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Some Recent Observations of Sea Surface
Elevation and Slope

by

H. G. Farmer

Technical Report

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ABSTRACT

Observations of the sea surface elevation and slope, upwind and cross wind, were made using a W.H.O.I. wave pole adapted with resistance wire sensing elements. The raw data is presented in bivariate distributions in combinations of these three variables, and various descriptive statistical parameters are given relating to the distributions and the original time base records.

Certain inconsistencies in the data are evident. The slope variances for three of the observations are in agreement with the results of Cox and Munk (1954). One other observation is in agreement if it is assumed that an error was made in noting down the instrument gain settings. The remaining three observations are not consistent with the other data nor with Cox and Munk. The cause for this can not be ascertained. There is definite evidence that the wave crests are sharpened and the troughs shallow and flat, i.e. as a trochoidal wave contrasted to a sine wave, and that the slopes generally on the downwind side of a wave are greater than those on the upwind side of a wave. These slopes as well as their difference decrease with decreasing elevation, crest towards trough.

A detailed discussion is given relating to two instrumental errors that were detected and removed from the data.

INTRODUCTION

During the month of October 1955 the Naval Research Laboratory and the Woods Hole Oceanographic Institution conducted a joint expedition to Bermuda where observations of radar sea return and of the ocean waves were made under varying sea conditions. The primary objective was to further the understanding of radar sea return and its relation to the actual sea surface. This report summarizes the results of the wave observations made by the W.H.O.I.

The research vessel "Atlantis" was equipped with three different wave measuring instruments. The principle observations were to be made from a W.H.O.I. wave pole (Farmer et al 1954) specially equipped with three resistance wire sensing elements to indicate sea surface elevation and slope. Should this equipment become lost or inoperative a W.H.O.I. Capacitance wave pole was kept in readiness. The third instrument was the Shipborne Wave Recorder developed by the National Institute of Oceanography, England, (Tucker 1952, 1954). The meteorological data collected was wind speed, from an anemometer mounted 18 ft. above sea level, wind direction, sea water and air temperature and humidity.

Depending on the forecasted weather the "Atlantis" was stationed at either of two previously selected positions such that the observations would be made on the windward side of Bermuda. The U.S. Hydrographic Office supplied daily twenty four hour wave forecasts which were telegraphed to Bermuda and then relayed



by radio to the "Atlantis". These were of considerable value in planning the operations from day to day.

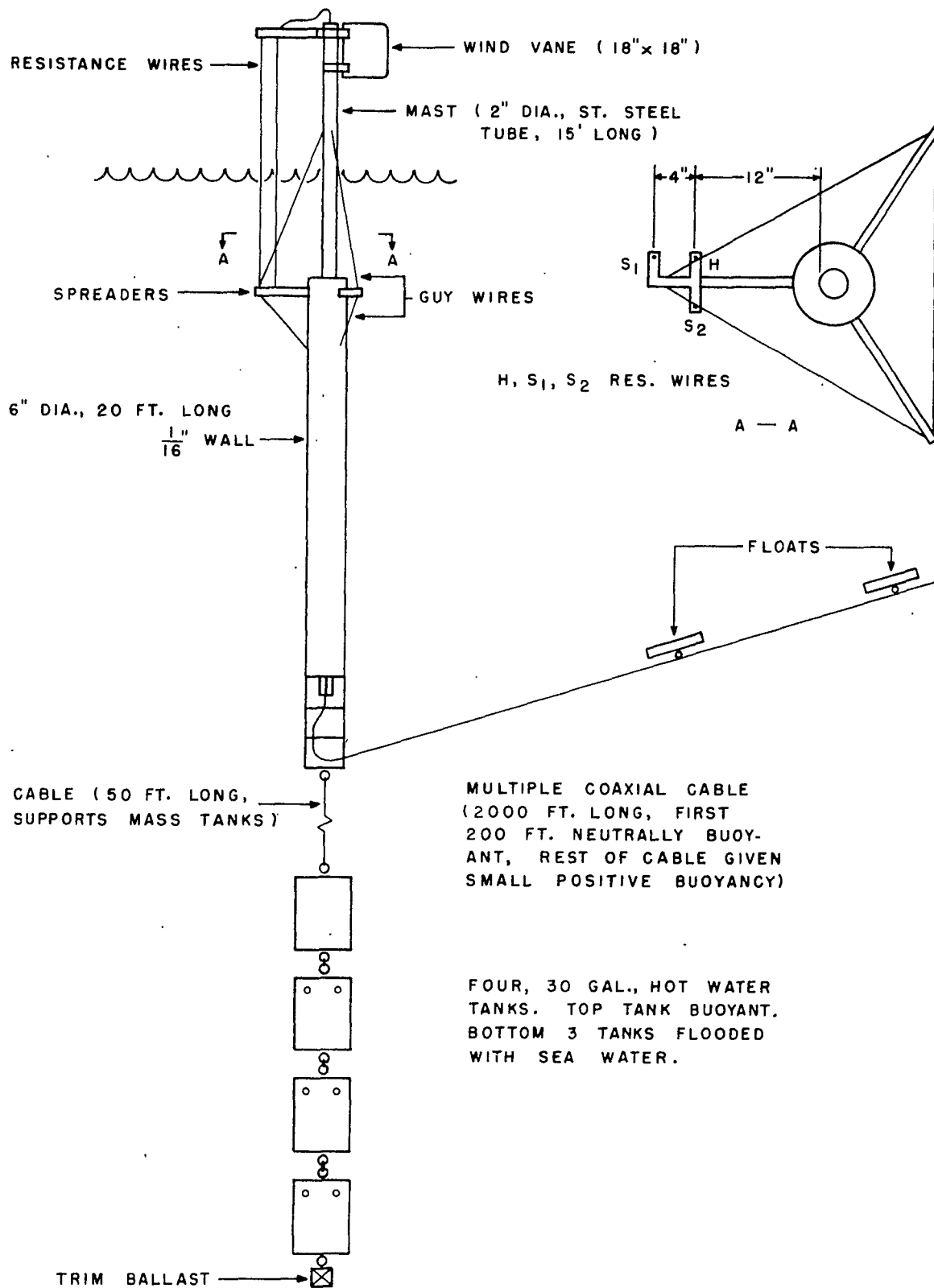
The slope as used in this experiment is actually an average slope determined from the difference in sea surface elevation measured on two vertically stretched wires spaced a fixed distance of four inches apart. Thus this slope differs from the true slope at a point on the surface as in the glitter patterns used by Cox and Munk (1954) and Schooley (1954). The proximity of such an average slope to the true slope is discussed in this report. Similar measurements of the average slopes have been made by Duntley (1950) and Gerhardt (1955). Duntley, using wire spacings of one inch and less, found a linear relation between slope variance and wind speed, but Cox and Munk found in comparing data that these results were two and one half times greater in magnitude than theirs. Gerhardt used a spacing of six inches (estimated). As yet the results of their data have not come to the attention of the writer. Both Duntley and Gerhardt made their observations from fixed platforms so that the sensing elements were rigidly held in space. This is the primary difference between these experiments and those described in this report.

INSTRUMENTATION

A wave pole similar in geometric shape to the W.H.O.I. wave pole described by Farmer et al (1954), was used as the stable platform or datum from which the measurements of sea surface elevations were made. An electrical cable connected the wave pole to the ship on which the various electronic and recording equipment was installed. The shape and overall dimensions of the wave pole are indicated in Fig. 1.

The sensing elements consisted of three stainless steel resistance wires, .020 inches diameter, which were supported parallel to and over the full length of the mast. The wave pole is ballasted so that the mast and consequently the resistance wires are approximately half submerged. Thus as the water level rises and falls with a passing wave, the resistance of the un-immersed portion of the wires is an indication of the elevation of the sea surface. A vane mounted on top of the mast orients the wave pole in the direction of the wind. The three sensing elements are so arranged that two wires are in a plane parallel to the up-downwind direction and two are in the cross wind plane. Each pair of wires has a constant spacing of four inches.

The electronic equipment associated with the elevation and slope computing circuits had been designed and built by the Engineering Experiment Station, Georgia Institute of Technology, for another research project. The equipment was transferred to the W.H.O.I. for possible use in this particular investigation. The electrical cable connecting the wave pole to the ship was 2000 ft. long and was composed of four RG 58 A/U coaxial cables



SCHEMATIC DIAGRAM OF RESISTANCE WIRE WAVE POLE

FIG. 1

married about a plastic covered B.T. cable. The composite cable was made buoyant by use of small plastic floats.

No report by the Engineering Experiment Station covering the details of the electronic equipment has come to the attention of the writer. A brief description of this equipment is as follows. The voltage which is used to excite the three sensing elements is generated by an oscillator operating at 120 kilocycles. The height computing circuit simply amplifies the voltage drop on the height sensing element, detects the signal and then amplifies again through several stages of D.C. amplification. In a slope computing circuit, say for the up-down direction, the two voltages representing the elevations on the up-downwind sensing elements, are each separately amplified and then the difference detected. This difference voltage is then amplified through several stages of D.C. amplification.

The data was then recorded on a Sanborn #150 four channel recorder. Two features of these circuits should be pointed out, the reasons for which will be evident in the discussion of the data. Firstly, all three computing circuits terminate in D.C. amplifiers. Should these D.C. amplifiers be unstable such that their zero operating level slowly drifts, the zero level of the recorded data will likewise drift. Secondly, in the slope computing circuits, the two input amplifiers that precede the difference circuit should be linear and identical in gain characteristics. The gain of one of these amplifiers is fixed while that

of the other is adjustable so as to account for small inequalities in the system connecting the sensing elements to the actual input of the computing circuit. The adjustment referred to as balance, is set, using an auxiliary circuit, so that there is zero output when there is zero slope at the sensing elements. If the balance is not adjusted for zero the effect is for a percentage of the height signal from one of the inputs, depending on the direction of imbalance, to be added to the slope. Thus, there is introduced a linear correlation between the slope and height. If the imbalance is great it can be visually seen in the data, otherwise a means of analysis must be used. The procedure for adjusting the balance proved to be satisfactory in the laboratory, however it did not prove so in the field.

The wave pole is of course not rigidly fixed in space but is in motion, principally in the vertical direction, horizontally in the plane of the direction of wave travel, and in rotation. An analysis encompassing these three degrees of motion with coupling terms has not been made. Neglecting the effect of the coupling terms an analysis of the vertical motion of the wave pole may be made. Its response is similar to the simple mechanical system consisting of a mass spring and dash pot under forced vibration. The exciting forces in this instance result from (a) the dynamic pressure, due to wave motion, which acts on the top and bottom of the main body of the wave pole and (b) the changing buoyancy of the system as the water level rises and

falls on the mast. The equation of motion becomes

$$M \ddot{z} + f \dot{z} + k z = (F_1 + F_2) \cos \omega t \quad (1)$$

The sea surface is represented by $a_0 \cos \omega t$, M is the total effective mass of the system, f the coefficient of damping, k the restoring force which is equal to the unit weight of water times the cross sectional area of the mast, ω the angular wave frequency, F_1 and F_2 the exciting forces, z the vertical coordinate and t time. The solution to this equation is

$$z = a_0 \mu (\varphi(T) + 1) \cos (\omega t + \psi) \quad (2)$$

μ is the amplification factor, ψ the phase angle and $\varphi(T)$ is a function of the period, T , and arises due to the dynamic attenuation of the pressure with depth. From previous experience it has been found that the ratio of the damping factor to critical damping is approximately $\frac{1}{2}$ and for the wave periods of interest i.e. $t \leq 15$ sec. the phase angle may be assumed 180° without serious error. Therefore the elevation indicated by the sensing elements will be

$$\xi = a_0 \cos \omega t - z \quad (3)$$

$$= a_0 [1 + \mu (\varphi(T) + 1) \cos \omega t] \quad (4)$$

The relative response of the system is consequently

$$R = 1 + \mu (\varphi(T) + 1) \quad (5)$$

and is shown in Fig. 2.

In the foregoing analysis the viscous forces due to the particle motion were not taken into account and were assumed small. When considering the horizontal motion of the wave pole the principal force arises from the particle motion. An estimate of this motion has been made, Farmer et al (1954), however, it was assumed in that case that the mass tanks were located immediately below the main wave pole. In the present wave pole these tanks were located approximately 50 ft. to 60 ft. below the main wave pole in order to improve the vertical response. Adjusting that analysis to fit the present wave pole, assuming a 7 second wave 6 ft. high, the amplitude of horizontal motion would be approximately 3.8% of half the wave length or 4.7 ft. The motion is 180° out of phase with that of the assumed sinusoidal wave. It is believed, however, that this amplitude is large in view of the results discussed subsequently. An adequate analysis of the rotational motion of the wave pole has not as yet been made so that there is no estimate of this motion.

In September of 1955 the W.H.O.I. had acquired a Shipborne Wave Recorder (subsequently to be referred to as SBWR) developed by the National Institute of Oceanography, England. The instrument was installed on the "Atlantis" and was used frequently on the October 1955 Bermuda cruise.

VERTICAL RESPONSE CHARACTERISTIC

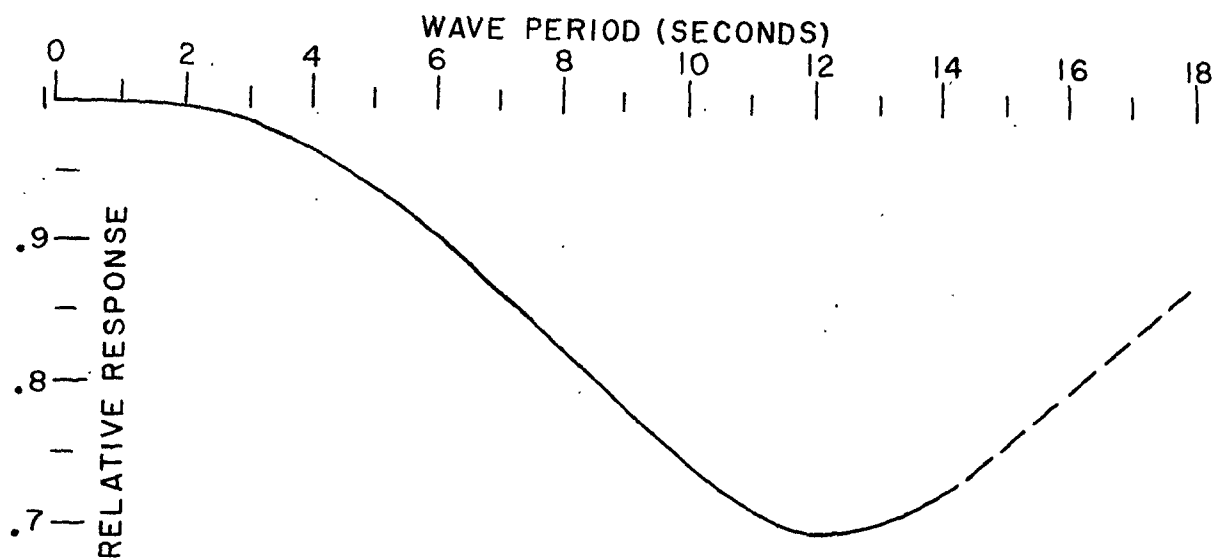


FIG. 2

REFERENCE AND COORDINATE SYSTEM THEORY OF OBSERVATIONS

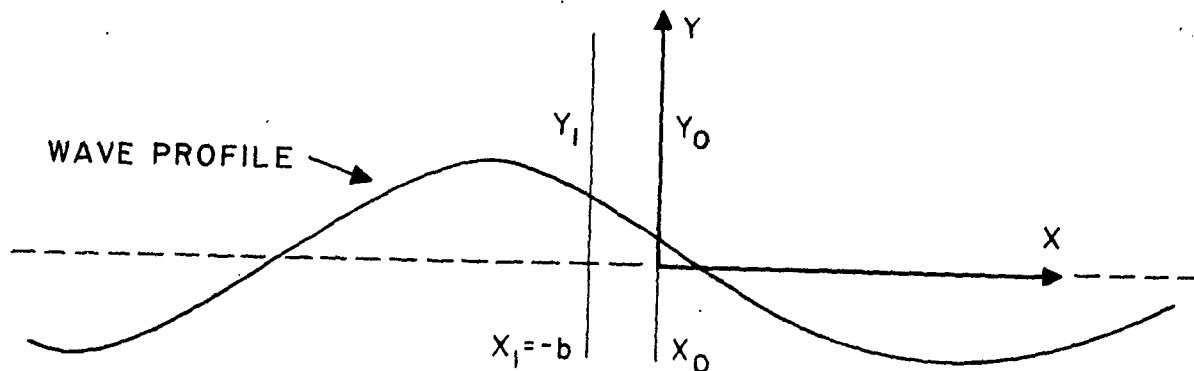


FIG. 3

THEORY OF OBSERVATIONS

In the experiment described in this report, the sea surface elevation was detected at two points in the plane of the up-downwind direction, a distance b apart. The difference in elevation was determined and a slope was defined as being equal to this difference in elevation divided by the horizontal distance b . More strictly speaking, this ratio is equal to the tangent of the angle the sea surface makes with a horizontal datum. However, for angles less than 30 degrees the tangent of the angle is approximately equal to the angle.

