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WAVES RECORDED AT
SEVEN STONES LIGHT VESSEL 1962-86

BY
S. BACON & D.J.T. CARTER

REPORT NO. 268

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1989

DOCUMENT DATA SHEET

AUTHOR BACON, S. & CARTER, D.J.T.	PUBLICATION DATE 1989

TITLE

Waves Recorded at Seven Stones Light Vessel 1962-86.

REFERENCE

Institute of Oceanographic Sciences Deacon Laboratory Report, No. 268, 94pp.

ABSTRACT

Measurements of waves have been made routinely at Seven Stones Light Vessel using a Shipborne Wave Recorder between 1962 and 1963, and from 1968 to the present, with a few breaks in recording. This report analyses all the analogue data taken up to 1986, and also presents digital data with spectra recorded between 1985-86. Information detailing the location, instrumentation and data return is presented. Obtained from the wave records are estimates of significant wave height, H_S, and zero-up-crossing period, T_Z. The observed probability distributions of H_S and of T_Z are presented; the H_S distributions are extrapolated to obtain estimates of the fifty-year return value of H_S. Observed joint probability distributions of (H_S,T_Z) and statistics of storm durations, with H_S above a specified threshold (also called 'persistence of storms'), are presented. Some evidence for a long-term change in the wave climate at Seven Stones is discussed.

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PROJECT	
PRICE	£24.00

KEYWORDS

EXTREME VALUES
SEVEN STONES/LV
SIGNIFICANT WAVE HEIGHT
WAVE DATA
WAVE SPECTRA

Copies of this report are available from:
The Library, Institute of Oceanographic Sciences Deacon Laboratory.

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1. INTRODUCTION

Wave measurements have been recorded routinely at Seven Stones Light Vessel (LV) between 1962-63, and from 1968 to the present, with occasional breaks in recording. This report describes the estimation of significant wave height, H_S, and zero-up-crossing period, T_Z, from chart records of sea surface elevation. Analogue (chart) measurements recorded up to 1986 and digital measurements recorded between 1985-86 are analysed; wave climate information as derived from H_S and T_Z is presented, together with some examples of wave spectra, and also evidence for long-term climate change at the site. Sections 3-7 refer to the analogue data; the digital data are discussed separately in Section 8.

There have been only two previous publications describing data from Seven Stones LV: Draper and Fricker (1965), which analysed data from the first year of operation; and Fortnum and Tann (1977), which analysed data from 1968 to 1974. For reasons discussed in Section 3 and Appendix I, results presented here are, to some extent, incompatible with those of the earlier authors.

2. LOCATION

The site at which the wave measurements were taken is shown in Figure 1, which also includes the position of the Scilly Isles Waverider buoy, referred to in Appendix IV. The LV lies between the Scilly Isles and Land's End, close east of the Seven Stones rocks at position 50° 003'.8 N 06° 004'.4 W, where the water depth is approximately 61m. The site is open to the Atlantic from directions NW to WSW, and SSW to S; there is a limited fetch of the order of 100 n.m. from NW to NE (South-East Ireland, the Irish Sea and South Wales) and from E to S (the English Channel and Brittany); and there is some sheltering by the Cornish mainland from E to NE, and by the Seven Stones rocks and the Scilly Isles from WSW to SSW. This sheltering is well illustrated in Figure 2, which shows H_S measurements from two overpasses by the American satellite Geosat in late 1986, individual H_S measurements within each overpass being approximately seven seconds apart in time. There is a considerable drop in H_S 'behind' the Scilly Isles, and this characteristic is typical of other tracks.

The tidal currents in the area reach around 1.5 knots at Springs, with directions of around 015° and 185°. This may cause an apparent increase in the steepness of waves, an effect which would be most pronounced for short, low-period waves.

3. MEASUREMENT AND RECORDING SYSTEMS

Seven Stones LV was fitted with a Shipborne Wave Recorder (SBWR) of Mark I from 1962 up to the 1981 LV refit, and of Mark II thereafter; see Tucker (1956) for a description of the SBWR Mark I, and Haine (1980) for the Mark II. The instruments provide information about the sea surface elevation which is recorded (usually) for a twelve minute period every three hours by pen on paper chart rolls. The method by which desired sea state parameters (H_S and T_Z) are derived is described in Appendix I. After obtaining these parameters from chart records, two corrections need to be applied: one to compensate for the frequency response of the electronics of the SBWR, and one for the hydrodynamic attenuation of the pressure fluctuations with depth as measured by the pressure sensing components of the SBWR. These corrections are described in some detail in Appendix I, but it is important to note here that the original scheme due to Tucker, and detailed, for example, in Crisp (1987) pp 32-34, for correcting for hydrodynamic attenuation of pressure fluctuations, is not used here. Pitt (1988) develops a new and more accurate correction scheme, and it is this which has been applied to the data analysed here. This new scheme generally has the effect of reducing the measured value of H_S in a manner dependent on T_Z, ship length and pressure sensor depth. On Seven Stones LV, the pressure sensor is deep mounted, so considerable alterations over the original correction scheme result, producing reductions of up to 20% in the corrected value of H_S. A comparison of the two correction schemes is presented in Appendix I. The length of the LV is 35m.

4. MAINTAINENCE AND CALIBRATION

A summary of the history of SBWRs on Seven Stones LV is given below, including the date and result of each calibration of the instrument, any action taken with respect to the data as a result of the calibration, and the measured pressure sensor depth. A description of the calibration method is given in Appendix II. All calibrations were carried out by IOS staff.

A decrease in accelerometer sensitivity means that wave heights were being under-read, and vice-versa, so that where corrections have been applied, they are of opposite sense to the change in accelerometer sensitivity. The magnitudes of the changes were determined by assuming linear changes in sensitivity and applying a 'quasi-linear' correction: in this case, a value of each month of operation assuming correct records at the start of each period on station after calibration and records in error by the mean of the accelerometer error at the end. Accelerometer sensitivity changes are referred to as P (port) and S (starboard).

November 1961: Mark I SBWR (valve type) installed in Seven Stones LV. Pressure sensor depth is 1.87m.

May 1964: instrument removed for calibration. Sensitivity changes were +3.6% (P) and +1.3% (S). The only available data, from 1962 to January 1963, are from the first half of the operational period, so the data have not been changed.

September 1967: there are no good data from this period; however, the instrument was calibrated, giving +7.4% (P) and +0.4% (S)

April 1971: on return for calibration, the starboard pressure sensor was found to have a burst diaphragm, and the port accelerometer had changed sensitivity by -25.5% (the starboard accelerometer change was +1.3%). These considerable problems were traced back to 1970, from the start of which year all data were discarded. The remaining data, 1968-69, are believed good and have not been altered.

January 1975: the calibration indicated large changes in sensitivity. Unfortunately, the calibration seems to have been performed wrongly, after the changing of some components of the instrument. It was decided at the time, after consideration of the routine monthly checks (described in Appendix II) that the data up to June 1974 were satisfactory but that subsequent data should be discarded (pers. comm. L. Draper). This decision has been accepted and these data have been left unaltered in this report.

April 1978: sensitivity changes -5.0% (P) and -3.1% (S), a mean final change of -4.1%. The data have been adjusted accordingly. Pressure sensor depth is now 2.44m.

July 1981: Mark I SBWR removed for final calibration check: -6.4% (P) and -16.3% (S). Mark II SBWR (solid state type) installed. The data from 1978-81 were found to be 'wrong' in a way which could not be accounted for simply by means of the SBWR sensitivity changes. No resolution of this problem was found at the time; details, and the present solution, are given separately in Appendix IV. Pressure sensor depth is now 2.61m.

November 1984: sensitivity changes 0.0% (P) and -0.1% (S); the data have not been altered.

December 1987: sensitivity changes -7.1% (P) and -1.3% (S), a mean final change of -4.2%. The data, up to December 1986, have been adjusted accordingly.

5. WAVE DATA COVERAGE

The total data return, and the data return per season, where the seasons are defined as follows, are given below.

Season	Months Covered	Number of valid records
Spring	March to May	11949
Summer	June to August	11547
Autumn	September to November	11710
Winter	December to February	11790
All		46996

Returns for each month are given in Table 1. Note that the 1962-63 data set contains 9 'extra' records taken between the regular three-hourly measurements. These 9 values ahve been included in all relevant analysis except for that of storm persistence. A record is defined as 'calm' if, on a chart record of sea surface elevation, the greatest crest height plus the greatest trough depth does not exceed 1 foot or 0.3m (1981 and before) or 0.5m (1982 and after). The change in definition arose with the change in chart scale units accompanying the Mark II SBWR. For the purpose of calculating H_S distributions, monthly mean H_S etc. it is assumed that $H_S(\text{calm}) = 0.25$m. Calm returns per month have not been tabulated separately since there is a low proportion of calms in the data (302 in all). Table 2A includes total and seasonal calm percentages.

6. DERIVATION OF SEA STATE PARAMETERS

When sample frequency spectra are available, significant wave height H_S and zero-up-cross period T_Z are defined as

$$H_S = 4\sqrt{m_0}$$

$$T_Z = \sqrt{\frac{m_0}{m_2}}$$

where m_0 is the zeroth moment of the spectrum (equal to the sea surface variance), and m_2 the second moment, and where the moment of order n of a continuous spectrum is defined as

$$m_n = \int_0^\infty f^n S(f) df$$

However, chart records do not readily provide spectral information, so a different method for extracting these parameters is used, the theory of which is available in works by Cartwright (1958) and Longuet-Higgins (1952); the practical application is described in papers by Tucker (1961) and Draper (1963). Critical reviews of this work are available in Tann (1976) and Crisp (1987); as mentioned previously, a brief summary is given in Appendix I.

Significant steepness, S_S, is defined by

$$S_S = \frac{2\pi H_S}{g T_Z^2}$$

The fifty-year return value of H_S, $H_S(50)$, is defined as the value of H_S which is exceeded on average once in fifty years.

7. SUMMARY ANALYSIS OF WAVE CLIMATE DATA

7.1 Statistics of significant wave height

The maximum value of H_S recorded at Seven Stones LV occurred on 17 October 1982 at 1500 hours with H_S = 11.13m and associated T_Z = 11.71s. The second highest value occurred on 16 January 1974 at 1800 hours with H_S = 10.99m and associated T_Z = 11.61s.

Some comb plots of month-long sequences of H_S are shown in Figure 3. January and February 1974, and March, November and December 1986 are included for reasons discussed below; August 1979 is included as the month of the Fastnet Race disaster, in which data can be seen the unusually severe storm responsible; and October 1982, which contains the highest H_S.

Estimates of the probability distributions of H_S are shown in Figure 4 which presents histograms giving the percentage occurrence over all data and over each season, with the H_S values grouped in 0.5m bins. These histograms are the marginal H_S distributions from the joint H_S:T_Z histograms ('scatterplots') which were constructed allowing for the variation in the number of records per month. The probability values for each bin and each histogram are set out in Table 2.

Estimates of the cumulative H_S non-exceedance probability distributions, presented as ogives, are given in Figure 5. These were calculated in the same manner as the histograms above, but with H_S values grouped in 0.1m bins to smooth the curves.

For each month over all data, values were produced for H_S of the mean, maximum, median and 90th percentile; these values are presented in Tables 3-6 respectively. Figures marked with an asterisk indicate 10-20% missing data; figures in parentheses indicate >20% missing data.

Fifty-Year Return Value of H_S

Estimates of the fifty-year return value of H_S, $H_S(50)$, were obtained by extreme value analysis, fitting a Fisher-Tippett Type I (FT-1) to monthly and to annual maxima, and by fitting FT-1 and Weibull distributions to the observed distributions of H_S, and extrapolating to the required probability. See Appendix III for details of fitting methods. Figures 6, 7 and 8 show the cumulative probability distribution of all H_S data and (respectively) the fitted FT-1, 3- and 2-parameter Weibull distributions. Figures 9 and 10 show the monthly and annual maxima (respectively) of H_S fitted to FT-1 distributions. The data points in these figures are located on the probability axis according to Gringorten's plotting positions: see Gringorten (1963). A summary of values of $H_S(50)$ and fitted distribution parameters is given in Table 7A, for all data, seasons and months; Table 7B for FT-1 fitted by moments to calendar years and 'summer-to-summer' years, where possible; and Table 7C for FT-1 fitted by maximum likelihood to monthly and to annual maxima.

With the quantity of available data, it is possible to comment both on comparisons of different methods of estimation and on comparisons between different parts of the data set using the same method of estimation. Since there is some evidence for a long-term change in the wave climate at Seven Stones LV, the latter topic is discussed further in Section 9. Here we discuss firstly the analysis of maxima and secondly the extrapolation of distributions fitted to all the data, assuming stationarity.

Firstly, the FT-1's fitted to monthly and to annual maxima of H_S: the data used are those shown in Table 4. Where a calendar month has two estimates for $H_S(50)$ in Table 7C, the first value is derived by using all maxima for that calendar month irrespective of data return; the second, 'censored', estimate is derived by excluding points from months with <80% data return. These latter estimates are calculated using only one or two fewer data points than the former, but three months (January, Febuary and November) show large differences between the two estimates. The November 'anomaly' occurs through exclusion of the overall November maximum H_S, which happened to fall in a month of <80% data return. However, the differences in the other two cases arise from the exclusion of unrepresentative sample maxima of low H_S from months with very few records. Therefore, the data shown in Figure 8 include all data for the months March-December, but exclude months of <80% data return for January and February. With this combination, the annual $H_S(50)$ is reduced to 13.59m, which is very similar to the 'censored' annual estimate. It is interesting that March stands out as the most extreme month by this method of estimation, whereas estimation by the cumulative distribution of H_S suggests December/January.

The two estimates of $H_S(50)$, 12.55m and 12.61m, derived by fitting annual maxima to FT-1's were produced by selecting two different sequences of values from the data. It can be seen that the resulting difference in estimates of $H_S(50)$ is not great. Figure 10 shows the sequence 'am1' from Table 7C; the two sequences 'am1' and 'am2' are detailed in Table 7D. Note that in order to obtain 17 annual maxima for 'am1', some gaps in the records were ignored. In particular, it was assumed that the maximum value from April 1977 to March 1978 was 7.44m, even though there were only 4 observations in February 1978 and none in March 1978. However, removing this year from the analysis results in a reduction in $H_S(50)$ by only 0.01m. Confidence limits for the estimate of $H_S(50)$ from this analysis of annual maxima can be obtained using Table 4 in Challenor (1979). Even with 17 maxima, they are very wide, with 90% confidence limits for $H_S(50)$ of 11.5m to 14.7m.

Secondly, distribution functions fitted to cumulative H_S probablility distributions: the two-parameter Weibull function fits poorly the complete distribution, so is, as usual, only fitted to the upper tail. Table 7A gives values of $H_S(50)$ for the two-parameter Weibull function fitted above 2,3,4 and 5m, with quoted percentage figures referring to the proportion of the total distribution which is included in the estimations. Figure 8 shows, as an example, the fit to all data above 3m. As the cutoff increases, the quantity of data fitted reduces drastically; also, the estimate of $H_S(50)$ tends towards 12.3-12.4m. The three-parameter Weibull distribution (Figure 7) is quite a good fit to the body of the distribution of H_S, but misses the tail and consequently underestimates $H_S(50)$, at 12.0m. The FT-1 function (Figure 6) similarly fits well to the body of the distribution, but seems rather to overestimate $H_S(50)$, at 13.6m: the tail of the data tends towards a lower value than the extrapolated line would suggest. These values of $H_S(50)$ were calculated assuming 3-hourly measurements, so are estimates of the value from 3-hourly measurements exceeded on average once in fifty years.

The discrepancies between estimates of $H_S(50)$ for calendar months obtained from cumulative H_S distributions and from maxima do not seem to be systematic. The three largest differences, January (cumulative=13.2m, maxima=11.4m), November (cumulative=11.1m, maxima=9.4m) and December (cumulative=13.3m, maxima=11.2m) contain two poor cumulative fits which overestimate (January and December) and a good fit (November) which appears more credible than the estimate from maxima. Two other large differences (February and September) appear to be a good fit and estimate, and a poor fit which underestimates (respectively).

Overall, for reasons to be discussed later, it is likely that $H_S(50)$ is different from any suggested value at this stage. However, given that the estimates derived from maxima are 13.6m (monthly) and 12.6m (annual), and if 12.0m and 13.6m are too low and too high, respectively, it seems likely that 12.5-13.0m is the correct overall estimate for $H_S(50)$.

Persistence

Estimates were calculated of the probability distributions of the persistence of H_S above given threshold levels of H_S: also known as persistence of 'storms' of H_S. For example (Table 8), since 1962 there have been over two thousand (measured) separate storms where H_S was greater than 2m; these storms have lasted from three hours (one record, the least measureable) to as much as thirty-three days! Figure 11 shows plots of the probability of exceedance of threshold versus minimum event duration for 2, 3, 4, 5 and 6m H_S thresholds; Table 9 gives the same statistics for thresholds from 2m to 10m in 0.5m steps for least duration up to 180 hours (7.5 days). Events longer than this are given separately in Table 10. For the purpose of these calculations, gaps in the data of no more than 3 records were filled by linear interpolation. Gaps longer than this interfere with the calculation of individual 'storm' durations, and it is obvious that run lengths can only be truncated by such gaps. In order to clarify the meaning of the given figures, an outline of the method of calculation is given below.

For each H_S threshold, the frequency distribution of 'storm' durations over all data was calculated. Table 8 presents statistics of storm durations derived from these initial calculations. Given the truism that we may not know what we have not measured, the only sensible way to deal with gaps in the data was to present the data in a strictly correct form that did not involve any adjustments to the data to account for gaps. So, for each threshold, each bin - representing not duration but minimum duration - contains the total number of storms of the given duration or of greater duration. In this way, the lowest bin (3 hours or more) contains the total of all events over the given threshold. For each threshold, the probability distribution is derived from the frequency distribution by dividing the number of events per bin by the total number of events above that threshold. Some example calculations using the data in Tables 8 and 9 are given below. A brief summary of the number of event ends affected by gaps is included in Table 8. Note that a gap preceded by an H_S of 6m will truncate events at all thresholds below 6m, hence the 'cumulative' appearance of these figures in the table. The number of gap ends is approximately 1-2% of the number of events at each threshold, so that about that percentage of the events at each threshold will have been truncated. It is hoped that the statistics as presented in Table 8 are, therefore, reasonably accurate, and that, if required, the data in Table 9 may be 'differenced' back into distributions of duration, rather than least duration. See example (iv) below.

Examples:

(i) What is the probability that if H_S increases above 3m, it will remain so for nine hours or more? Table 9, row 3, column 3, probability=0.538 or about 54%.

(ii) What is the expected number of events per year with $H_S \geq 3$m and duration≥9 hours? Table 8, row 3, column 3, mean number of events per year of $H_S \geq 3$m is 105.7; probability × number of events=56.9 per year.

(iii) On average in any year, for how long will conditions be of $H_S \geq 2$m? Table 8, row 1, column 5, 40.6% of total time finds these conditions, or a little over 148 days per year.

(iv) If H_S increases above 4m, what is the probability that it will remain above 4m for 6 hours? Table 9, row 5, columns 2 and 3, prob($H_S \geq 4$;duration≥6) = 0.724, prob($H_S \geq 4$;duration≥9) = 0.499; so prob($H_S \geq 4$;duration=6) = 0.724-0.499 = 0.225, or 22.5%.

It is worth commenting on the extremes of 'storm' duration found in this analysis (see Table 10). Of the five longest events over 2m, two during from 1986 (33 days, ending December, and 21 days, ending March) and two during 1974 (both of 23 days, ending January and February). Of the five events above 3m, two are from 1974 (the same events as before, but 12 and 8 days at this level). The only outlier at 3.5m is the later 1974 event, which spent 8 days at 3.5m. Thoroughly unpleasant. Considering the cumulative statistics of H_S, it can be seen that January and February 1974 and March and December 1986 are the highest mean H_S for the respective months, and that the 1974 90 percentiles are the highest, and the 1986 the second highest for those months. Some of these data are included with the comb plots of H_S in Figure 3.

7.2 Statistics of Zero-Up-Crossing Period

The maximum recorded value of T_Z occurred on 16 June 1976 at 1500 hours with T_Z = 14.85s and associated H_S = 2.44m. Two example comb plots of month-long sequences of T_Z are included with those of H_S in Figure 3: June 1976, containing the greatest T_Z recorded, and February 1979, when, on the 13th, an unusual storm of very long waves overwhelmed Chesil Beach on the south coast of England (Draper and Bownass 1983).

Estimates of the probability distributions of T_Z are included in Figure 4; these histograms are computed in the same manner as the accompanying H_S histograms. The probability value for each bin and each histogram are set out in Table 2.

7.3 Statistics of the Joint Distribution of H_S and T_Z

Figure 12 shows the annual and seasonal joint probability distributions (or 'scatterplots') of H_S and T_Z with probabilities plotted in parts per thousand to the nearest integer. Included in these figures are lines of significant steepness of $^{1}/_{7}$, $^{1}/_{10}$, $^{1}/_{15}$ and $^{1}/_{20}$. When computing the scatterplots, allowance was made for the variation in the number of records per month throughout the year by computing a scatterplot for each calendar month, then combining the resulting monthly scatterplots (suitably weighted for different numbers of days per month) into plots representing the whole year and the seasons.

8. DIGITAL DATA 1985-86

During the LV refit of 1984, a digital onboard data recording and processing system was installed to run in parallel with the existing analogue system. The digital system was designed to produce an estimate of the wave spectrum from a 34-minute long record of sea surface elevation taken every $1\ ^{1}/_{2}$ hours: see Appendix I for a description of the estimation method. No comparisons will be made here between the analogue and digital measurements; the reader is referred to Pitt (1988) for further information on this topic, where comparisons are made between coincident individual records. The digital data return, and, from 1986, the analogue, are so patchy that no firm conclusions could be drawn over their relative merits. Table 11 summarises the data return and the statistics of H_S derived from these measurements; it can be seen that overall, the data return from this system was very poor. Fortunately, it chose to work well during a period of some interest, the very rough months of November and December 1986. Here, the opportunity is afforded of presenting some of the sample spectra and of informing the interested reader of the existence of these data.

Figure 13 shows comb plots of sequences of digital H_S estimates over November-December 1986; also included are July 1985 values. Comparing these with the analogue estimates of the same data in Figure 3, it is interesting that a statistical technique using five measurements from a wave record can provide such an accurate estimate of H_S as compared with the full spectral H_S. These two months of spectral data are presented in Figure 14; also included, for comparison, is a relatively quiescent period from July 1985. The spectra are drawn in blocks of nine days per plot, with time read 'book-fashion' as y-axis top-down, and frequency plotted on a logarithmic scale on the x-axis. The contours of spectral density (m^2Hz^{-1}) are drawn at intervals chosen for clarity rather than by any system. Lowest density contours are broken (- - - -), mid-density are chained (-·-·-·-·-) and highest density full. Contours are drawn at the following values of spectral density:

Range	Low			Mid			High					
Density (m^2Hz^{-1})	0.01	0.1	1.0	3.3	10.0	20.0	35.0	50.0	100.0	150.0	200.0	250.0

Printing costs do not permit the inclusion of colour versions of these plots, which are easier to 'read'; the interested reader is referred to the authors, who can provide colour contour figures of the spectra. Some points of interest to be mentioned with regard to the spectra include (i) the presence of what is believed to be tidal-frequency modulation of the spectra, presumably active at all spectral frequencies, but visible often at high frequency (e.g. following 1986 day 335 at 0.3-0.4Hz) and occasionally at low frequency; (ii) storm development with increasing wind speed is shown clearly: the spectral peak moves progressively to lower frequencies (e.g. following 1986 day 344, there are three significant storms in evidence, at around 24, 72 and 144 hours); (iii) there are many example of multiple-peaked spectra, where the 'left-over' swell of one storm is present with the higher-frequency components of newer, growing seas, as on the previous example; (iv) the very high 10m H_S storm (after 1986 day 326) has unusually low-frequency components, with some energy recorded at the lowest frequency used, about 0.03Hz, or 30s period.

