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VERIFICATION PROCEDURES FOR THE SEASAT MEASUREMENTS OF THE VECT--ETC(U)
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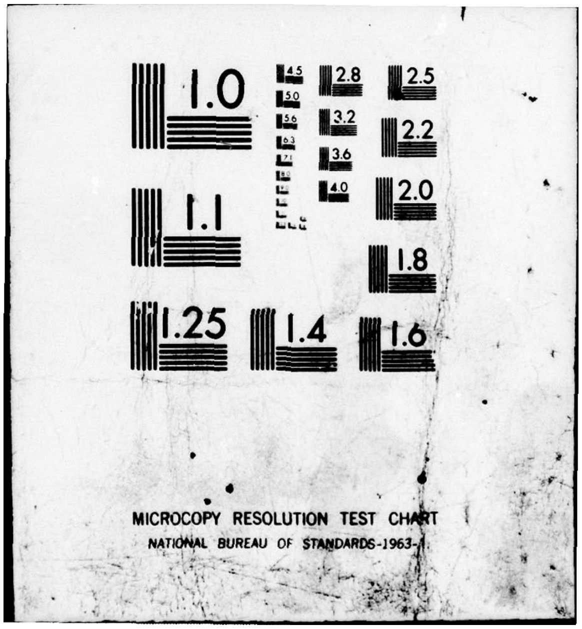

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VERIFICATION PROCEDURES FOR THE SEASAT MEASUREMENTS OF THE VECTOR WIND WITH THE SASS

by

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Abstract

Various relationships between the friction velocity and the roughness length in boundary layer models are studied in terms of the verification of the SASS on SEASAT. It is shown that verification against a measured wind at a known anemometer height is preferable to verification against a theoretical value of the friction velocity.

The effect of the different models is small when they are used to refer all measured winds to one elevation.

A model is proposed that has the features of two quite different models and the height of the anemometer for verification purposes is recommended to be 19.5 meters.

Objective

The objective of this report is to clarify the problem of the verification of the vector winds obtained from backscatter measurements with the SASS on SEASAT. These backscatter measurements, of course, have to be corrected for attenuation. Once this correction for attenuation is made, a relationship has been obtained between the backscatter measurements at pairs of cells that permits the recovery of the synoptic scale vector wind that would have been measured at 19.5 meters in a neutrally stratified atmosphere.

The stated objective of the SASS measurements has been to specify the magnitude of the wind to within plus or minus two meters per second, or 10%, whichever is worse. This stated objective does not define the height above the sea surface at which the verification is to be accomplished. Since the synoptic scale winds in the planetary boundary layer decrease with decreasing elevation and become lower as the sea surface is approached, clearly it would be to the advantage of the verification techniques to use as low an elevation above the sea surface as possible. Conventionally, most oceanographic data is referred to an elevation of 10 meters above the sea surface. However, for numerous reasons, it seems advisable to use an elevation of 19.5 meters for the verification of the SASS measurements. The reasons for the choice of 19.5 meters will be discussed later.

The relationship between the vector wind and the radar backscattering cross section, σ^o_{VV} or σ^o_{HH}, has been determined from a basic set of data* obtained with aircraft by the AAFE Langley Research Program. These data consist of 63 data sets for circle flights in which backscatter was measured as a function of wind direction relative to the pointing direction of the radar beam for a fixed incident angle at approximately 10 degree increments around a full circle. The winds at an elevation of 19.5 meters during these circle flights ranged from about 4.6 m/sec to about 20 m/sec, and the incident angles varied from 19^o to 65^o. Data for both vertical and horizontal polarizations were obtained.

The first series of data, consisting of flights with a flight series number of 318, were for winds that varied from 4.6 to 13.5 m/sec during the JONSWAP experiments. The meteorological winds were determined from measurements based on 10 minute averages at an offshore lower for an elevation of approximately 10 meters above the sea surface. The actual wind for a particular circle flight was interpolated to the tower measurements so as to correspond as closely as possible to the time during which the circle flights were made and referred to 19.5 meters. However, due to the turbulent nature of the wind over the

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*Provided by W. L. Jones.

surface of the water, the measured wind at the tower need not have corresponded exactly to the wind where the circle flight data were obtained.

For a second series of flights, with a flight series number of 335, for which data near 15 and 20 m/sec were obtained, the aircraft made wind measurements with an inertial navigation system at an elevation of approximately 150 meters above the sea surface before and after the radar measurements were taken. These winds were referred to 19.5 meters above the sea surface, and interpolated in time between the measurement preceding the circle flights and the measurement at the conclusion of the flights so as to obtain a value during the time of the circle flights. Again, due to the nature of the turbulent motions of the air over the ocean, there may be an additional discrepancy involved. These effects contribute an uncertainty of about ± 1 m/sec for the actual meteorological wind speed to be related to a particular circle flight. These uncertainties propagate into the details of whatever relationship is found between backscatter and wind speed.

The data that have been obtained provide the best estimate possible at the present time for the relationship between the wind over the ocean surface at 19.5 meters and the backscatter. There are reasons to believe that the turbulence of the wind over the water caused most of the fluctuations in the backscatter measurements.

Individual values of the backscatter for a particular aspect angle, incident angle, and nominal meteorological wind speed could actually have been produced by a wind that was stronger or weaker than the longer term anemometer average. The backscatter measurements were taken over an area and a time that would be the equivalent of an anemometer average from two minutes to ten minutes. The largest scatter in the fit between the radar backscatter measurements and the meteorological wind speeds occurred when the equivalent anemometer averaging time was low, such as for values of two, three, and four minutes.

Relationship between Backscatter and Wind Speed

The relationship between backscatter and wind speed can be summarized by equations (1) and (2),

$$\sigma^o = \sigma^o \; (U_{19.5}, \chi, \theta) \qquad (1)$$

$$U_{19.5} = U(\sigma^o, \chi, \theta) \qquad (2)$$

These equations state that a relationship exists between the measured value of the backscatter, whether it be horizontal or vertical polarization, the wind speed measured at 19.5 meters, the angle between the wind direction and the pointing direction of the radar beam χ , and the incident angle, θ . It is possible to derive this particular relationship, partially on a theoretical basis as has been done by Chan and Fung (1977) in terms of the capillary wave spectra determined by Mitsuyasu and Honda (1974). Other theoretical relationships can be obtained that refer the measured backscatter values to the friction velocity, u_*. This particular step depends on certain assumptions that will be clarified in a later section of this report.

Although the equations as presented in Pierson and Salfi (1977), for example, do not so state, there exists a minimum wind speed at 19.5 meters, or at any other height as corrected, such that the capillary waves will not be generated and such that the equations (1) and (2) will not hold. In wind-water tunnel studies, the minimum wind speed corresponds to a friction velocity, u_*, of 12 cm/sec. For this particular friction velocity, according to Pierson and Stacy (1973), the spectrum of the capillary waves increases by four orders of magnitude just as the friction velocity passes through this value. Apparently this is the friction velocity that corresponds to a wind profile near the surface of the water such that there can be an initial generation of the short capillary-gravity waves.

Models for U(z)

Models for the variation of wind with height in the first 150 to 200 meters above the sea surface have been a subject of investigation by those who study the planetary boundary layer for many years. The situation with reference to these models is still not fully settled.

Pierson, (1964) in the study of the generation of waves by wind was interested in the problem of relating the height of the fully developed wind generated sea (if one exists) to the square of the wind speed. At that time, there were three different equations of the form

$$H = A\,U^2/g \qquad (3)$$

and the values of the constant, A, were very different.