Referring to Fig. 3, and the coordinate system x, y , the horizontal axis x lies at the mean sea level positive to the right, and the y axis is positive vertically upwards. Consider a system of infinitely long crested waves traveling in the positive x direction. At the two points of observation (0) and (1) a distance x apart, the elevations, expressed in Fourier Series are

$$y_0(t) = \sum_0^{\infty} a_i \cos(\mu_i t + \epsilon_i) \quad (1)$$

$$y_1(t) = \sum_0^{\infty} a_i \cos\left(-\frac{x\mu_i^2}{g} + \mu_i t + \epsilon_i\right) \quad (2)$$

a_i is the amplitude of the component cosine waves, μ_i the angular frequency, g the acceleration of gravity and ϵ_i the random phase angle.

Averaging the square of these equations with respect to

time the mean square elevation σ_y^2 is given by

$$\sigma_{y_0}^2 = \sigma_{y_1}^2 = \frac{1}{2} \int_0^\infty A^2(\mu) d\mu \quad (3)$$

where, in converting to the integral notation $A^2(\mu) d\mu$ replaces a_i^2 and $A^2(\mu)$ is called the power spectrum, Rice (1944,45).

The slope $s(t)$, as defined above, is (4) and considering $x_0 = 0$, the origin of the coordinate system, this becomes (5)

$$s(t) = \frac{y_0 - y_1}{x_0 - x_1} \quad (4)$$

$$s(t) = \frac{y_1 - y_0}{x_1} \quad (5)$$

Introducing $x_1 = -b$ in (5) as indicated in Fig. 3, the slope on the side of the wave facing the positive x direction is negative in sign. This slope is that normally on the downwind side of the wave.

Substituting the expression for y_0 and y_1 , (1) and (2), in (5) after simplifying

$$s(t) = \sum_0^\infty \frac{\sqrt{2}}{x_1} \left(1 - \cos \frac{\mu_i^2 x_1}{g}\right)^{1/2} a_i \cos(\mu_i t + \epsilon_i + \phi_i) \quad (6)$$

Here ϕ_i is the phase angle resulting from a vector summation.

From (6) the slope spectrum is evidently (7) and the slope variance becomes (8).

$$S^2(\mu) = \frac{2}{x_1^2} \left(1 - \cos \frac{\mu_i^2 x_1}{g}\right) A^2(\mu) = X A^2(\mu) \quad (7)$$

$$\sigma_s^2 = \frac{1}{2} \int_0^\infty \frac{2}{x_1^2} \left(1 - \cos \frac{\mu_i^2 x_1}{g}\right) A^2(\mu) d\mu \quad (8)$$

In (7), considering the coefficient of $A^2(\mu)$, the term in brackets never exceeds the magnitude two and is an oscillatory function.

Using the series expansion of the cosine function, it is found that as

$$x_1 \rightarrow 0 \quad \bar{X} \rightarrow \frac{\mu_1^2}{g^2} = k^2 \quad (9)$$

$$\text{and} \quad x_1 \rightarrow \infty \quad \bar{X} \rightarrow 0 \quad (10)$$

(10) follows directly from the original definition of the slope and (9) is consistent with the slope spectrum as given by Cox and Munk (1954).

$$S_o^2(\mu) = k^2 A^2(\mu) \quad (11)$$

Further it may be shown that the spectrum

$$S^2(\mu) \leq S_o^2(\mu) \quad (12)$$

$$\text{from which} \quad \bar{X} \leq k^2 \quad (13)$$

The slope expressed in (7) is not the average slope at the point 0 or 1, but is actually an average slope over the distance x , immediately adjacent to either of the points 0 or 1. To investigate the correlation of the two variables $y_o(t)$ and $s(t)$ the covariance is determined as in (14) and (15). The correlation coefficient is then given in (16).

$$\mu_{11} = E(y_o(t) \cdot s(t)) \quad (14)$$

$$\mu_{11} = -\frac{1}{2x_1} \int_0^\infty \left\{ 1 - \cos \frac{\mu_1^2 x_1}{g} \right\} A^2(\mu) d\mu = -\frac{x_1}{2} \sigma_s^2 \quad (15)$$

$$\rho = \frac{\mu_{11}}{\sigma_s \sigma_y} = -\frac{x_1}{2} \frac{\sigma_s}{\sigma_y} \quad (16)$$

The σ_s and σ_y in (15) and (16) are as defined in (8) and (3).

They also are the standard deviations of the marginal distribu-

tions of the joint distribution in $y_0(t)$ and $s(t)$.

For a normal bivariate distribution, (Cramer, 1954), the conditional frequency function of $s(t)$ relative to some value y is also normal with a mean $\bar{m}_s$ given by (17) and a standard deviation (18).

$$\bar{m}_s - m_s = \rho \frac{\sigma_s}{\sigma_y} (y - m_y) \quad (17)$$

$$\bar{\sigma}_s = \sigma_s \sqrt{1 - \rho^2} \quad (18)$$

Here, and subsequently, the bar will be used to distinguish between properties of a conditional ($\bar{\sigma}$) and a marginal distribution (σ). Thus it is evident in (17) that the conditional mean slope is a linear function of the elevation.

Introducing the correlation coefficient from (16) we obtain (19). With the orientation of the two points x_0 and x_1 as in Fig. 3, i.e. x_0 the point of elevation observation, and x_1 in the negative x direction, upwind, $x_1 = -b$ and (19) becomes (19a).

$$\bar{m}_s - m_s = -\frac{x_1}{2} \frac{\sigma_s^2}{\sigma_y^2} (\gamma - m_\gamma) \quad (19)$$

$$\bar{m}_s - m_s = \frac{b}{2} \frac{\sigma_s^2}{\sigma_y^2} (\gamma - m_\gamma) \quad (19a)$$

(19a) shows that with this particular orientation of x_0 and x_1 , the slope of the equation expressing $\bar{m}_s$ as a function of y is always positive.

The way in which the elevation $y_0(t)$ and slope $s(t)$ became correlated may be qualitatively seen with the assistance of Fig. 4 a,b. The solid curve depicts the distribution if the slope was the mean slope at the point of observation. There is

no correlation and the mean slopes are independent of the elevation. In referring to Fig. 4b, as the point of elevation observation (2) is moved away from the midpoint, say towards (0); the elevation to be correlated with the slope determined from points (0) and (1) is slightly reduced. On the opposite side of the wave there would be an increase in elevation. In the foregoing analysis this elevation change would amount to $(y_0 - y_1)/2$. In Fig. 4a the arrows and the dashed curve indicate how the distribution would be skewed. Correlation is introduced but the marginal distributions are unaffected.

As will be pointed out later in the discussion it is of interest to investigate the magnitude of the correlation as given in (16). To do so exactly would require the evaluation of the integral in (8) using the spectrum proposed by Neumann (1953). This integral, however, can not be simply evaluated. Therefore as a first approximation the spectrum (11) will be used together with the expression for the energy spectrum given by Neumann. Cox and Munk have substantially verified this spectrum for the gravity wave range. The ratio of standard deviations of slope to elevation are found to equal equation (20) for fully developed seas.

$$\frac{\sigma_s}{\sigma_y} = \frac{4}{\sqrt{3}} \frac{g}{W^2} \quad (20)$$

g is the acceleration of gravity and w is wind speed at standard elevation. Therefore equation (16) will become

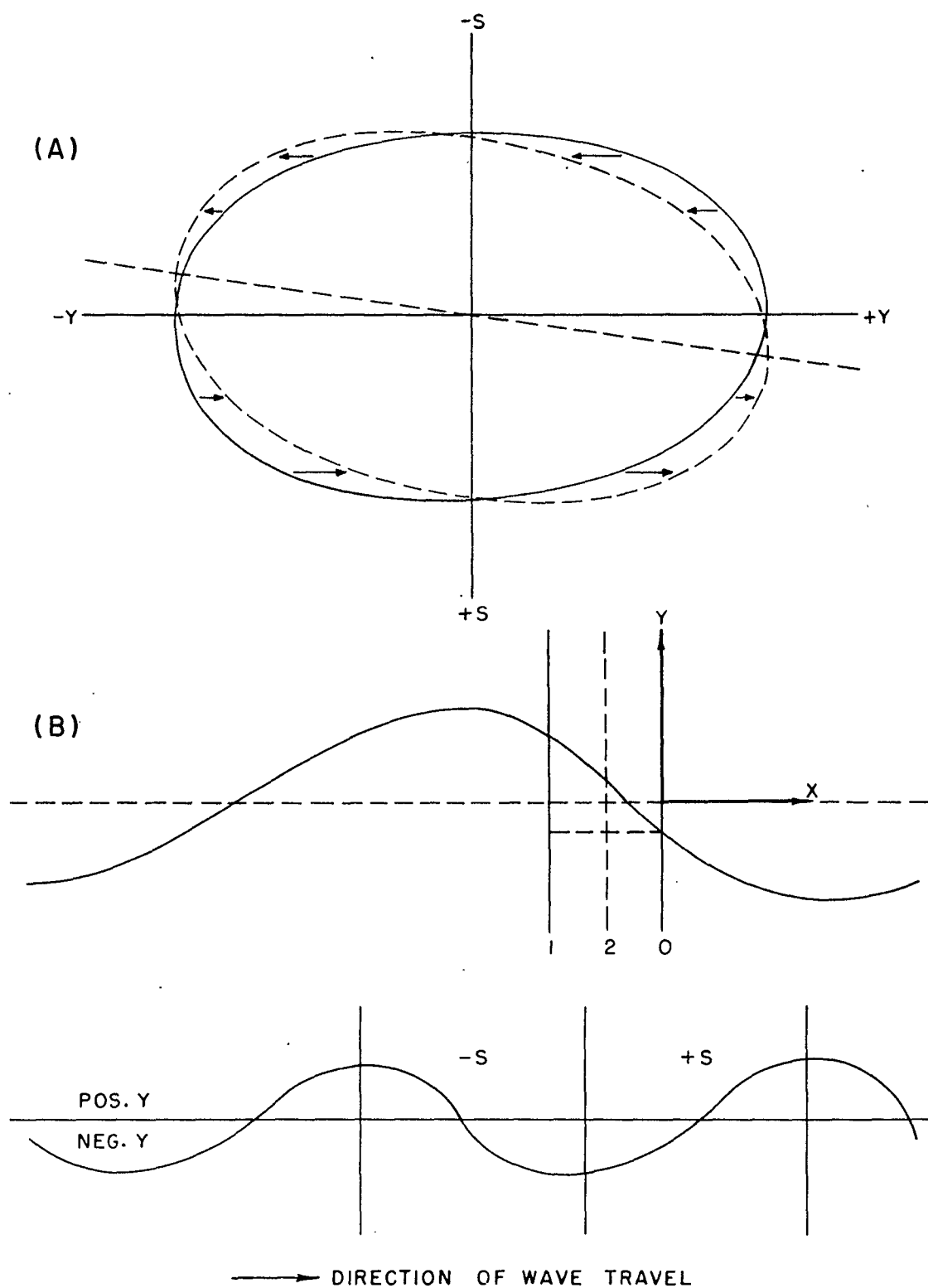


ILLUSTRATION OF YS CORRELATION

FIG. 4

$$\rho = -\frac{2}{\sqrt{3}} \frac{X_1 z}{W^2} \quad (21)$$

With x , equal to one-third foot, the correlation coefficients for wind speeds of 10, 20 and 40 ft./sec. are determined as .124, .031 and .0077 respectively. The slopes of the equations (19) or (19a) for the same wind speeds are found to be .091, .0057 and .00036 respectively. Only for the low wind speed of 10 ft./sec. does the correlation coefficient and the slope of equation (19) appear to be significant. Referring to the equation (18) the conditional slope standard deviation will differ from the marginal standard deviation by only a factor of 2% for winds of 10 ft./sec. For greater winds the difference becomes negligible.

ANALYSIS

During the course of the analysis it was discovered that the data contained some inconsistencies and in part some unaccountable errors such that it did not seem advisable to present the data in the originally planned form of a trivariate frequency distribution. Instead the data is presented in bivariate distributions of elevation and slope, up-downwind and cross wind. Thus, this section will be devoted to the necessary analysis and the apparant errors present.

At the time of recording the data the traces of the three individual channels were visually centered on the recording

paper. Early in the cruise it became evident that the mean or zero level on each of the channels slowly varied with time. Unfortunately it was not possible to locate the cause and correct for it. Subsequently, back in the laboratory tests have indicated that this may have resulted, at least in part, by an instability in the D.C. amplifiers at the output of each of the computing circuits. The drift was sufficiently great that it was necessary to eliminate it prior to any subsequent analysis.

The data was first read from the chart paper and tabulated so as to retain the simultaneity of the elevation and two slopes. Readings were taken at intervals of 1/5 second and the record length was from 12 to 18 minutes. Generally the fourth channel of the recorder was used for a wave record from the N.I.O. SBWR. There was no apparant drift in the SBWR so that it was used as a reference in the following procedure. For each variable, i.e. elevation, slopes and SBWR, the full record was split up into one minute intervals and the average of each interval determined using the 1 second observations. The means were then plotted versus time. It was noted that there was considerable scatter about the mean of the SBWR indicating that the wave periods were not being averaged out. Two minute averages were then determined. These were running averages, the mean of the 1 and 2 minute, the 2 and 3, and the 3 and 4, etc. Plotting these again, generally the scatter was within plus and minus 0.2 mm. (the SBWR calibration being 4 mm. = 1 foot). Three minute running averages were then taken and the SBWR scatter was reduced to

about plus and minus 0.1 mm. On the elevation and slope records when the two and three minute averages were plotted on the same axis, they fell on top of each other forming a reasonably smooth curve, through which a line was drawn freehand. From this curve, corrections reference to an arbitrary datum were determined, these corrections being every half minute (on three records the correction was every one minute). When collating the data into the frequency distributions each observation was corrected accordingly.

In a few instances when fitting the smooth curve to the two and three minute averages the points were such that it was not clear how the smooth line should be drawn. These portions of the data were not used. It is difficult to say, quantitatively, how completely this drifting mean is removed from the data for the mean itself is determined by an approximate procedure. There is also the effect of the finite jump at the end of a period with one correction value and the beginning of the following period with another correction value. On rare occasions this step exceeded one millimeter.

The frequency distributions for observations at six different times are included in Appendix A at the end of this report. There are three different distributions, elevation (y) vs. up-downwind (s_1), elevation (y) vs. cross wind slope (s_2) and up-downwind (s_1) vs. cross wind slope (s_2). The ys_1 distribution is given for each observation, however, the ys_2 and s_1s_2 distributions were not completed in all instances.

The coordinates are in millimeter units as read from the original record and corrected. The calibrations noted at the time of recording are indicated at the top of each sheet. Positive elevations are to the right of the mean and negative elevations to the left. For the up-downwind direction negative slopes are above the mean and positive slopes below. In referring to the sensing element arrangement in Fig. 1 and as discussed in the other sections a negative slope in the up-downwind directions indicates the water level is high on the s_1 wire and low on the y wire. Following the same code for the cross wind direction a negative slope on the distributions will fall either above or to the left of the mean and a positive slope below or to the right of the mean. Opposite each coordinate axis is the corresponding marginal distribution and their mean and variance, in millimeter units, are also indicated at the top of each sheet. The straight line drawn through the ys_1 and ys_2 distributions is the linear least squares regression line of the conditional mean slope on y . The mean slope was determined for each class interval of elevation and then in computing the regression line each mean was weighted according to the square root of the number of observations in that interval. Generally the mean slopes of the elevation class intervals falling within plus and minus two standard deviations fitted well the regression line, whereas outside this range there was considerable scatter. This is as might be expected considering that there are so few observations at the extremities of the distributions. For the 22 Oct.(2) data the

root mean square error between the regression line and the observations is .06 mm. when using the weight factor as described above, or if each mean is weighted equally the error is 1.0 mm. The equations of these regression lines are given in Table IV.

In all twenty records were obtained, however, because of the experimented errors that are apparently present all the data has not been analysed. The data of seven records is summarized in this report. Table I gives the general meteorological conditions on the indicated days. Table II summarizes the results of the SBWR, this data being taken at the same time as the wave pole observations.

To determine the properties of the slope distributions it has been necessary to assume that the observed conditional slope distribution relative to the regression line described above closely approximates the marginal distribution that should have been obtained. This is further discussed in the next section. Such an assumption requires that the correlation between the two variables be small. At the end of the previous section the correlations were estimated and found to be very small for winds exceeding 20 ft./sec. It is expected that some error will be introduced by the above assumption for winds in the order of 10 ft./sec. In Table III there is summarized the several descriptive statistical parameters of the individual elevation and conditional slope distributions. γ_1 is the standardized third moment or coefficient of skewness, and γ_2 is the standardized fourth moment or coefficient of excess. The number of maxima

per minute and the average period $\tilde{T}$ were determined from the original record, $\tilde{T}$ have been computed from the number of zero up-crossings. The column labeled (r) is, in the case of elevations, the ratio of the total number of positive elevations to negative elevations, and for up-downwind slope, the ratio of the total number of negative slopes to positive slopes (negative slopes being those generally accorded to the downwind side of the wave).

