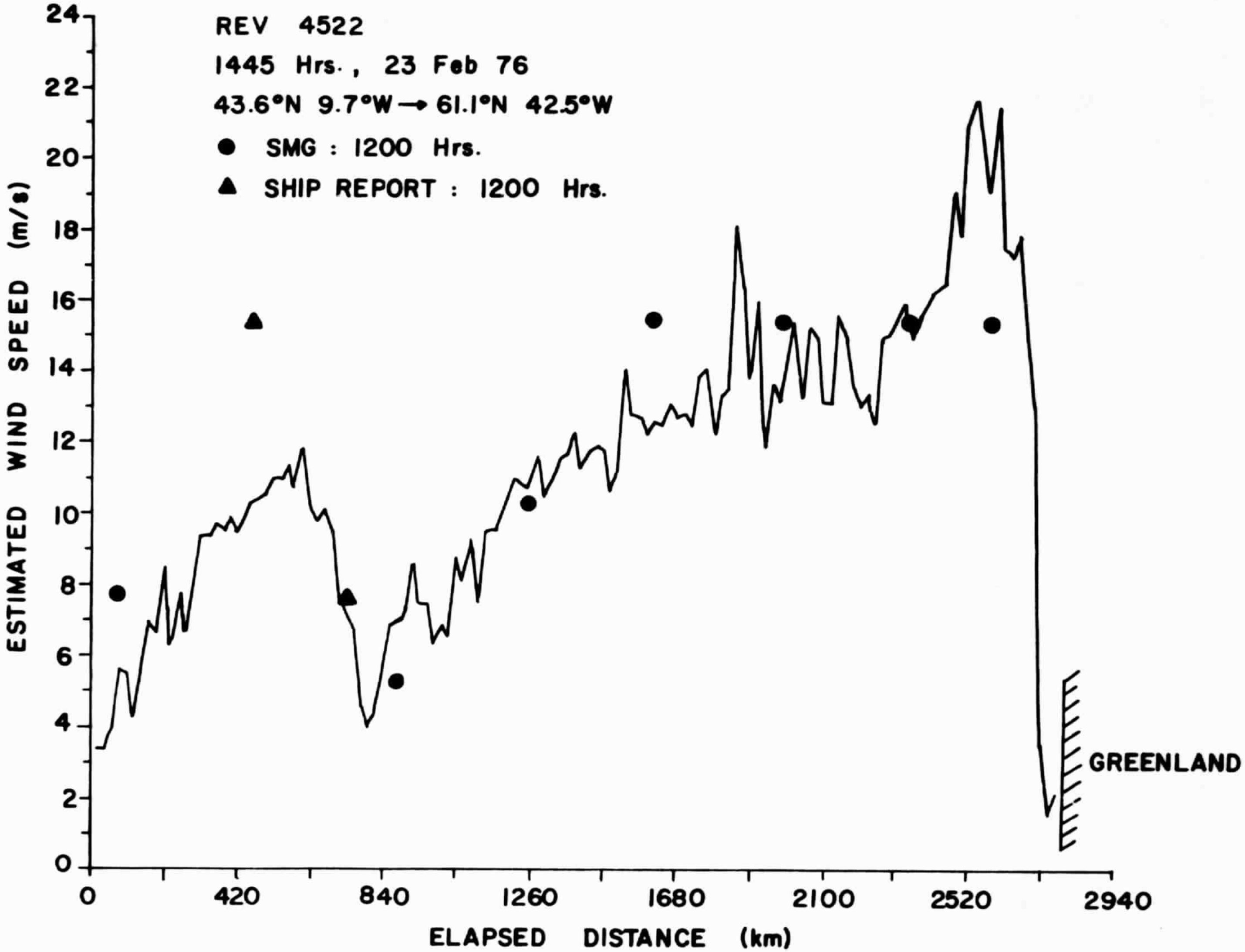

Figure 12. Altimeter, ship report, and SMG estimates of wind speed for rev 4522 for swell surface conditions.

dynamic situations, i.e. there is a marked change in the wind speed over the extent of the ground track. In these cases as in the data in Figure 5, the SMG results appear to be quantized replicas of the altimeter data.

In conclusion, it appears that the use of $\sigma°(0°)$ data to infer surface wind speed shows great promise as an accurate measurement tool. The results presented here certainly justify the need for more detailed study and comparisons with other in situ measurements. Based upon the real time needs of users, the curves in Figure 4 may, at the present time, be sufficiently accurate for estimating wind speed along the subsatellite ground track.

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16. Abstract

One of the most controversial topics in the general area of microwave remote sensing of the sea is the use of backscattered power to infer surface wind speed. The controversy is due in large measure to inadequate detailed knowledge of how the centimeter wavelength components of the ocean surface height spectrum respond to the wind. Although present remote sensing efforts are primarily directed toward the use of large angle microwave scattering to infer surface wind, there is sufficient justification to expect that near normal incidence scattering can also provide a means for estimating surface winds. This study represents an initial effort to determine the extent to which GEOS-3 σ° (0°) data can be used to infer surface wind speed.

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