In these equations, the wind speed was measured at some height above the sea surface, the the significant wave height was given. It was noticed that of three equations that had been given, one, determined by Moskowitz (1964), referred to winds measured by the British weather ships that were equipped with the Tucker shipborne wave recorder. The anemometer height was 19.5 meters above the sea surface for these ships. Another relationship had been given by Sverdrup and Munk (1947), which was related to a wind measured at an elevation of 10 meters above the sea surface. A third relationship by Neumann (1953) referred to winds measured 7.5 meters above the sea surface with a hand-held anemometer on the bridge of a merchant ship. If the effect of variation of wind with height was considered, based on the then available drag coefficients as a function of the wind speed at 10 meters, much, but not all, of the discrepancy between these three constants could be removed.

In subsequent work on the development of spectral ocean wave forecasting models, the convention, for that series of studies, was that the wind should be referred to the anemometer height of the British weather ships. It was not clear at that time what the correct relationship was for the variation of wind with height, with reference to the drag coefficient.

Some of the results of Pierson (1964), can be found in Neumann and Pierson (1966); for example, the relationship between the drag coefficient at 10 meters and the wind speed at 10 meters, as defined by five different authors is given in one of the figures.

Further observational data and theoretical investigations have not effectively settled the problem of the appropriate equation to describe the variation of wind with height over the surface of the ocean. Two recent equations have been published, one by Cardone (1969)* and another, based upon a review of most of the available data, by Garratt (1977).

The governing equations for these two models for a neutrally stratified atmosphere is equation (4), where $\kappa = 0.41$.

$$U(z) = u_* \kappa^{-1} \ln (z/z_0(u_*)) \tag{4}$$

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*See Overland and Gemmill (1977).

The difference in the various theories is the form of the relationship for the roughness length, z_o, as a function of the friction velocity, u_*. In Cardone (1969), which will be referred to as model A hereafter, the roughness length is given by equation 5A, and in Garratt (1977), which will be referred to as model B hereafter, the roughness length is given by equation 5B. A third equation, (5C), for model C is shown that contains desirable features of both model A and model B.

$$z_o = 0.684\, u_*^{-1} + 4.28 \times 10^{-5} u_*^2 - 0.043 \qquad (5A)$$

$$z_o = 1.469 \times 10^{-5} u_*^2 = 1.44 \times 10^{-2} g^{-1} u_*^2 \qquad (5B)$$

$$z_o = 0.3905\, u_*^{-1} + 1.6046 \times 10^{-5} u_*^2 - 0.017465 \qquad (5C)$$

It should be noted that the earlier results which expressed the drag coefficient, as a function of the wind measured at 10 meters above the sea surface, can all be transformed into a form that describes the roughness length, z_o, as a function of the friction velocity. Thus it would be possible to obtain five more equations of a form similar to 6A, 6B and 6C to be compared.

For a neutrally stratified atmosphere, equation 4 and one of 5A, 5B or 5C close the problem and define the friction velocity (or the wind stress) as a unique function of the wind that would be measured at any height above the sea surface.

Figure 1 is a graph of z_0 versus u_* for model A and model B. In model A, the roughness length for low values of u_* becomes infinite. The roughness length reaches a minimum near a value of u_* of 20 cm/sec, and then increases again to values near 0.42 cm at a value for u_* of 105 cm/sec. For Model B, the friction velocity is zero at $u_* = 0$ and a portion of a parabola for other values of u_*. At 105 cm/sec, it achieves a value of approximately 0.16 cm. For a range of friction velocities from approximately 20 to 30 cm/sec, the two values for z_0 are close, but at higher values of u_*, they differ by more than a factor of two. Also plotted in Figure 1 as the vertical bar is the value of u_* of 12 cm/sec. It is quite possible that the roughness of the surface of the ocean is different for friction velocities less than this, and neither of these equations may hold because of the change in the character of the sea surface. For winds in the atmosphere that produce this average friction velocity (or wind stress on the sea surface) turbulent fluctuations will produce areas of roughened water and areas of glassy calm, as characterized in the literature by "catspaws."

Given either equation 5A or 5B, equation 4 defines the wind speed at any height, z, above the sea surface as a function of u_*. The wind speeds that result at 19.5 meters have been used on the horizontal axis of Figure 2 to produce a plot of u_* on the vertical axis. Since z_0