To investigate the variation of negative and positive slopes with elevation the least squares regression line through the conditional slope means was assumed to correspond to zero slope. For each class interval of height the root mean square (rms) positive and negative slope was determined and these values were plotted as a function of elevation. The coordinates were normalized by dividing each rms slope by the rms slope of the complete conditional distribution, and by using units of standard deviation for the elevation. A slightly different presentation is to use the cumulative rms slope, i.e. for each class interval of elevation the assigned cumulative rms slope is that for all the observations in that interval and above. The results of these computations are given in the figures in Appendix B. The lines connecting the small circles correspond to the positive slopes. The x's refer to the negative slopes and the dots refer to the difference between the negative and positive slopes.

DISCUSSION

In the foregoing sections the manner of data collection and analysis has been discussed. It is believed that this data is the first that has been collected and presented in the form as given in this report. Unfortunately the theory of ocean waves has not advanced sufficiently to account for the nonlinearities present in wind generated waves. Thus in attempting to understand and qualify the results in this report one is led to comparison to linear theories, other observations and as a final resort one's intuition.

An inspection of the frequency distributions and the results given in Table III indicate that there are two pronounced inconsistencies or errors present in the data. The first refers to an improper orientation of the regression line of mean slope on elevation and the second concerns an inconsistency in the slope calibration.

In the section on Theory of Observations it was shown, using a linear theory that the slope of the regression line on the ys_1 distribution should be positive. On the distributions the regression line should therefore run roughly from the upper left to the lower right. Only on the 22 Oct. (2) data does the regression line follow this trend. In Table III B it may be noted that the skewness of all the up-downwind slope distributions is negative. Such skewness indicates a greater probability (reference to a normal distribution) of large negative slopes and low positive slopes and a less probability of large positive

slopes and low negative slopes. Such skewness is in accordance with the results of Cox and Munk. From the original calibration of the slope computing circuits a negative slope would lie above the mean and a positive slope below the mean in a presentation as these frequency distributions. Therefore the skewness appears consistent with the calibration as well as observation. This has been pointed out in order to eliminate the possibility of the two wires, which determine the up-downwind slope, from being reversed. If there was a reversal of wires the positive and negative slopes would reverse on the distribution. It appears then that the only effect which would cause such an erroneous orientation of the regression line would be an improper adjustment of the balance setting as described in the section of Instrumentation. Unfortunately it is not possible to separately or independently determine the correlation due to imbalance and correct the data.

The effect of the correlation due to imbalance mentioned above is merely to skew the overall distribution. The marginal distribution of elevation is unaltered. Reference to the distribution figures, the conditional slope distribution for each class interval of elevation is displaced vertically by an amount proportional to the elevation. The overall conditional slope distribution about the mean regression line will be unaffected by this correlation with no error introduced into the calibration.

The sea conditions at the times of observation ranged rather broadly. Only on the 22 Oct. and 24 Oct. could the wave condi-

tions be considered even approximately pure sea (some swell was present) and fully developed. On the 14 Oct. the observation was immediately followed by a heavy squall. Swell was unnoticeable but the sea was not fully developed. On the 13 Oct. and 26 Oct. there was only a light breeze present, however on the former day, the 13 Oct., there was a moderate swell running while for the latter day a heavy swell was running. The conditional slope variances for these days are given in Table III B,C.

To provide a basis for comparison an estimate was made of the energy spectrum for the 14, 22, 24 and 26 Oct. and the corresponding slope variance determined. The slope spectrum used was that derived in the section Theory of Observations. These predicted slope variances are indicated in the last column of Table III B. The wind speed on the 13 Oct. was changing sufficiently to make a prediction difficult, but the conditions were such as to suggest results similar to the 26 Oct. Some variability in these variances should be expected. The spectrum proposed by Neumann was used and it was necessary to extrapolate the wind speed from a height of 18 ft. to 30 ft. (Hay 1955). These corrected wind speeds are indicated in the last column of Table III A. Also for convenience the results of Cox and Munk are indicated in Fig. 5.

The slope variances, up-downwind and cross wind, for the 13, 14 and 22 (2) Oct. are in fair agreement with the results of Cox and Munk and the predicted variances. The results of the 22 (1), 24 and 26 Oct. however are considerably greater than

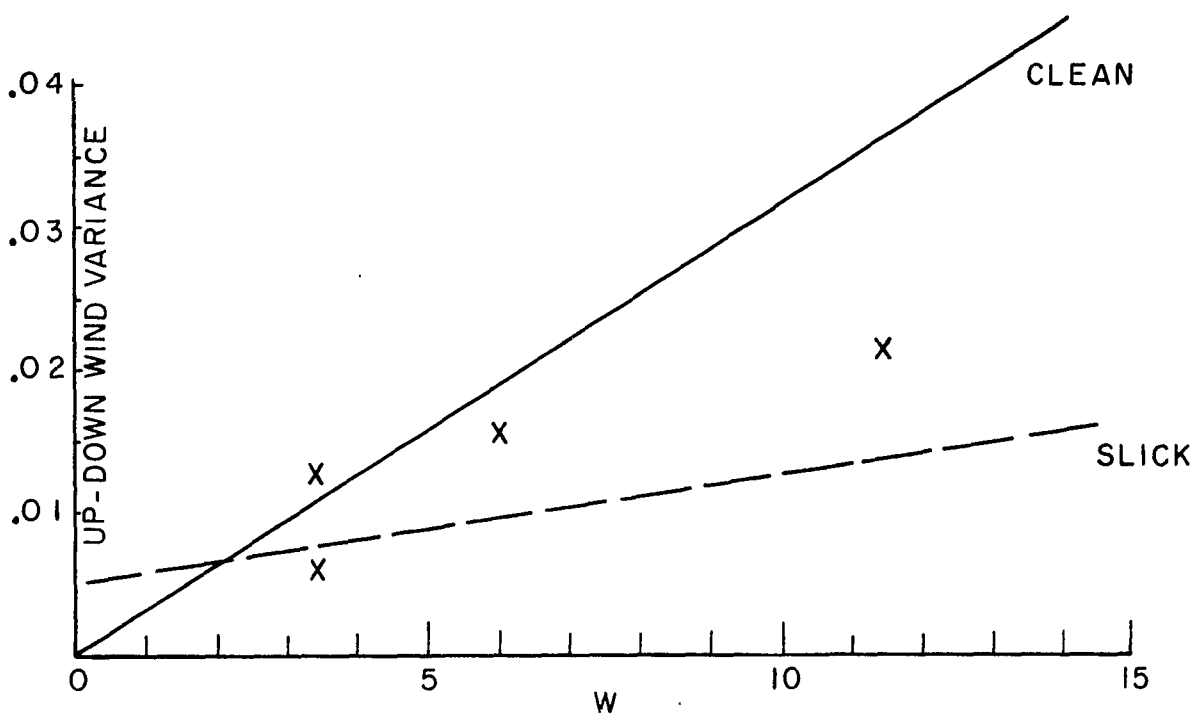
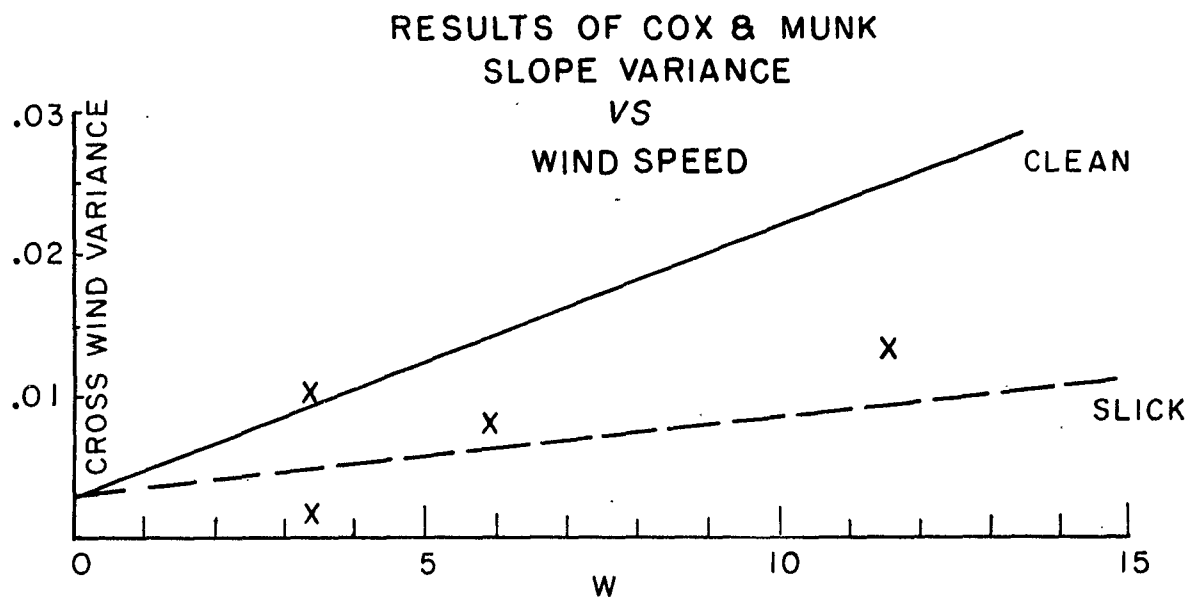
should be expected. There is the possibility that the gain settings which effect the sensitivity of the recorder, and consequently the calibration, were not correctly noted down at the time of recording. The calibration could have been multiplied by factors of 2, 2.5, 4, 5 etc. but it is believed that the most likely factors would have been just 2 and 4. If it is assumed that on the 26 Oct. the calibration was multiplied by 4, the slope variance is multiplied by 16 and good agreement is obtained with the prediction and Cox and Munk. The high swell present on this day and on the 13 Oct. would increase the variance over that for just the wind waves, however the scatter in the observations of Cox and Munk could account for this. The observations of the 24 Oct. can not be reconciled to the prediction by simple multiplication factors of 2 or 4. Oddly enough a factor of 2.5 would effect good agreement but this setting can not be justified. The results of the two records of the 22 Oct. differ considerably. It seems highly unlikely that two different gain settings could have been used. It is of interest to note that the slope variance and the average period for the 22 Oct. (1) data are about twice that for the 22 Oct. (2) data. Also the peakedness of the 22 Oct. (1) data is very small while for the 14 Oct. and 22 Oct. (2) data it is very high. As pointed out in the previous section the column (r) for the up-downwind slope is the ratio of the total number of observations of negative slopes to positive slopes. In all cases this ratio is less than unity, but the figures for the 22 Oct. (1) and 24 Oct (1) and (2)

are noticeably less than the others.

Again referring to Table III the coefficients of skewness of the elevation distributions are all positive. This skewness indicates a tendency for the wave crests to be more peaked and for the troughs to be flatter and more shallow, i.e. a tendency towards a trochoidal shape. The ratio (r) of the total number of positive elevations to negative elevations is also always less than unity and is therefore qualitatively in agreement with the positive skewness. (r), however, and consequently the elevation skewness will be effected by the horizontal motion of the wave pole. The computed (r) for simple trochoidal waves indicate similar values as that given in the Table III A, i.e. (r) equals .905 and .952 for trochoidal waves of steepness $1/20$ and $1/40$ respectively. Thus it may be reasonable to assume that the amplitude of the horizontal motion of the wave pole is not great, the value indicated in the section on Instrumentation being considered large. The skewness in both the elevation and up-down-wind slope distributions show some increase with wind speed and in the latter case show rough agreement with Cox and Munk. As there are so few observations and the scatter rather large no attempt has been made to seek a definite relationship between these variables.

In Appendix B figures indicating the variation of the rms slopes as a function of elevation are given. There is little to guide one in attempting to interpret these figures other than visual observation and intuition. In all instances there is con-

siderable variability in the normalized slopes above and below two standard deviations in elevation. This is accountable by virtue of the sparsity of observations, as can be noted from the marginal distributions given in Appendix A. The general trend of the positive and negative slopes and their difference is to decrease with decreasing elevation, crest towards trough. It is also clearly evident that the negative slopes are greater than the positive, this also having been indicated by the skewness of the full distribution. As a negative slope corresponds to that on the downwind side of a wave this is in agreement with what is generally observed. On the 26 Oct., when there was little wind and heavy swell, the difference in positive and negative slopes is very small. On the 14 Oct. and 22 Oct. the slope difference is distinct, approaching as much as 0.3 standard deviation at a positive elevation of about one standard deviation. The data of the 24 Oct. show differences even greater than this in the elevation range of plus and minus one standard deviation.



WIND SPEED IN METERS/SEC AT 41 FT. ABOVE SEA LEVEL

X REFERS TO DATA FROM 13, 14, 22(I) & 26 OCT.

26 OCT. CALIBRATION CORRECTED BY FACTOR OF 4

FIG.5

TABLE I
METEOROLOGICAL DATA

<u>Date</u>	<u>Bermuda Time</u>	<u>Approx. Position</u>	<u>OBS. WIND (18 ft.)</u>		<u>TEMPERATURE</u>		
			<u>Speed MPH</u>	<u>Dir True</u>	<u>Air</u>	<u>Water</u>	<u>Humidity</u>
13 Oct.	1550	33N 64W	5 inc.	----	80.0	80.0	----
14 Oct.	1035	33N 64W	20	135°	----	----	----
22 Oct (1)	1451	33N 64W	10-11	320°	77.5	78.0	59.5%
22 Oct (2)	1618	33N 64W	7-10	305°	75.0	----	66.0%
24 Oct (1)	1241	32-13 N 64-08 W	12-16	070°	74.0	77.5	----
24 Oct (2)	1647	32-13 N 64-08 W	11	070°	73.5	77.5	57.5%
26 Oct	1506	32-23 N 64-11 W	6	340°	77.0	77.5	62.0%

TABLE II
SHIPBORNE WAVE RECORDER

<u>Date</u>	<u>WAVE HEIGHT (ft.)</u>			<u>Crests Per Minute</u>	<u>$\tilde{T}$(sec)*</u>
	<u>$\bar{H}$</u>	<u>$\bar{H}_{1/3}$</u>	<u>$\bar{H}_{1/10}$</u>		
13 Oct	----	---	---	7.3	9.18
14 Oct	2.5	3.9	4.5	11.3	5.76
22 Oct (1)	1.6	2.6	3.2	11.1	6.94
22 Oct (2)	1.6	2.4	3.0	10.1	6.50
24 Oct (1)	4.2	6.6	8.3	7.7	8.82
24 Oct (2)	3.2	5.6	7.3	8.8	7.60
26 Oct	3.8	6.2	7.7	7.9	8.20

* Average period determined from number of zero up crosses per minute.

TABLE III

W.H.O.I. WAVE POLE

A. ELEVATION (σ in ft.)

Date	σ	γ_1	γ_2	Maxima Per. Min.	$\tilde{T}(\text{sec})$	r	Corr. Wind Speed ft/sec.
13 Oct.	.87	+.30	-.16	24.8	5.56	.893	9
14 Oct.	1.18	+.33	+.46	22.8	3.98	.902	33
22 Oct (1)	.76	+.11	+.13	34.1	3.70	.934	18
22 Oct (2)	.72	+.07	+.07	28.8	3.64	.964	15
24 Oct (1)	1.25	+.12	-.11	24.2	4.35	.986	24
24 Oct (2)	1.34	+.40	+.70	24.2	5.08	.902	18
26 Oct	1.21	+.18	-.07	24.8	5.90	.982	10

B. UP-DOWN WIND SLOPE (σ in rad.)

Date	σ^2	γ_1	γ_2	Maxima Per Min.	$\tilde{T}(\text{sec})$	r	Predicated $\sigma^2 \pm .002$
13 Oct	.013	-.15	+.09	114	1.56	.960	-----
14 Oct	.021	-.44	+1.35	160	1.52	.927	.016
22 Oct (1)	.041	-.38	-.10	115	2.16	.845	.012
22 Oct (2)	.016	-.71	+2.59	122	1.22	.918	.011
24 Oct (1)	.096	-.97	+.13	103	3.02	.760	.014
24 Oct. (2)	.126	-.51	-.78	107	3.22	.795	.012
26 Oct.	.103	-.11	-.87	103	3.46	.975	.006

TABLE III

C. CROSS WIND SLOPE (σ in rad.)

<u>Date</u>	<u>$\bar{\sigma}^2$</u>	<u>γ_1</u>	<u>γ_2</u>	<u>Maxima Per Min.</u>	<u>$\tilde{T}$ (sec)</u>
13 Oct	.010	+.18	-.18	112	1.03
14 Oct	.014	+.01	+.50	121	1.07
22 Oct (1)	----	----	----	155	1.35
22 Oct (2)	.008	-.36	+ 1.22	114	.98
24 Oct (1)	.029	-.45	-.17	111	1.66
24 Oct (2)	----	----	----	118	2.08
26 Oct	.031	+.10	-.79	118	2.42

TABLE IV

The least squares regression lines

<u>Date</u>	<u>ys_1</u>	<u>ys_2</u>
14 Oct	$m_{s_1} = 24.64 - .367(y-26.30)$	$m_{s_2} = 26.41 - .356(y-23.80)$
22 Oct (1)	$m_{s_1} = 22.27 - .121(y-25.05)$	-----
22 Oct (2)	$m_{s_1} = 23.19 + .166(y-26.30)$	$m_{s_2} = 28.42 - .089(y-26.30)$
24 Oct (1)	$m_{s_1} = 25.08 - .141(y-25.05)$	$m_{s_2} = 24.66 + .260(y-25.05)$
24 Oct (2)	$m_{s_1} = 23.44 - .206(y-27.55)$	-----
26 Oct	$m_{s_1} = 24.68 - .022(y-27.55)$	$m_{s_2} = 25.74 - .220(y-27.55)$

CONCLUSIONS

The primary function of this report is the presentation of the data given in Tables I and III and Appendices A and B. No definite quantitative conclusions may be drawn.