9. EVIDENCE FOR CLIMATE CHANGE AT SEVEN STONES LV

There has already been one article published which examined these data for evidence of climate change: Carter and Draper (1988), and which used the H_S data corrected for hydrodynamic response using the old scheme. It is intended to set out here the same evidence reworked with the revised data set, together with some additional information.

One measure of the 'wave climate' is the annual mean of H_S, formed from the mean of the twelve monthly mean values of H_S. If one accepts only those months with data return ≥80%, it is possible to form 13 complete annual mean values of H_S, with 'obvious' divisions of data up to 1974 and a 'choice' of years afterwards. Table 12 shows these mean values and the periods over which they were calculated, together with their ranking value, with the annual means ordered from low to high. With the values ordered in this way, a non-parametric ranking test can be used to test the hypothesis that the first half of the values (1962-74) and the second half (1975/6-86) are identically distributed. The sum of the ranks for the first half of the data is formed and compared with the distribution of the sum assuming no trend (Wilcoxon ranking test, see Pearson and Hartley, 1976). For either set of data, the hypothesis of no trend is rejected at the 98-99% level. Figure 15 shows the first sequence of values from Table 12; within the considerable inter-annual scatter, there is a tendency for the values to rise over time. Fitting a regression of H_S on the year gives a slope of about 0.022m/year, corresponding to an increase of 28% in H_S over the 23 years spanning the measurements. The standard error of the slope is 0.005.

Whether the extreme values such as $H_S(50)$ have tended to increase over 1962-86 is more difficult to say. One might expect that the tails of the distribution would increase with the mean. However, this need not be so, as pointed out by Hogben (1989) who suggests that the increase in the means could be explained by an increase in the height of the swell and not by an increase in the locally generated sea; and that in severe storms the swell component is negligible.

Some indication of an increase in $H_S(50)$ is provided by the cumulative distributions and the 50-year return values of H_S. Table 7B gives values of $H_S(50)$ for individual years estimated from Fisher-Tippett Type I distributions, and it can be seen that the range of values in the first half of the data, 10.8-15.5m, is less than that in the second half, 12.5-16.5m. Cumulative distributions of H_S were formed separately for the two halves of the data, and are shown in Figure 16, with fitted FT-1 distributions: two different divisions were used, one 1962-74 and 1974-86, the other 1962-78 and 1978-86. The results are summarised below, with A and B FT-1 location and scale parameters respectively.

Data Period	A (m)	B (m)	$H_S(50)$ (m)
1962-74	1.41	0.97	12.99
1975-86	1.62	1.03	13.85

Data Period	A (m)	B (m)	$H_S(50)$ (m)
1962-78	1.45	0.97	13.01
1978-86	1.66	1.05	14.12

Figure 16 shows how the cumulative distributions of the two halves of the data diverge with increasing probability: the later data distribution is shifted to greater H_S. Applying the Wilcoxon ranking test to 14 estimates of $H_S(50)$ from independent years in Table 7B gives a 90% probability that an assumption of stationarity is incorrect. However, applying the test to the corresponding 14 recorded annual maxima gives a probability of less than 90%.

Another approach is to fit annual maxima using the model suggested for a linear trend by Smith (1986) in which the location parameter of the FT-1 is a function of time, ie,

$$\mathrm{Prob}(H<h) = \exp[-\exp[-(h-(A+at))/B]]$$

Fitting to the 14 annual maxima by maximum likelihood with t=0 for 1962/3 and t=1 for 1985/6 gives A=8.12m, B=0.97m and a=1.14m; so $H_S(50)$, defined as the annual maximum which would be exceeded with a probability of 2%, goes from 11.92m (t=0) to 13.06m (t=1), an increase of nearly 10% over 23 years. However, comparing the fit of this distribution with the FT-1 (with a=0) shows that there is no evidence of of an improved fit beyond that expected from the introduction of a third parameter (the distributions were compared using the asymptotic result that twice the difference in log likelihoods from the two fits is distributed χ^2 - see Kendall and Stuart 1951). Applying the same comparison to analyses of monthly maxima showed only three months (January, March and June) for which there was about a 90% probability or higher (not allowing for multiple tests) that the omission of the parameter 'a' was incorrect.

Therefore, there is some evidence from the data that $H_S(50)$ increased over the period 1962-86, perhaps by 10%, but the data set is too short to provide firm evidence for the increase.

To summarise, there does seem to be a trend in the measured data from 1962 to 1986, although obviously the trend could not persist endlessly forwards or backwards; and failing any physical understanding for the trend, any extrapolation forward is not justifiable. Further, there is some indication, as seen in the monthly H_S mean and maximum values and the 'storm' durations, that 1972-74 constituted a 'peak' of activity around that time, and that 1986, and possibly 1987-88 in view of the severity of recent winters, may constitute another. Until we have a better understanding, particularly of the physics, of these variations in wave climate, it would seem reasonable to use the estimate of $H_S(50)$ assuming stationarity given in section 7.1 for future design criteria.

10. ACKNOWLEDGEMENTS

Thanks are due to Trinity House and to the Masters and crew of Seven Stones LV for the installation and conscientious maintainence of the SBWR. Thanks are also due to numerous colleagues past and present within IOS DL, and others, who were concerned over the years with the collection and processing of the data analysed within this report. The collection of the data from 1974 until the present and the preparation of this report were funded by the Department of Energy. The early data collection (1962-73) was funded by IOS DL (then NIO).

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TABLE1

Monthly Data Returns

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1962	9	225	247	242	246	238	246	246	236	243	236	245
1963	237	-	-	-	-	-	-	-	-	-	-	-
1968	248	232	247	240	246	240	247	248	240	248	240	247
1969	248	224	248	238	245	214	235	243	238	245	227	248
1971	-	-	-	-	-	-	247	247	238	248	240	248
1972	247	230	242	239	248	240	244	248	240	248	240	246
1973	248	224	248	216	248	240	248	247	240	247	240	246
1974	247	224	247	240	247	239	-	-	-	-	-	-
1975	-	-	-	239	248	240	248	246	240	244	239	248
1976	247	229	248	237	247	240	248	247	240	206	240	246
1977	224	224	247	240	247	240	247	245	240	248	238	247
1978	247	4	-	-	-	212	245	245	239	247	240	243
1979	238	206	230	236	245	239	246	247	140	232	235	248
1980	247	232	246	240	246	240	246	245	239	246	235	241
1981	231	223	244	239	244	34	-	187	157	131	221	244
1982	246	219	244	237	246	238	240	248	235	246	238	233
1983	231	223	247	240	246	237	233	240	236	247	238	246
1984	243	229	246	240	244	-	-	-	-	-	-	-
1985	196	218	244	235	209	227	236	241	235	232	235	246
1986	245	220	240	228	106	197	125	141	212	149	177	203

TABLE 2A

H_s Histogram Values (% Occurrence)

Data Period	Bin Upper Limit (m)											
	Calm	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**
All	0.64	1.72	15.43	20.38	17.72	13.35	9.93	7.11	4.70	3.26	2.07	1.39
Spring	0.36	0.72	15.42	22.52	19.83	14.14	9.77	6.12	4.23	2.41	1.68	1.05
Summer	1.86	4.60	29.46	28.09	18.51	9.81	4.51	1.73	0.79	0.38	0.11	0.08
Autumn	0.33	1.36	13.00	20.11	18.27	14.65	11.70	8.01	4.93	3.15	1.94	1.11
Winter	0.00	0.15	3.57	10.60	14.23	14.83	13.83	12.68	8.94	7.15	4.59	3.33

Data Period	Bin Upper Limit (m)											
	6.0	**6.5**	**7.0**	**7.5**	**8.0**	**8.5**	**9.0**	**9.5**	**10.0**	**10.5**	**11.0**	**11.5**
All	0.90	0.59	0.33	0.22	0.13	0.06	0.04	0.02	0.02	0.01	O(0)	O(0)
Spring	0.69	0.49	0.24	0.12	0.07	0.05	0.04	0.03	0.00	0.00	0.01	-
Summer	0.03	0.02	0.01	0.00	0.01	-	-	-	-	-	-	-
Autumn	0.73	0.24	0.20	0.09	0.07	0.03	0.02	0.01	0.02	0.02	0.00	0.01
Winter	2.17	1.62	0.90	0.67	0.38	0.14	0.09	0.03	0.05	0.03	0.01	-

TABLE 2B

T_Z Histogram Values (% Occurrence)

Data	Bin Upper Limit (s)											
Period	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
All	0.02	0.30	1.18	3.07	6.37	9.90	12.21	12.58	12.58	11.30	9.13	7.55
Spring	0.02	0.38	1.32	3.68	7.99	11.41	12.83	12.70	12.33	9.90	8.34	7.07
Summer	0.04	0.68	2.54	5.28	9.58	14.45	16.53	15.32	12.43	8.55	5.60	3.55
Autumn	0.00	0.12	0.61	2.51	5.16	8.02	10.92	12.23	13.61	13.51	10.76	8.61
Winter	0.00	0.00	0.21	0.75	2.69	5.62	8.48	10.02	11.95	13.32	11.88	11.04

Data	Bin Upper Limit (s)										
Period	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0
All	4.86	3.67	2.30	1.07	0.70	0.33	0.14	0.06	0.03	0.01	0.01
Spring	4.31	3.16	2.14	0.84	0.63	0.38	0.12	0.06	0.04	-	-
Summer	1.72	1.04	0.46	0.16	0.09	0.03	0.02	0.04	0.01	0.02	0.01
Autumn	5.31	3.81	2.12	1.06	0.74	0.31	0.12	0.07	0.06	0.01	0.01
Winter	8.16	6.73	4.52	2.23	1.35	0.60	0.29	0.09	0.02	0.03	0.02

TABLE 3

Monthly Mean H_S (m)

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1962	(3.65)	2.83	1.85	2.23	1.65	1.32	1.15	1.66	1.65	1.66	2.25	2.57
1963	1.85	-	-	-	-	-	-	-	-	-	-	-
1968	2.69	2.07	2.33	1.59	1.48	1.52	1.00	1.33	2.09	2.12	2.28	2.74
1969	2.55	2.20	1.73	2.15	1.56	1.36*	1.25	1.51	1.40	1.96	2.58	2.50
1971	-	-	-	-	-	-	1.07	1.53	1.34	1.99	2.38	2.76
1972	3.40	3.23	2.73	2.43	2.37	1.49	1.01	1.17	1.01	1.66	2.40	3.62
1973	2.48	2.54	1.61	1.48*	1.43	1.30	1.16	1.32	1.95	1.53	1.89	2.41
1974	4.40	3.41	2.20	1.32	1.90	1.36	-	-	-	-	-	-
1975	-	-	-	1.87	1.35	1.28	1.31	1.36	1.94	2.02	2.53	1.79
1976	2.98	2.63	2.76	1.52	1.87	1.51	1.15	0.78	1.67	2.61*	2.58	2.89
1977	2.95	3.24	2.95	2.22	1.48	1.31	1.27	1.28	1.56	2.34	2.92	2.65
1978	3.10	(2.16)	-	-	-	1.50*	1.60	1.24	1.90	1.49	2.48	3.69
1979	2.47	2.57	2.88	1.87	1.75	1.19	1.12	1.82	(1.35)	2.26	2.78	3.73
1980	2.60	3.05	2.65	1.34	1.26	1.75	1.63	1.59	2.41	2.72	2.73	3.15
1981	2.66	2.50	3.03	1.80	2.18	(1.81)	-	(1.27)	(1.93)	(2.74)	2.27	2.95
1982	3.05	3.06	3.06	1.48	1.71	1.70	1.03	1.90	1.80	3.18	3.13	3.43
1983	3.41	2.89	2.49	1.82	1.80	1.33	1.05	1.12	2.49	2.53	1.91	3.38
1984	4.37	3.14	2.01	1.66	1.32*	-	-	-	-	-	-	-
1985	(2.72)	2.30	2.76	2.79	1.86	1.73	1.43	2.35	1.66	1.72	2.21	3.35
1986	3.98	2.86	3.46	2.18	(2.62)	1.16*	(1.25)	(1.63)	1.31*	(2.32)	(4.13)	4.07

*:	missing 10-20% data
( ):	missing >20% data

TABLE 4

Monthly Maximum H_S (m)

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1962	(4.06)	7.77	7.17	8.95	6.11	3.48	3.86	4.44	6.47	6.03	7.66	7.55
1963	5.18	-	-	-	-	-	-	-	-	-	-	-
1968	7.07	4.53	6.18	4.99	4.45	3.08	2.79	4.98	6.81	5.47	5.27	8.24
1969	7.81	5.70	3.63	5.52	3.46	4.57*	3.69	3.18	3.40	5.08	8.03	6.98
1971	-	-	-	-	-	-	2.36	3.60	4.28	5.72	6.32	7.70
1972	7.97	7.59	9.36	7.56	6.85	4.16	3.40	4.01	2.61	5.37	6.89	7.00
1973	7.12	7.66	5.59	5.05*	5.00	3.43	3.80	4.32	5.35	3.83	5.06	6.39
1974	9.84	8.67	5.48	3.57	5.20	4.01	-	-	-	-	-	-
1975	-	-	-	6.30	3.33	2.70	3.58	3.72	6.90	4.74	6.00	6.03
1976	7.30	6.11	10.68	4.48	3.79	3.67	3.15	2.05	5.70	7.71*	6.15	9.07
1977	7.33	7.01	7.37	6.41	4.13	4.09	3.36	5.05	4.48	5.67	6.41	6.81
1978	7.44	(2.74)	-	-	-	3.09*	4.08	3.25	5.33	3.60	5.34	9.34
1979	6.71	5.38	6.50	4.99	5.33	3.32	3.34	7.80	(2.63)	5.88	5.75	10.57
1980	7.55	8.16	9.28	3.49	3.99	5.14	2.94	3.72	7.60	7.64	6.12	7.55
1981	6.11	5.57	6.53	6.39	5.56	(2.95)	-	(3.80)	(5.96)	(5.19)	4.93	8.25
1982	5.96	7.17	6.88	4.39	3.91	4.31	2.53	4.57	4.77	11.13	7.64	8.75
1983	9.19	7.49	6.27	4.54	6.13	4.23	3.53	2.71	9.01	7.93	6.55	8.67
1984	9.64	10.22	6.08	3.87	5.07*	-	-	-	-	-	-	-
1985	(6.37)	6.28	7.18	9.37	6.21	6.97	3.05	5.34	4.86	5.74	5.37	7.17
1986	8.36	5.87	7.93	5.10	(5.82)	3.70*	(2.72)	(6.29)	3.55*	(5.62)	(10.24)	8.79*

*: missing 10-20% data

( ): missing >20% data

TABLE 5

Monthly Median H_S (m)

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1962	(3.68)	2.54	1.63	1.72	1.51	1.14	1.00	1.54	1.38	1.27	1.81	2.27
1963	1.63	-	-	-	-	-	-	-	-	-	-	-
1968	2.54	1.94	1.97	1.30	1.35	1.41	0.85	1.24	1.76	1.99	2.24	2.46
1969	2.34	1.88	1.75	1.97	1.53	1.05*	1.12	1.42	1.40	1.78	2.21	2.33
1971	-	-	-	-	-	-	1.04	1.52	1.11	1.66	2.19	2.71
1972	3.34	3.09	2.20	2.01	2.04	1.47	0.81	1.01	0.88	1.46	2.05	3.55
1973	2.36	2.23	1.34	1.21*	1.24	1.17	1.03	1.00	1.66	1.45	1.64	2.18
1974	4.34	3.18	1.91	1.23	1.74	1.22	-	-	-	-	-	-
1975	-	-	-	1.78	1.21	1.26	1.12	1.31	1.71	2.01	2.41	1.44
1976	2.77	2.41	2.56	1.41	1.92	1.34	0.93	0.70	1.56	2.38*	2.31	2.46
1977	2.82	3.19	2.64	2.18	1.30	1.10	1.08	1.02	1.27	2.20	2.90	2.43
1978	2.96	(2.23)	-	-	-	1.45*	1.54	1.13	1.88	1.36	2.50	3.72
1979	2.18	2.63	2.97	1.81	1.59	0.99	1.11	1.68	(1.27)	2.09	2.64	3.39
1980	2.44	2.89	2.41	1.30	1.19	1.55	1.61	1.59	2.26	2.49	2.73	2.91
1981	2.46	2.32	2.92	1.43	1.93	(1.92)	-	(1.13)	(1.76)	(2.78)	2.14	2.66
1982	2.95	2.92	2.79	1.38	1.63	1.61	1.06	1.84	1.48	2.84	3.10	3.05
1983	3.25	2.52	2.28	1.73	1.58	1.11	1.04	1.03	2.14	2.43	1.50	3.23
1984	4.02	2.34	1.64	1.55	1.20*	-	-	-	-	-	-	-
1985	(2.56)	2.03	2.56	2.55	1.66	1.53	1.37	2.23	1.44	1.37	2.00	3.02
1986	3.95	2.84	3.26	1.97	(2.57)	1.07*	(1.22)	(1.24)	1.12*	(2.13)	(3.83)	3.96*

*: missing 10-20% data

( ): missing >20% data

TABLE 6

Monthly 90th Percentile H_s (m)

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1962	(4.06)	4.51	3.05	4.84	2.72	2.47	2.19	2.83	2.95	3.46	4.56	4.67
1963	3.46	-	-	-	-	-	-	-	-	-	-	-
1968	4.21	3.36	4.34	2.87	2.64	2.36	1.76	2.13	3.71	3.19	3.39	4.54
1969	4.36	4.08	2.78	3.65	2.38	2.77*	2.07	2.39	2.22	3.16	4.30	3.90
1971	-	-	-	-	-	-	1.64	2.12	2.11	3.43	4.04	4.25
1972	5.53	5.46	5.35	4.40	4.31	2.27	1.95	2.07	1.69	2.72	4.15	5.52
1973	3.68	4.23	2.97	2.67*	2.37	2.00	1.88	2.61	3.66	2.24	3.28	3.86
1974	6.22	6.17	3.95	1.96	3.28	2.08	-	-	-	-	-	-
1975	-	-	-	2.98	2.23	1.93	2.54	1.98	3.31	2.97	4.38	3.19
1976	4.70	4.23	4.21	2.38	2.76	2.48	2.06	1.24	3.22	4.30*	4.58	5.40
1977	4.98	4.74	5.07	3.44	2.38	2.36	2.25	2.45	2.92	3.57	4.39	4.19
1978	5.29	(1.85)	-	-	-	2.32*	2.66	2.12	3.29	2.44	3.47	5.41
1979	4.11	3.51	4.30	2.81	2.65	2.14	1.70	3.06	(2.18)	3.41	4.15	5.99
1980	4.04	4.71	4.17	2.14	1.94	3.00	2.46	2.43	3.58	4.56	4.16	4.84
1981	4.39	3.92	4.76	3.19	3.31	(2.31)	-	(1.92)	(3.51)	(4.35)	3.27	4.81
1982	4.26	4.49	5.19	2.29	2.60	2.58	1.63	3.01	3.52	4.90	4.70	5.71
1983	5.20	4.93	4.00	3.26	3.18	2.64	1.60	1.83	4.60	4.11	3.74	5.36
1984	7.19	6.03	3.88	2.54	2.12*	-	-	-	-	-	-	-
1985	(3.86)	4.05	4.33	4.77	3.15	2.81	2.42	3.60	3.10	3.31	3.87	5.41
1986	5.98	4.43	5.25	3.63	(3.63)	2.12*	(2.05)	(3.82)	2.36*	(3.85)	(6.05)	5.96*

*:	missing 10-20% data
( ):	missing >20% data

TABLE 7A

50-Year Return Values of H_S

Function Type	Data Period	Number of Records	A (location) (m)	B (scale) (m)	C (shape)	$H_S(50)$ (m)
Fisher-Tippett Type 1	All	46996	1.54	1.01		13.60
	Spring	11949	1.51	0.93		11.24
	Summer	11547	1.03	0.58		7.18
	Autumn	11710	1.61	0.93		11.37
	Winter	11790	2.31	1.13		14.17
	January	4097	2.39	1.14		13.16
	February	3586	2.18	1.05		12.08
	March	3915	1.91	1.08		12.05
	April	4026	1.39	0.84		9.30
	May	4008	1.31	0.69		7.80
	June	3755	1.10	0.58		6.58
	July	3781	0.92	0.51		5.72
	August	4011	1.09	0.64		7.13
	September	3845	1.27	0.83		9.12
	October	3907	1.64	0.88		9.94
	November	3958	1.98	0.97		11.10
	December	4125	2.36	1.16		13.31
3-parameter Weibull	All		0.38	1.92	1.37	12.03
2-parameter Weibull	All above 2m	(43.9%)		2.27	1.52	11.56
	All above 3m	(20.8%)		2.20	1.45	12.13
	All above 4m	(9.0%)		2.15	1.41	12.40
	All above 5m	(3.7%)		2.15	1.42	12.37

TABLE 7B

50-Year Return Values of H_s

Fisher-Tippett Type I fitted to Individual Years

Data Period	Number of Records	A (location) (m)	B (scale) (m)	$H_s(50)$ (m)
2:62-1:63	2896	1.33	0.97	12.91
68	2923	1.44	0.87	11.79
6:68-5:69	2913	1.45	0.84	11.41
69	2853	1.41	0.83	11.34
7:71-6:72	2914	1.60	1.08	14.48
72	2912	1.54	1.17	15.49
7:72-6:73	2890	1.27	0.95	12.60
73	2892	1.30	0.80	10.77
7:73-6:74	2912	1.46	1.06	14.10
4:75-3:76	2916	1.48	0.87	11.84
76	2875	1.50	1.00	13.47
4:76-3:77	2846	1.54	1.04	13.93
77	2887	1.61	0.99	13.37
6:78-5:79	2825	1.60	0.91	12.48
79	2742	1.60	0.96	13.04
6:79-5:80	2798	1.50	1.03	13.81
80	2903	1.69	0.95	13.04
6:80-5:81	2873	1.83	0.90	12.60
8:81-7:82	2610	1.64	0.94	12.82
82	2870	1.78	1.03	14.08
6:82-5:83	2865	1.76	1.08	14.59
83	2864	1.56	1.08	14.43
6:83-5:84	2879	1.48	1.24	16.23
85	2754	1.70	0.95	12.95
6:85-5:86	2691	1.86	1.05	14.32
86	2243	1.87	1.23	16.45

TABLE 7C

50-Year Return Values of H_S

Fisher-Tippett Type I fitted to Monthly and Annual Maxima

Month number unflagged: all data fitted

Month number flagged with asterisk: data from months with <80% data return excluded

am: annual maxima; mm: monthly maxima.