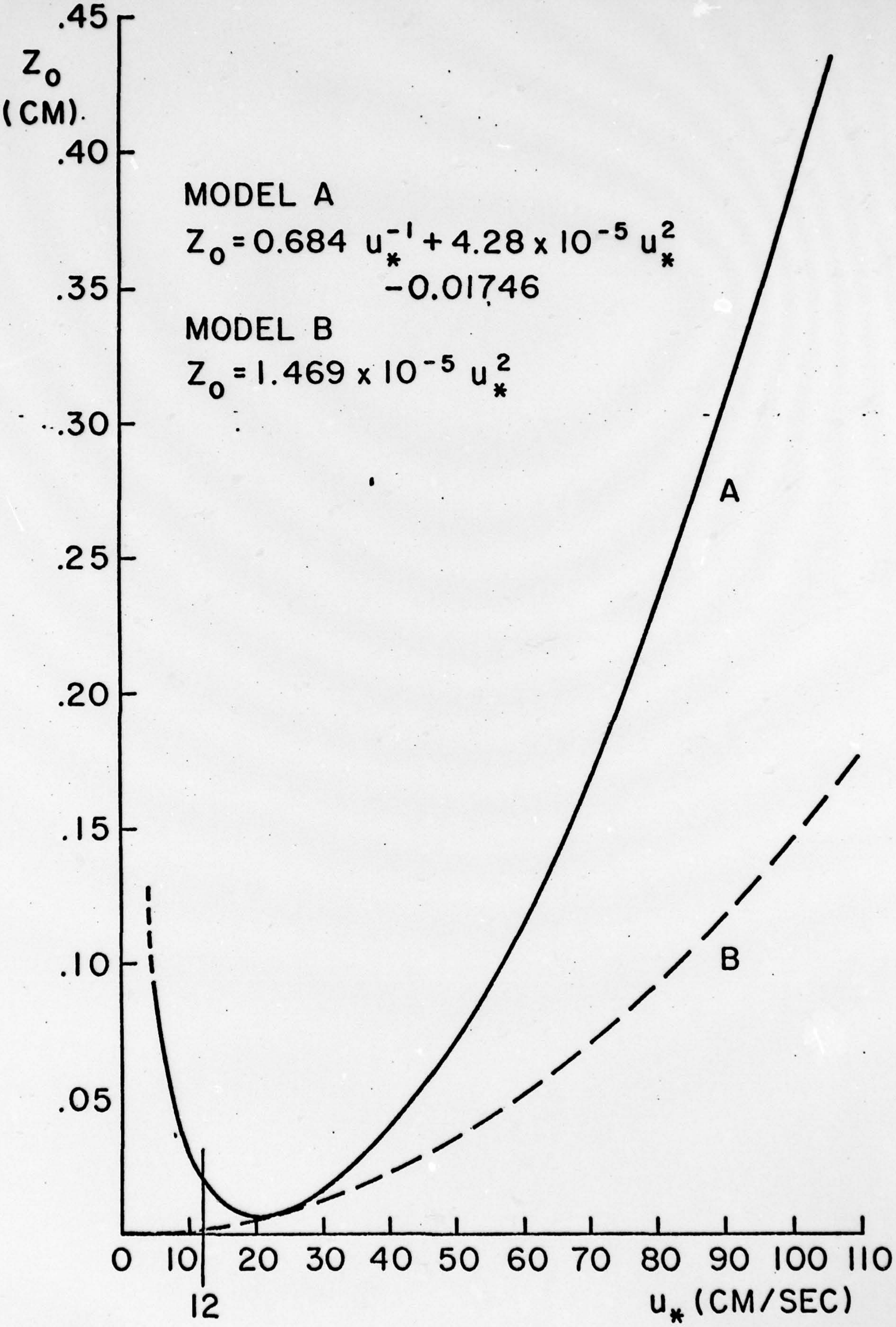


FIG. 1 Z_0 VERSUS u_*

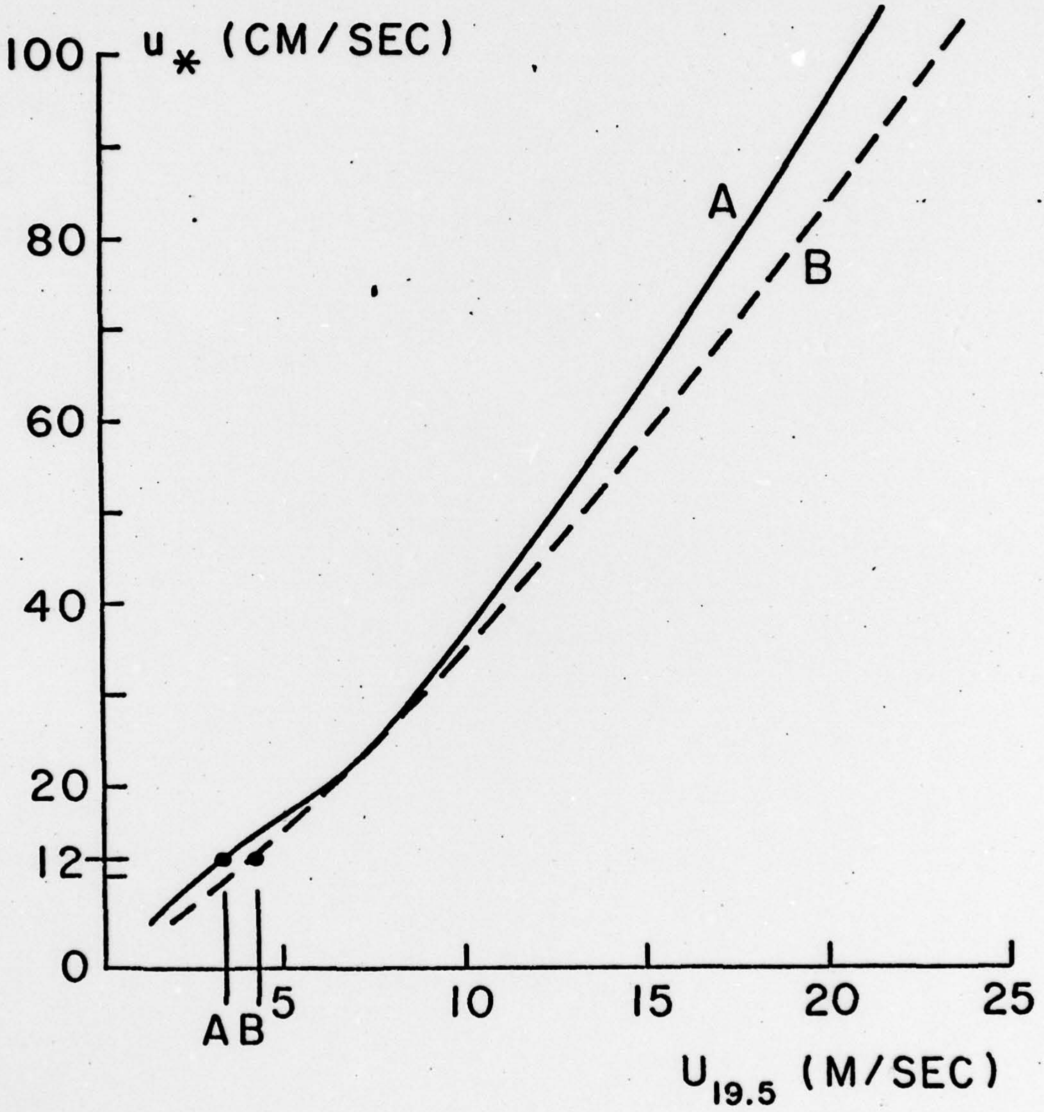


FIG. 2 u_* VERSUS $U_{19.5}$

for equation 5A is always greater than z_o for 5B, the wind for the same friction velocity will be higher for model B than it will be for model A. Conversely, for the same wind measured 19.5 meters above the sea surface, u_* will be higher for model A than for model B. Also shown on Figure 2 are two vertical lines corresponding to the intersection of curve A. and curve B with a u_* of 12 cm/sec. This suggests that for a wind less than approximately 3.4 m/sec for model A, and 4 m/sec for model B, the wind will cease to generate any waves at all.

There is always the possibility, expressed by many authors and most recently by Melville (1977), that the roughness length may not be simply a function of the friction velocity. Melville, for example, relates the Charnock number, $z_o g/u_*^2$, to a dimensionless wave height, which is in turn related to the actual gravity wave height and the phase speed of the short waves in the absence of swell. The nondimensional wave height becomes a function of three parameters, which are different quantities derived from the properties of ocean waves. If this is indeed the case for fully developed seas, where the spectrum of the waves would be fully defined and not varying, it would then follow that there would again be a unique relationship between u_* and z_o. However, the relationship would also be a function of fetch near coast lines and of fetch and duration and in midocean, as well as a function of other effects when dead seas and other sources of variation in the waves are considered.

The results by Melville are difficult to test at this stage of their development because they are somewhat vague in the meaning of the term, "short waves in the absence of swell." For example, if the short waves are those waves that very quickly achieve equilibrium with the wind and that correspond to frequencies of one and a half times the spectral peak and higher, then it would follow almost immediately that a unique relationship between the friction velocity and the roughness length would exist over most parts of the ocean. For the larger and higher waves on the sea surface, it appears that the wind profile shifts up and down over these waves and that it is the shorter waves and their roughness properties that determine the form of the wind profile over the water.

Melville (1977) also appears to believe that a friction velocity of 23 cm/sec is somehow related to the wind speed and phase speed of waves with a minimum phase speed. One wonders about this because if a friction velocity of 12 cm/sec is used, which, according to observation in a wind-water tunnel, is approximately the friction velocity that corresponds to the initial generation of waves, it can be calculated from model A that at a distance of 2.02 centimeters above the water surface the wind would be 23 cm/sec, and that for model B, at a distance of 0.227

centimeters above the surface the wind would be 23 cm/sec. Since it is the actual wind that generates waves, as shown by the theories of both Miles (1957) and Phillips (1958), a friction velocity of 12 cm/sec is not inconsistent with the initial roughening of the sea surface.

The real problem to be answered is why winds less than this do not generate any waves at all. The answer can be found in a summary of the research on the problem found in Phillips (1966), where it is shown that waves for a certain wind speed do not grow because viscous effects overcome growth effects and that, for wind speeds higher than this, growth effects overcome viscous effects. This particular theory does not explain the further growth in the capillary waves that was observed by Mitsuyasu and Honda (1974).