In considering a correlation of various aspects of the sea surface to radar sea return one of the features of the ocean waves believed important is their nonlinearity or asymmetry. Thus it was hoped that the bivariate distributions of elevation and up-downwind slopes and elevation and cross wind slope would yield information of this sort.

The general shape of the slope and elevation marginal distributions are essentially as would be expected. The waves appear to have higher crests and shallow flat troughs as depicted by trochoid in contrast to a sine wave. Also the negative slopes are generally larger than the positive slopes i.e. the downwind side of a wave is generally steeper than the upwind side. It is found that the difference in the rms negative and positive slopes are in the order of two tenths of the total up-downwind rms slope. Further these slopes and their difference tend to decrease with decreasing elevation, crest towards trough.

The slope variances of the 13, 14, 22(1) and 26 (calibration corrected by factor of 4) October are in essential agreement with the results of Cox and Munk. However the inconsistencies with the remaining data suggest the possibility of some instrumental error still undetected in the data. All the slope variances as indicated in Table III B and C are larger than

what were predicted and the results on slicks of Cox and Munk. Even though the results of Duntley were also larger than Cox and Munk this is difficult to rationalize in light of the spectrum derived for the average slopes as used in this experiment.

Nevertheless it is hoped that the data and results given in this report will be of interest and value to other investigators. The writer also believes that further experimentation of this sort, with improved instrumental techniques, will yield more conclusive results leading toward a better understanding of ocean waves.

ACKNOWLEDGMENTS

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APPENDIX A

TIME-1035 YS₁ m_y = 24.91 σ_y^2 = 22.13 y_{4mm} = 1 ft.

[illegible]

$$s \ 1 \text{ mm} = 2.1^\circ$$

y 4mm = 1 ft.

	ELEVATION	Y	SLOPE S ₂	
0.1				
2.1				
4.1				
6.1				
8.1				
10.1				
12.1				
14.1				
16.1				
18.1				
20.1				
22.1				
24.1				
26.1				
28.1				
30.1				
32.1				
34.1				
36.1				
38.1				
40.1				
42.1				
44.1				
46.1				
48.1				
50.1				

DATE - 22 OCT. 55

 $m_{S_1} = 22.54$ $\sigma_{S_1}^2 = 30.41$

s Imm = 2.1°

TIME - 1220

YS₁ $m_y = 24.32$ $\sigma_y^2 = 37.02$

y 8mm = 1ft.

	0.05	2.55	5.05	7.55	10.05	12.55	15.05	17.55	20.05	22.55	25.05	27.55	30.05	32.55	35.05	37.55	40.05	42.55	45.05	47.55	50.05
	ELEVATION										Y										
0.1																					
2.1																					
4.1																					
6.1																					
8.1																					
10.1																					
12.1																					
14.1																					
16.1																					
18.1																					
20.1																					
22.1																					
24.1																					
26.1																					
28.1																					
30.1																					
32.1																					
34.1																					
36.1																					
38.1																					
40.1																					
42.1																					
44.1																					
46.1																					
48.1																					
50.1																					
	2	6	16	41	69	145	292	377	414	343	304	159	124	60	32	13	2	1			2400

s 1 mm = 2.1°

$$y \quad 8\text{mm} = 1\text{ft.}$$
[illegible]

$$s \quad 1 \text{ mm} = 2.1^\circ$$
$$\sigma_{S_2}^2 = 6.36$$
[illegible]

s 1mm = 2.1°

y 4mm = 1 ft.

		ELEVATION										SLOPE %												
		0.05	2.55	5.05	7.55	10.05	12.55	15.05	17.55	20.05	22.55	25.05	27.55	30.05	32.55	35.05	37.55	40.05	42.55	45.05	47.55	50.05		
9.9																								
7.9																								
7.9																								
5.9										1		1										2		
5.9																								
3.9																								
3.9																								
1.9												1		1								2		
-1.9																								
+0.1								1		1	1	1	3		2		1					10		
0.1																								
2.1									1		2	2	1	2			1	1				10		
2.1																								
4.1									1	3	1	3	3	1			1	2				15		
4.1																								
6.1									1	3	6	6	9	3	1		1					30		
6.1																								
8.1							1			6	7	9	4	5	4							36		
8.1																								
10.1									6	10	13	10	14	5	3	1	1					63		
10.1																								
12.1							1	1	8	7	14	11	9	5	8	3						67		
12.1																								
14.1							2	1	7	7	12	9	15	6	4		1					64		
14.1																								
16.1								1	9	9	12	17	14	8	3	1						74		
16.1																								
18.1							1	5	14	13	20	17	26	6	4	1						107		
18.1																								
20.1								2	7	16	21	24	29	5	8	2						114		
20.1																								
22.1							2	5	12	15	22	28	29	8	9	1	1	1				133		
22.1																								
24.1							1	2	14	17	30	34	41	31	13	4		1				188		
24.1																								
26.1							1	13	29	45	34	38	18	17	8	2	3	1				209		
26.1																								
28.1							1	2	4	13	30	52	43	42	26	20	8	2				243		
28.1																								
30.1							1	1	6	15	32	51	44	49	37	30	5	2	1	1		275		
30.1																								
32.1								3	2	18	21	51	41	41	37	23	7	6	2	1		253		
32.1																								
34.1								4	12	29	30	42	28	26	20	8	5					204		
34.1																								
36.1							1	4	7	20	18	31	32	23	13	11	2	4				166		
36.1																								
38.1									2	11	11	19	15	20	11	4	3	1				97		
38.1																								
40.1									2	2	6	8	4	4	3							29		
40.1																								
42.1										1	2	1	2	1								7		
42.1																								
44.1																								
44.1																								
46.1																								
46.1																								
48.1							2	8	30	110	257	382	427	434	380	207	104	33	20	4		2398		
48.1																								
50.1																								
50.1																								
52.1																								

s 1mm = 2.1°

y 4mm = 1ft.

[illegible]

s 1 mm = 2.1°

$$y \quad 4 \text{ mm} = 1 \text{ ft.}$$
[illegible]

$$s \ 1 \text{ mm} = 2.1^\circ$$
$$y \quad 8 \text{ mm} = 1 \text{ ft.}$$
[illegible]

$$s \ 1 \text{ mm} = 2.1^\circ$$
$$y \quad 8 \text{ mm} = 1 \text{ ft.}$$
[illegible]

$s \ 1\text{mm} = 2.1^\circ$
$$\sigma_{S_2}^2 = 27.51$$

	0.1	2.1	4.1	6.1	8.1	10.1	12.1	14.1	16.1	18.1	20.1	22.1	24.1	26.1	28.1	30.1	32.1	34.1	36.1	38.1	40.1	42.1	44.1	46.1	48.1
9.9 7.9											SLOPE S ₂														
7.9 5.9																									
5.9 3.9																									
3.9 1.9																									
-1.9 +0.1										1														1	
0.1 2.1								1		2															3
2.1 4.1									3	2	2														7
4.1 6.1			1						2	4	7	1	1												16
6.1 8.1									1	5	9	12	3	6											36
8.1 10.1				1			4	3	12	15	14	11	7	1											68
10.1 12.1					1			5	19	21	31	18	10	2											107
12.1 14.1								7	14	25	45	37	20	7	3										158
14.1 16.1								7	17	26	46	45	32	15	4										192
16.1 18.1						1		4	15	33	48	38	37	16	16	1									209
18.1 20.1								2	4	30	36	41	43	33	13	3	1								206
20.1 22.1							1	4	6	13	32	34	38	32	16	8	1		1						186
22.1 24.1								3	5	16	15	43	49	45	35	16	3	1							231
24.1 26.1								2	2	3	13	24	38	37	30	33	4	4	1						191
26.1 28.1									2	6	12	15	31	32	37	23	19	6	4						187
28.1 30.1									1		7	16	18	32	55	57	22	11	7	2					228
30.1 32.1								1		1	10	13	22	29	41	41	38	33	9	1					239
32.1 34.1									1	1	1	8	16	21	51	48	48	33	11	2					241
34.1 36.1										1	1	11	14	41	31	37	32	22	11	1					202
36.1 38.1									1	1	4	3	9	14	27	29	24	18	8		1				139
38.1 40.1											2	1	11	11	15	23	15	15	3	1					97
40.1 42.1												2	4	7	5	4	8	8	2						40
42.1 44.1												1	1	1	1	4	5	2	1						16
44.																									

APPENDIX B

14 OCT 55

UP-DOWN WIND SLOPE

S_1

RMS SLOPE

σ / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

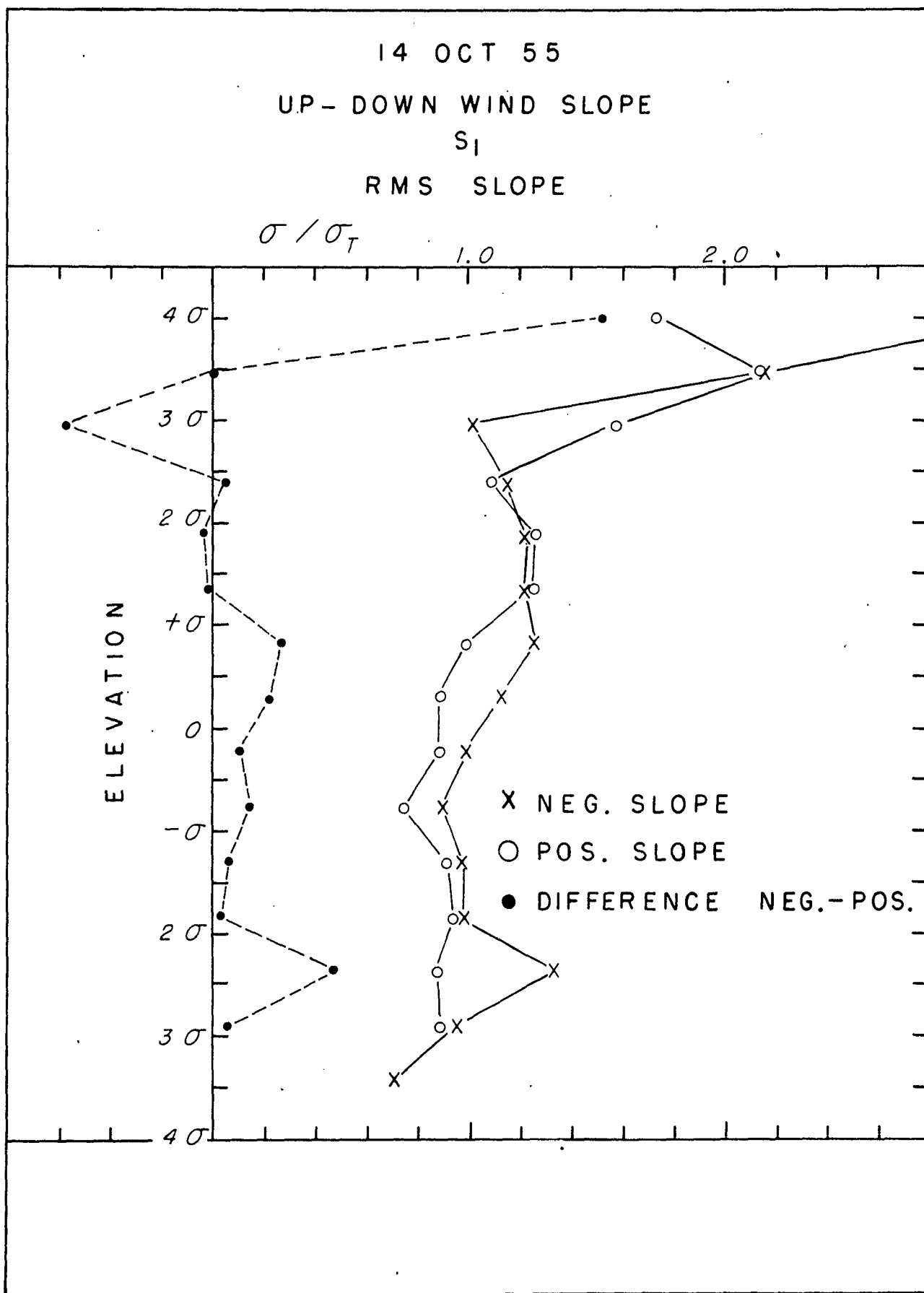
3σ

4σ

X NEG. SLOPE

O POS. SLOPE

● DIFFERENCE NEG.-POS.