Month/Year	Number of months/ years	A (location) (m)	B (scale) (m)	$H_S(50)$ (m)
1	18	6.55	1.46	12.26
*1	16	6.93	1.15	11.40
2	17	5.83	1.77	12.76
*2	16	6.28	1.22	11.02
3	16	6.21	1.54	12.21
4	17	4.83	1.23	9.64
5	17	4.44	0.93	8.07
*5	16	4.39	0.91	7.95
6	17	3.52	0.67	6.14
*6	16	3.58	0.68	6.23
7	16	3.02	0.47	4.84
*7	15	3.05	0.48	4.93
8	17	3.68	1.08	7.91
*8	15	3.59	1.06	7.71
9	17	4.45	1.50	10.32
*9	15	4.61	1.45	10.25
10	17	5.28	1.26	10.20
*10	15	5.30	1.35	10.58
11	17	5.98	0.90	9.42
*11	16	5.78	0.75	8.71
12	17	7.43	0.95	11.15
All (mm)				14.45
*All (mm)				13.61
All (am1)	17	8.62	1.01	12.55
All (am2)	14	8.75	0.99	12.61

TABLE 7D

Sequences of Annual Maximum H_S

Data Period	Annual Maximum H_S (m)
2:62-1:63	8.95
1:68-12:68	8.24
1:69-12:69	8.03
7:71-6:72	9.36
7:72-6:73	7.66
7:73-6:74	9.84
4:75-3:76	10.68
4:76-3:77	9.07
*4:77-3:78	7.44
6:78-5:79	9.34
6:79-5:80	10.57
6:80-5:81	7.64
*6:81-5:82	8.25
6:82-5:83	11.13
6:83-5:84	10.22
1:85-12:85	9.37
*1:86-12:86	10.24

The above data values form the sequence of annual maximum H_S 'am1'. The sequence 'am2' was formed by omitting the values marked with asterisks, and by taking the last year to run from 2:85 to 1:86. All months of poor data return were excluded thereby.

TABLE 8

Statistics of H_S 'Storm' Durations

H_S Threshold (m)	Total Number of Events	Mean Number of Events per Year	Number of Gap Ends	Mean Duration (hours)	% of Time above Threshold	Variance of Duration	Standard Deviation of Mean Duration
2.0	2236	139.0	44	25.61	40.61	1495.14	0.818
2.5	1946	121.0	28	21.79	30.08	1078.48	0.744
3.0	1700	105.7	18	17.46	21.05	665.87	0.626
3.5	1361	84.6	12	14.45	13.95	410.47	0.549
4.0	1016	63.2	10	12.65	9.12	262.09	0.508
4.5	776	48.3	5	10.61	5.85	173.15	0.472
5.0	581	36.1	4	9.03	3.72	113.92	0.443
5.5	421	26.2	1	7.60	2.27	73.75	0.418
6.0	269	16.7	1	7.08	1.35	58.86	0.468
6.5	180	11.2		6.22	0.79	36.30	0.449
7.0	118	7.3		5.36	0.45	24.78	0.458
7.5	75	4.7		4.54	0.24	22.98	0.554
8.0	38	2.4		5.05	0.14	27.17	0.846
8.5	26	1.6		4.50	0.08	14.40	0.744
9.0	17	1.1		4.14	0.05	17.87	1.025
9.5	9	0.6		4.50	0.03	15.75	1.323
10.0	8	0.5		1.50	0.01	0.0	0.0

TABLE 9

Persistence of 'Storms' of H_s

H_s Threshold (m)	Least Duration (hours) 3	6	9	12	15	18	21	24	27
2.0	1.0	7.88E-1	5.87E-1	4.87E-1	4.19E-1	3.85E-1	3.56E-1	3.23E-1	2.97E-1
2.5	1.0	7.85E-1	5.61E-1	4.72E-1	4.01E-1	3.64E-1	3.25E-1	2.98E-1	2.72E-1
3.0	1.0	7.61E-1	5.38E-1	4.24E-1	3.51E-1	3.09E-1	2.75E-1	2.46E-1	2.18E-1
3.5	1.0	7.27E-1	4.99E-1	3.89E-1	3.23E-1	2.79E-1	2.48E-1	2.17E-1	1.95E-1
4.0	1.0	7.24E-1	4.99E-1	3.93E-1	3.20E-1	2.73E-1	2.32E-1	1.94E-1	1.62E-1
4.5	1.0	6.96E-1	4.60E-1	3.62E-1	2.84E-1	2.40E-1	1.88E-1	1.53E-1	1.29E-1
5.0	1.0	6.87E-1	4.46E-1	3.17E-1	2.50E-1	1.81E-1	1.45E-1	1.17E-1	8.78E-2
5.5	1.0	6.15E-1	3.82E-1	2.68E-1	2.04E-1	1.62E-1	1.09E-1	8.79E-2	5.46E-2
6.0	1.0	6.17E-1	3.75E-1	2.53E-1	1.86E-1	1.41E-1	8.92E-2	5.95E-2	3.72E-2
6.5	1.0	6.06E-1	3.50E-1	2.33E-1	1.50E-1	1.06E-1	6.67E-2	2.78E-2	1.11E-2
7.0	1.0	5.76E-1	3.22E-1	1.61E-1	1.02E-1	8.47E-2	1.69E-2	8.47E-3	8.47E-3
7.5	1.0	4.53E-1	2.40E-1	1.20E-1	9.33E-2	6.67E-2	1.33E-2	1.33E-2	1.33E-2
8.0	1.0	4.74E-1	2.89E-1	1.84E-1	1.05E-1	7.89E-2	2.63E-2	2.63E-2	
8.5	1.0	5.77E-1	1.92E-1	1.15E-1	1.15E-1				
9.0	1.0	4.12E-1	1.76E-1	1.76E-1	1.18E-1				
9.5	1.0	4.44E-1	3.33E-1	2.22E-1					
10.0	1.0								

H_s Threshold (m)	Least Duration (hours) 30	33	36	39	42	45	48	51	54
2.0	2.79E-1	2.57E-1	2.33E-1	2.20E-1	2.05E-1	1.91E-1	1.75E-1	1.57E-1	1.49E-1
2.5	2.45E-1	2.19E-1	1.97E-1	1.80E-1	1.68E-1	1.55E-1	1.42E-1	1.32E-1	1.24E-1
3.0	1.95E-1	1.78E-1	1.58E-1	1.44E-1	1.32E-1	1.24E-1	1.14E-1	1.06E-1	9.18E-2
3.5	1.78E-1	1.59E-1	1.44E-1	1.26E-1	1.03E-1	9.18E-2	7.49E-2	6.17E-2	5.44E-2
4.0	1.42E-1	1.23E-1	1.08E-1	8.76E-2	7.48E-2	6.20E-2	4.72E-2	3.44E-2	2.76E-2
4.5	1.04E-1	8.63E-2	6.70E-2	4.90E-2	4.12E-2	3.09E-2	2.06E-2	1.68E-2	1.29E-2
5.0	6.71E-2	5.51E-2	3.61E-2	2.92E-2	1.72E-2	1.38E-2	5.16E-3	3.44E-3	3.44E-3
5.5	4.28E-2	3.33E-2	2.38E-2	1.90E-2	1.19E-2	7.13E-3	4.75E-3	2.38E-3	2.38E-3
6.0	2.60E-2	2.23E-2	1.86E-2	1.49E-2	1.12E-2	7.43E-3			
6.5	1.11E-2	1.11E-2							
7.0	8.47E-3								

TABLE 9 (continued)

H_S Threshold (m)	Least Duration (hours)								
	57	60	63	66	69	72	75	78	81
2.0	1.36E-1	1.31E-1	1.24E-1	1.17E-1	1.11E-1	1.05E-1	9.88E-2	9.26E-2	8.86E-2
2.5	1.15E-1	1.07E-1	9.51E-2	8.74E-2	8.12E-2	7.76E-2	7.24E-2	6.58E-2	6.17E-2
3.0	7.76E-2	7.00E-2	6.53E-2	5.82E-2	5.29E-2	4.88E-2	4.59E-2	4.41E-2	4.18E-2
3.5	4.41E-2	3.75E-2	3.23E-2	3.01E-2	2.65E-2	2.42E-2	2.35E-2	2.28E-2	2.06E-2
4.0	2.46E-2	2.07E-2	1.77E-2	1.77E-2	1.57E-2	1.38E-2	1.18E-2	1.08E-2	9.84E-3
4.5	1.03E-2	1.03E-2	9.02E-3	9.02E-3	7.73E-3	5.15E-3	3.87E-3	2.58E-3	2.58E-3
5.0	3.44E-3	3.44E-3	3.44E-3	3.44E-3	3.44E-3	1.72E-3	1.72E-3	1.72E-3	1.72E-3
5.5	2.38E-3								

H_S Threshold (m)	Least Duration (hours)								
	84	87	90	93	96	99	102	105	108
2.0	8.63E-2	8.05E-2	7.60E-2	7.29E-2	7.02E-1	6.71E-2	6.44E-2	6.08E-2	5.99E-2
2.5	5.96E-2	5.76E-2	5.45E-2	5.24E-2	4.93E-2	4.37E-2	4.11E-2	4.01E-2	3.55E-2
3.0	3.94E-2	3.71E-2	3.35E-2	3.12E-2	2.71E-2	2.47E-2	2.24E-2	2.06E-2	1.82E-2
3.5	1.76E-2	1.62E-2	1.54E-2	1.32E-2	1.18E-2	1.18E-2	1.03E-2	1.03E-2	8.08E-3
4.0	9.84E-3	8.86E-3	7.87E-3	5.91E-3	4.92E-3	4.92E-3	4.92E-3	2.95E-3	1.97E-3
4.5	2.58E-3	2.58E-3	2.58E-3	2.58E-3	2.58E-3	1.29E-3	1.29E-3	1.29E-3	1.29E-3
5.0	1.72E-3	1.72E-3	1.72E-3	1.72E-3	1.72E-3	1.72E-3	1.72E-3	1.72E-3	1.72E-3

H_S Threshold (m)	Least Duration (hours)								
	111	114	117	120	123	126	129	132	135
2.0	5.46E-2	5.23E-2	4.96E-2	4.92E-2	4.56E-2	4.34E-2	4.20E-2	4.11E-2	4.03E-2
2.5	3.44E-2	3.19E-2	3.19E-2	3.03E-2	2.88E-2	2.83E-2	2.67E-2	2.36E-2	2.26E-2
3.0	1.65E-2	1.65E-2	1.53E-2	1.29E-2	1.24E-2	1.24E-2	1.18E-2	1.12E-2	1.00E-2
3.5	7.35E-3	6.61E-3	6.61E-3	5.88E-3	5.14E-3	4.41E-3	4.41E-3	3.67E-3	2.94E-3
4.0	1.97E-3	1.97E-3	9.84E-4	9.84E-4	9.84E-4	9.84E-4	9.84E-4	9.84E-4	9.84E-4
4.5	1.29E-3	1.29E-3	1.29E-3	1.29E-3	1.29E-3	1.29E-3	1.29E-3	1.29E-3	1.29E-3
5.0	1.72E-3	1.72E-3	1.72E-3	1.72E-3	1.72E-3	1.72E-3			

Table 9 (continued)

H_s Threshold (m)	Least Duration (hours)								
	138	141	144	147	150	153	156	159	162
2.0	3.89E-2	3.85E-2	3.44E-2	3.35E-2	3.31E-2	3.18E-2	3.00E-2	3.00E-2	2.77E-2
2.5	2.26E-2	2.16E-2	2.06E-2	2.00E-2	1.85E-2	1.80E-2	1.80E-2	1.70E-2	1.64E-2
3.0	8.24E-3	7.06E-3	6.47E-3	5.88E-3	5.88E-3	5.29E-3	5.29E-3	4.71E-3	4.71E-3
3.5	2.94E-3	2.94E-3	2.20E-3	2.20E-3	2.20E-3	2.20E-3	2.20E-3	1.47E-3	1.47E-3
4.0	9.84E-4	9.84E-4	9.84E-4	9.84E-4	9.84E-4	9.84E-4	9.84E-4	9.84E-4	
4.5	1.29E-3	1.29E-3	1.29E-3	1.29E-3	1.29E-3				

H_s Threshold (m)	Least Duration (hours)					
	165	168	171	174	177	180
2.0	2.73E-2	2.68E-2	2.59E-2	2.41E-2	2.37E-2	2.28E-2
2.5	1.54E-2	1.44E-2	1.39E-2	1.34E-2	1.34E-2	1.28E-2
3.0	4.12E-3	3.53E-3	3.53E-3	3.53E-3	2.94E-4	2.94E-4
3.5	7.35E-4	7.35E-4	7.35E-4	7.35E-4	7.35E-4	7.35E-4

TABLE 10

Numbers of 'Storms' of Duration > 180 Hours

H_s Threshold (m)	Duration of 'Storm' (hours)											
	180-200	200-220	220-240	240-260	260-280	280-300	300-350	350-400	400-450	450-500	500-600	600-800
2.0	8	7	6	1	6	4	6	3	2	3	3	1
2.5	3	5	4	2	4	1	2	2	0	1		
3.0	2	0	0	0	3							
3.5	1											

TABLE 11

Summary of Statistics of Digital H_S Data

Year	Month	Data Return	Mean H_S (m)	Maximum H_S (m)	Median H_S (m)	90 Percentile H_S (m)
1985	1	228	2.96	5.99	2.93	4.06
	2	250	2.70	4.90	2.54	4.31
	3	478	2.76	7.34	2.54	4.13
	4	460	2.64	7.99	2.35	4.47
	5	410	1.76	6.02	1.55	3.02
	6	417	1.63	5.82	1.35	2.88
	7	455	1.56	3.15	1.42	2.46
	8	416	2.33	4.88	2.26	3.48
	9	451	1.84	4.63	1.57	2.91
	10	462	1.97	5.44	1.43	3.99
	11	290	2.40	4.92	2.42	4.03
	12	30	4.49	5.31	4.50	5.17
1986	1	231	3.78	7.21	3.75	5.82
	2	152	2.28	5.23	2.05	4.33
	5	133	2.55	5.32	2.61	3.85
	6	150	1.04	1.99	0.95	1.68
	7	256	1.59	3.45	1.46	2.65
	8	244	1.86	7.06	1.33	3.85
	9	171	1.71	3.35	1.80	2.65
	10	93	2.01	4.09	1.85	3.33
	11	422	3.91	10.54	3.71	6.22
	12	455	3.83	7.87	3.69	5.73

TABLE 12

Annual Mean Values of H_S

Data Period (1)	Mean H_S (m)	Rank (1)	Data Period (2)	Mean H_S (m)	Rank (2)
2:62-1:63	1.889	2	as 1	1.889	2
1:68-12:68	1.937	4	as 1	1.937	4
1:69-12:69	1.896	3	as 1	1.896	3
7:71-6:72	2.227	10	as 1	2.227	10
7:72-6:73	1.807	1	as 1	1.807	1
7:73-6:74	2.071	6	as 1	2.071	5
4:75-3:76	1.985	5	1:76-12:76	2.079	6
4:76-3:77	2.143	8	1:77-12:77	2.181	8
6:78-5:79	2.120	7	9:78-8:79	2.102	7
6:80-5:81	2.346	11	10:79-9:80	2.254	11
6:82-5:83	2.382	12	1:82-12:82	2.377	13
6:83-5:84	2.190	9	1:83-12:83	2.185	9
5:85-4:86	2.399	13	2:85-1:86	2.345	12

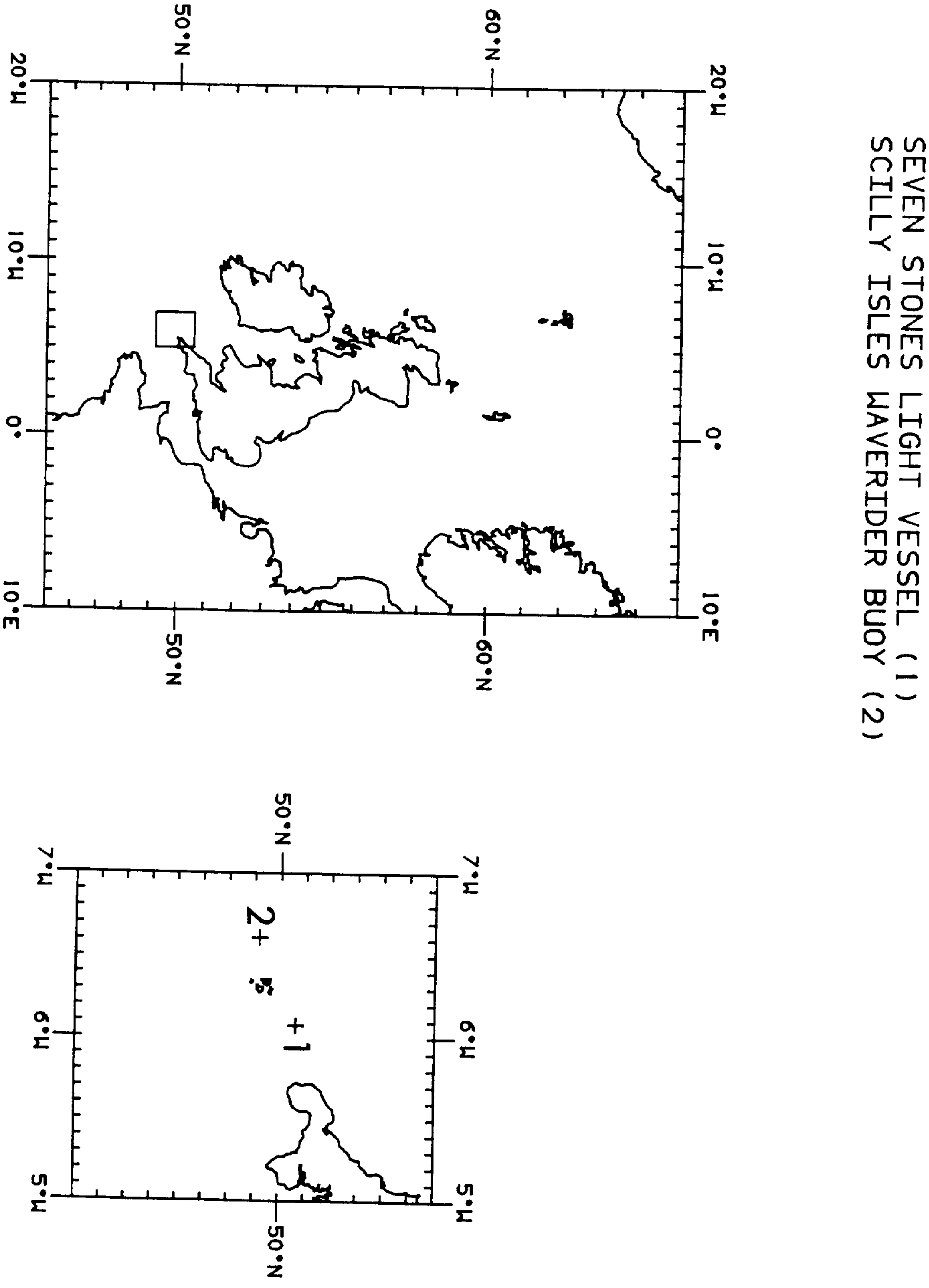
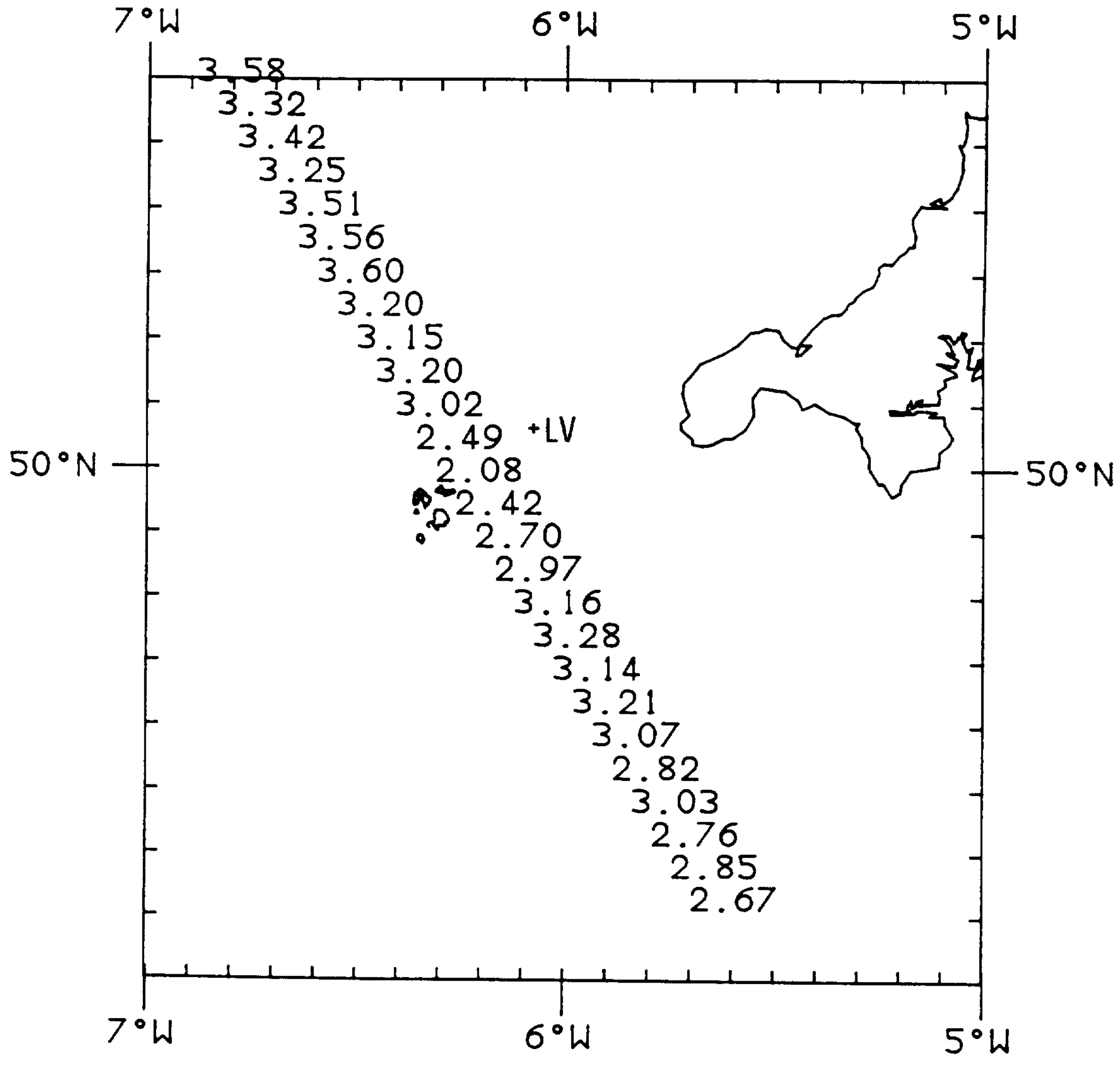