To continue, however, with the analysis of the consequences of model A and model B, Figure 3 shows a graph of the wind stress on the sea surface (u_*^2 times the air density, $\rho = 10^{-3}$), as a function of the wind that would be measured 19.5 meters above the sea surface in a neutrally stratified atmosphere. Again since z_0 for model B is less than z_0 for model A, the same wind speed produces a higher stress for model A than for model B. Despite the differences between these models for z_0, both of these curves are more or less parabolic in shape.

The importance of Figures 2 and 3 lies in the fact

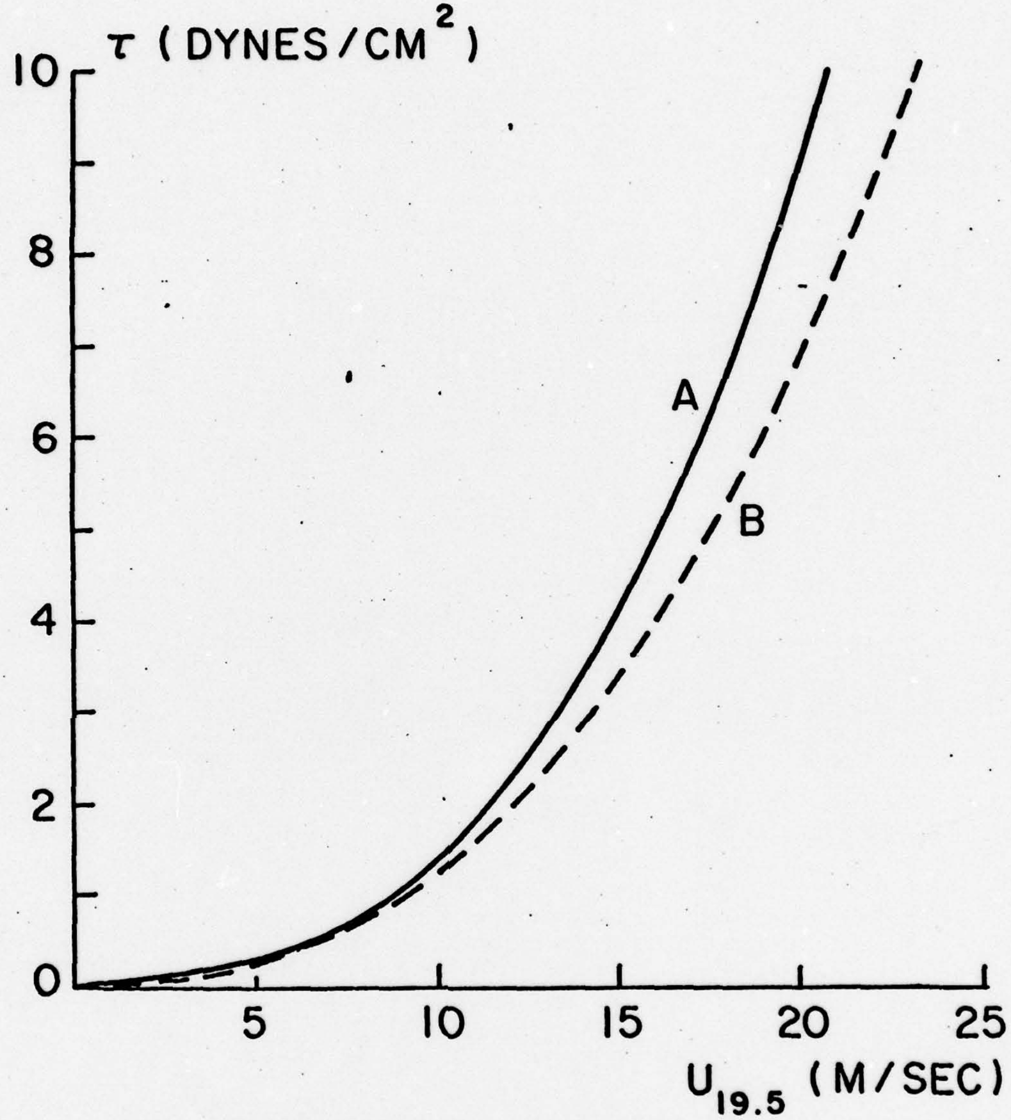


FIG. 3 STRESS VERSUS $U_{19.5}$

that these two different models for the same wind measured at an anemometer height of 19.5 meters, produce substantially different values for u_* and for the stress. Since most meteorological applications have to do with the wind measured at a known height above the sea surface, the friction velocity and the wind stress are derived quantities. The model that is used can produce quite different values for these two quantities for any further theoretical analysis.

Figure 4 emphasizes this effect. The actual and percentage differences in u_* are shown as a function of the wind measured at 19.5 meters in terms of the quantities that would be calculated with model A. The solid curve shows the difference between the wind stress that results from model A and the wind stress that results from model B for wind speeds measured at 19.5 meters. For example, at 20 m/sec, model A produces a value for u_* that is 11.8 cm/sec higher than that for model B. In the range from 5 to 8.5 m/sec, the differences are under 1 cm/sec.

The percentage difference obtained by dividing the value for the solid curve by the value of the friction velocity from model A is shown by the dashed line. The percentage differences can exceed 8% for winds above 12.5 m/sec and can be as high as 12.5% for winds over 20 m/sec.