14 OCT 55

UP-DOWN WIND SLOPE

S_1

CUMULATIVE RMS SLOPE

σ_C / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

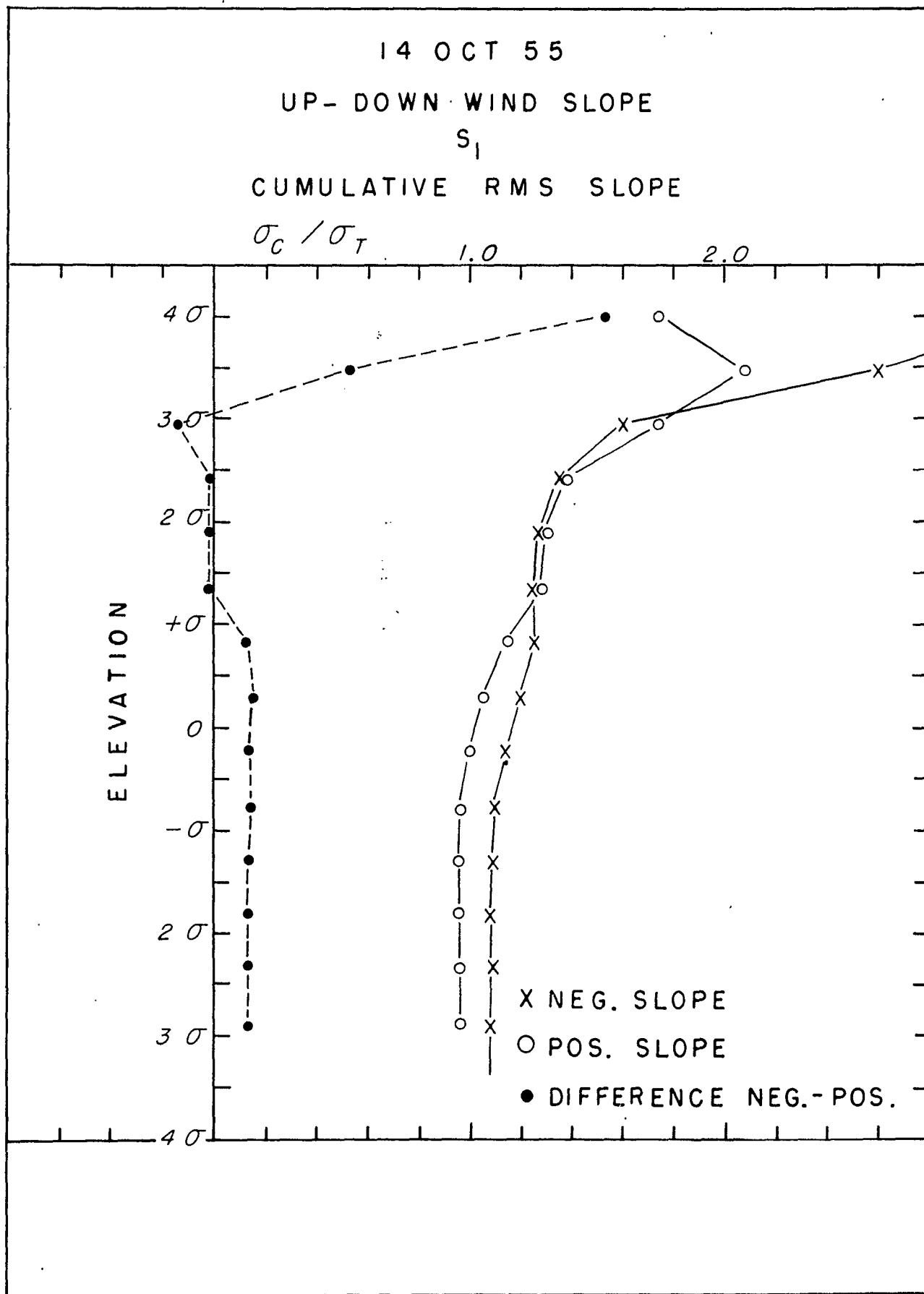
3σ

4σ

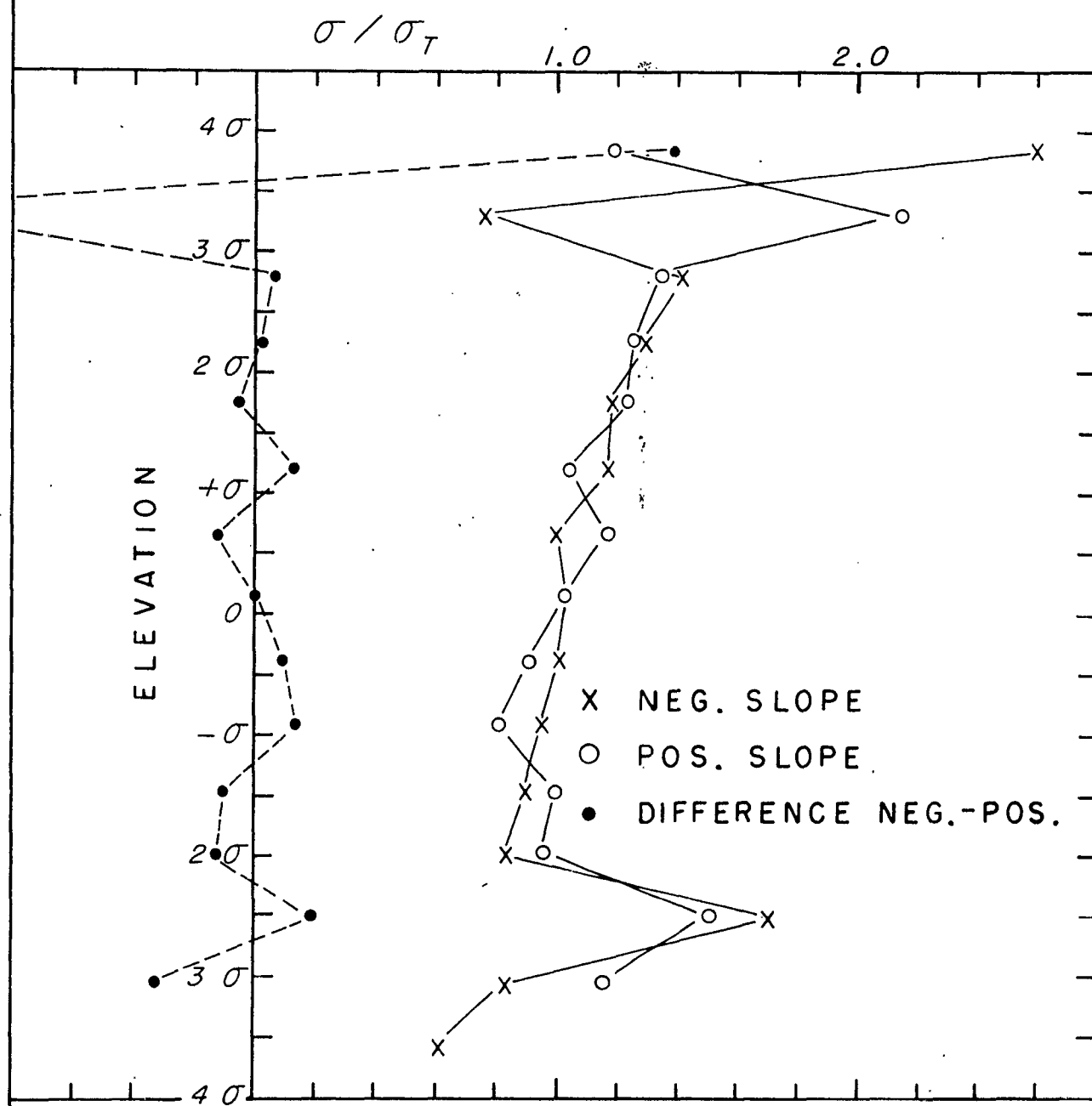
X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



14 OCT 55
CROSS WIND SLOPE
 S_2
RMS SLOPE



14 OCT 55

CROSS WIND SLOPE

S_2

CUMULATIVE RMS SLOPE

σ_C / σ_T

1.0

2.0

ELEVATION

4 σ

3 σ

2 σ

+ σ

0

- σ

2 σ

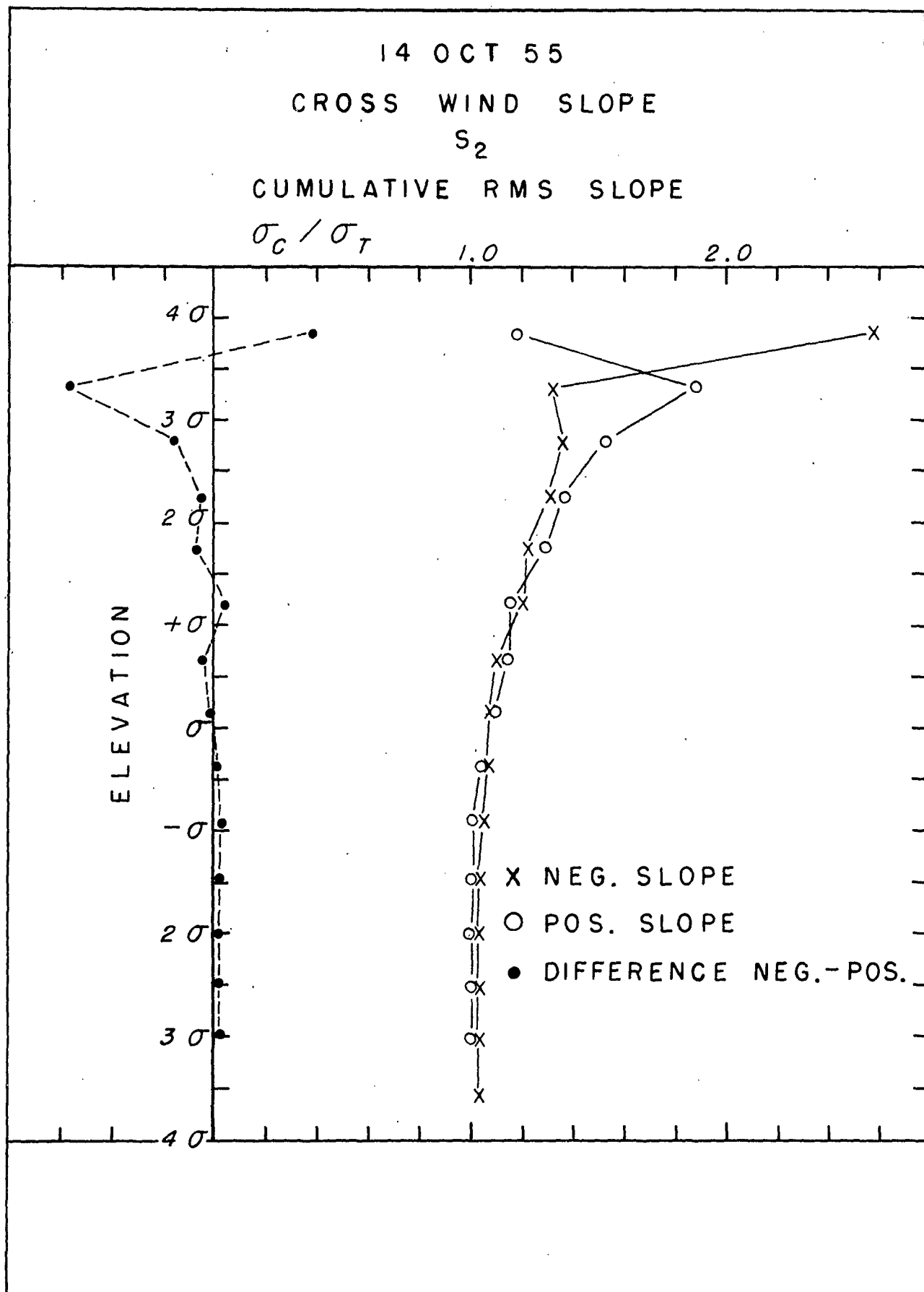
3 σ

4 σ

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



22 OCT 55 (1)

UP-DOWN WIND SLOPE

S_1

RMS SLOPE

σ / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

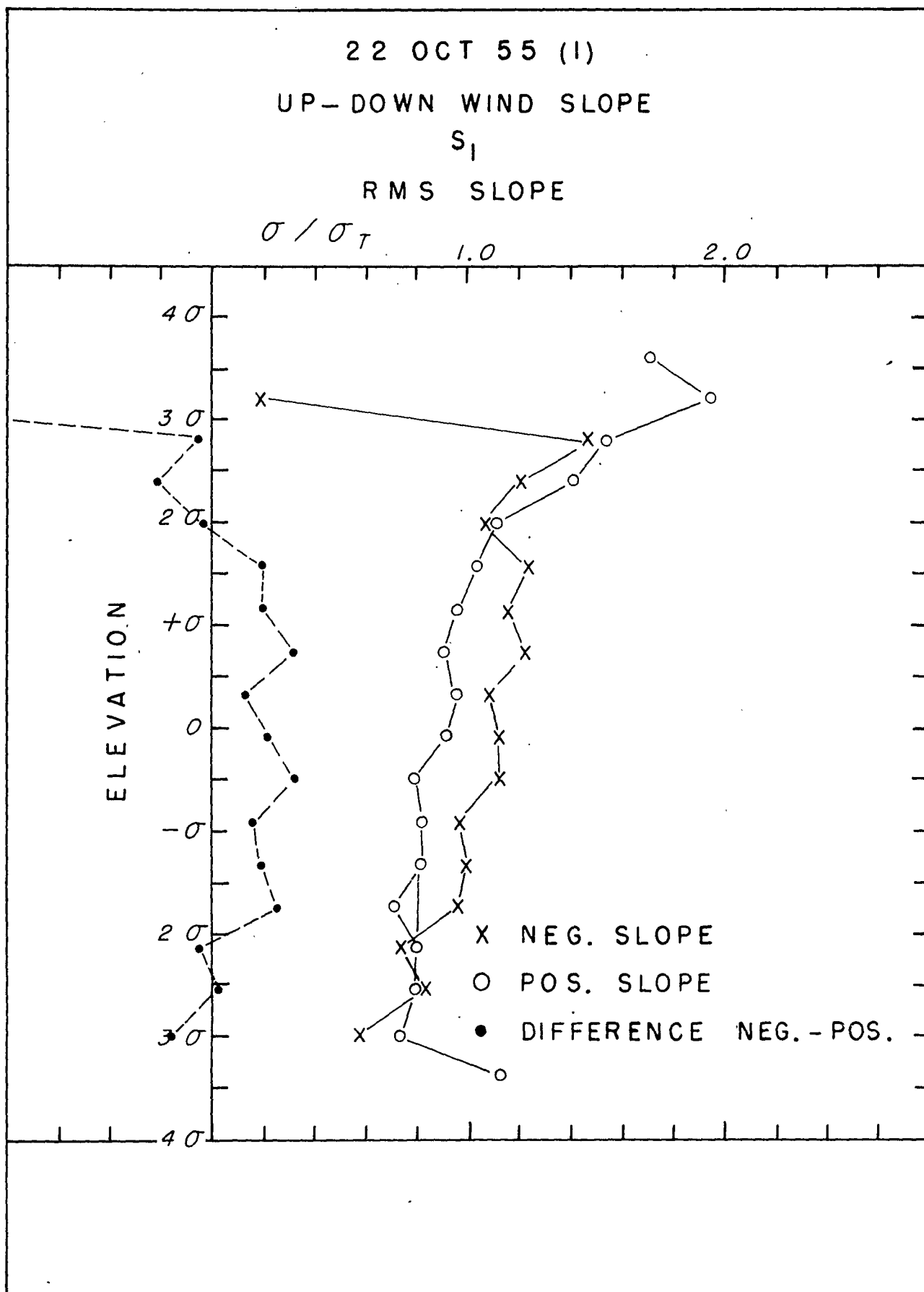
3σ

4σ

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG. - POS.