SEVEN STONES LIGHT VESSEL (1)
SCILLY ISLES WAVERIDER BUOY (2)
20°W
10°W
0°
10°E
50°N
60°N
7°W
6°W
5°W
50°N
1
2

Figure 1

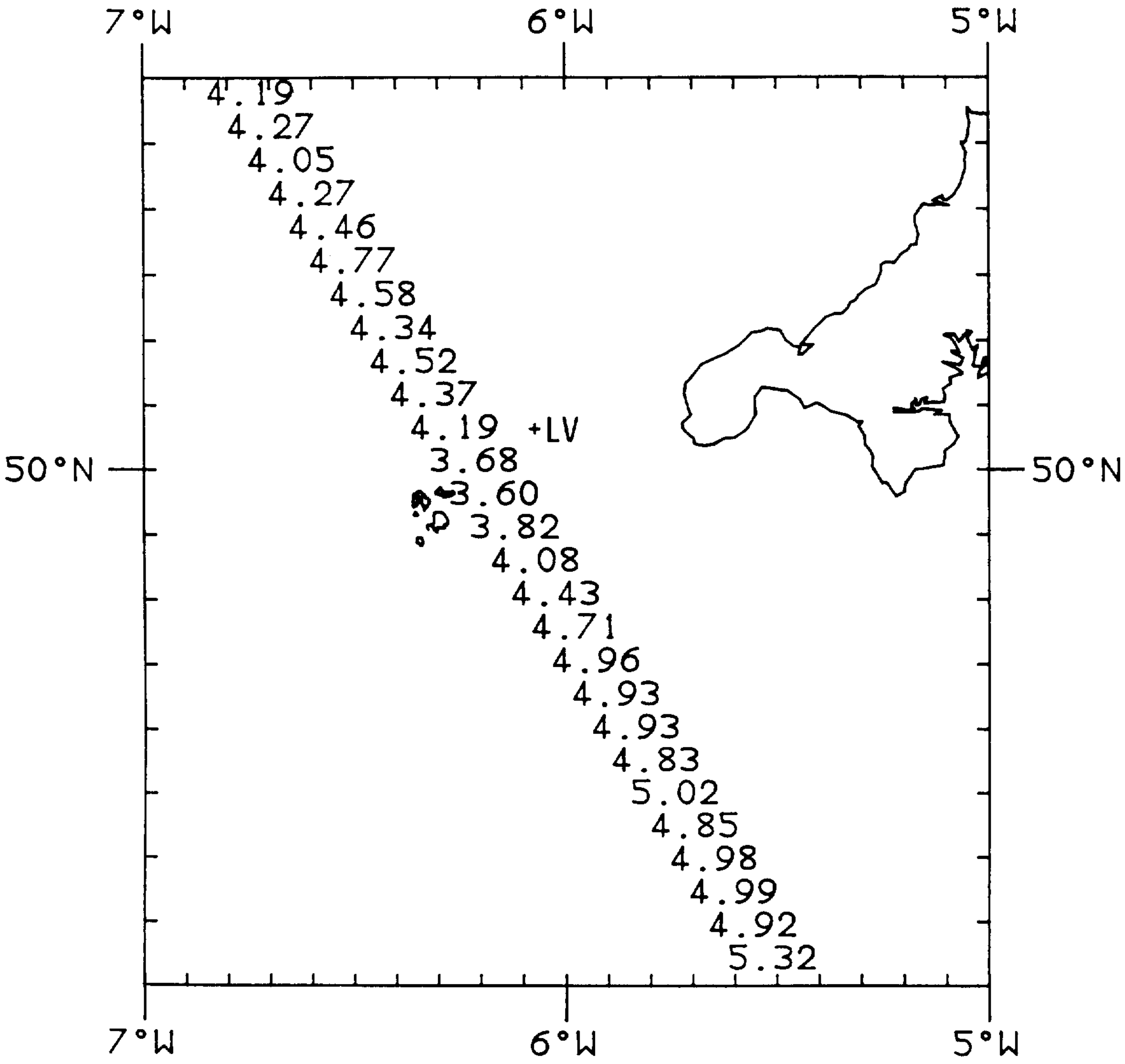
SEVEN STONES LV SBWR
Hs from GEOSAT OVERPASS



DAY 326 YEAR 1986
TIME 0001 Hours

Figure 2 (a)

SEVEN STONES LV SBWR
Hs from GEOSAT OVERPASS



DAY 343 YEAR 1986
TIME 0114 Hours

Figure 2 (b)

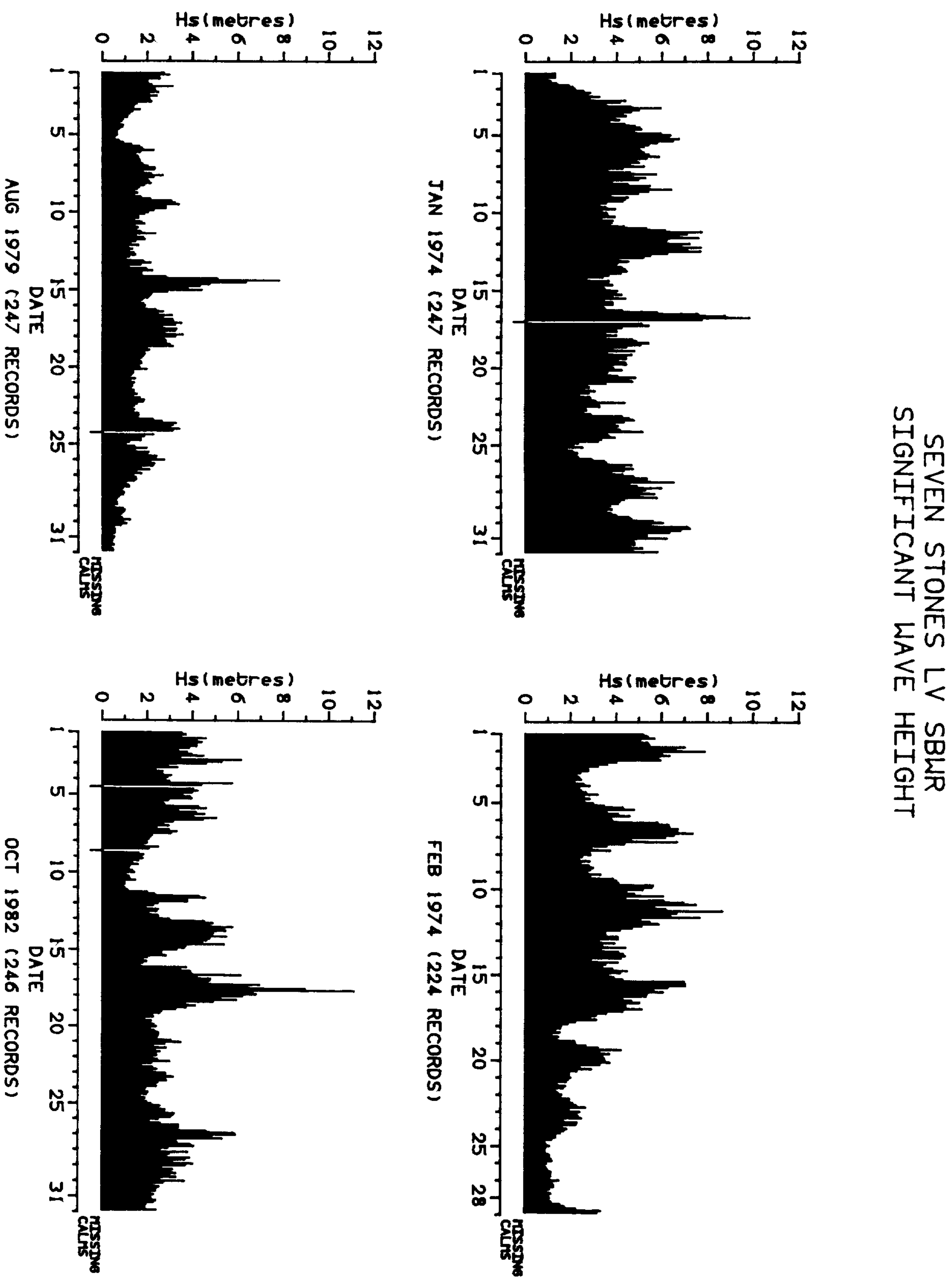
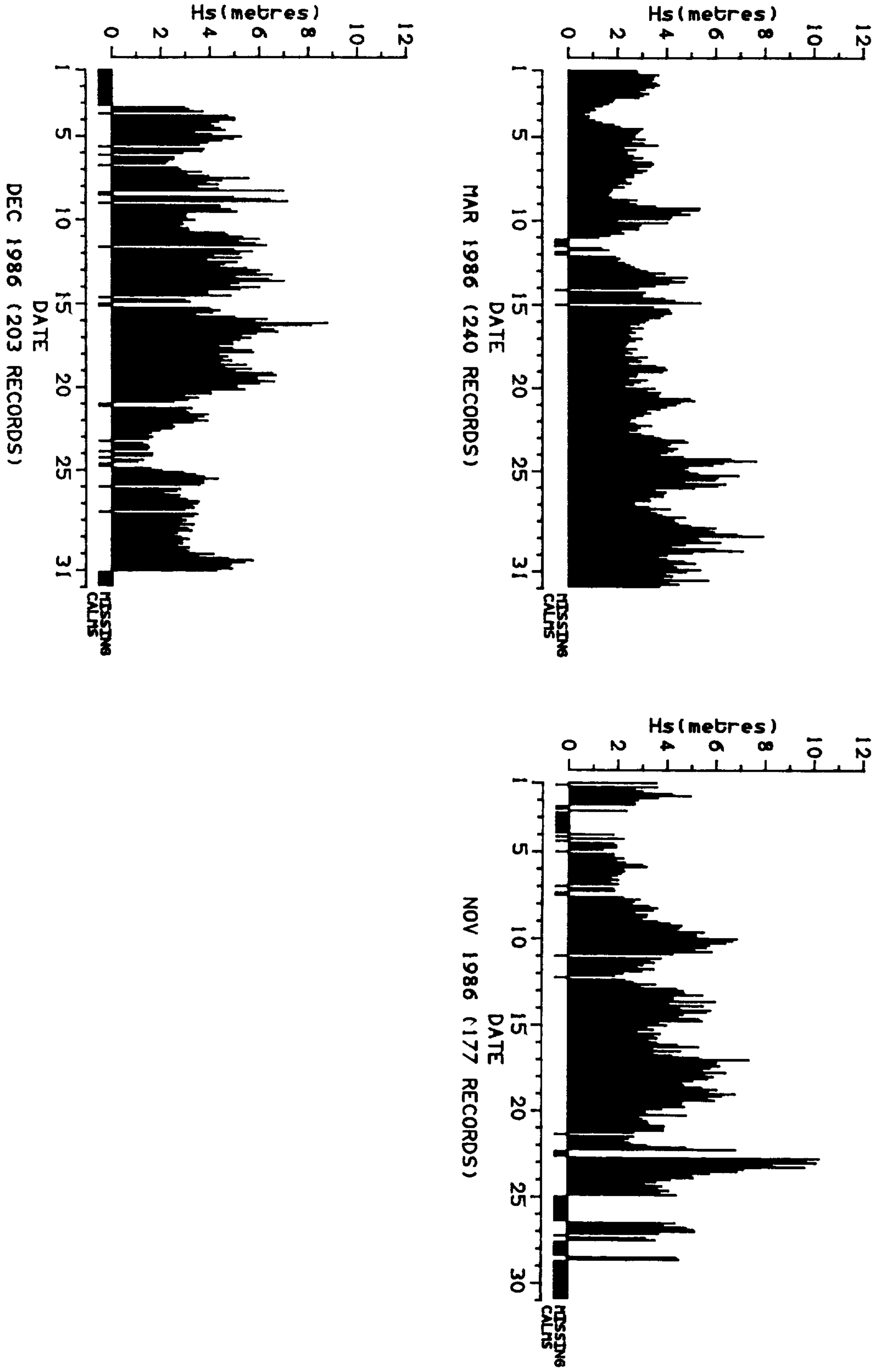

SEVEN STONES LV SBWR
SIGNIFICANT WAVE HEIGHT
Hs(metres)
0 2 4 6 8 10 12
DATE
JAN 1974 (247 RECORDS)
FEB 1974 (224 RECORDS)
AUG 1979 (247 RECORDS)
OCT 1982 (246 RECORDS)
1 5 10 15 20 25 31
1 5 10 15 20 25 28
MISSING
CALMS

Figure 3 (a-d)

SEVEN STONES LV SBWR
SIGNIFICANT WAVE HEIGHT



MAR 1986 (240 RECORDS)

NOV 1986 (177 RECORDS)

DEC 1986 (203 RECORDS)

Figure 3 (e-g)

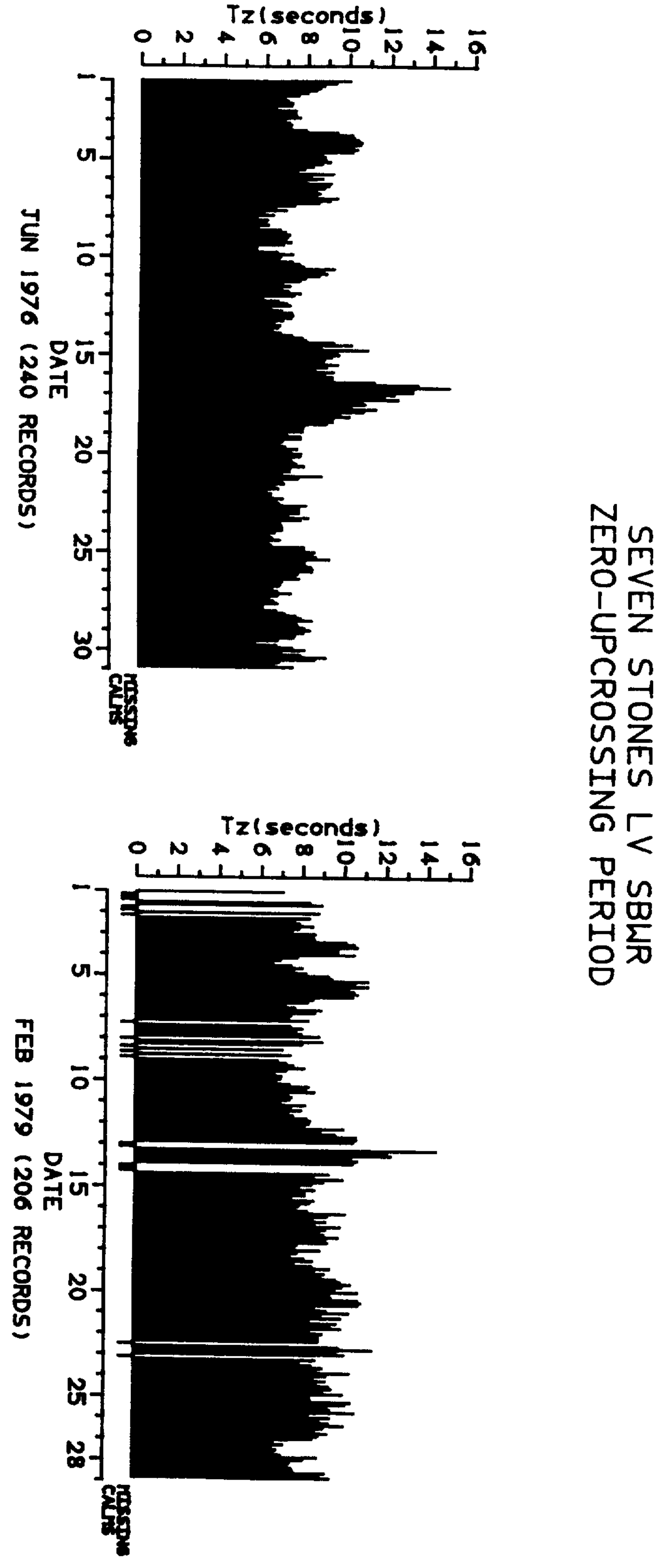

SEVEN STONES LV SBWR
ZERO-UPCROSSING PERIOD
Tz(seconds)
0
2
4
6
8
10
12
14
16
1
5
10
15
20
25
30
DATE
JUN 1976 (240 RECORDS)
MISSING
CALMS
Tz(seconds)
0
2
4
6
8
10
12
14
16
1
5
10
15
20
25
28
DATE
FEB 1979 (206 RECORDS)
MISSING
CALMS

Figure 3 (h-i)

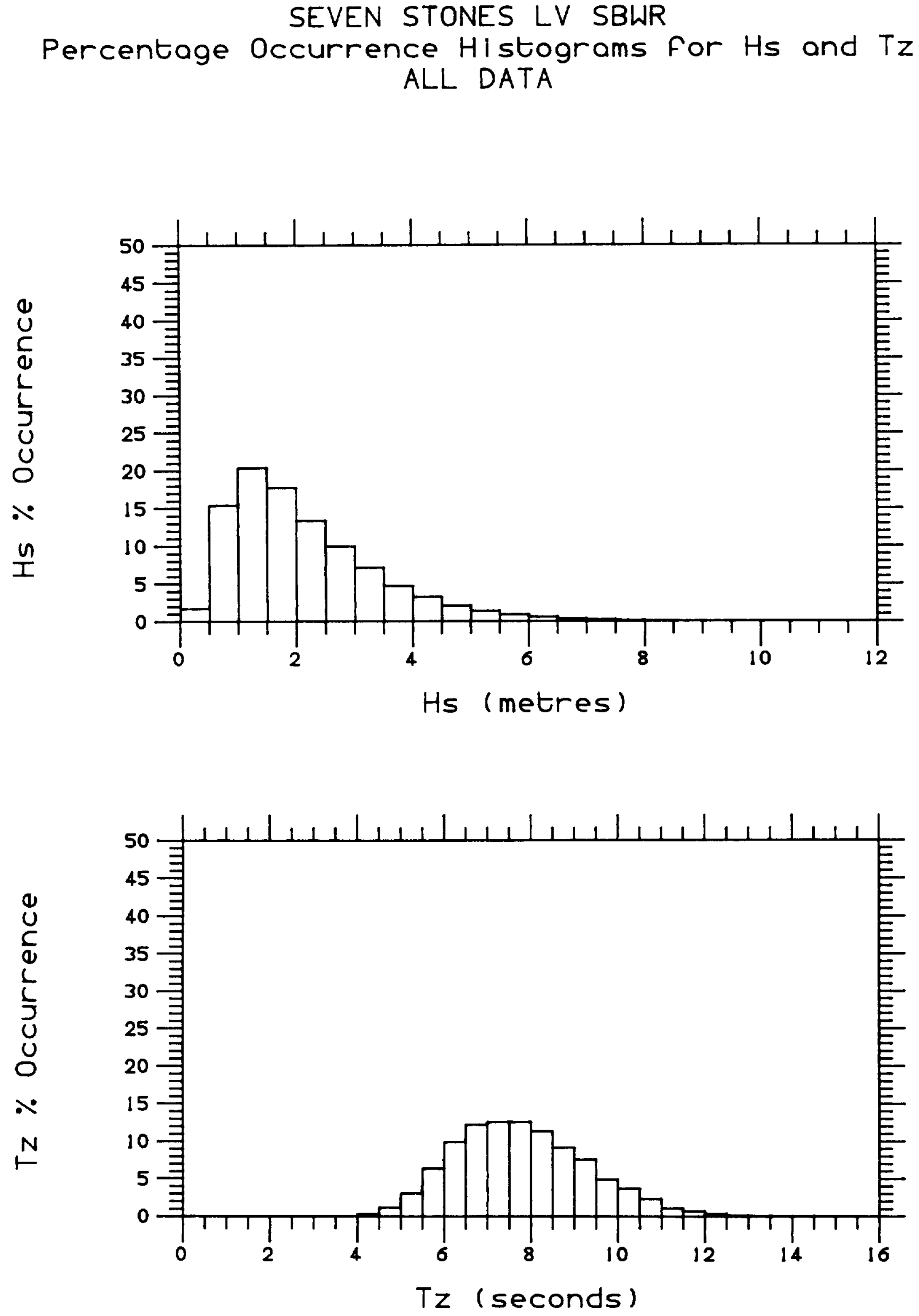

SEVEN STONES LV SBWR
Percentage Occurrence Histograms for Hs and Tz
ALL DATA
Hs % Occurrence
50
45
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
Hs (metres)
Tz % Occurrence
50
45
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
Tz (seconds)

Figure 4 (a-b)

SEVEN STONES LV SBWR
Percentage Occurrence Histograms for Hs and Tz
SPRING

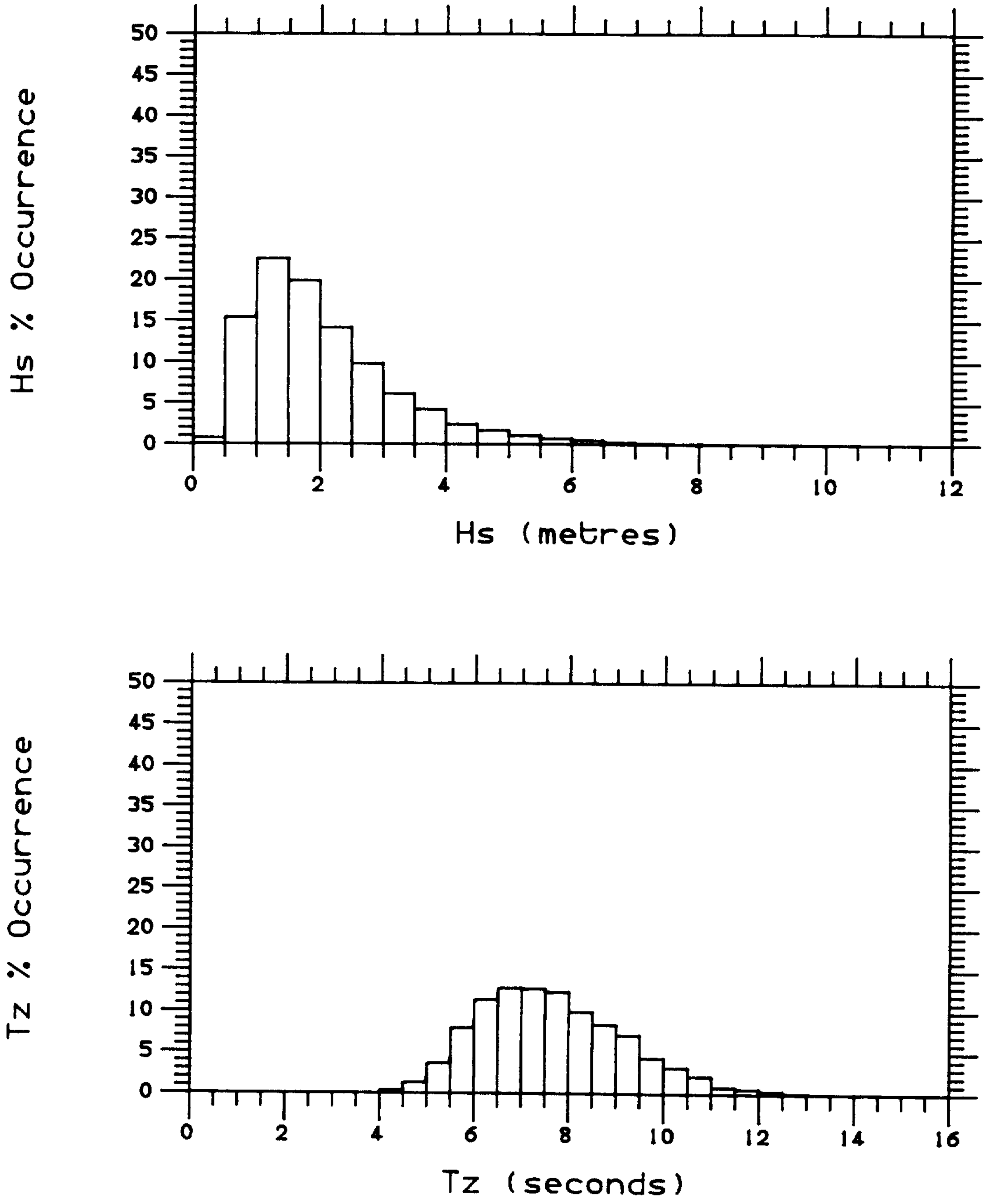


Figure 4 (c-d)