The differences compound when the wind stress is

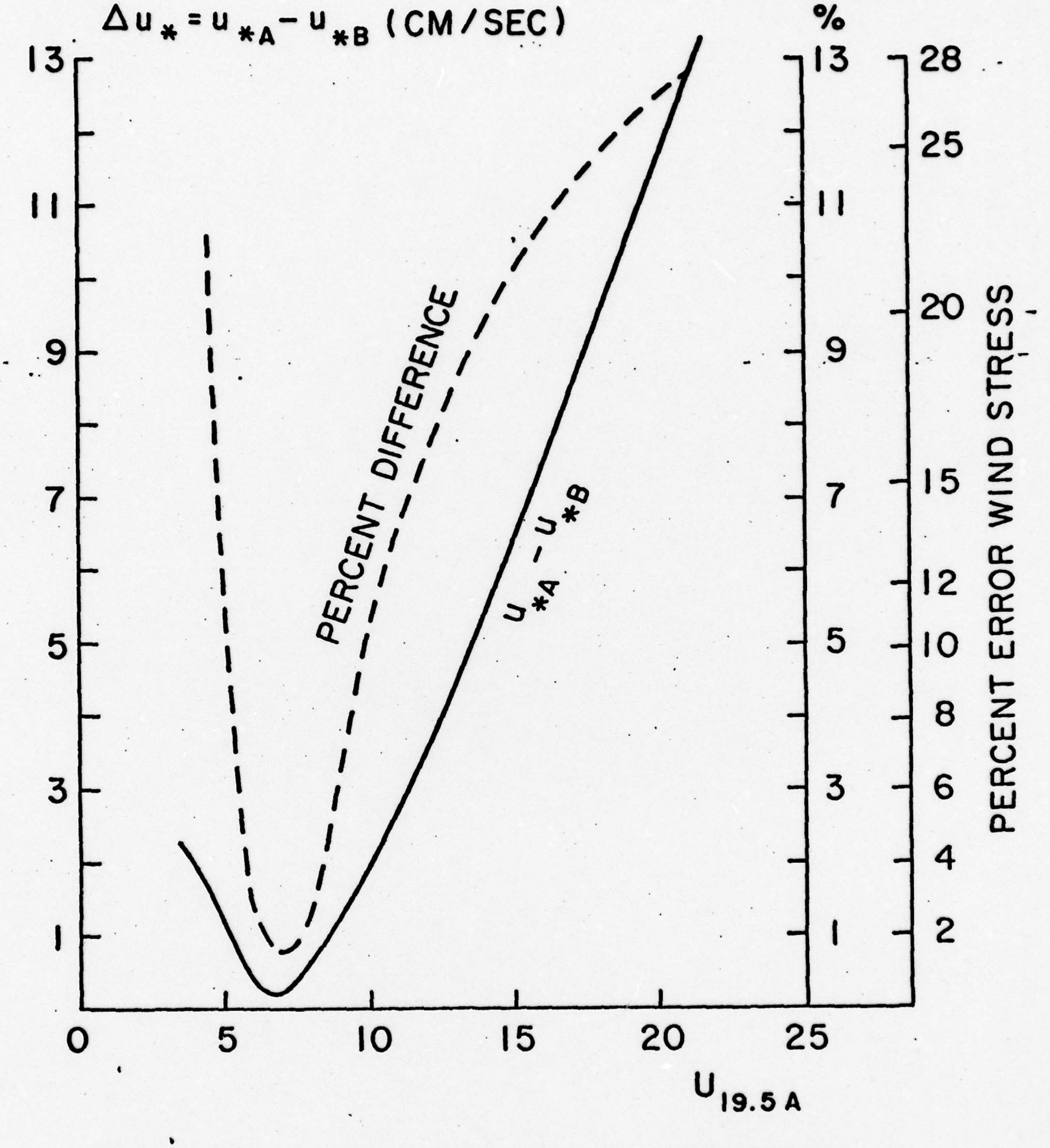


FIG. 4 ACTUAL AND PERCENTAGE DIFFERENCES IN u_*

calculated. The wind stress can differ by as much as 25 to 28% for the higher ranges of wind speed. For numerous theoretical investigations, it is important to be able to define the friction velocity and the wind stress. If this is done, the study must be interpreted with care and a reference must always be made to the exact relationship that has been used to calculate z_0 and u_*.

Model C

The layer of air closest to the sea surface must change from laminar flow to fully rough flow as the wind speed increases. Model A used the form chosen for z_0 so as to describe this change in the character of the air flow near the surface. The investigation by DeLeonibus (1971) indicates that the drag coefficient may first decrease with increasing wind speed and then increase. The equation for model B does not have this feature.

Model C is an attempt to fit model A for low values of u_* and model B for high values. The curve in Figure 5 is the graph of equation 5C. The dots are the values from equation 5A. The plus signs are the values for equation 5B.

The circled points are the values of z_0 and u_* given by Mitsuyasu and Honda (1974) as measured in a wind-water tunnel as a part of the study of the growth of capillary-gravity waves. The fetch in meters for each point is also shown. The values of z_0 for a wind-water tunnel are

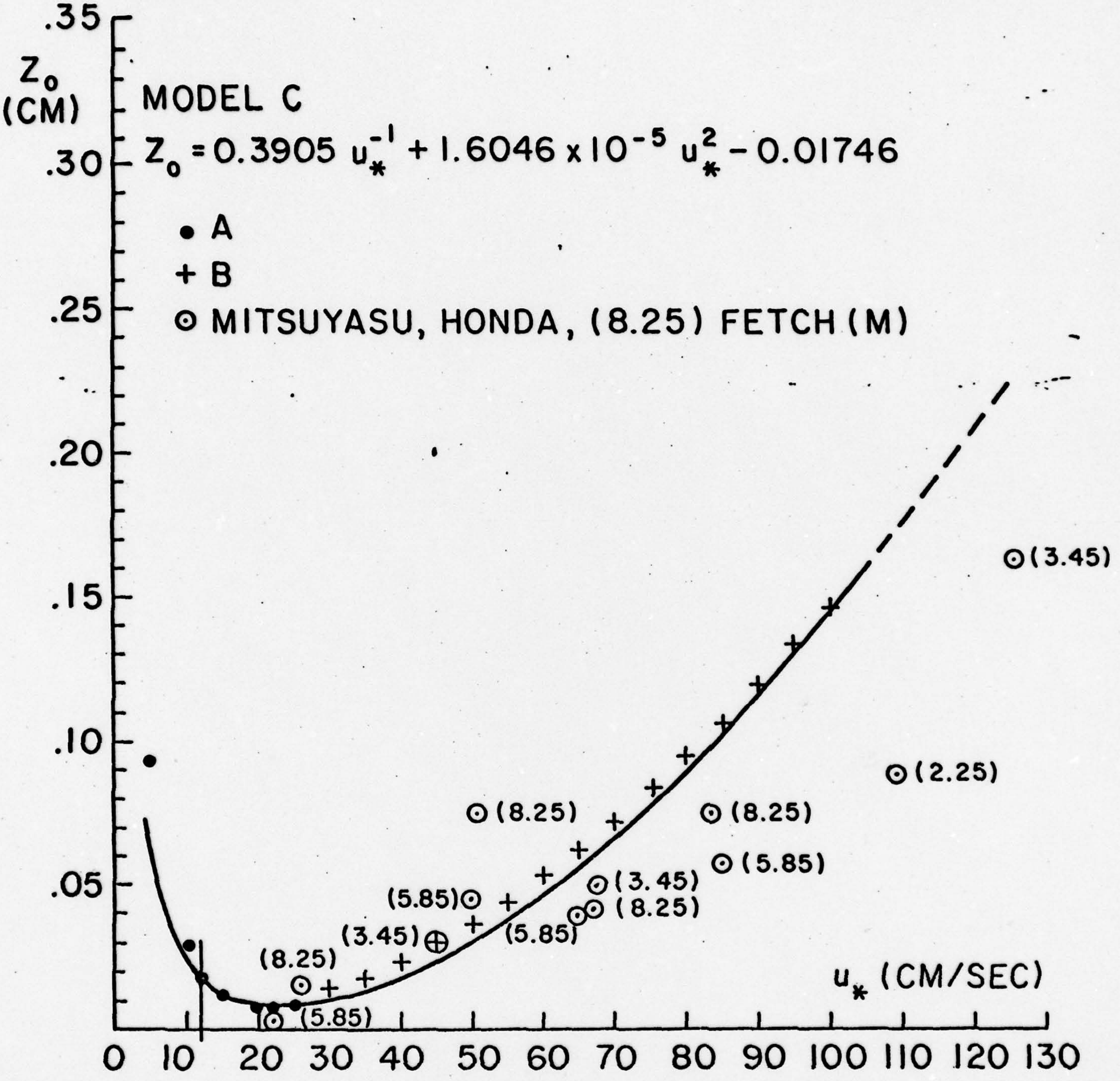
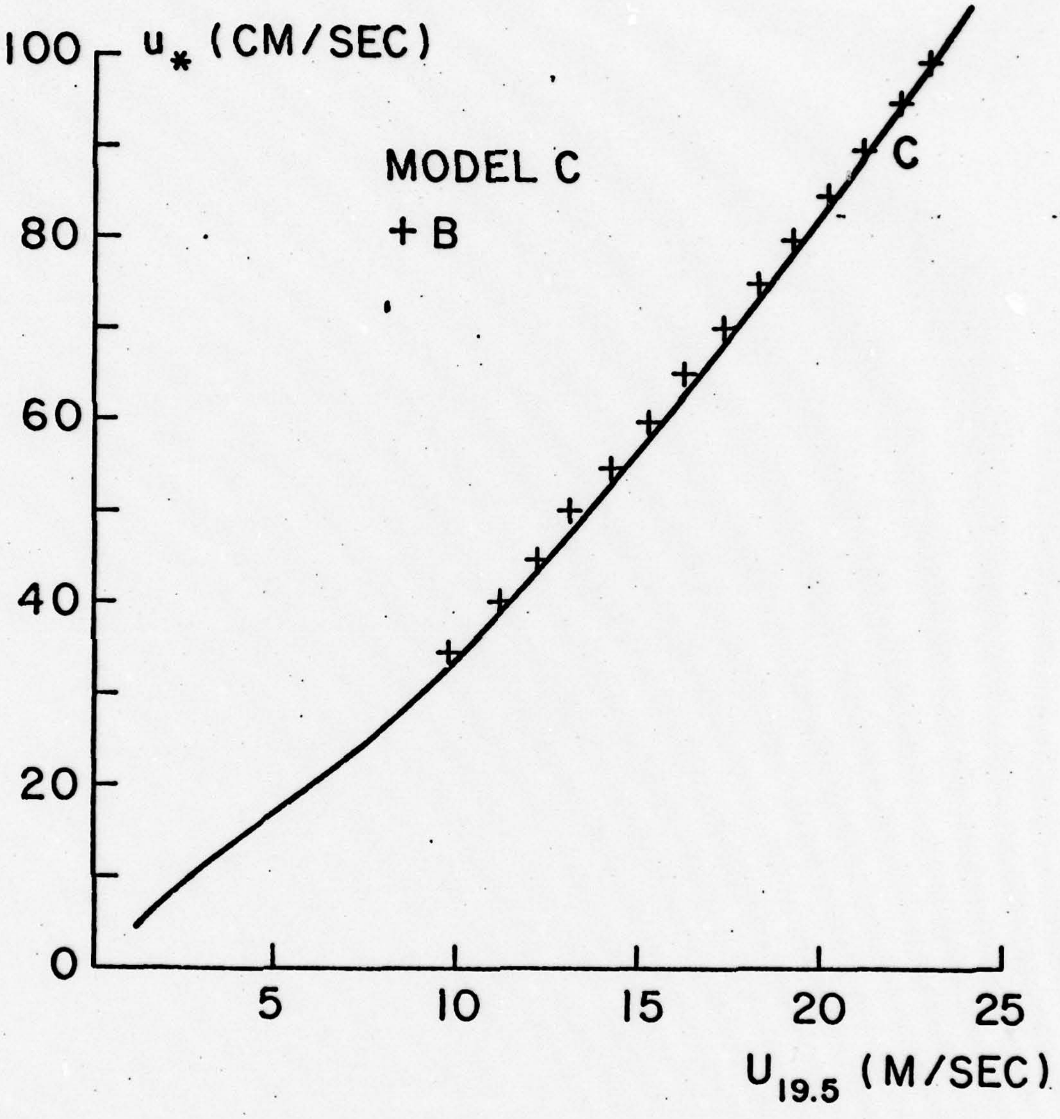