22 OCT 55 (1)

UP-DOWN WIND SLOPE

S_1

CUMULATIVE RMS SLOPE

σ_C / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

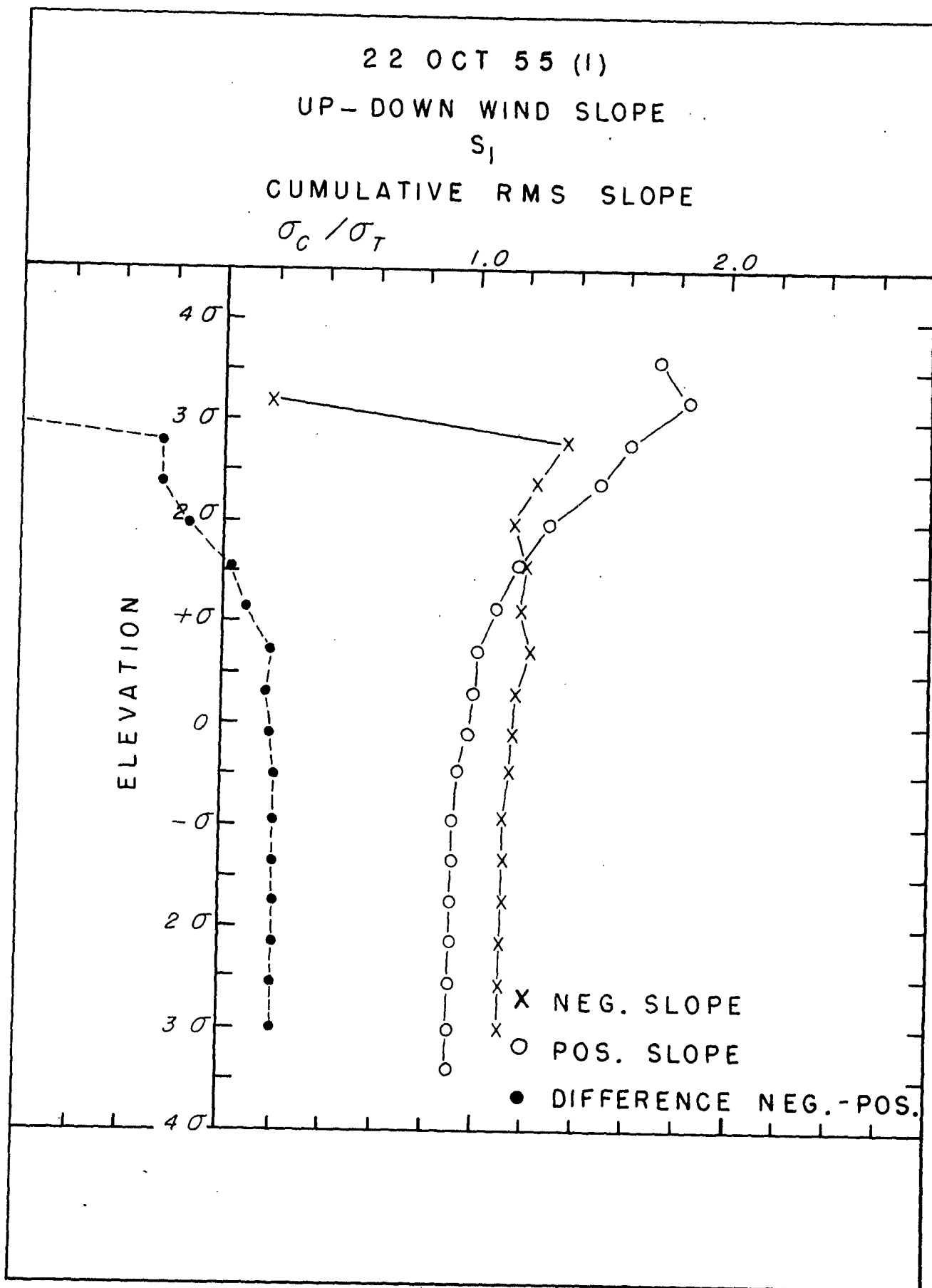
3σ

4σ

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



22 OCT 55 (2)

UP-DOWN WIND SLOPE

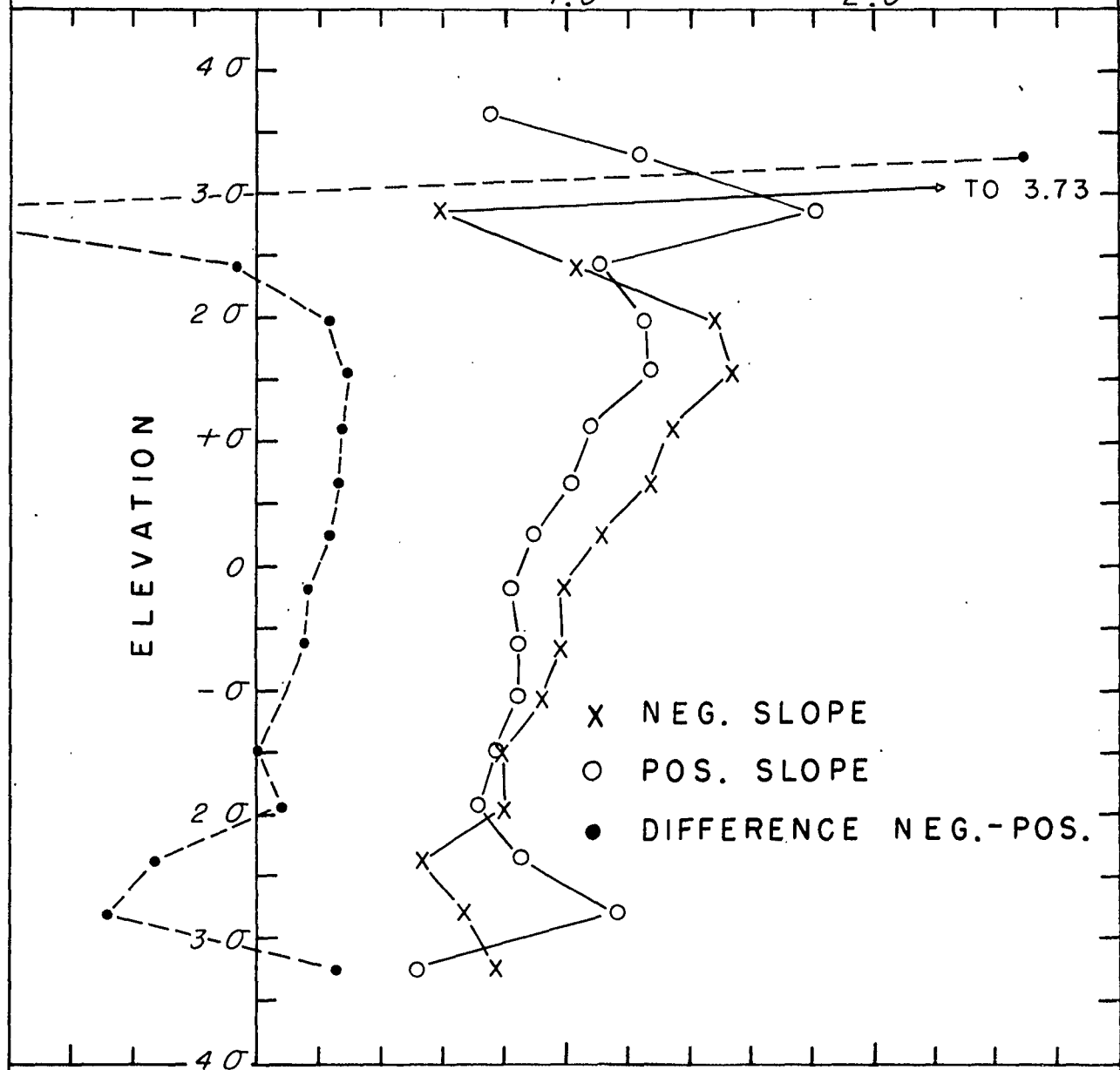
S_1

RMS SLOPE

σ / σ_T

1.0

2.0



22 OCT. 55 (2)

UP-DOWN WIND SLOPE

S_1

CUMULATIVE RMS SLOPE

σ_C / σ_T

1.0

2.0

ELEVATION

4 σ

3 σ

2 σ

+ σ

0

- σ

2 σ

3 σ

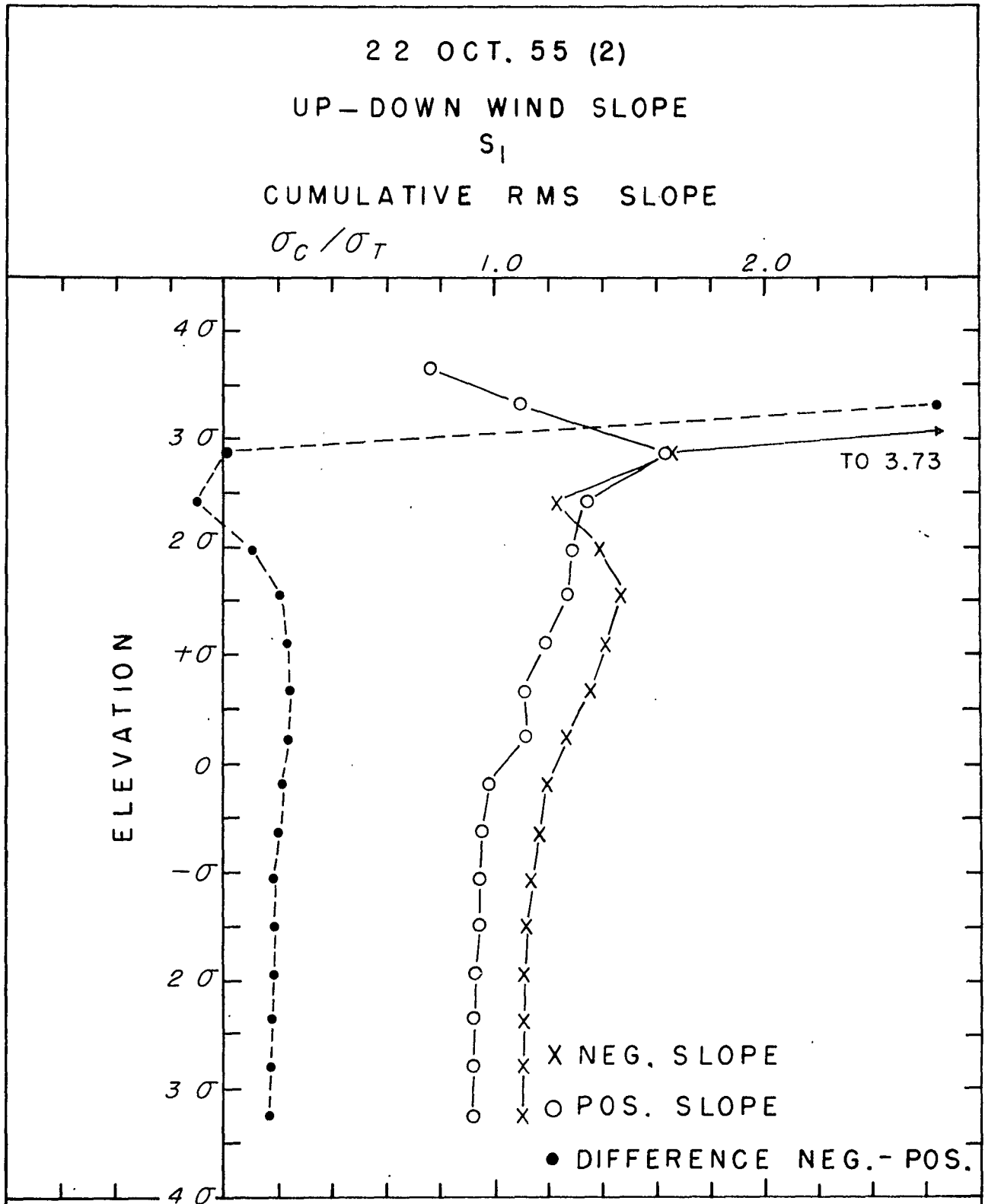
4 σ

TO 3.73

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.- POS.



22 OCT 55 (2)

CROSS WIND SLOPE

S_2

RMS SLOPE

σ / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

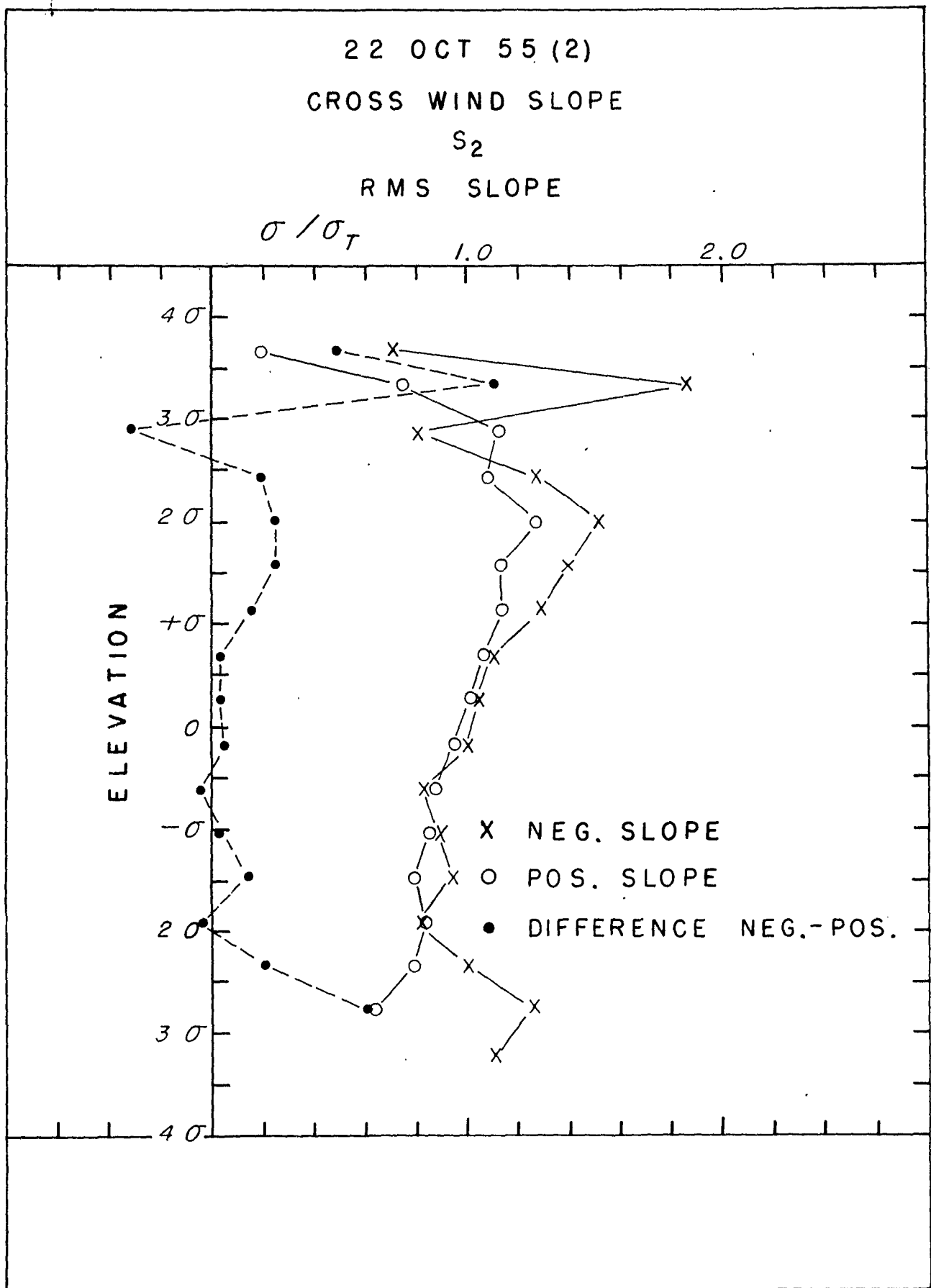
3σ

4σ

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



22 OCT 55 (2)

CROSS WIND SLOPE

S_2

CUMULATIVE RMS SLOPE

σ_C / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

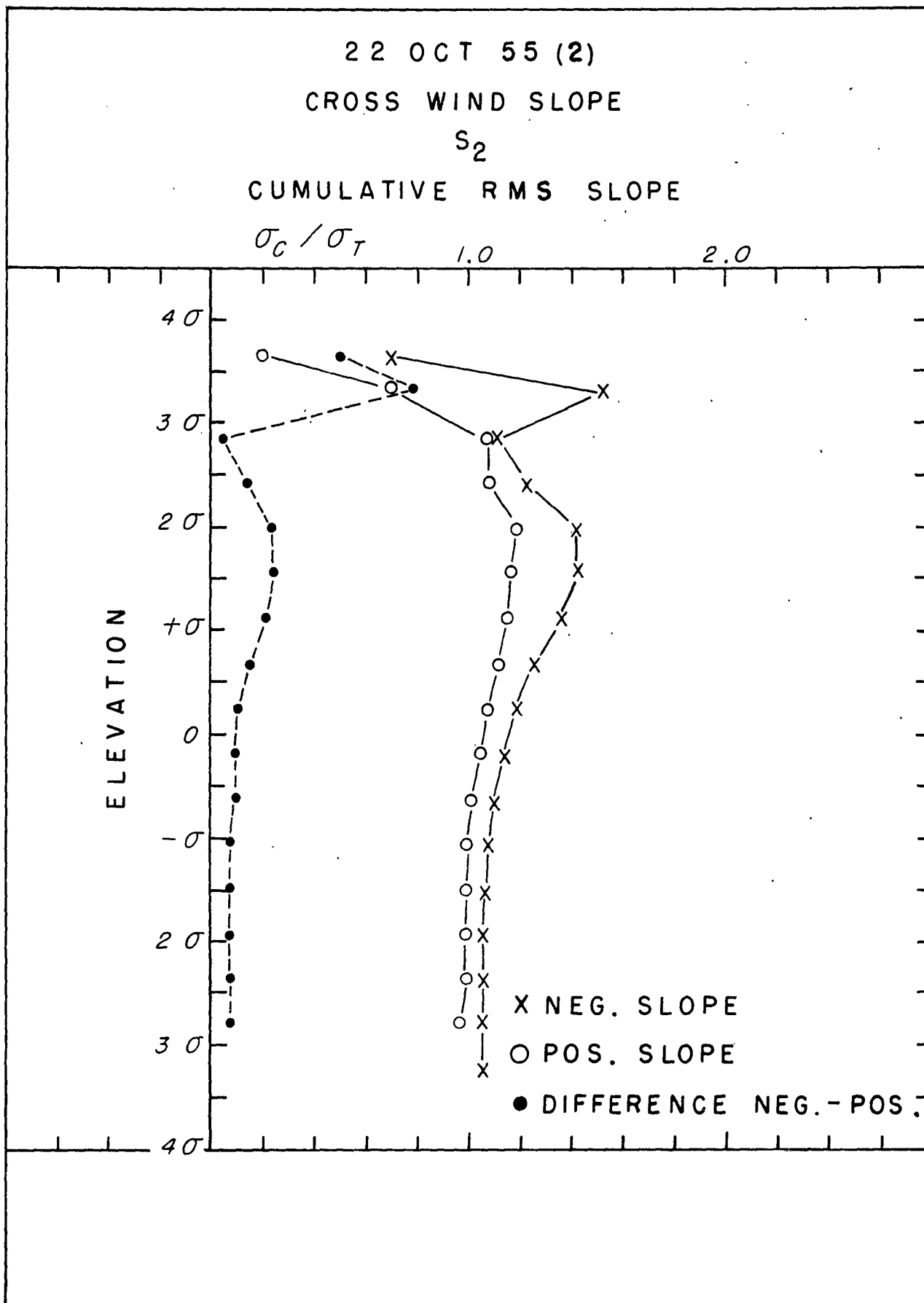
3σ

4σ

X NEG. SLOPE

O POS. SLOPE

● DIFFERENCE NEG.-POS.



24 OCT 55 (1)

UP-DOWN WIND SLOPE

S_1

RMS SLOPE

σ / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

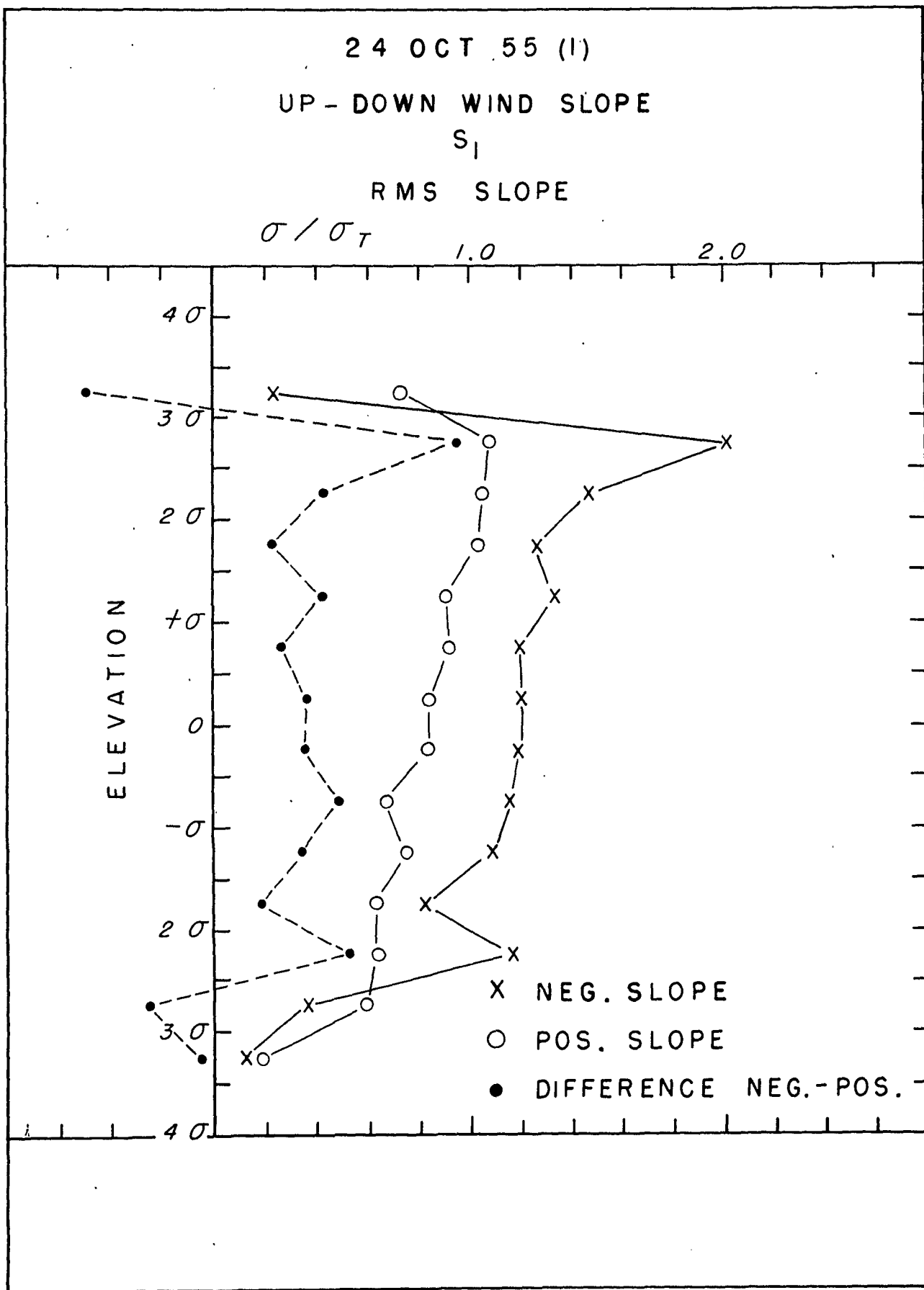
3σ

4σ

X NEG. SLOPE

O POS. SLOPE

● DIFFERENCE NEG.-POS.