SEVEN STONES LV SBWR
Percentage Occurrence Histograms for Hs and Tz
SUMMER

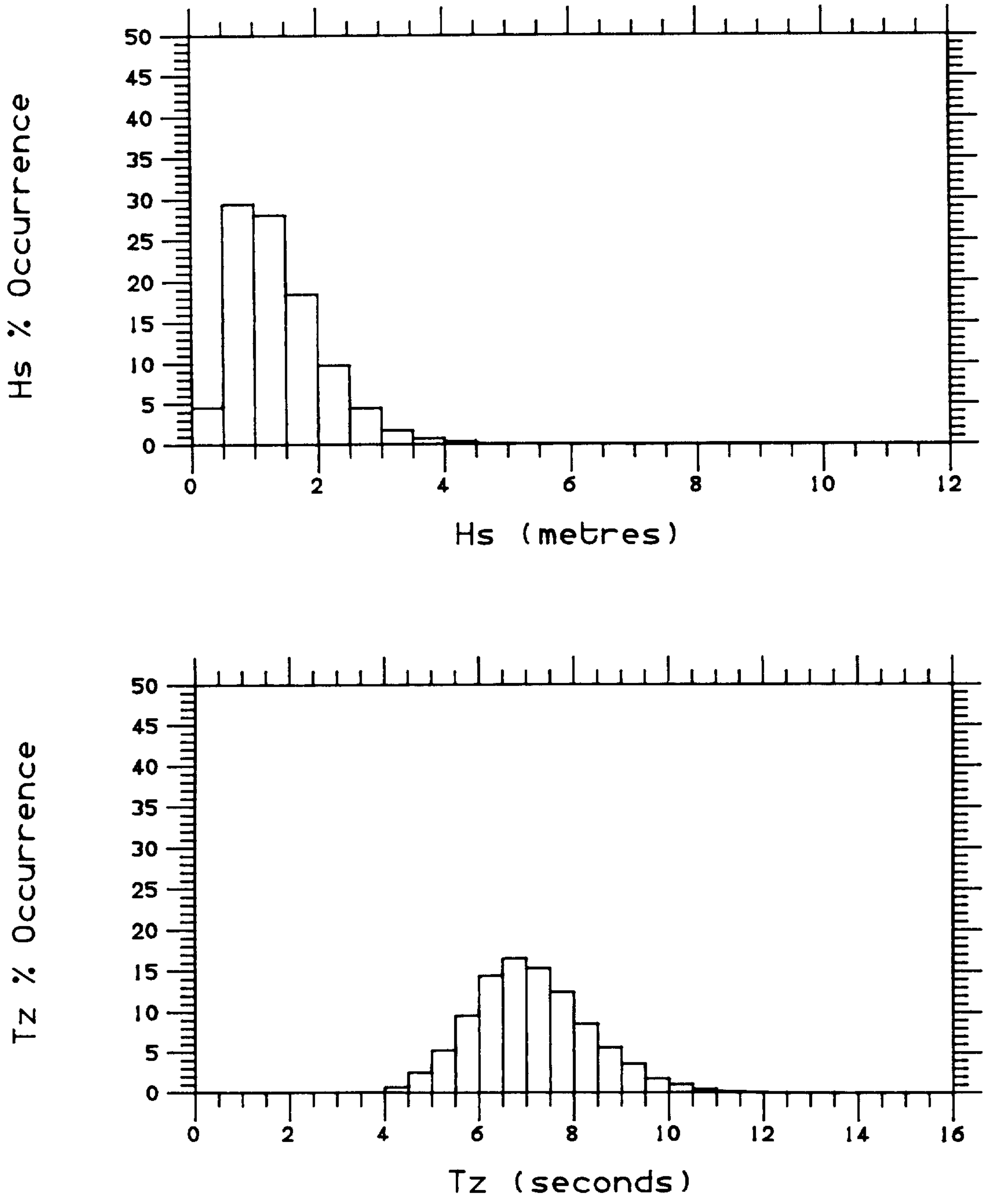


Figure 4 (e-f)

SEVEN STONES LV SBWR
Percentage Occurrence Histograms for Hs and Tz
AUTUMN

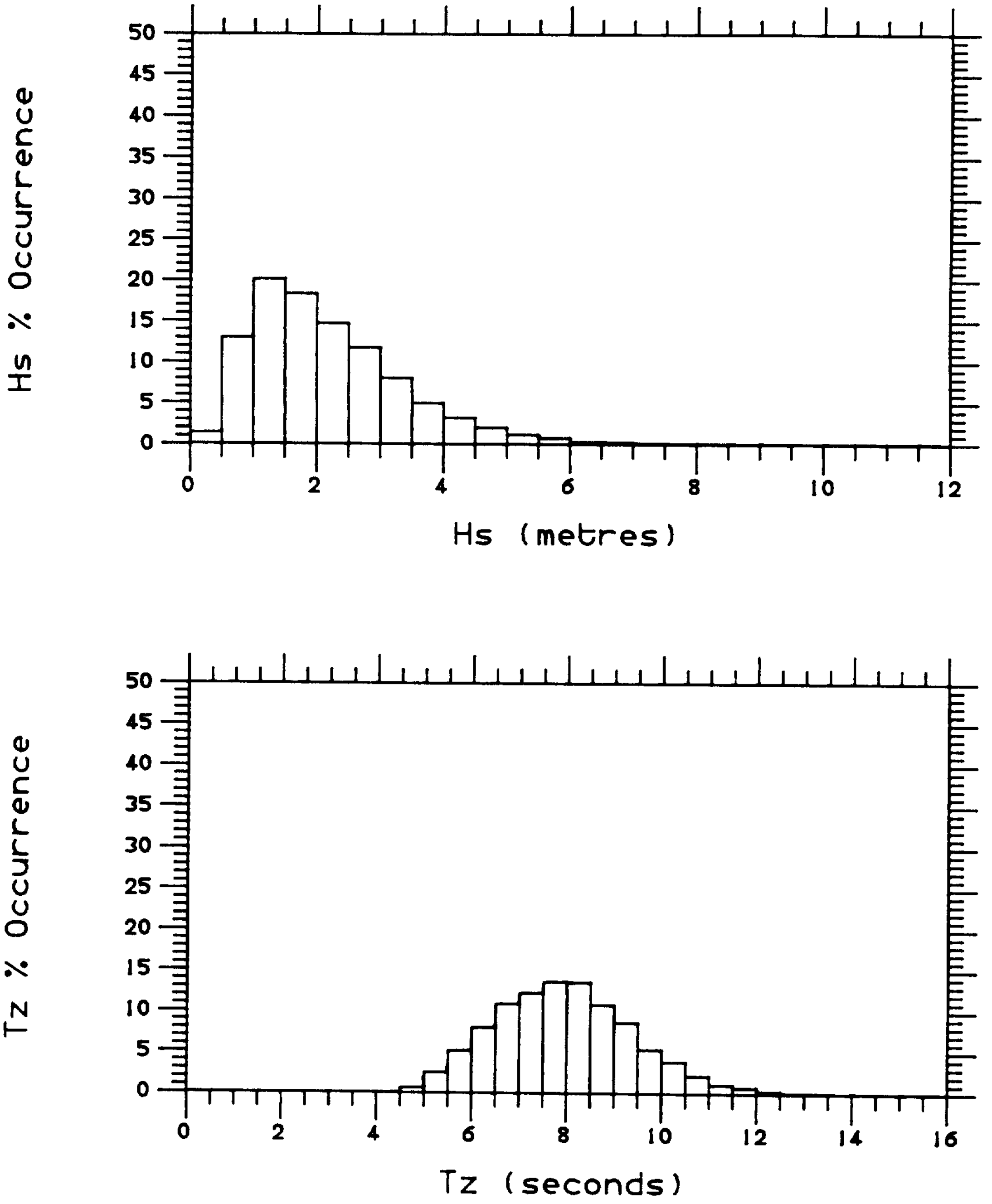


Figure 4 (g-h)

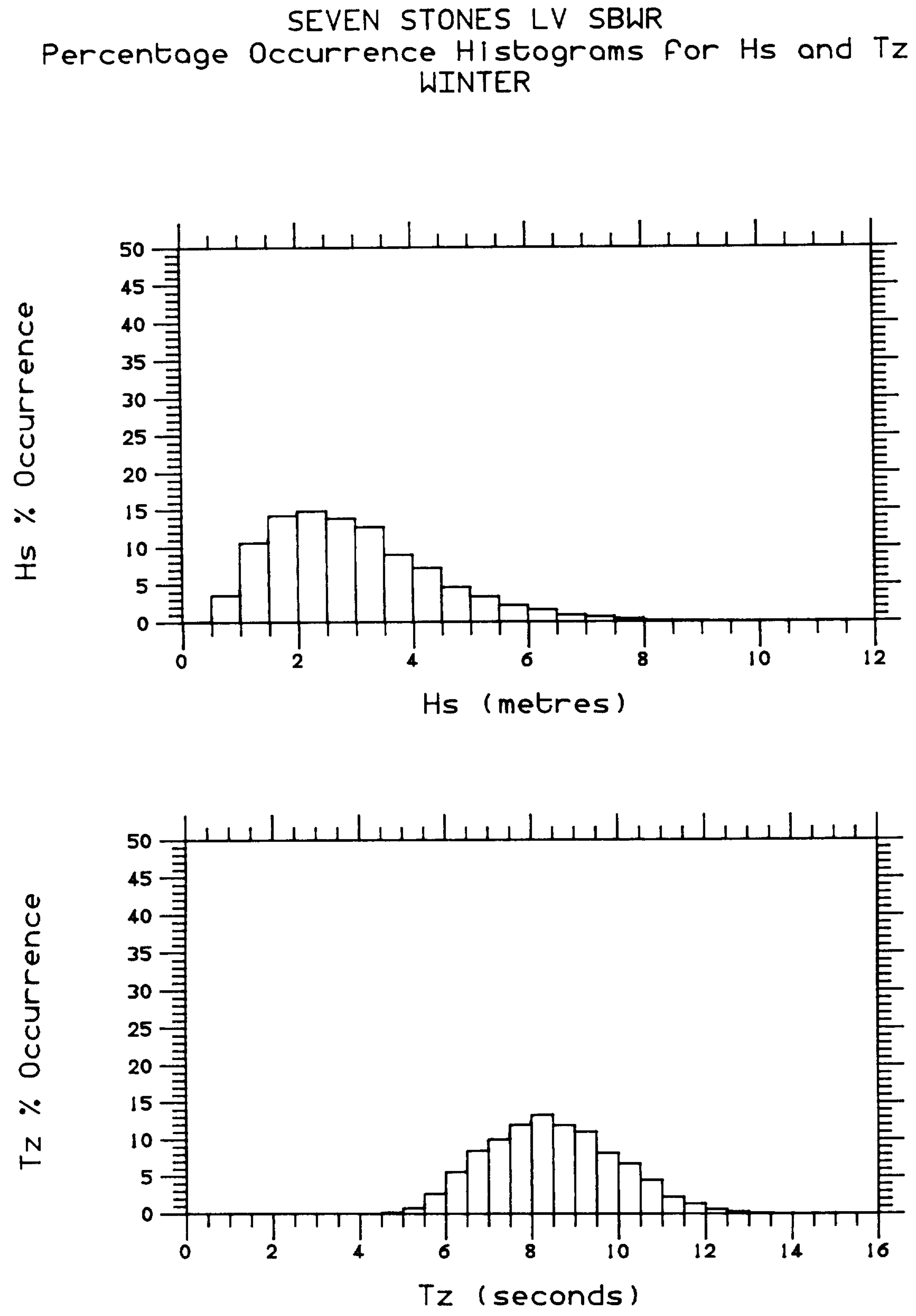

SEVEN STONES LV SBWR
Percentage Occurrence Histograms for Hs and Tz
WINTER
Hs % Occurrence
0
5
10
15
20
25
30
35
40
45
50
0
2
4
6
8
10
12
Hs (metres)
Tz % Occurrence
0
5
10
15
20
25
30
35
40
45
50
0
2
4
6
8
10
12
14
16
Tz (seconds)

Figure 4 (i-j)

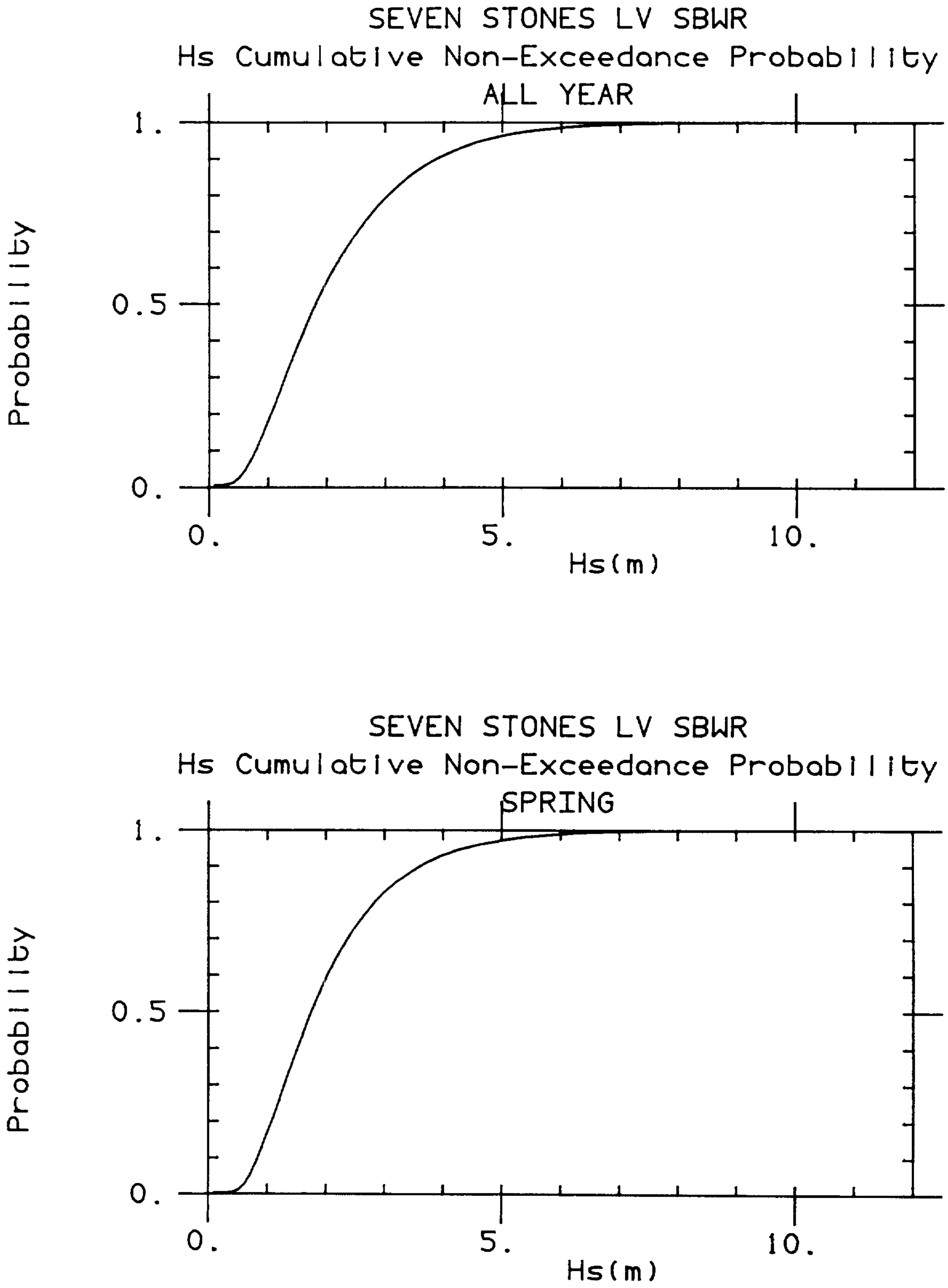
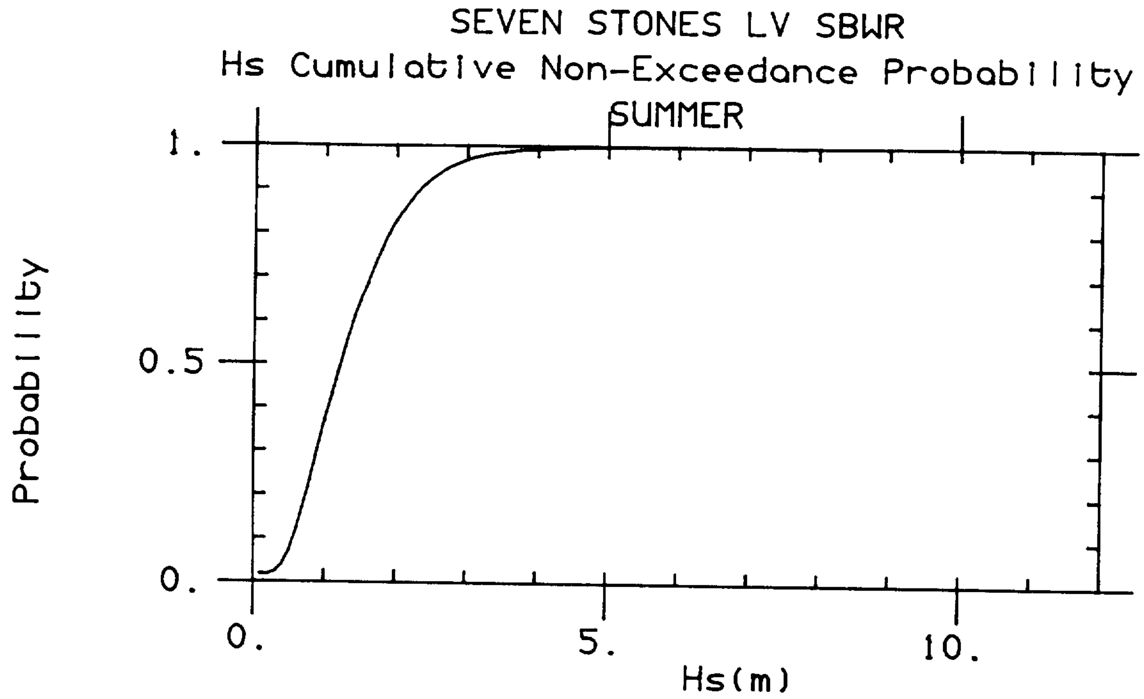

SEVEN STONES LV SBWR
Hs Cumulative Non-Exceedance Probability
ALL YEAR
Probability
1.
0.5
0.
0.
5.
10.
Hs(m)
SEVEN STONES LV SBWR
Hs Cumulative Non-Exceedance Probability
SPRING
Probability
1.
0.5
0.
0.
5.
10.
Hs(m)

Figure 5 (a-b)


SEVEN STONES LV SBWR
Hs Cumulative Non-Exceedance Probability
SUMMER
Probability
1.
0.5
0.
0.
5.
10.
Hs(m)

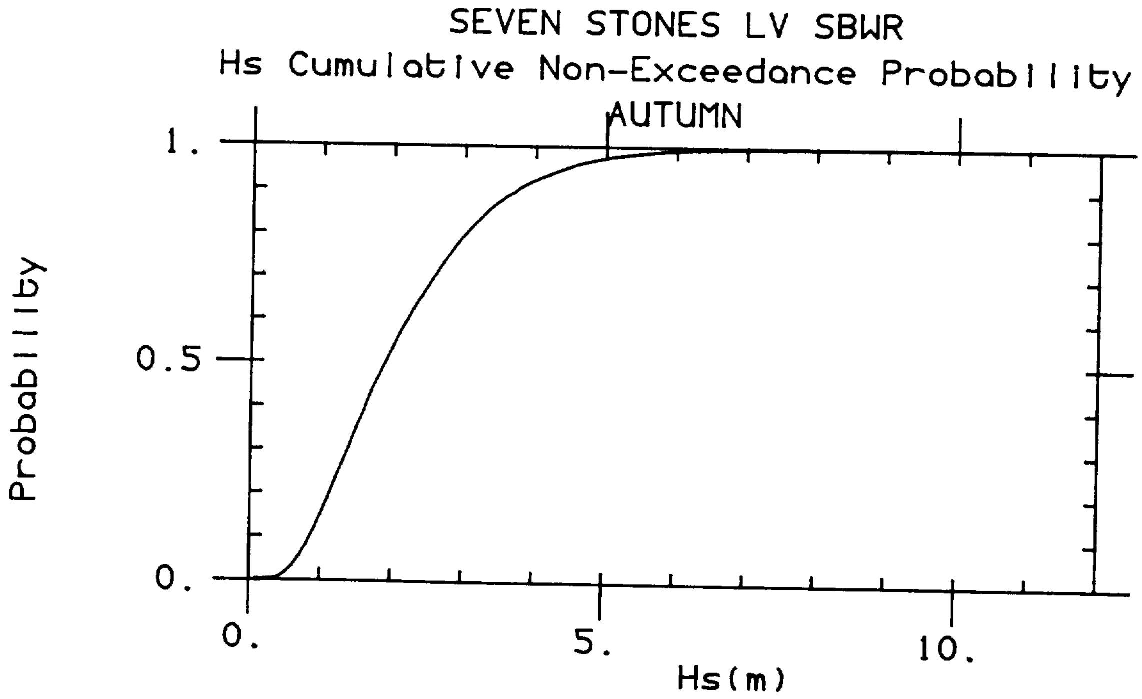

SEVEN STONES LV SBWR
Hs Cumulative Non-Exceedance Probability
AUTUMN
Probability
1.
0.5
0.
0.
5.
10.
Hs(m)

Figure 5 (c-d)

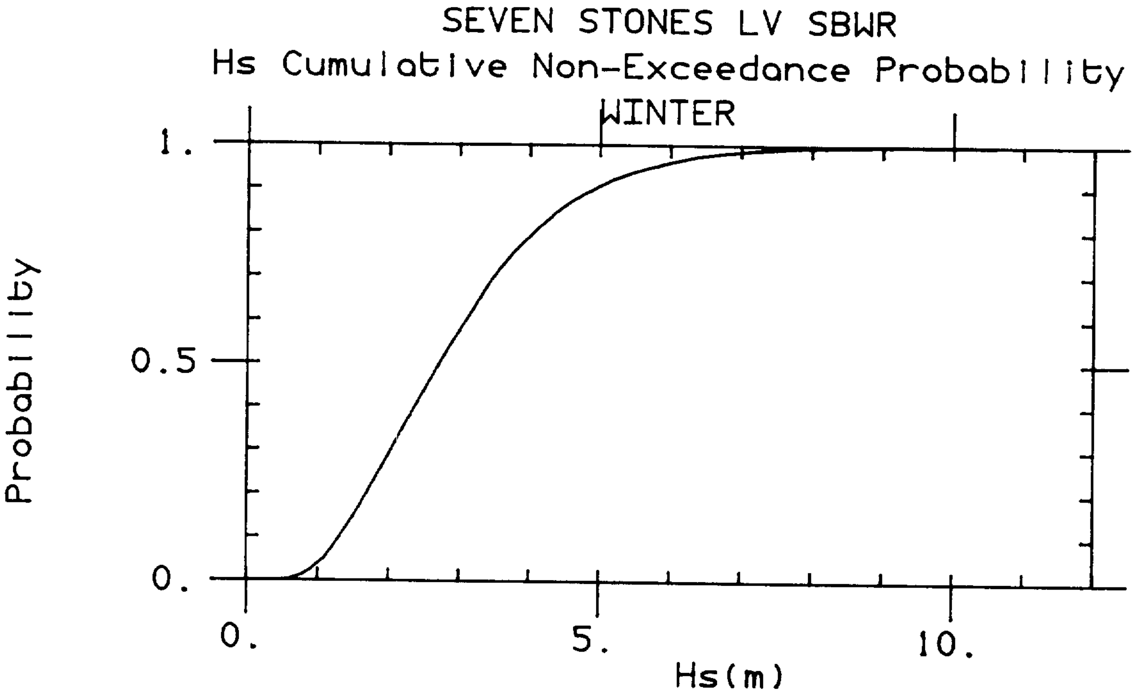

SEVEN STONES LV SBWR
Hs Cumulative Non-Exceedance Probability
WINTER
Probability
1.
0.5
0.
0.
5.
10.
Hs(m)

Figure 5 (e)