FIG. 5 Z_0 VERSUS u_* FOR MODEL C

smaller than those of model B (or C) and much smaller than those of model A for high values of u_*. Oceanic conditions with higher waves and with more breaking waves could easily increase z_0 so as to fit model B (or C).

Figure 6 is a graph of u_* as a function of $U_{19.5}$ for model C. Corresponding points for model A are virtually coincident with this curve for $U_{19.5}$ less than 9 m/sec. The points for model B are shown by the plus signs.

Table 1 gives the various quantities plotted in some of the graphs. There are large differences between the two values of $U_{19.5}$ for models A and B for high values of u_*, and there are large percentage differences for low values of u_*. Model C is within 5 cm/sec of model A for low values of u_*. All three models are close together for u_* near 23 cm/sec. The column labeled DIFF in Table 1 is the difference between model C and the closer of model A or B. It is doubtful that even SEASAT measurements will be able to resolve these slight differences as to the superiority of B or C. There are enough differences between A and either B or C to be of interest in models of the wind stress on the sea surface. The greatest difference between model B and model C is 26 cm/sec at u_* equal to 40 cm/sec.



F.IG. 6 u_* VERSUS $U_{19.5}$ FOR MODEL C

TABLE 1. z_0 (CM) AND $U_{19.5}$ (M/SEC) AS A FUNCTION OF u_* (CM/SEC) FOR THE THREE MODELS OF THE TEXT AND VARIOUS DIFFERENCES

u_*	z_0 (A)	z_0 (B)	z_0 (C)	$U_{19.5}$ (A)	$U_{19.5}$ (B)	$U_{19.5}$ (C)	B - A	DIFF
5	0.09357	0.00037	0.06104	1.21	1.90	1.26	0.69	.05
10	0.02838	0.00147	0.02319	2.72	3.44	2.69	0.72	- .03
12	0.01886	0.00212	0.01739	3.38	4.02	3.40	0.64	.02
15	0.01093	0.00331	0.01218	4.42	4.86	4.38	0.44	- .04
20	0.00702	0.00588	0.00848	6.11	6.20	6.02	0.09	- .09
22	0.00751	0.00711	0.00805	6.69	6.72	6.62	0.03	- .07
23	0.00808	0.00773	0.00800	6.95	6.97	6.96	0.02	.01
24	0.00885	0.00846	0.00805	7.20	7.23	7.26	0.03	.03
25	0.00981	0.00918	0.00819	7.44	7.48	7.55	0.04	.07
30	0.01702	0.01322	0.01000	8.52	8.71	8.91	0.19	.20
35	0.02767	0.01800	0.01336	9.53	9.90	10.15	0.37	.25
40	0.04128	0.02351	0.01797	10.50	11.05	11.31	0.55	.26
45	0.05757	0.02976	0.0237	11.45	12.17	12.42	0.72	.25
50	0.07638	0.03673	0.03046	12.38	13.27	13.50	0.89	.23
55	0.09761	0.04445	0.03818	13.28	14.34	14.54	1.06	.20
60	0.1212	0.05290	0.04681	14.18	15.39	15.57	1.21	.18
65	0.1471	0.06208	0.05633	15.05	16.42	16.57	1.37	.15
70	0.1752	0.07200	0.06674	15.91	17.43	17.56	1.52	.13
75	0.2056	0.08265	0.07800	16.75	18.42	18.52	1.67	.10
80	0.2382	0.09404	0.09012	17.58	19.39	19.48	1.81	.09
85	0.2730	0.1062	0.10302	18.40	20.36	20.42	1.96	.06
90	0.3100	0.1190	0.1169	19.20	21.30	21.34	2.10	.04
95	0.3492	0.1326	0.1315	19.99	22.23	22.25	2.24	.02
100	0.3905	0.1469	0.1469	20.77	23.16	23.16	2.38	.00

Consequences with Reference to the Verification of the SASS on SEASAT

The preceding material has shown that discrepancies of 10% and higher exist in the specification of the friction velocity given the wind measured at a known anemometer height above the sea surface, depending upon the model used. The relationship between the friction velocity and the winds over the surface of the ocean depends upon which of many models is used, according to the present understanding of the subject. Two of the models that have been compared produce this sort of discrepancy. For some applications of the data from SEASAT it will be important to make a choice, based upon the best available information, of a model for the calculation of the friction velocity and the wind stress.