24 OCT. 55 (1)

UP-DOWN WIND SLOPE

S_1

CUMULATIVE RMS SLOPE

σ_c / σ_T

1.0

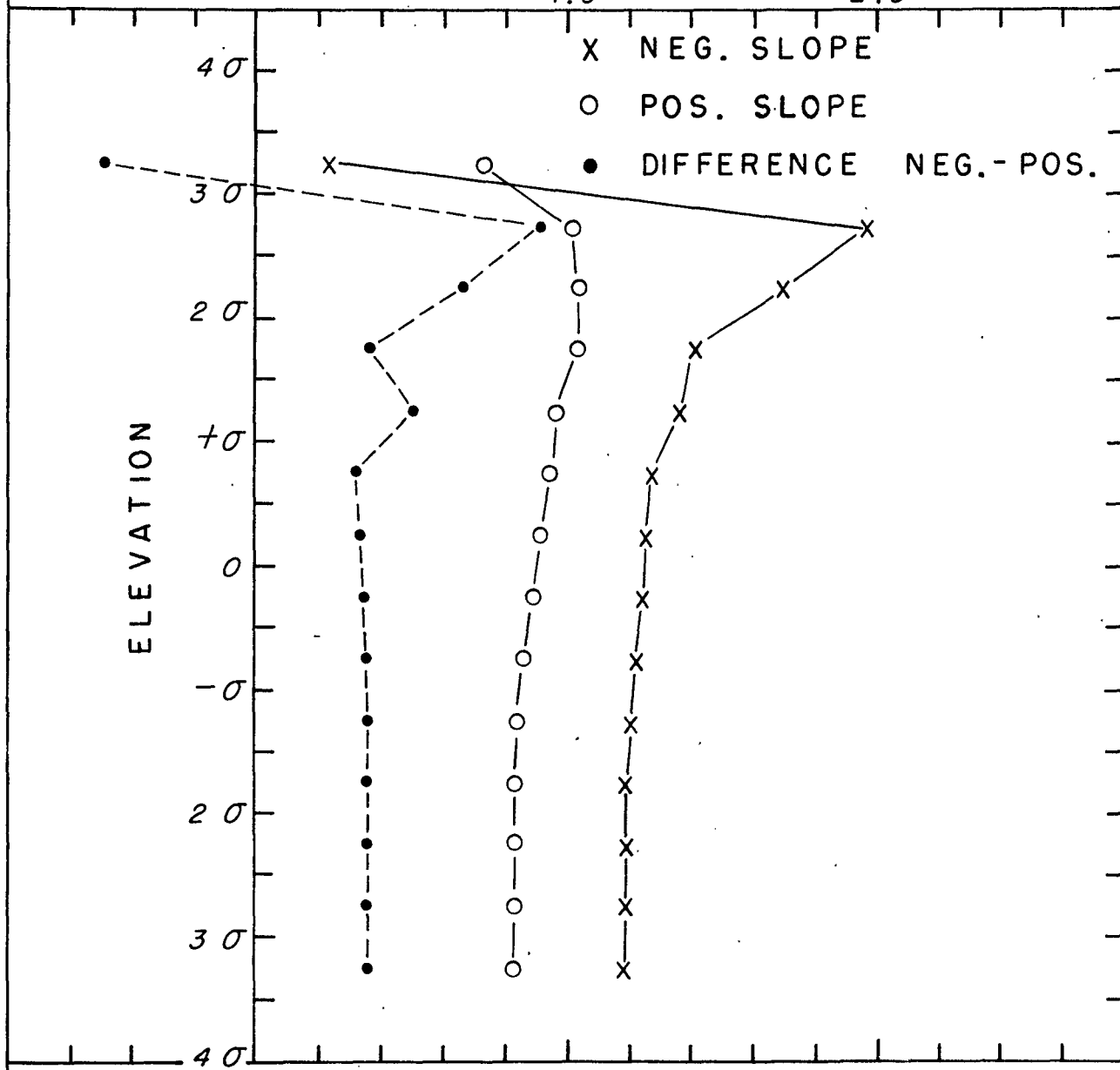
2.0

ELEVATION

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



24 OCT 55 (1)

CROSS WIND SLOPE

S_2

RMS SLOPE

σ / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

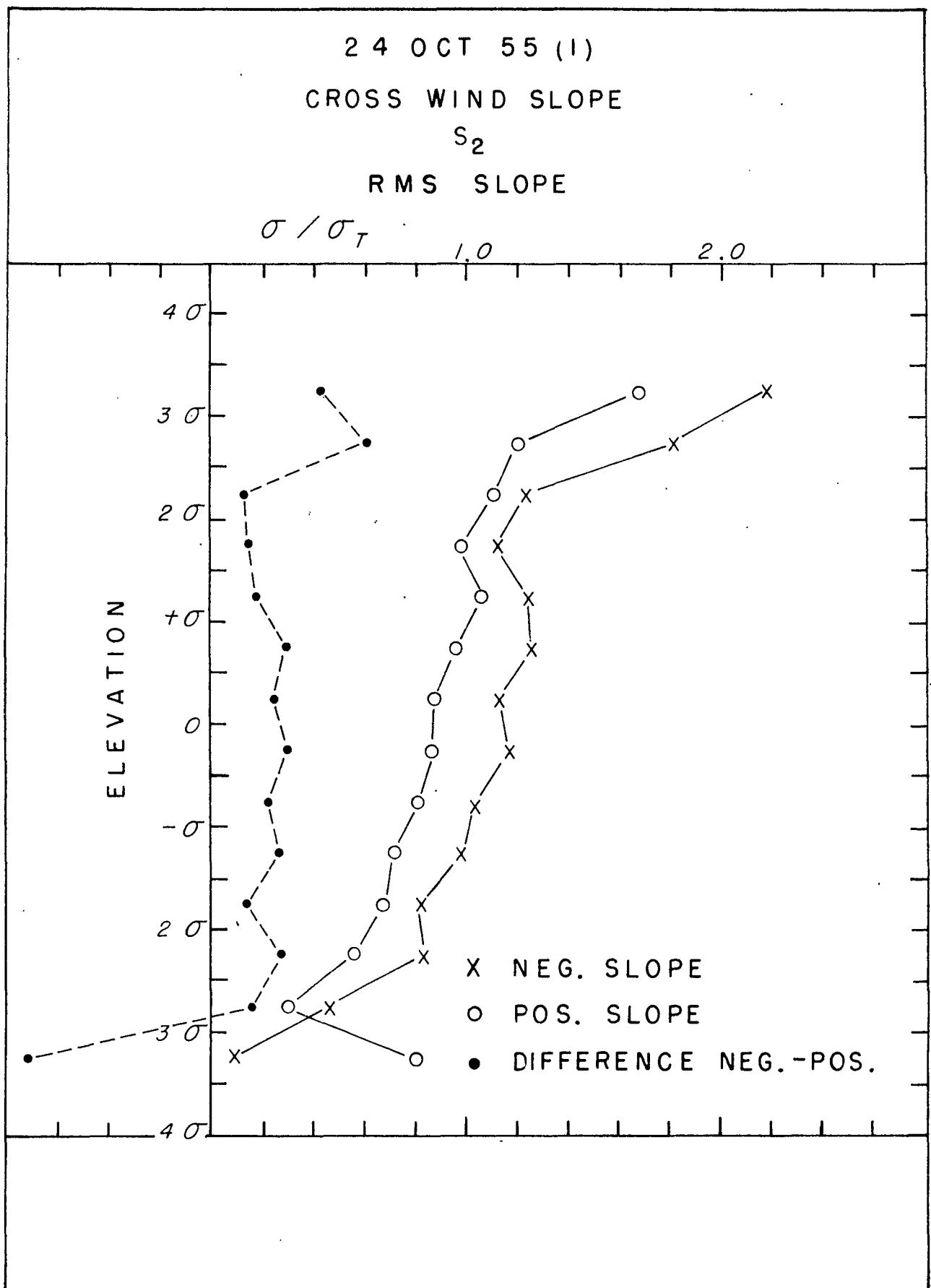
3σ

4σ

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



24 OCT 55 (1)

CROSS WIND SLOPE

S_2

CUMULATIVE RMS SLOPE

σ_C / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

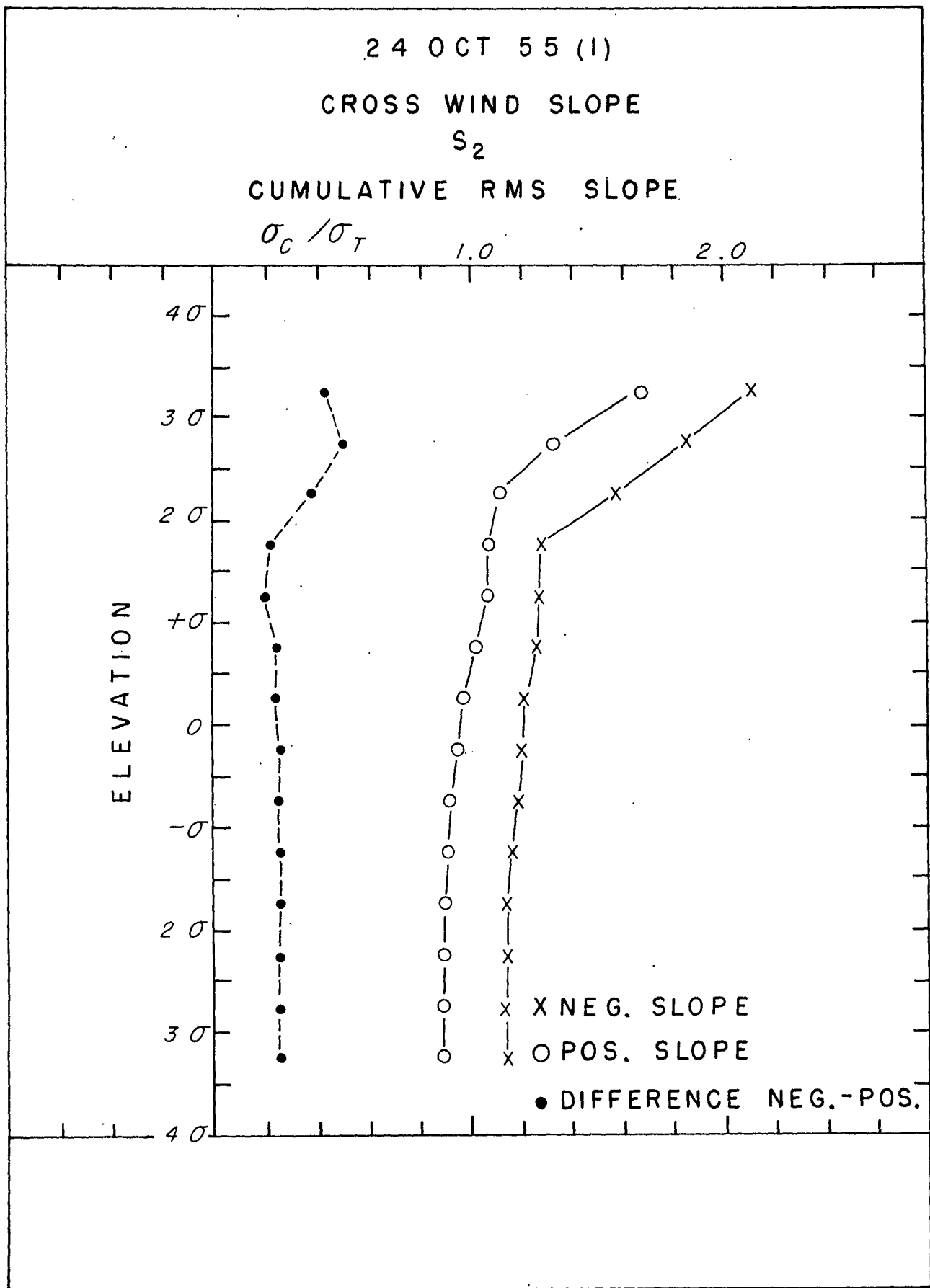
3σ

4σ

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



24 OCT 55 (2)

UP-DOWN WIND SLOPE

S_1

RMS SLOPE

σ / σ_T

1.0

2.0

ELEVATION

40

30

20

+0

0

-0

20

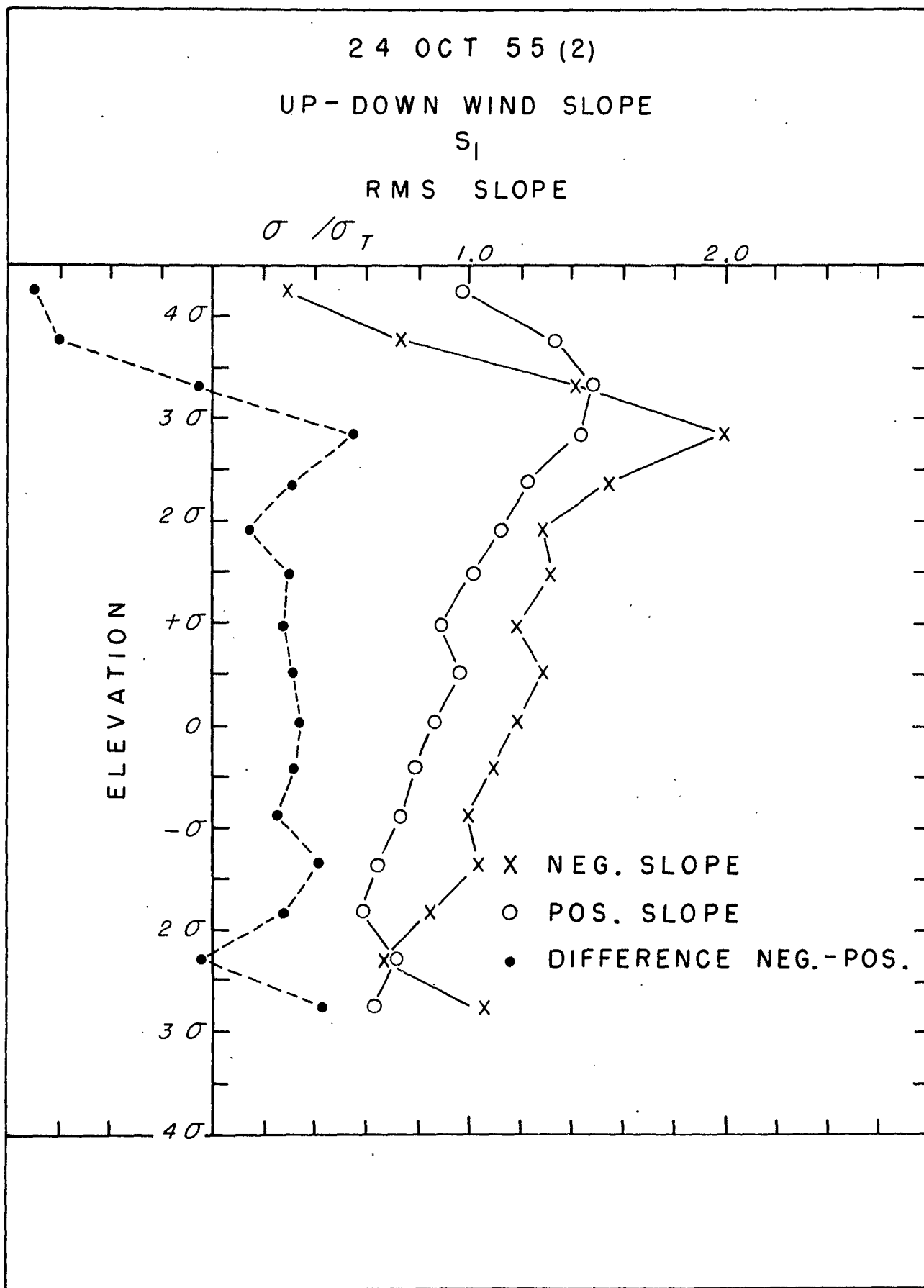
30

40

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



24 OCT 55 (2)

UP-DOWN WIND SLOPE

S_1

CUMULATIVE RMS SLOPE

σ_C / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

0

$-\sigma$

2σ

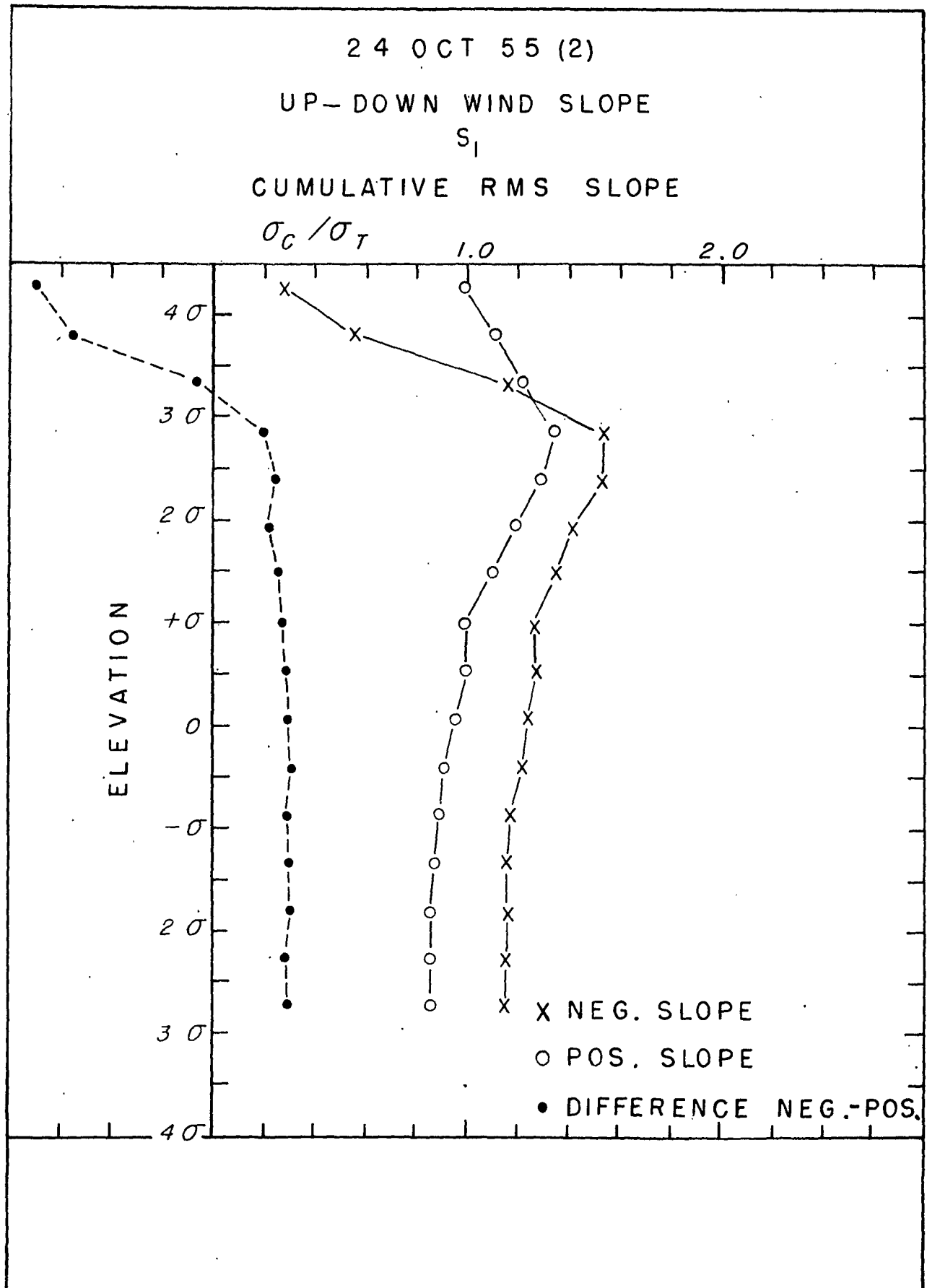