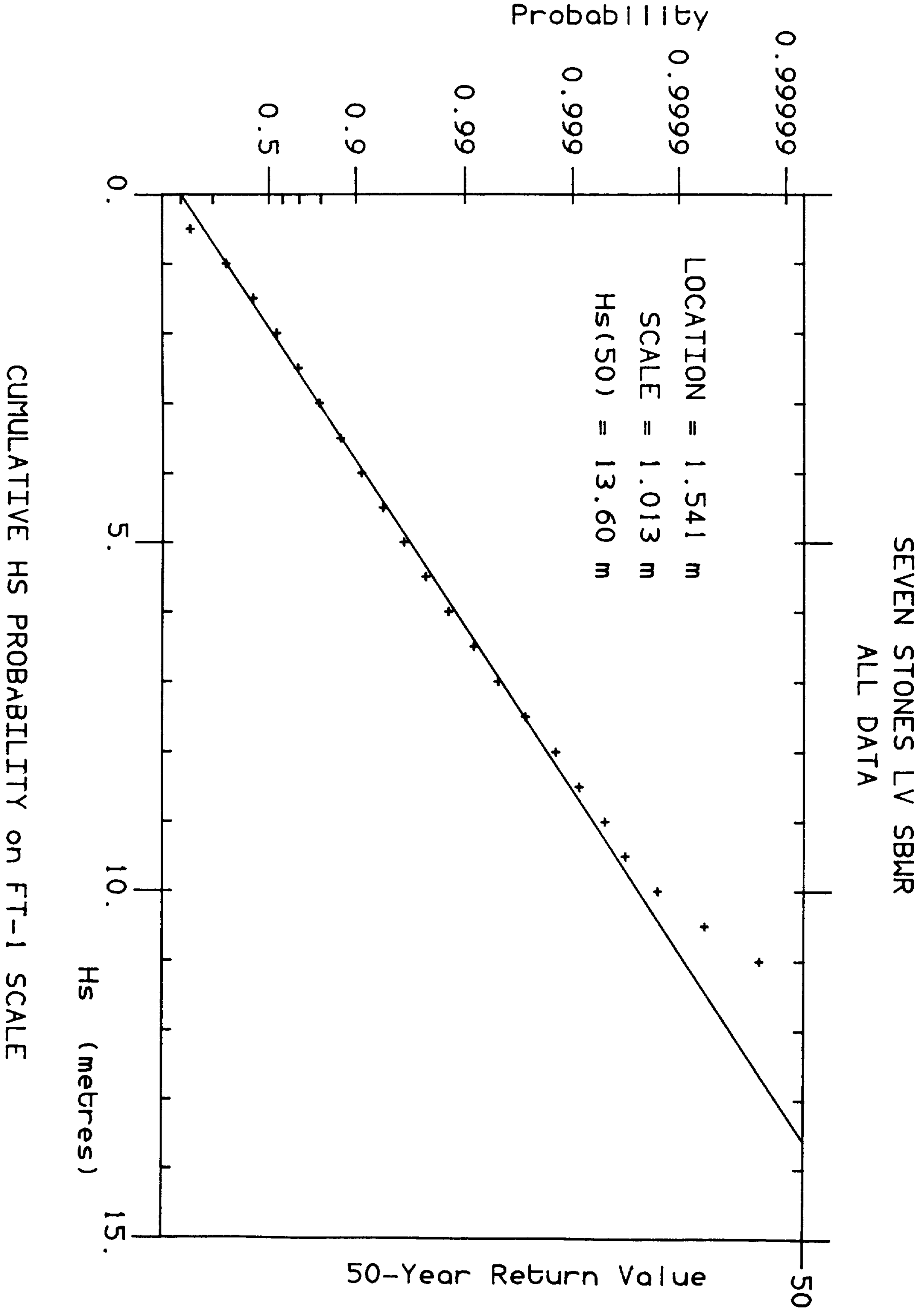

SEVEN STONES LV SBWR
ALL DATA
LOCATION = 1.541 m
SCALE = 1.013 m
Hs(50) = 13.60 m
Probability
0.99999
0.9999
0.999
0.99
0.9
0.5
0.
5.
10.
15.
Hs (metres)
50
50-Year Return Value
CUMULATIVE HS PROBABILITY on FT-1 SCALE

Figure 6

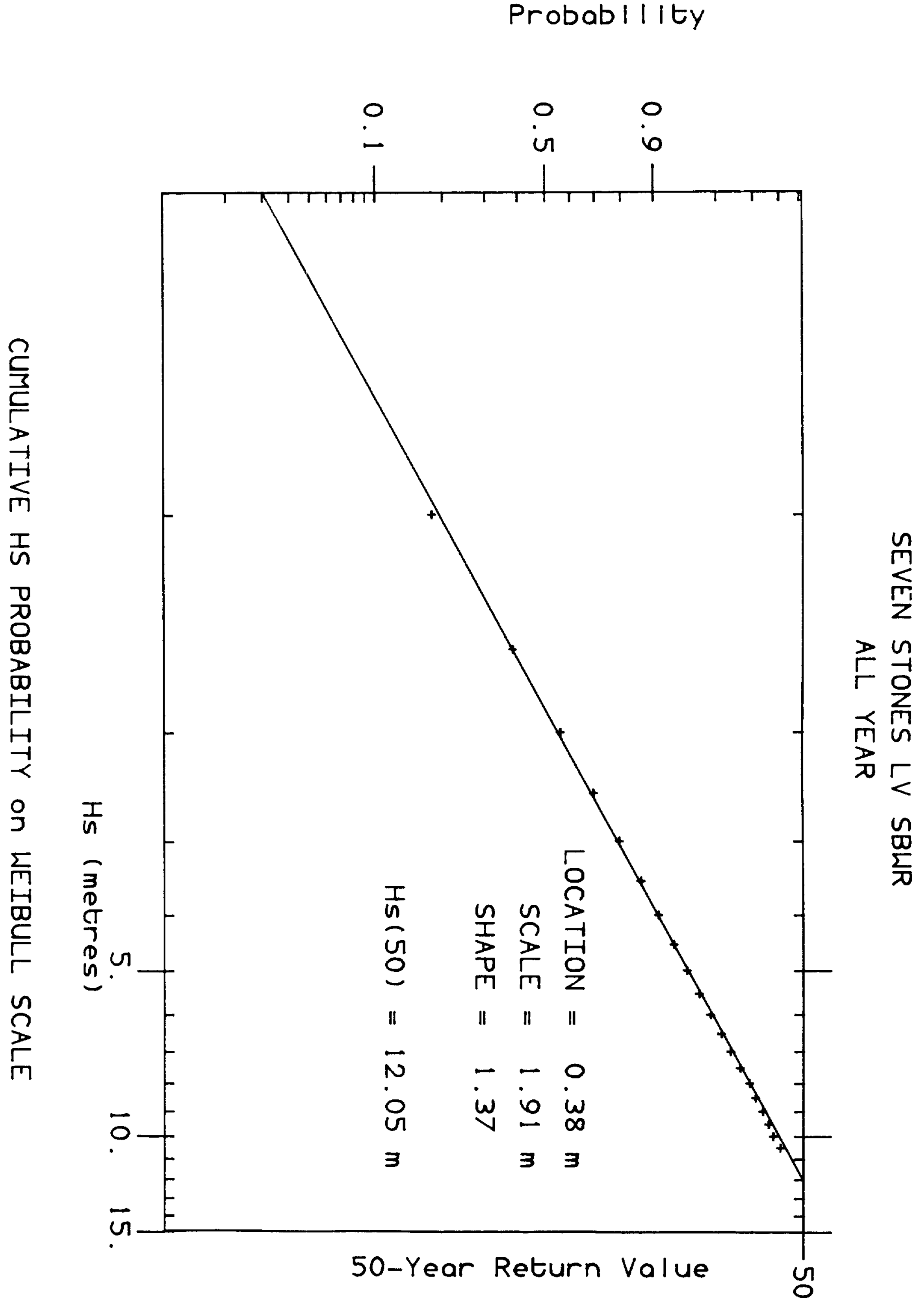

SEVEN STONES LV SBWR
ALL YEAR
Probability
0.1
0.5
0.9
50
50-Year Return Value
LOCATION = 0.38 m
SCALE = 1.91 m
SHAPE = 1.37
Hs(50) = 12.05 m
5.
10.
15.
Hs (metres)
CUMULATIVE HS PROBABILITY on WEIBULL SCALE

Figure 7

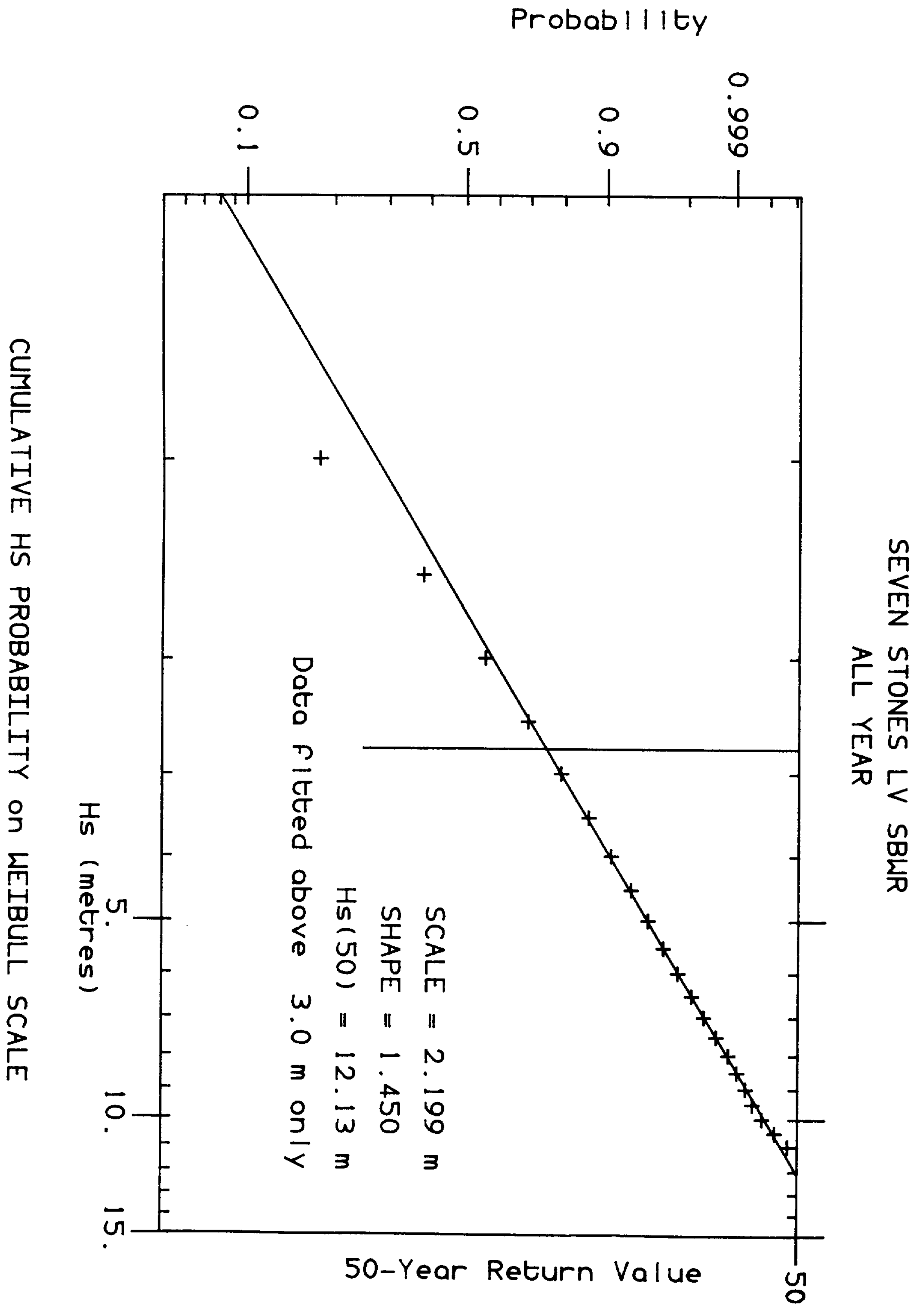

SEVEN STONES LV SBWR
ALL YEAR
Probability
0.1
0.5
0.9
0.999
SCALE = 2.199 m
SHAPE = 1.450
Hs(50) = 12.13 m
Data fitted above 3.0 m only
5.
10.
15.
Hs (metres)
50-Year Return Value
50
CUMULATIVE HS PROBABILITY on WEIBULL SCALE

Figure 8

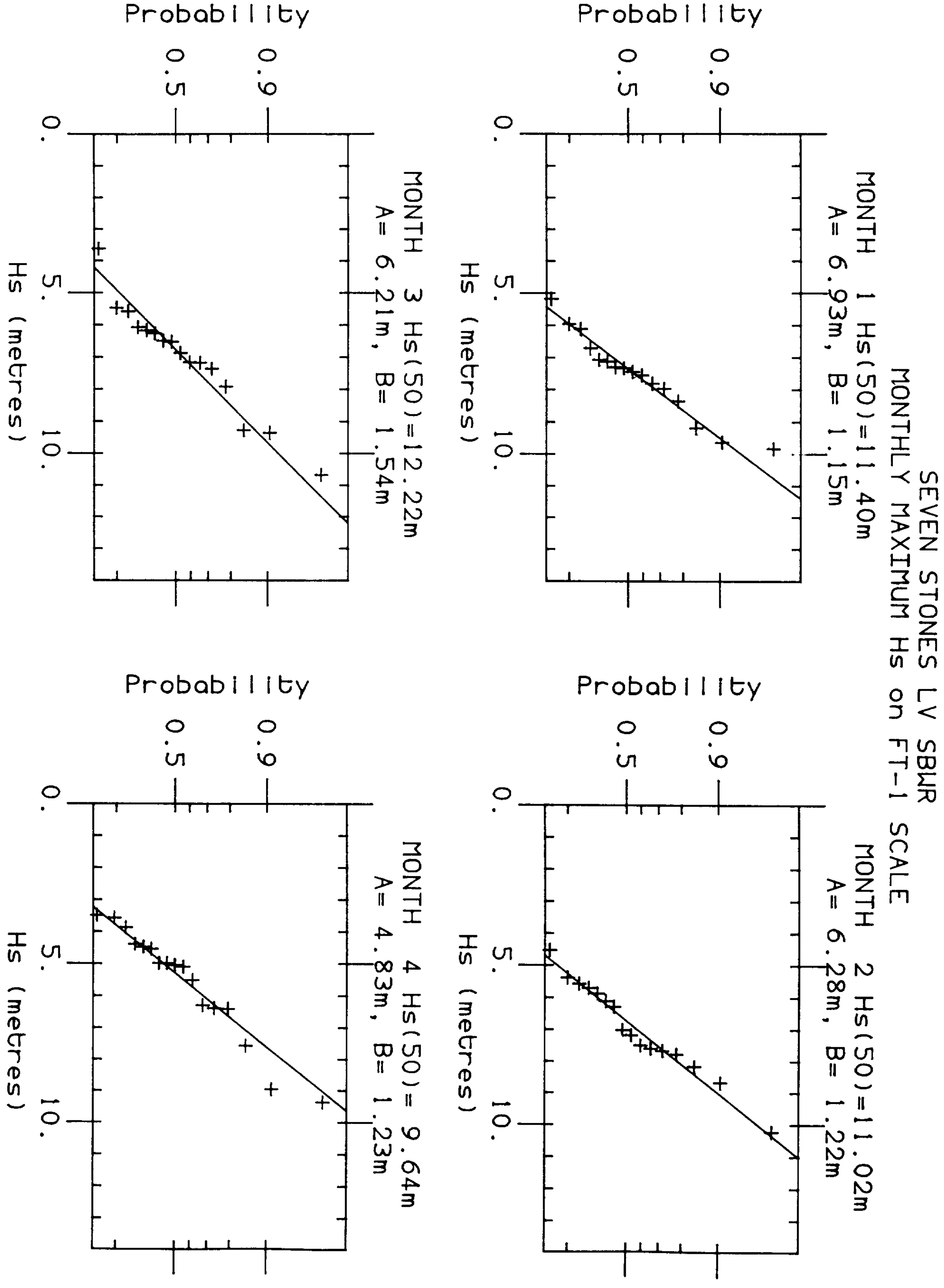

SEVEN STONES LV SBWR
MONTHLY MAXIMUM Hs on FT-1 SCALE
MONTH 1 Hs(50)=11.40m
A= 6.93m, B= 1.15m
MONTH 2 Hs(50)=11.02m
A= 6.28m, B= 1.22m
MONTH 3 Hs(50)=12.22m
A= 6.21m, B= 1.54m
MONTH 4 Hs(50)= 9.64m
A= 4.83m, B= 1.23m
Probability
0.5
0.9
Hs (metres)
0.
5.
10.

Figure 9 (a-d)

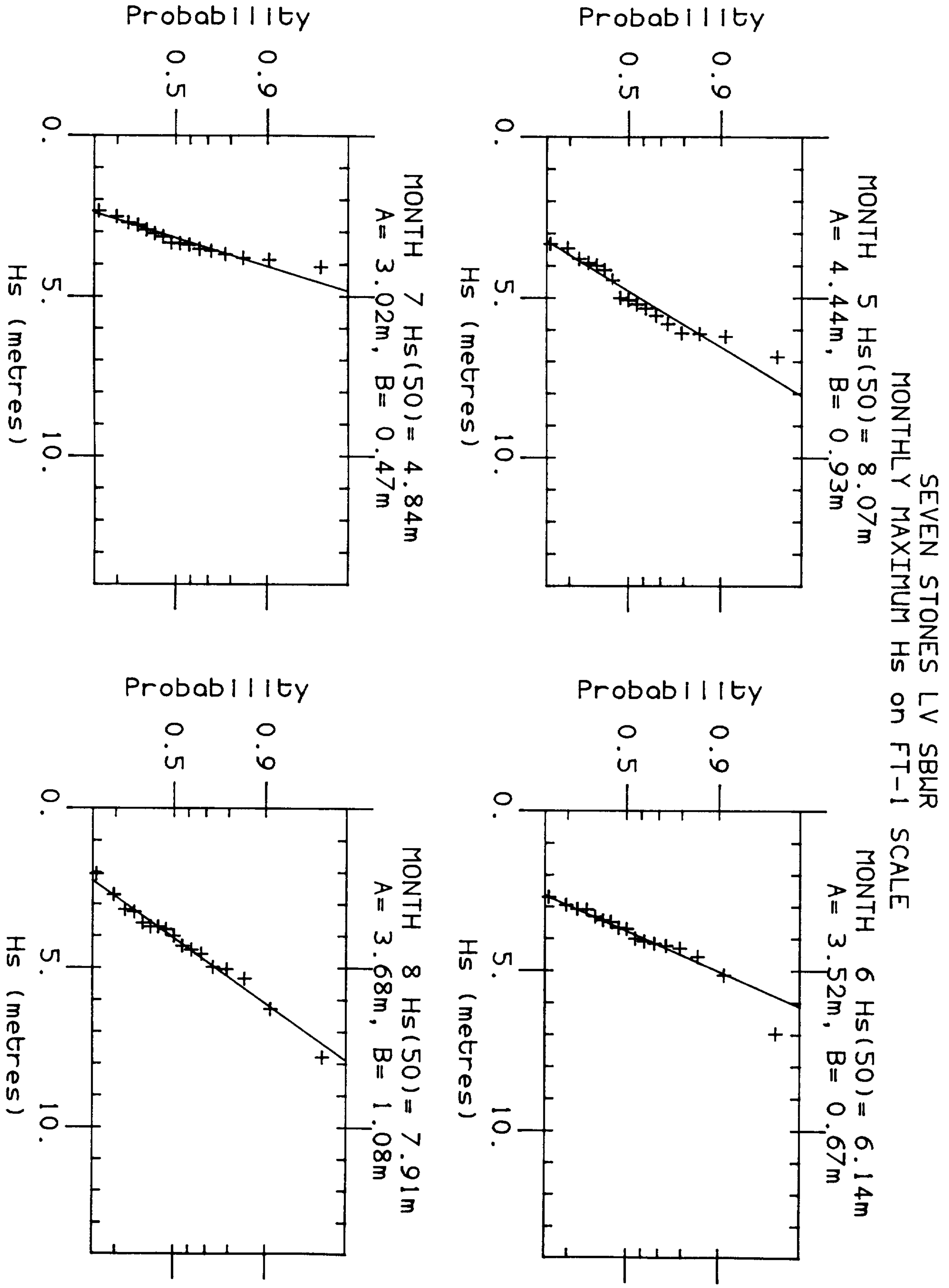

SEVEN STONES LV SBWR
MONTHLY MAXIMUM Hs on FT-1 SCALE
MONTH 5 Hs(50)= 8.07m
A= 4.44m, B= 0.93m
MONTH 6 Hs(50)= 6.14m
A= 3.52m, B= 0.67m
MONTH 7 Hs(50)= 4.84m
A= 3.02m, B= 0.47m
MONTH 8 Hs(50)= 7.91m
A= 3.68m, B= 1.08m
Probability
0.5
0.9
0.
5.
10.
Hs (metres)

Figure 9 (e-h)

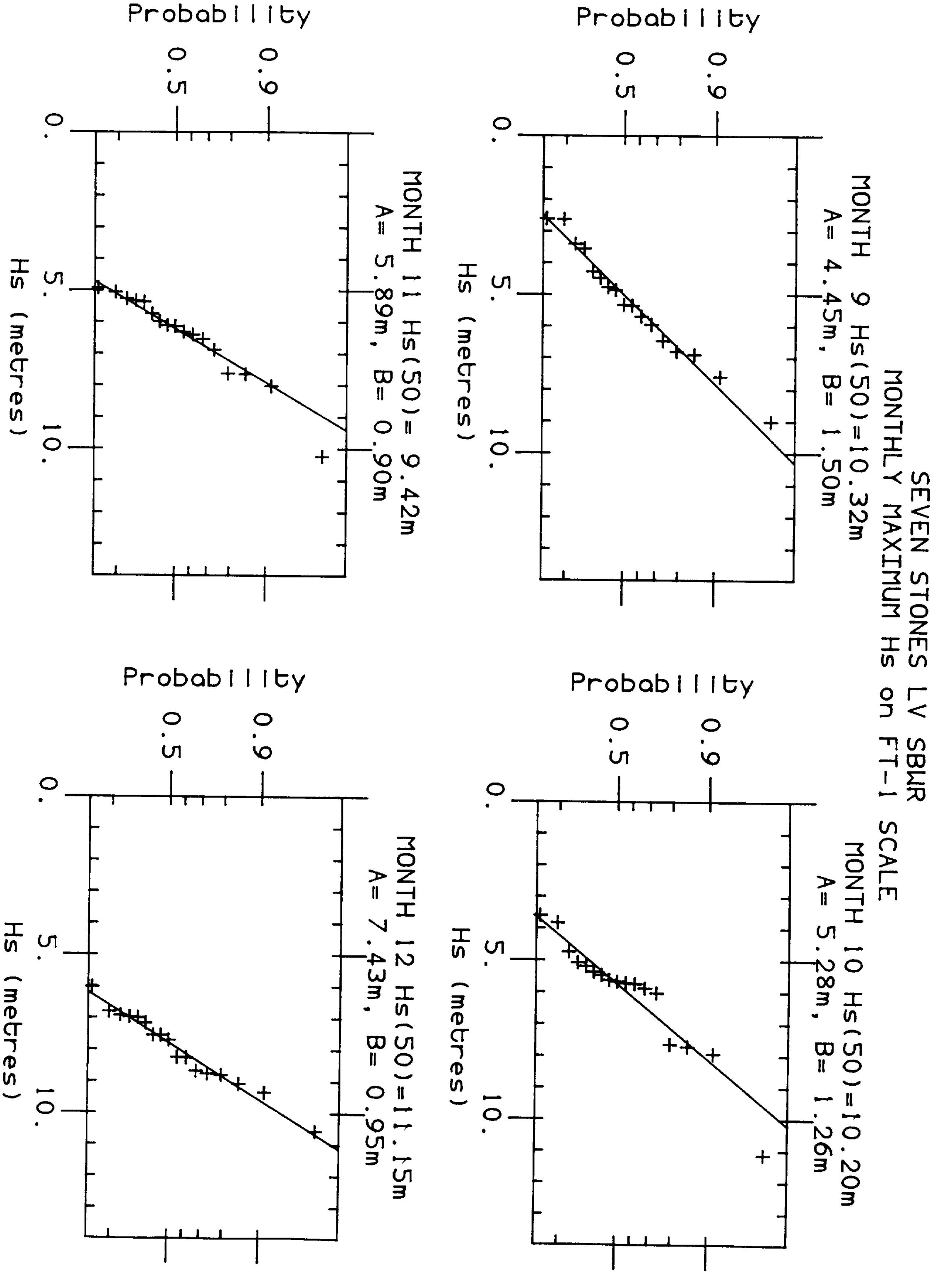

SEVEN STONES LV SBWR
MONTHLY MAXIMUM Hs on FT-1 SCALE
MONTH 9 Hs(50)=10.32m
A= 4.45m, B= 1.50m
MONTH 10 Hs(50)=10.20m
A= 5.28m, B= 1.26m
MONTH 11 Hs(50)= 9.42m
A= 5.89m, B= 0.90m
MONTH 12 Hs(50)=11.15m
A= 7.43m, B= 0.95m
Probability
0.5
0.9
0.
5.
10.
Hs (metres)