However, at the start of this paper, the objectives of the SEASAT program with reference to the measurement of the wind near the surface of the ocean were given. It was pointed out that backscatter measurements have been referred to a wind measured at 19.5 meters above the sea surface, and that the objective is to specify the wind and <u>not</u> u_* and <u>not</u> the stress.

The problem can be put in a slightly different perspective. If any one of these models is correct, then that particular model defines the wind very close to the sea surface. In turn, that particular model defines how the shortest waves on the surface, namely the capillary-gravity waves, with the lengths to which the radar responds, are generated. Thus, if, say, model B is the correct one, then u_* and the wind profile for the first few meters above the surface are defined by that model and that is the relationship that produced the roughness elements that cause the backscatter. It follows then that the only requirement is to make sure that the winds at the assigned reference elevation have been correctly obtained. This means especially that a wind for the synoptic scale, averaged for preferably 20 to 30 minutes, should be used for verification.

As pointed out earlier, the two series of data that were used obtained winds at an elevation of about 150 meters above the sea surface and at an elevation of about 10 meters above the sea surface. These winds were changed to 19.5 meter winds by using model A as described above. The question then arises as to what kind of errors were introduced should model B have been the correct one. It is not difficult to show that the errors introduced by the use of a different model are not large, compared to the differences that have been described in the preceding material.

It should first of all be noted that the differences between the wind that would be measured at two different anemometer heights, a_1 and a_2, is a function solely of the logarithm of the ratio of these two heights and the friction velocity. This is indicated by equation (6).

$$U(a_1) - U(a_2) = u_* \kappa^{-1} \ln (a_1/a_2) \tag{6}$$

The roughness length cancels out when the difference in the winds at two elevations is computed, so that equation 6 applies for all three models.

The differences that result between the three models are that the wind at a particular anemometer height is associated with a different friction velocity as indicated by Figure 2 and Figure 6.

Figure 7 shows graphs of the difference between the wind at 19.5 meters and at 10 meters, based on the wind measured at 10 meters, that would result from model A and model B and also graphs of the difference between the wind at 150 meters and the wind at 19.5 meters for a wind measured at 150 meters. The errors in moving from 150 meters to 19.5 meters along a wind profile are related to the vertical distances between these two curves, and not to the fact that the friction velocities differ by fairly large amounts for high wind speeds. The same statement is true for the process of moving from 10 meters to 19.5 meters for the lower pair of curves.

With the effects of atmospheric stability neglected, the error that might be introduced by referring winds measured at different elevations above the sea surface to

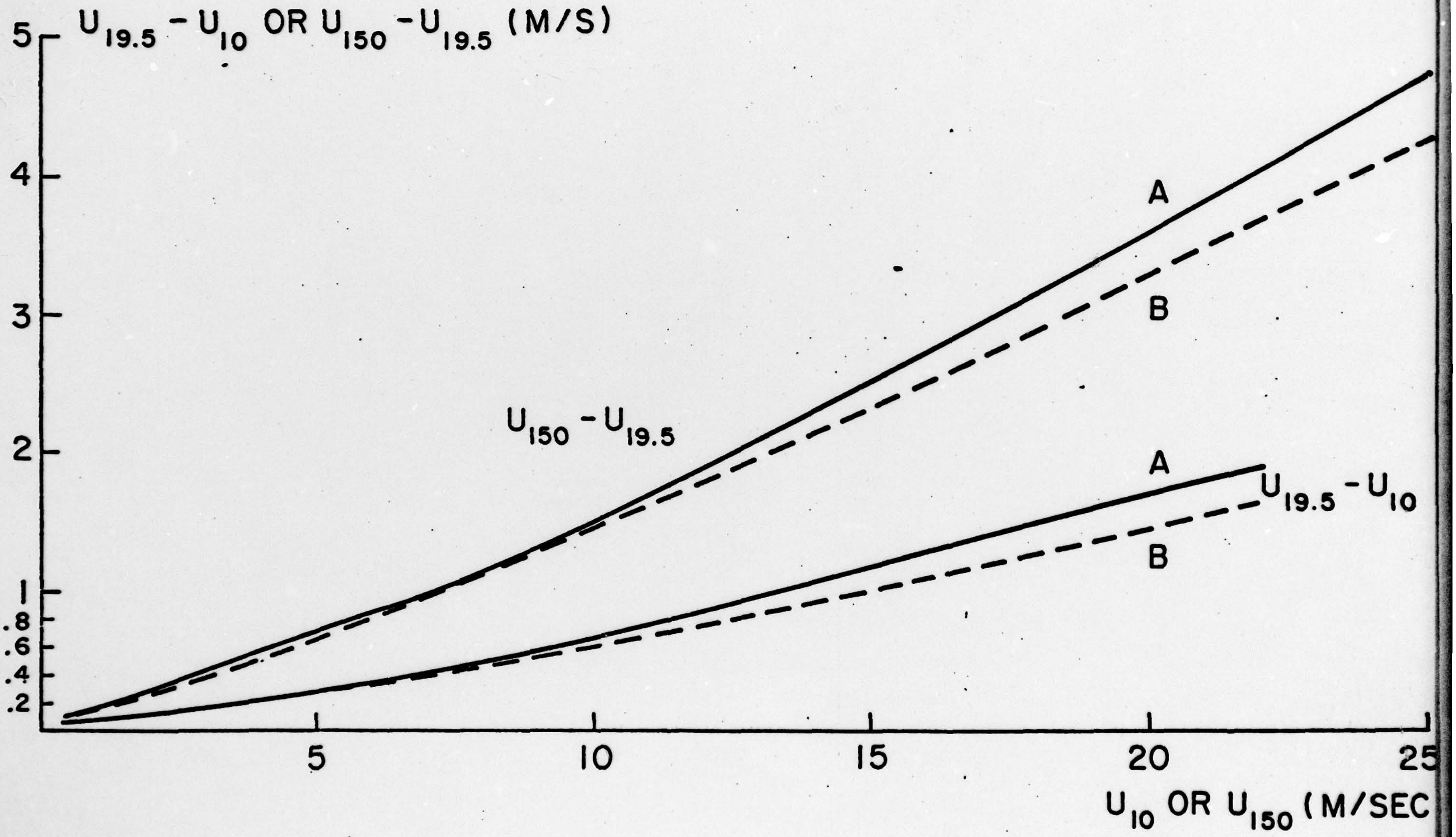


FIG. 7 RELATIONSHIPS AMONG U_{150}, $U_{19.5}$ AND U_{10}

a common elevation of 19.5 meters, are given in Table 2 in terms of Figure 7 and some of the values that were obtained during the AAFE circle flight measurements. The sensitivity of this correction to two of many different models is thus illustrated.

The wind speeds were corrected to 19.5 meters, using model A. Thus, these calculations indicate the type of discrepancies that might have been introduced if model B were the correct one to have been used. From Figure 7, and for the first series of the JONSWAP measurements, the winds that were measured at 10 meters are tabulated in Table 2 in the left hand column (actually recovered by going backwards from the wind at 19.5 meters). For a 4.4 m/sec, the correction required to refer the wind to 19.5 meters is approximately 0.2 m/sec for both model A and model B. Similarly for a wind of 5.2 m/sec, the correction is essentially the same. For a wind of 8.9 m/sec at 10 meters, the corrections are slightly different; for model A it is approximately 0.6 m/sec and for model B, 0.5 m/sec, so that the wind at 19.5 meters would be 9.5 and 9.4 m/sec respectively. The same kind of result is obtained for 11.2 and 12.6 m/sec so that the procedure of increasing the winds so that they are referred to an elevation of 19.5 meters introduces a discrepancy of 0.1 m/sec, or approximately a one percent difference for the JONSWAP series.