3σ

4σ

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



26 OCT 55

UP-DOWN WIND SLOPE

S_1

RMS SLOPE

σ / σ_T

1.0

2.0

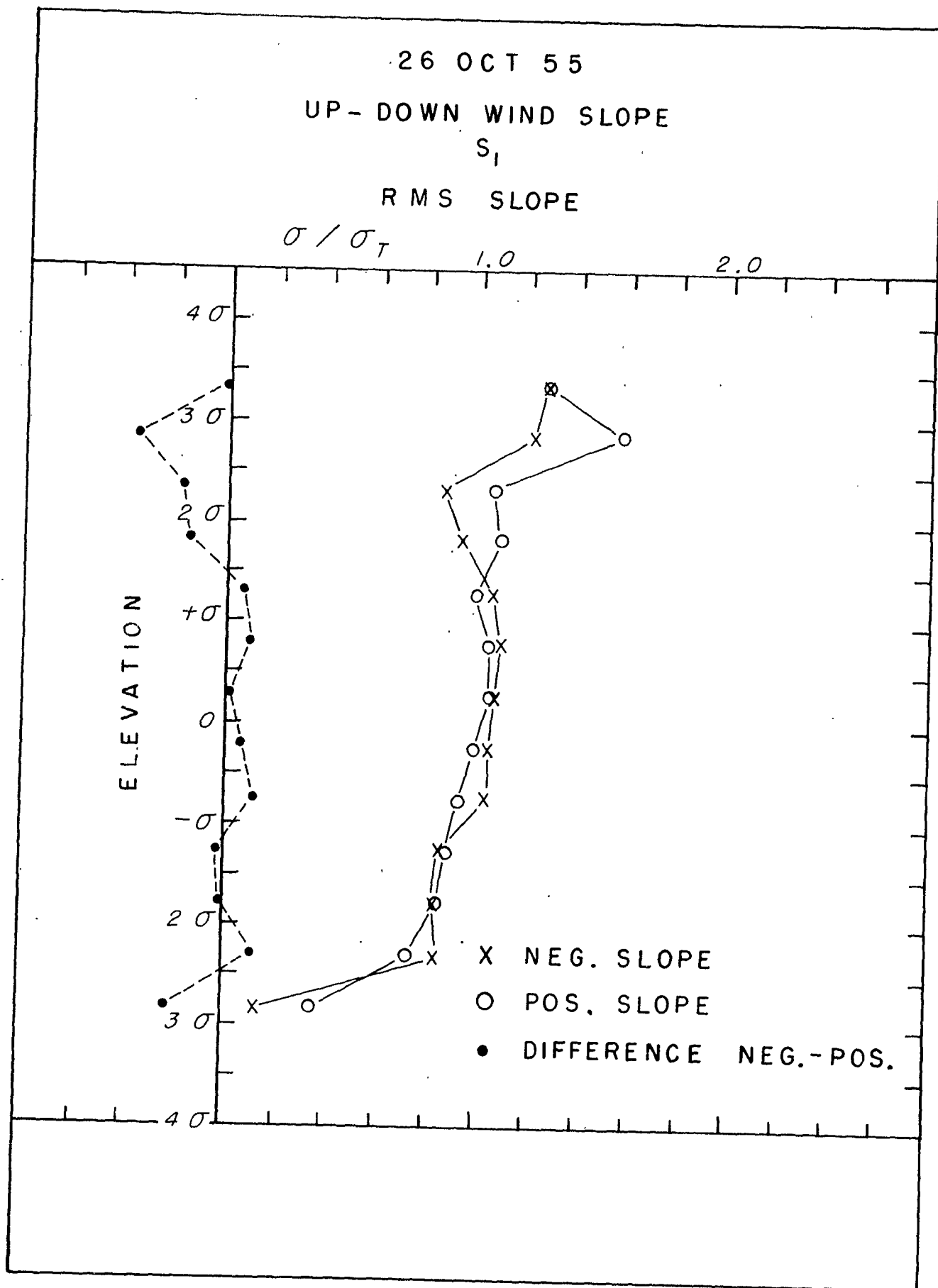
ELEVATION

4 σ
3 σ
2 σ
+ σ
0
- σ
2 σ
3 σ
4 σ

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



26 OCT 55

UP-DOWN WIND SLOPE

S_1

CUMULATIVE RMS SLOPE

σ_C / σ_T

1.0

2.0

ELEVATION

4σ

3σ

2σ

$+\sigma$

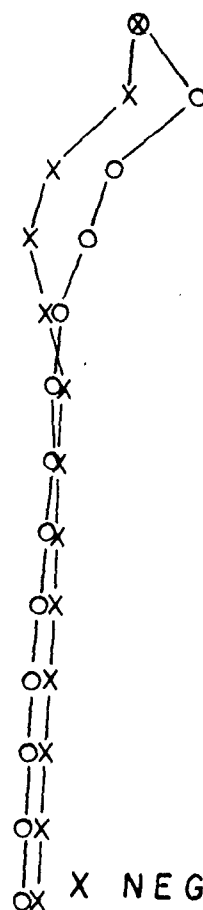
0

$-\sigma$

2σ

3σ

4σ



X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE .NEG.-POS.

26 OCT 55
CROSS WIND SLOPE
 S_2
RMS SLOPE

σ / σ_T

1.0

2.0

ELEVATION

4 σ

3 σ

2 σ

+ σ

0

- σ

2 σ

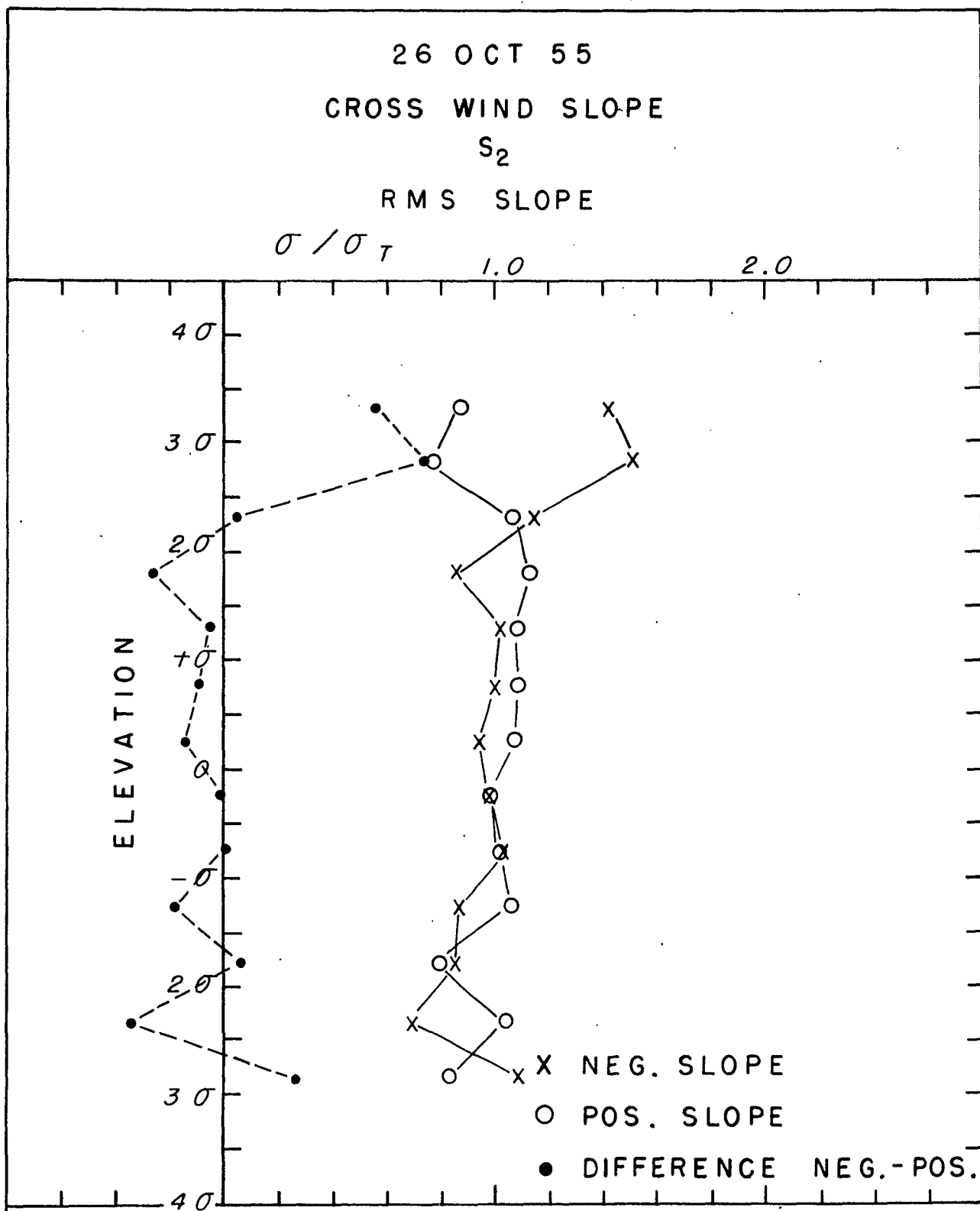
3 σ

4 σ

X NEG. SLOPE

O POS. SLOPE

• DIFFERENCE NEG.-POS.



26 OCT 55

CROSS WIND SLOPE

S_2

CUMULATIVE RMS SLOPE

σ_C / σ_T

1.0

2.0

ELEVATION

4 σ

3 σ

2 σ

1 σ

0

-1 σ

2 σ

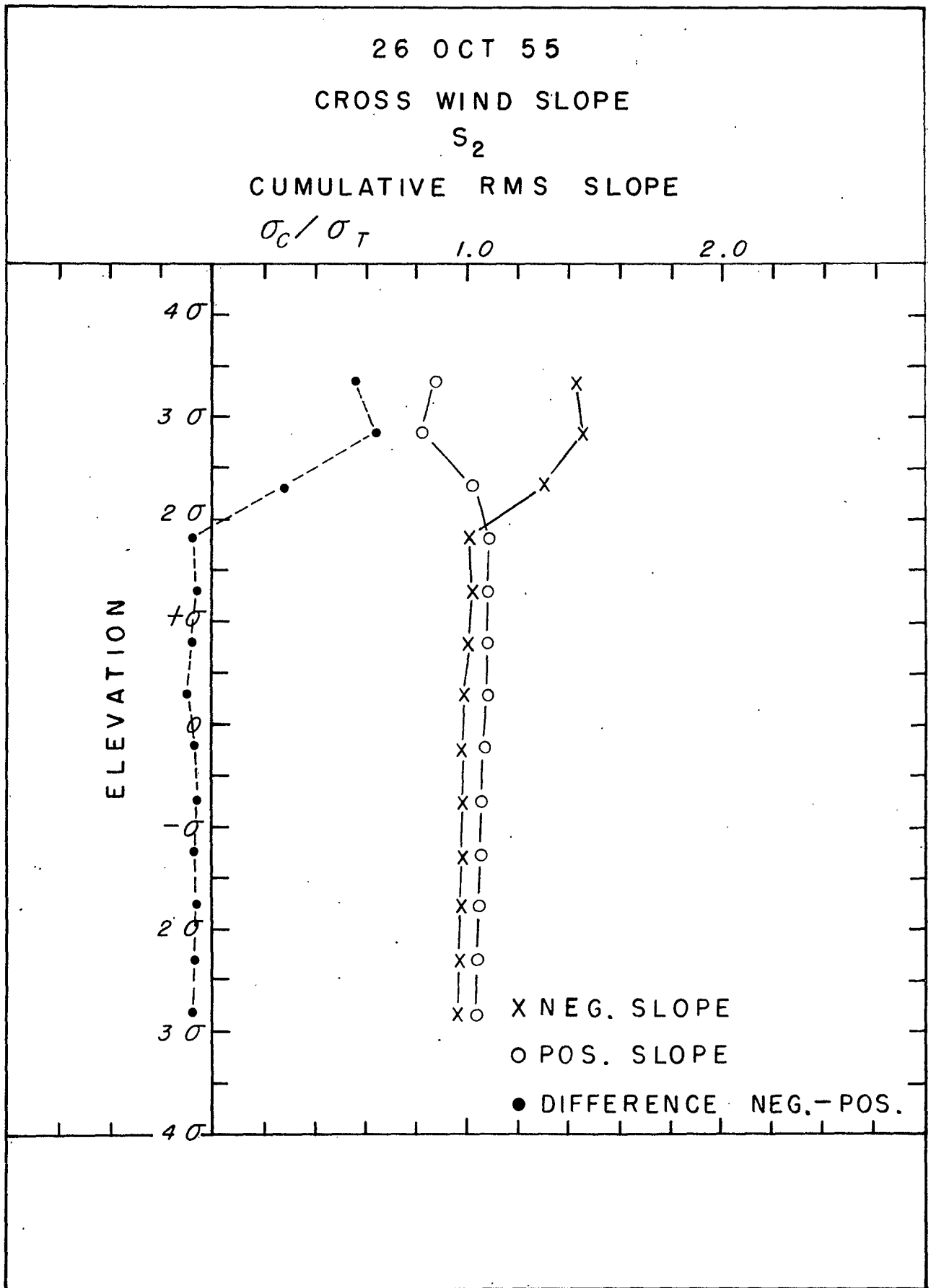
3 σ

4 σ

X NEG. SLOPE

O POS. SLOPE

● DIFFERENCE NEG. - POS.



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