Figure 9 (i-l)

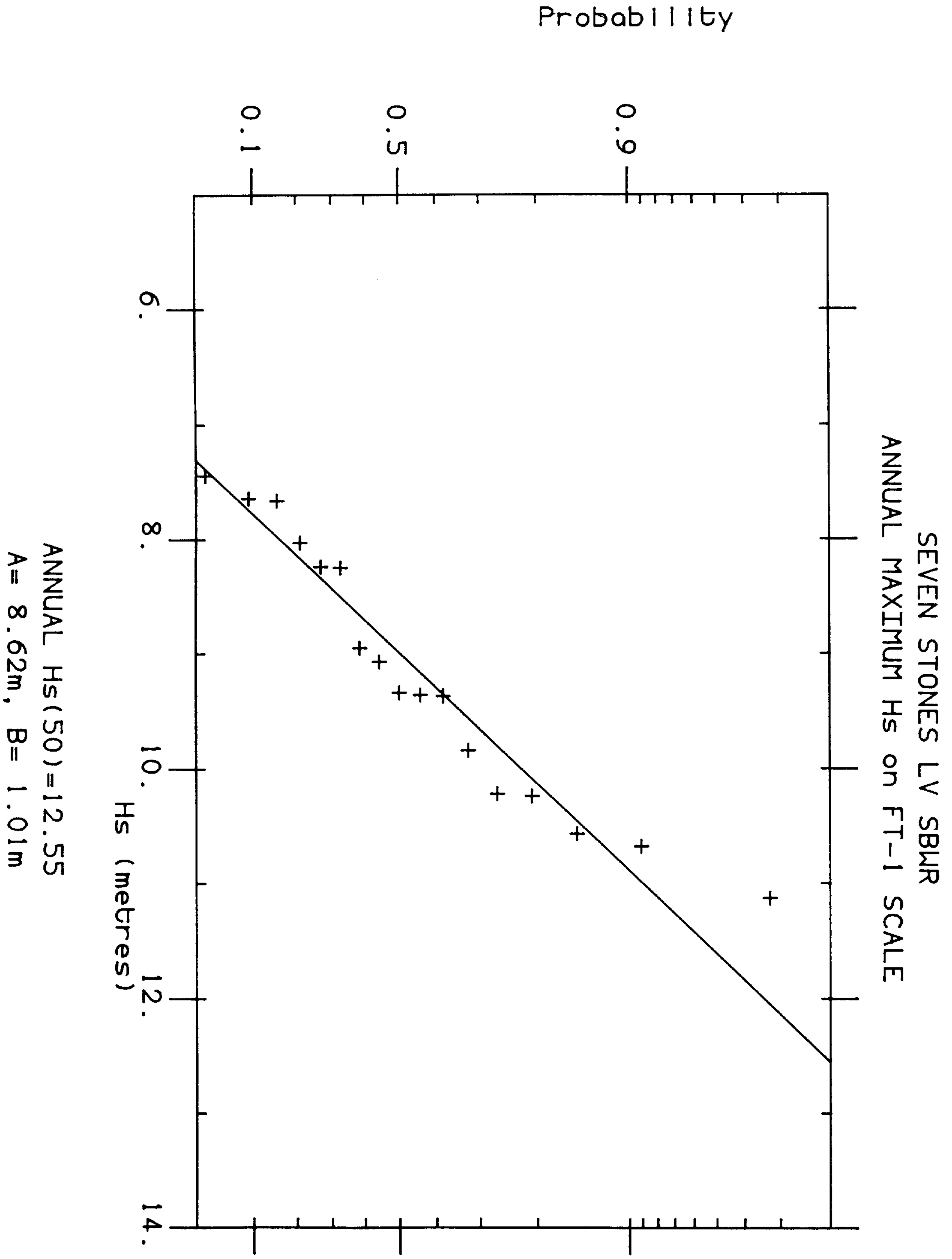

SEVEN STONES LV SBWR
ANNUAL MAXIMUM Hs on FT-1 SCALE
Probability
0.1
0.5
0.9
6.
8.
10.
12.
14.
Hs (metres)
ANNUAL Hs(50)=12.55
A= 8.62m, B= 1.01m

Figure 10

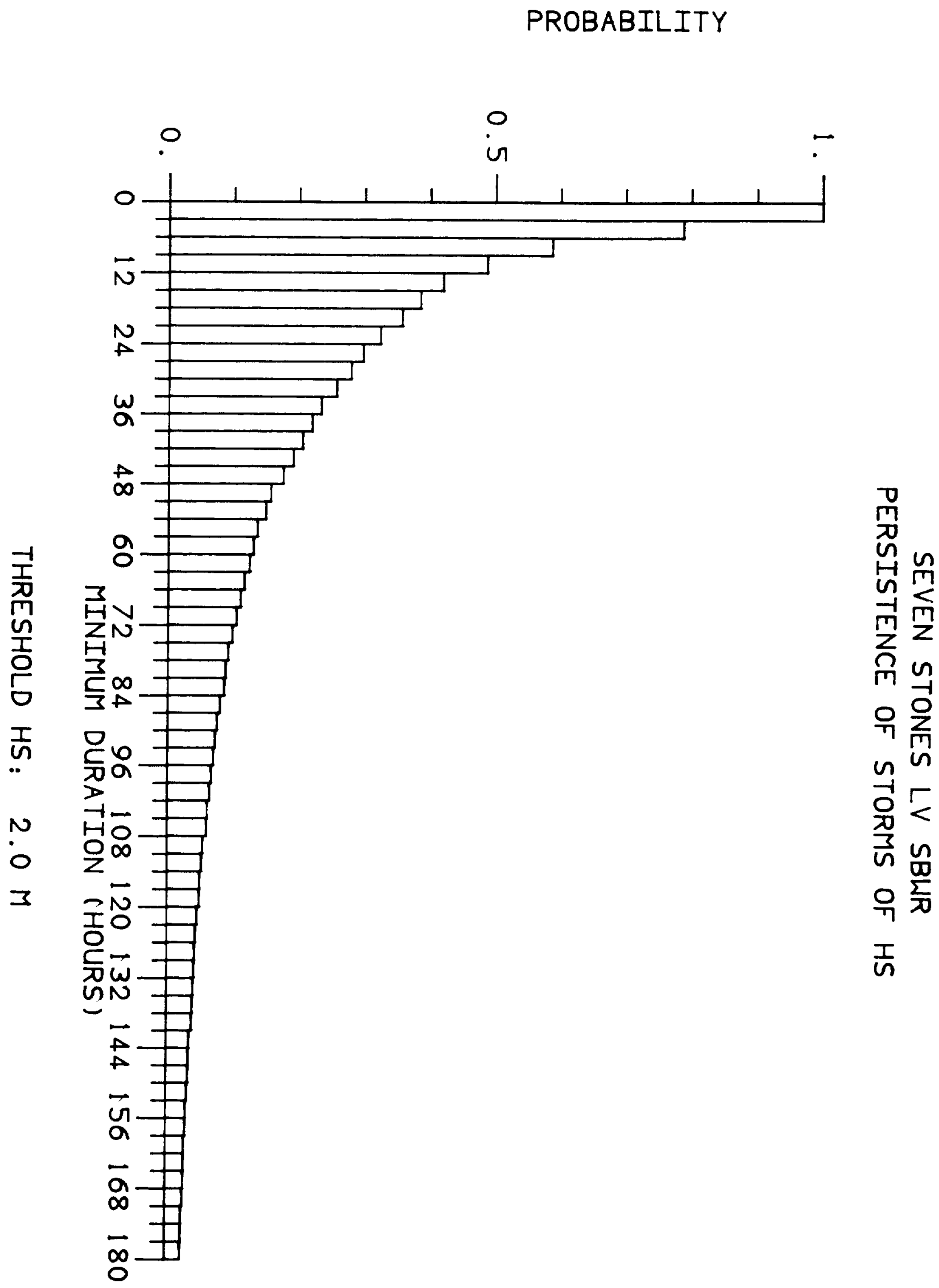

SEVEN STONES LV SBWR
PERSISTENCE OF STORMS OF HS
PROBABILITY
0.
0.5
1.
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
MINIMUM DURATION (HOURS)
THRESHOLD HS: 2.0 M

Figure 11 (a)

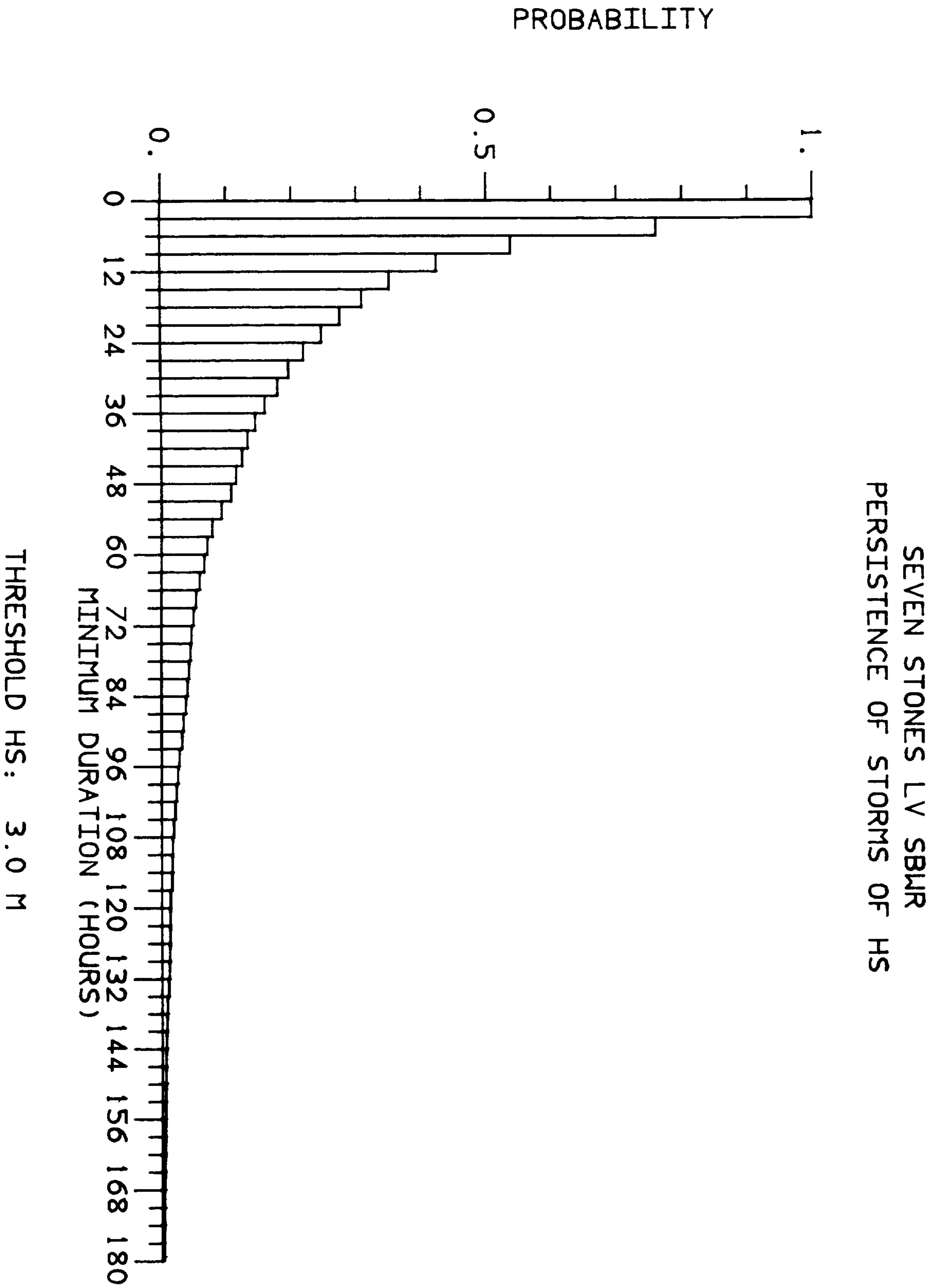

SEVEN STONES LV SBWR
PERSISTENCE OF STORMS OF HS
PROBABILITY
0.
0.5
1.
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
MINIMUM DURATION (HOURS)
THRESHOLD HS: 3.0 M

Figure 11 (b)

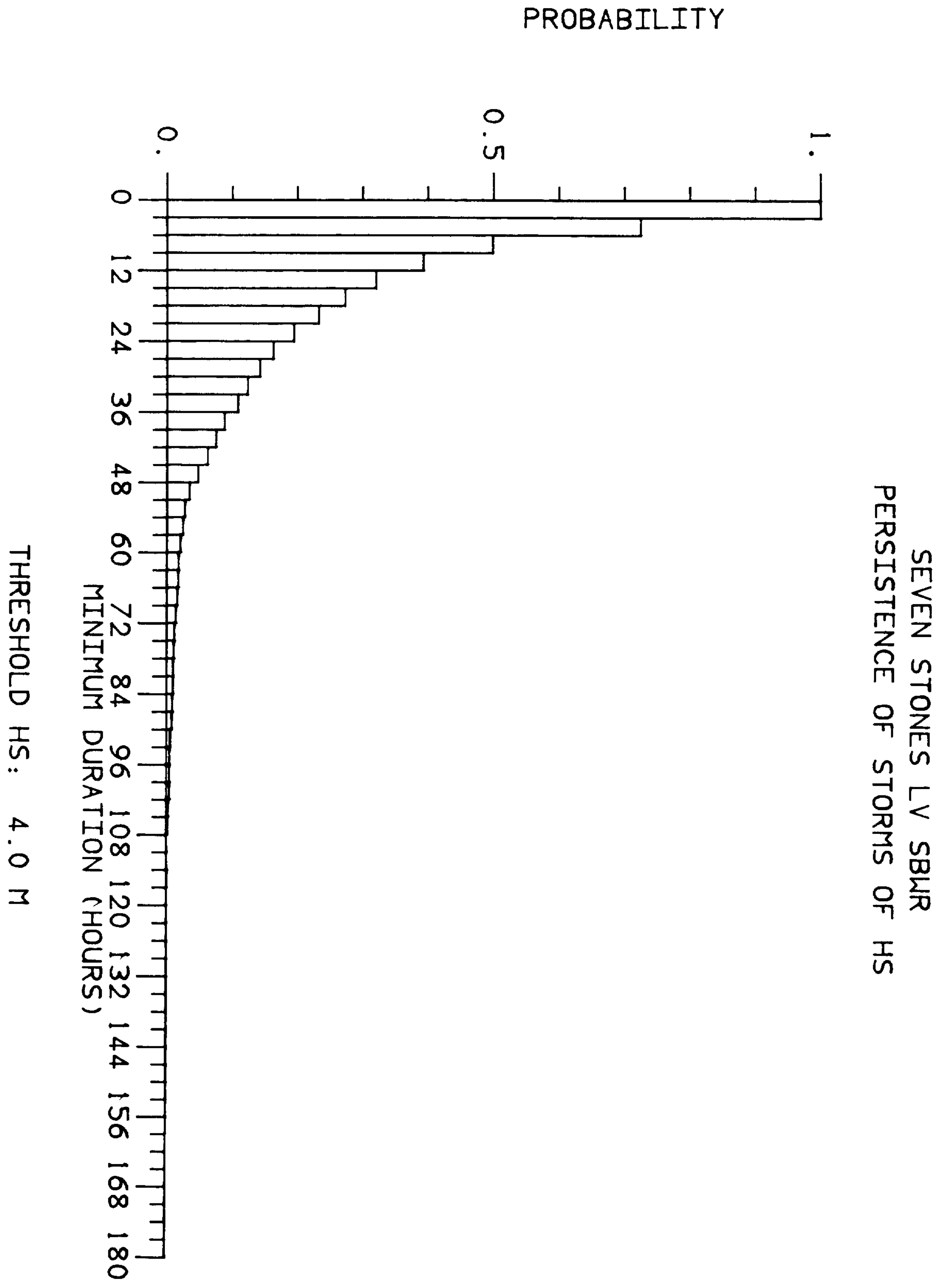

SEVEN STONES LV SBWR
PERSISTENCE OF STORMS OF HS
PROBABILITY
0.
0.5
1.
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
MINIMUM DURATION (HOURS)
THRESHOLD HS: 4.0 M

Figure 11 (c)

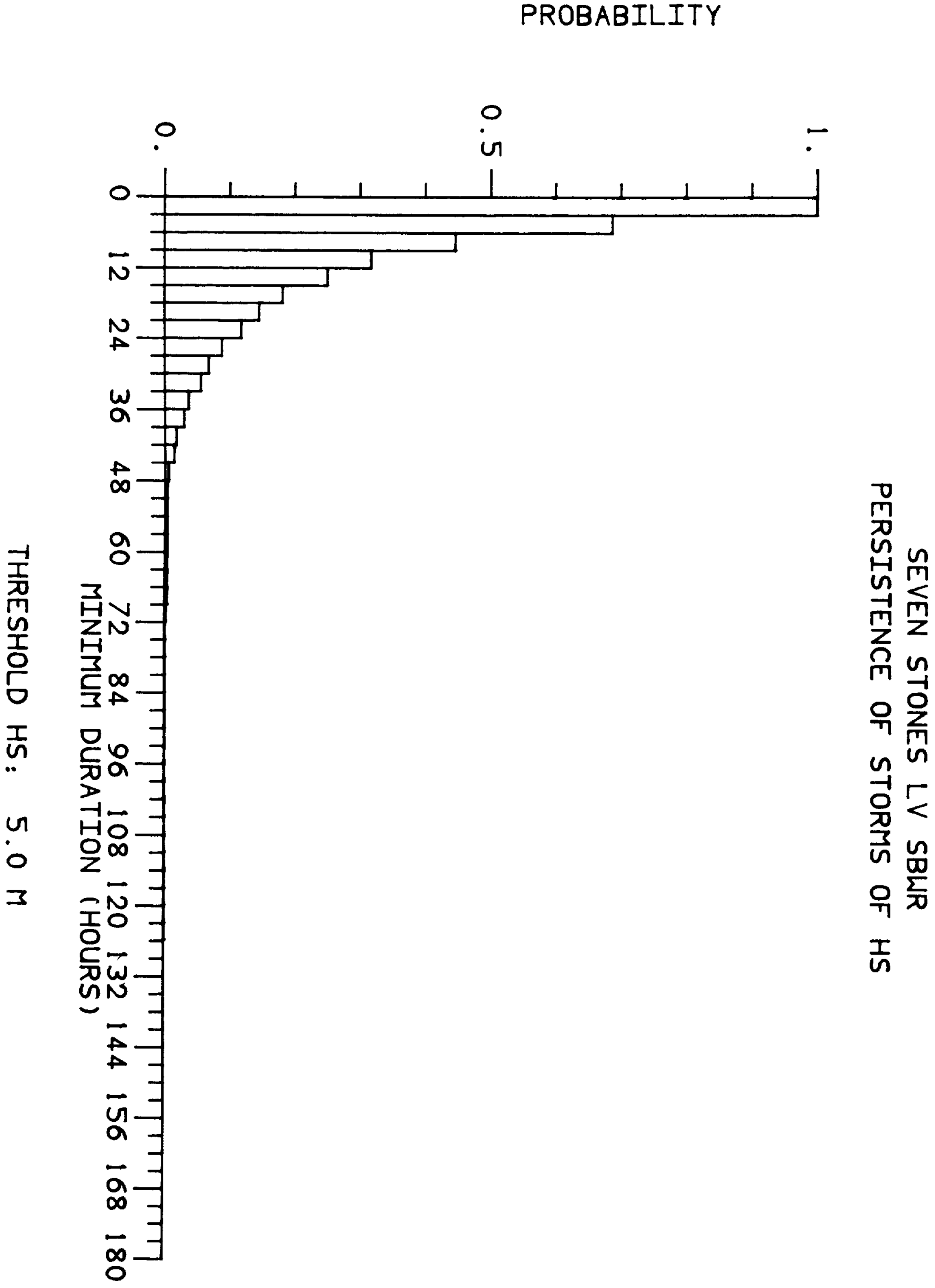

SEVEN STONES LV SBWR
PERSISTENCE OF STORMS OF HS
PROBABILITY
1.
0.5
0.
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
MINIMUM DURATION (HOURS)
THRESHOLD HS: 5.0 M

Figure 11 (d)

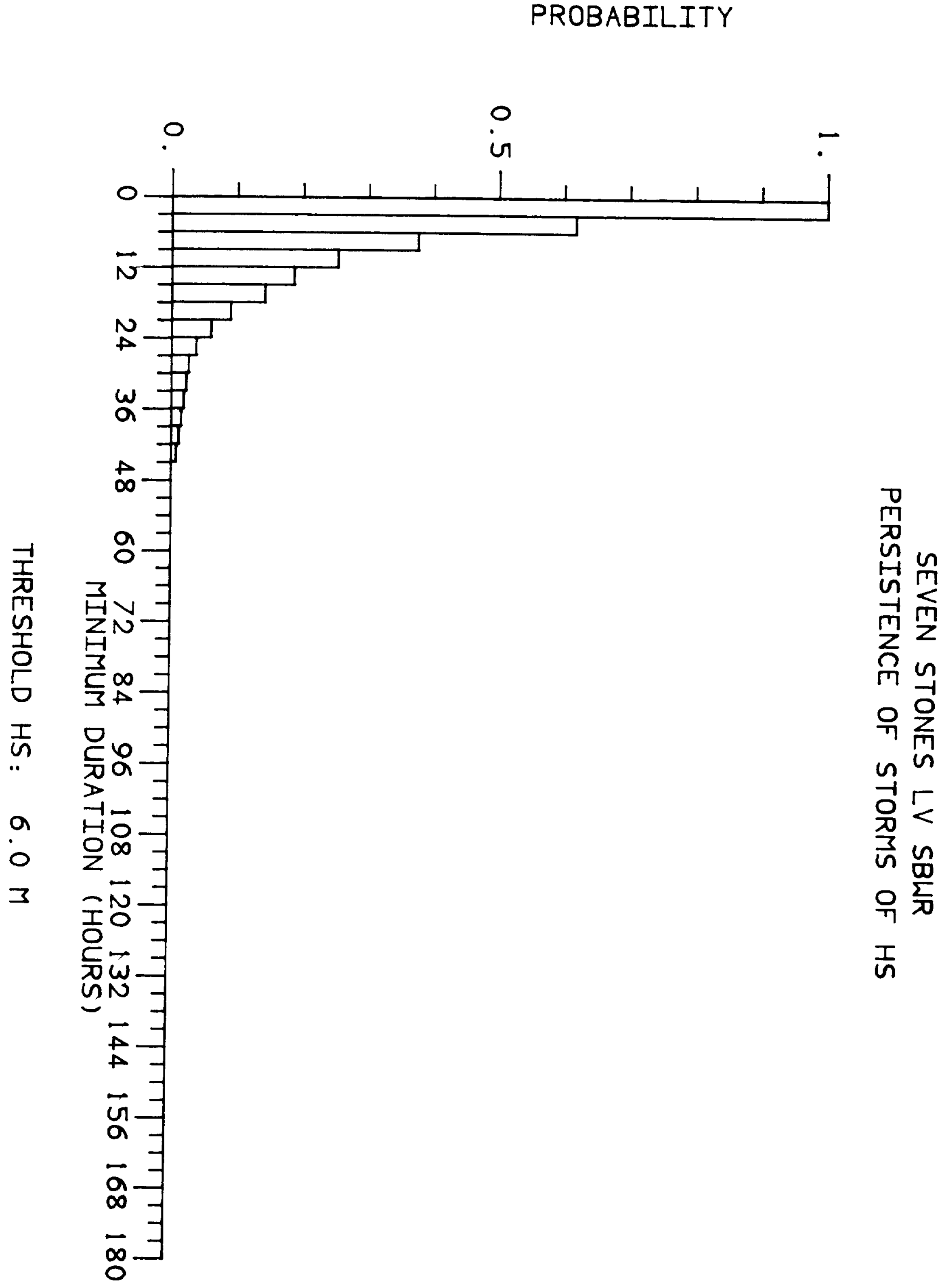

SEVEN STONES LV SBWR
PERSISTENCE OF STORMS OF HS
PROBABILITY
0.
0.5
1.
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
MINIMUM DURATION (HOURS)
THRESHOLD HS: 6.0 M