TABLE 2. ERRORS IN REFERRING WIND TO AN ELEVATION OF 19.5 METERS

JONSWAP SERIES

U_{10} (Measured)	CORRECTIONS		$U_{19.5}$		DIFF	%
	A	B	A	B		
4.4	0.2	0.2	4.6	4.6	0	0
5.2	0.3	0.3	5.5	5.5	0	0
8.9	0.6	0.5	9.5	9.4	0.1	1%
11.2	0.8	0.7	12.0	11.9	0.1	1%
12.6	0.9	0.8	13.5	13.4	0.1	1%

INERTIAL NAVIGATION SERIES

U_{150} (Measured)	CORRECTIONS		$U_{19.5}$		DIFF	%
	A	B	A	B		
18.2	- 3.2	- 2.95	15	15.25	0.25	1.7
24.7	- 4.7	- 4.2	20	20.5	0.5	2.5

The results are similar for that series of circle flights for which the winds were determined by means of inertial navigation data with the aircraft flying at approximately 150 meters above the sea surface. A wind of 18.2 m/sec measured at 150 meters would be decreased by 3.2 m/sec using model A and 2.95 m/sec using model B. The resulting winds at 19.5 meters would be 15 and 15.25 m/sec. The difference would be 0.25 m/sec with an error of 1.7 percent. The corresponding results for a wind near 20 meters are also shown. Two different models with marked differences in the form for z_0, marked differences in the values of u_* and very marked differences in the stress on the surface of the ocean still yield winds at 19.5 meters with differences of the order of 1 to 2 percent when measurements at 10 meters and 150 meters are referred to 19.5 meters.

Therefore, the SASS data should be verified against a wind measured at a known elevation above the sea surface, preferably corrected to 19.5 meters by means of an agreed upon relationship between the roughness length and the friction velocity. If this particular relationship is not the correct one, it will produce errors insofar as the specification of u_* and the wind stress are concerned that could be substantial. However, insofar as describing the wind at the particular elevation above the sea surface that has been chosen, the error will not be very large.

An anemometer height of 19.5 meters is suggested for verification purposes because (1) that height is closer to the heights of the anemometers on most ships than 10 meters and (2) estimates of the wind by observers on ships without anemometers correspond more nearly to this height than to 10 meters. Moreover, it is the height for which the wind is specified in FNWC models for most of Navy applications including wave forecasts that use the SOWM (Lazanoff and Stevenson (1975)).

These results demonstrate that the correction involved in adjusting all winds to an altitude above the sea surface of 19.5 meters is much smaller than the kinds of differences that can occur from different models relating the friction velocity to the roughness length in various theories. In essence, the correction involved is the difference of a difference. The major corrections are within 0.25 m/sec. They differ by at most 0.5 m/sec for high winds for corrections from 150 to 19.5 meters. The percentage errors are quite small.

No matter what the correct relationship is between the roughness length and the friction velocity for open ocean conditions, the wind at 19.5 meters will probably be quite well specified by the equations that have been derived that relate the wind to the backscatter measurements based upon the AAFE data. Whatever differences there are between the SASS values for the wind and the surface truth Data Buoy measurements, which will be used for verification, will have been caused by the inability to have specified the meteorologically determined winds for the AAFE data to within ± 1 m/sec. This is a problem in re-calibration, and not a permanent source of error in the SASS data.

The investigators who then use these winds in planetary boundary layer theories to compute the stress of the wind on the sea surface would then have a choice of many different models to make this last step. It would be essential in inter-comparing various theoretical results to document which of the many different models is used.

For purposes of using SASS data at JPL and at NEPRF and FNWC, model C is recommended at the present time for the calculation of the wind profile and the stress on the sea surface.

The Effects of Atmospheric Stability

The winds for the AAFE series of circle flights were not only referred to 19.5 meters, but also the effects of atmospheric stability were removed so that the wind referred to was the wind that would have existed for a zero air-sea temperature difference, given the wind that was measured at some other elevation and the air-sea temperature difference at the time of the measurement. It would be difficult to derive analytically results that would be as simple as the ones just presented for the neutral stability case. However, the equations that were used can be shown, and it is clear that the correction for atmospheric stability effects is substantially the same for the various models so that the conclusions reached on the basis of neutral stability will carry over to the case of non-neutral stability.

The appropriate equations, based on the Monin and Obukhoff (1953) similarity theory and the empirically determined nondimensional wind sheer profiles that were used, are given by equations 7 and 8. The correction to the wind profile is given by the function, ψ (z/L'). The stability length can be calculated from ship report data.

$$U(z) = u_* \kappa^{-1} \left(\ell n \, (z/z_o(u_*)) - \psi \, (z/L') \right) \tag{7}$$

$$L' = u_* \bar{\theta} \, U(a) \, \kappa^{-1} \, g^{-1} \, (\theta_a - \theta_s)^{-1} \tag{8}$$

Equation 8 is the first to be considered for any model that would extend the neutral case to stable or unstable air. The air-sea temperature difference would be the same. The anemometer height corresponding to the height at which the air temperature is measured, a, would be the same for any model moving either up or down on the wind profile, and the differences in the wind speed, U(a), would be comparable to those just tabulated. The major difference between the different values of L' that would result would be caused by the friction velocity that enters into this equation. The friction velocity can differ in the models by approximately 10 to 12 percent. Thus, the denominator of the ratio, z/L', that enters into the calculation of the wind at a given elevation, can differ by 10 to 12 percent.

In general, the correction to the wind at a given elevation above the sea surface is about 10 percent of the wind that would be calculated for a neutrally stratified atmosphere. And a change of 10 percent in the calculation of the height will not change this correction by, say, more than 10% of this correction. The wind calculated for two different models for z_0 and everything else the same in equations 7 and 8 should, therefore, not be substantially different at a given elevation above the sea surface.

Additional Theoretical Considerations

These results indicate that probably the best way to proceed in the demonstration that the SASS has met its objectives, is to refer the values of the wind from the radar measurements to the wind as measured at some elevation above the sea surface. This does not remove the problem of properly defining the relationship between the roughness length, the friction velocity and the wind stress in planetary boundary layer models. The results simply suggest that this problem need not be solved before the applicability of the SASS to measuring the winds is demonstrated.

There still remains the essential problem of relating the spectrum of the capillary-gravity waves, which is controlled very strongly by the friction velocity and by the wind close to the sea surface, to the backscatter measurements and to the total wind profile. The data obtained in wind-water tunnels can be helpful as shown in Figure 5. Further wind-water tunnel data for light winds would make it possible to define the wind that just generates the waves and the z_0 versus u_* behavior at this wind speed. The only way to proceed is to obtain extremely high quality data over the ocean so as to specify the spectrum of the waves correctly and so as to define the full wind profile for any stability condition. Encouraging results have been obtained recently as indicated by Mitsuyasu (1977). Much more data of this nature will be required before the full problem is solved.

These considerations also enter into the problem of a model for the planetary boundary layer to be used in eliminating the aliased winds that result from the backscatter measurements. This particular problem is much more extensive than can be discussed in this paper. It will be covered when procedures for eliminating the incorrect winds are described in a future paper.

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