Figure 11 (e)

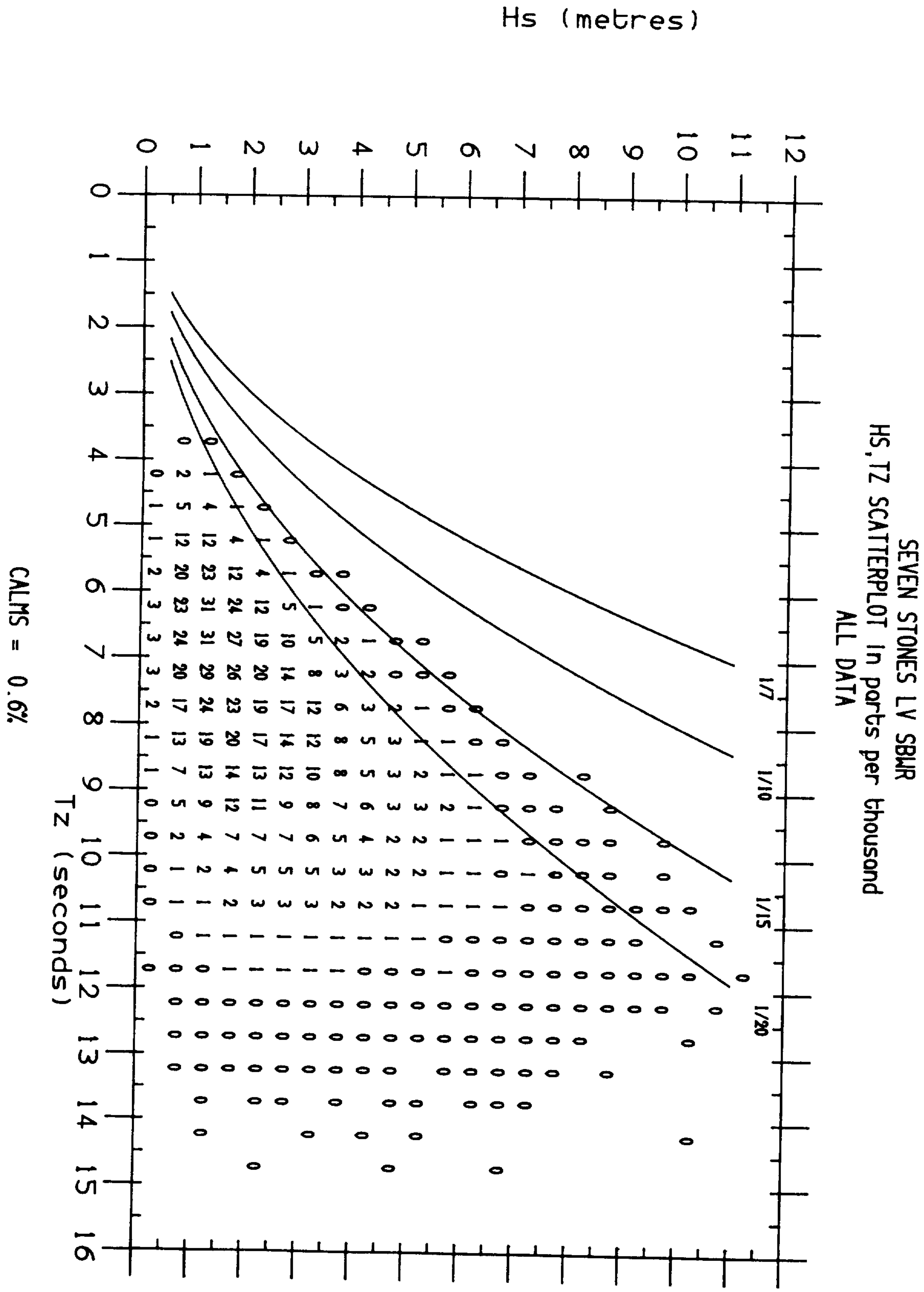

SEVEN STONES LV SBWR
HS,TZ SCATTERPLOT in parts per thousand
ALL DATA
Hs (metres)
Tz (seconds)
1/7
1/10
1/15
1/20
CALMS = 0.6%
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Figure 12 (a)

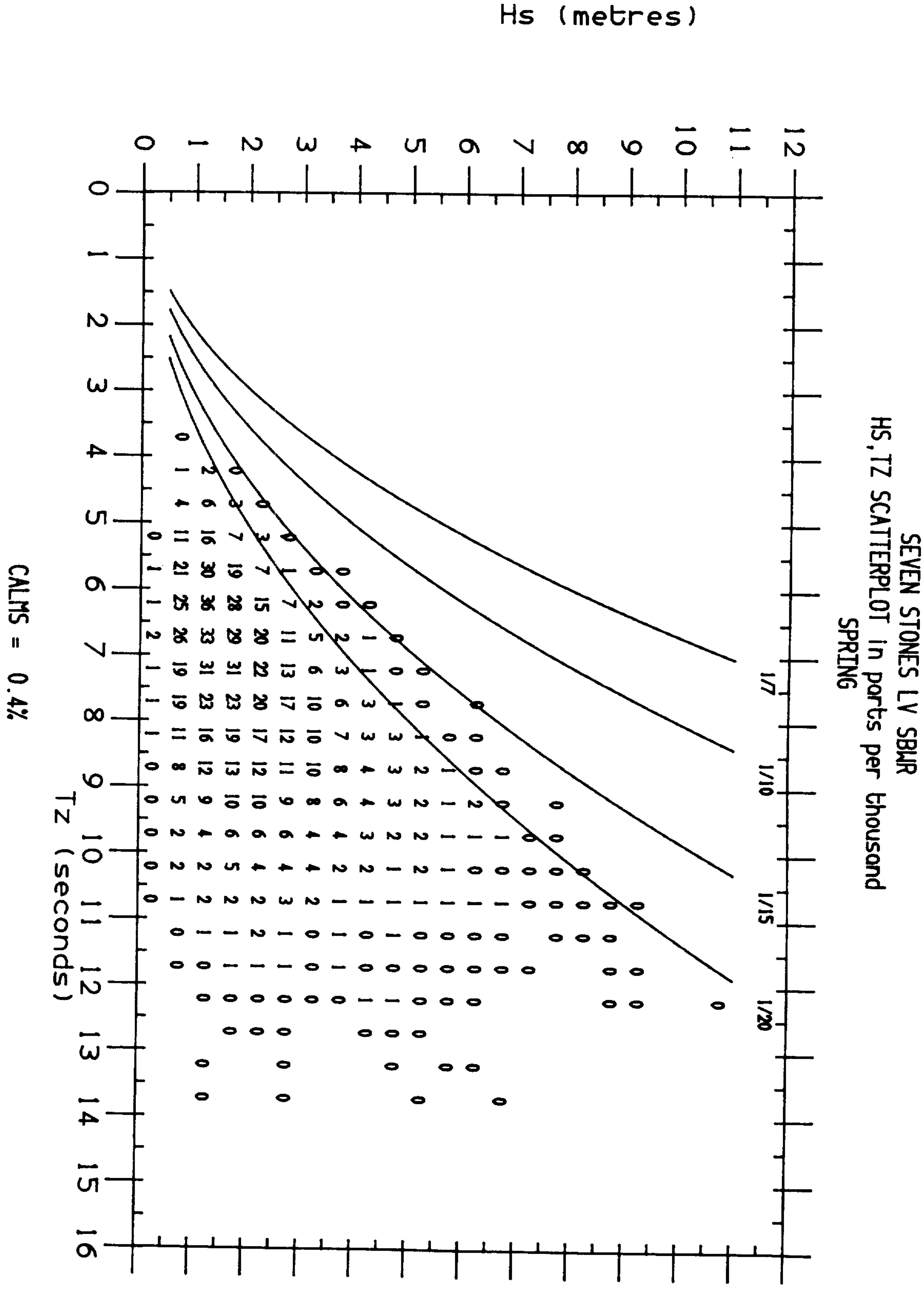

SEVEN STONES LV SBWR
HS,TZ SCATTERPLOT in parts per thousand
SPRING
Hs (metres)
Tz (seconds)
1/7
1/10
1/15
1/20
CALMS = 0.4%
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Figure 12 (b)

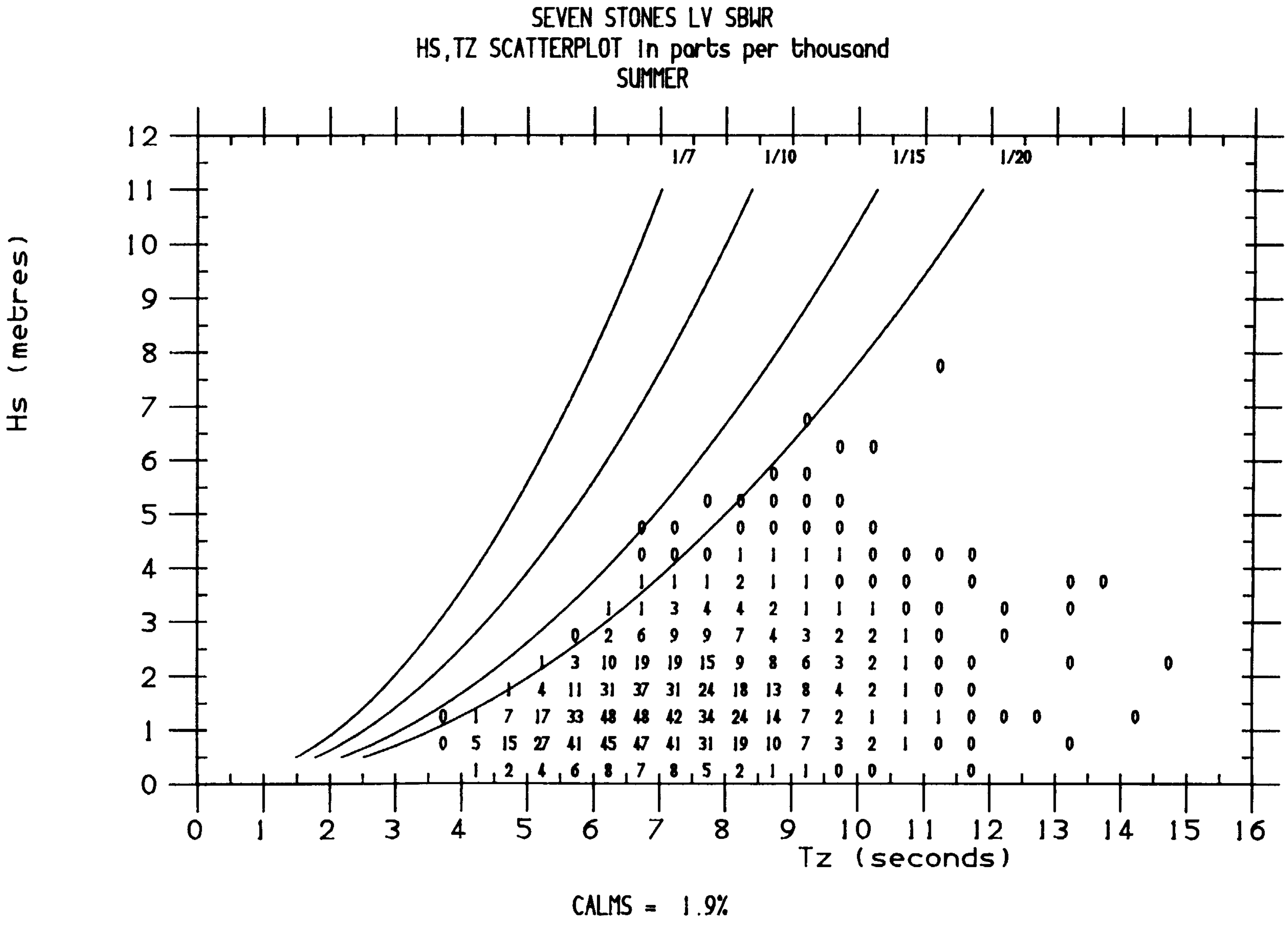

SEVEN STONES LV SBWR
HS,TZ SCATTERPLOT In parts per thousand
SUMMER
Hs (metres)
Tz (seconds)
0 1 2 3 4 5 6 7 8 9 10 11 12
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
1/7
1/10
1/15
1/20
0
0
0 0
0 0
0 0 0 0 0
0 0 0 0 0 0 0
0 0 0 1 1 1 1 0 0 0 0
1 1 1 2 1 1 0 0 0 0 0 0
1 1 3 4 4 2 1 1 1 0 0 0 0
0 2 6 9 9 7 4 3 2 2 1 0 0
1 3 10 19 19 15 9 8 6 3 2 1 0 0 0 0
1 4 11 31 37 31 24 18 13 8 4 2 1 0 0
0 1 7 17 33 48 48 42 34 24 14 7 2 1 1 1 0 0 0 0
0 5 15 27 41 45 47 41 31 19 10 7 3 2 1 0 0 0
1 2 4 6 8 7 8 5 2 1 1 0 0 0
CALMS = 1.9%

Figure 12 (c)

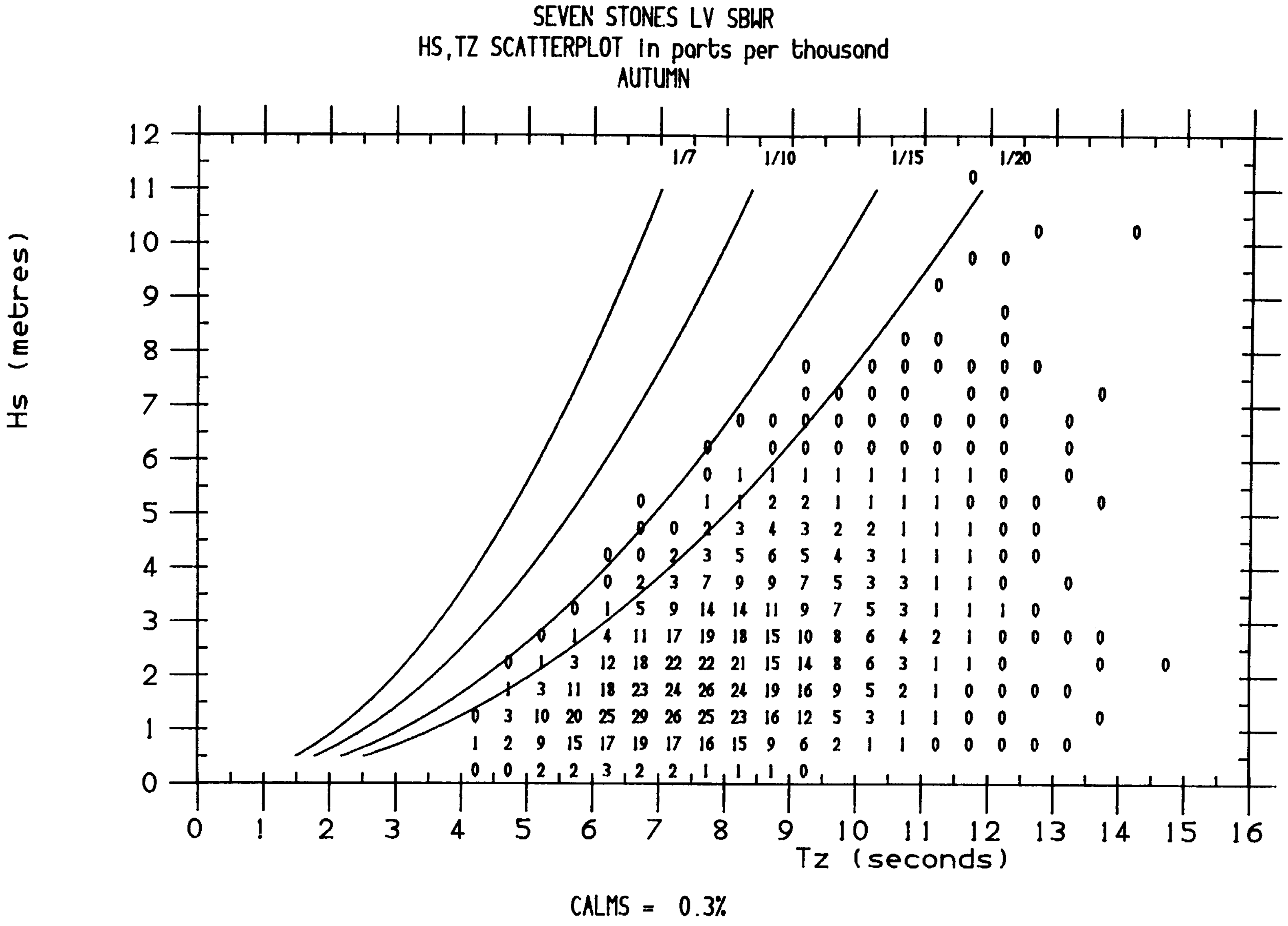

SEVEN STONES LV SBWR
HS,TZ SCATTERPLOT in parts per thousand
AUTUMN
Hs (metres)
0
1
2
3
4
5
6
7
8
9
10
11
12
Tz (seconds)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
1/7
1/10
1/15
1/20
0
0 0
0 0
0
0
0 0 0
0 0 0 0 0 0 0 0
0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0
0 1 1 1 1 1 1 1 1 0 0
0 1 1 2 2 1 1 1 1 0 0 0 0
0 0 2 3 4 3 2 2 1 1 1 0 0
0 0 2 3 5 6 5 4 3 1 1 1 0 0
0 2 3 7 9 9 7 5 3 3 1 1 0 0
0 1 5 9 14 14 11 9 7 5 3 1 1 1 0
0 1 4 11 17 19 18 15 10 8 6 4 2 1 0 0 0 0
0 1 3 12 18 22 22 21 15 14 8 6 3 1 1 0 0 0
1 3 11 18 23 24 26 24 19 16 9 5 2 1 0 0 0 0
0 3 10 20 25 29 26 25 23 16 12 5 3 1 1 0 0 0
1 2 9 15 17 19 17 16 15 9 6 2 1 1 0 0 0 0 0
0 0 2 2 3 2 2 1 1 1 0
CALMS = 0.3%

Figure 12 (d)

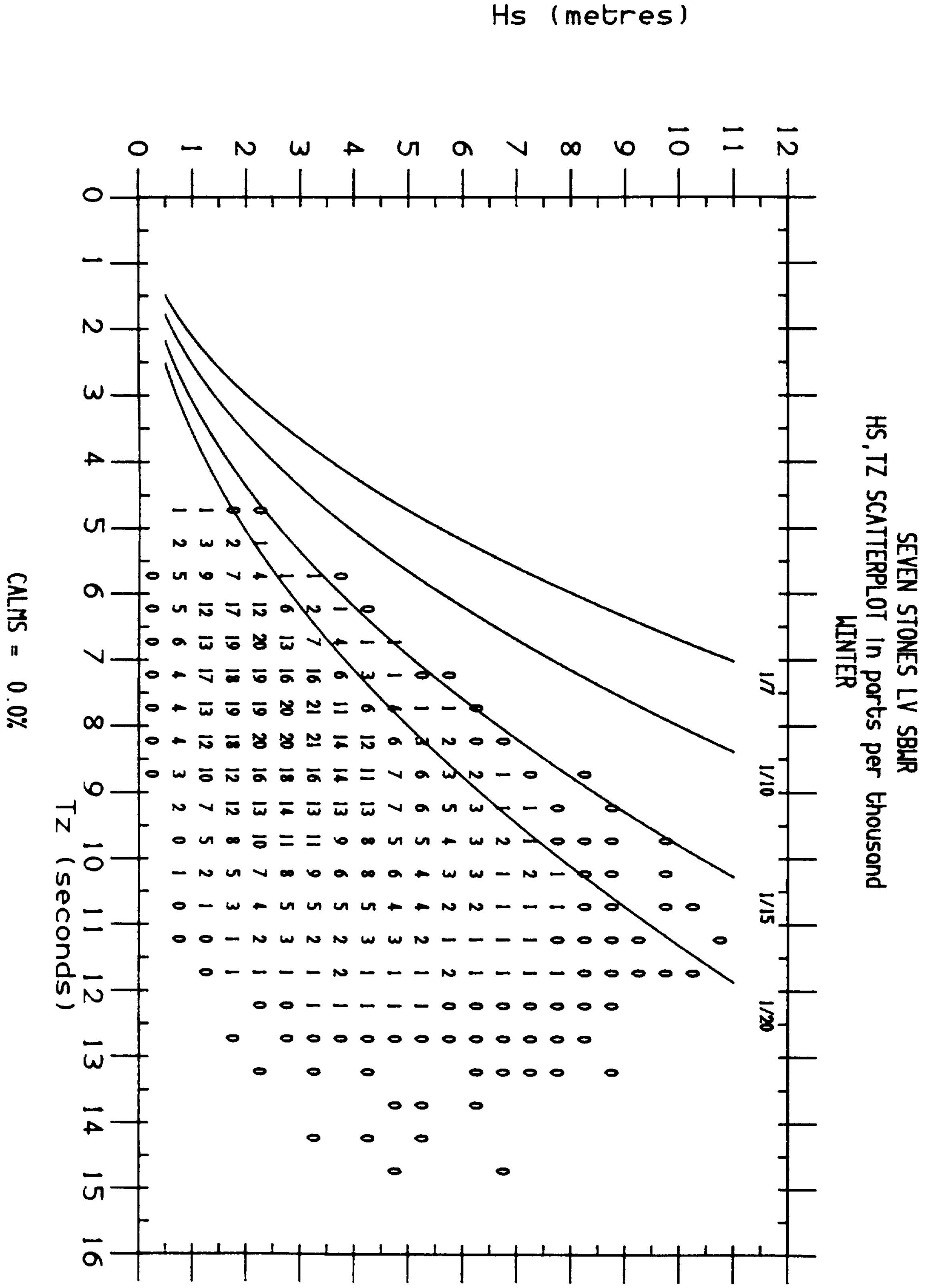

SEVEN STONES LV SBWR
HS,TZ SCATTERPLOT in parts per thousand
WINTER
Hs (metres)
Tz (seconds)
1/7
1/10
1/15
1/20
CALMS = 0.0%
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Figure 12 (e)

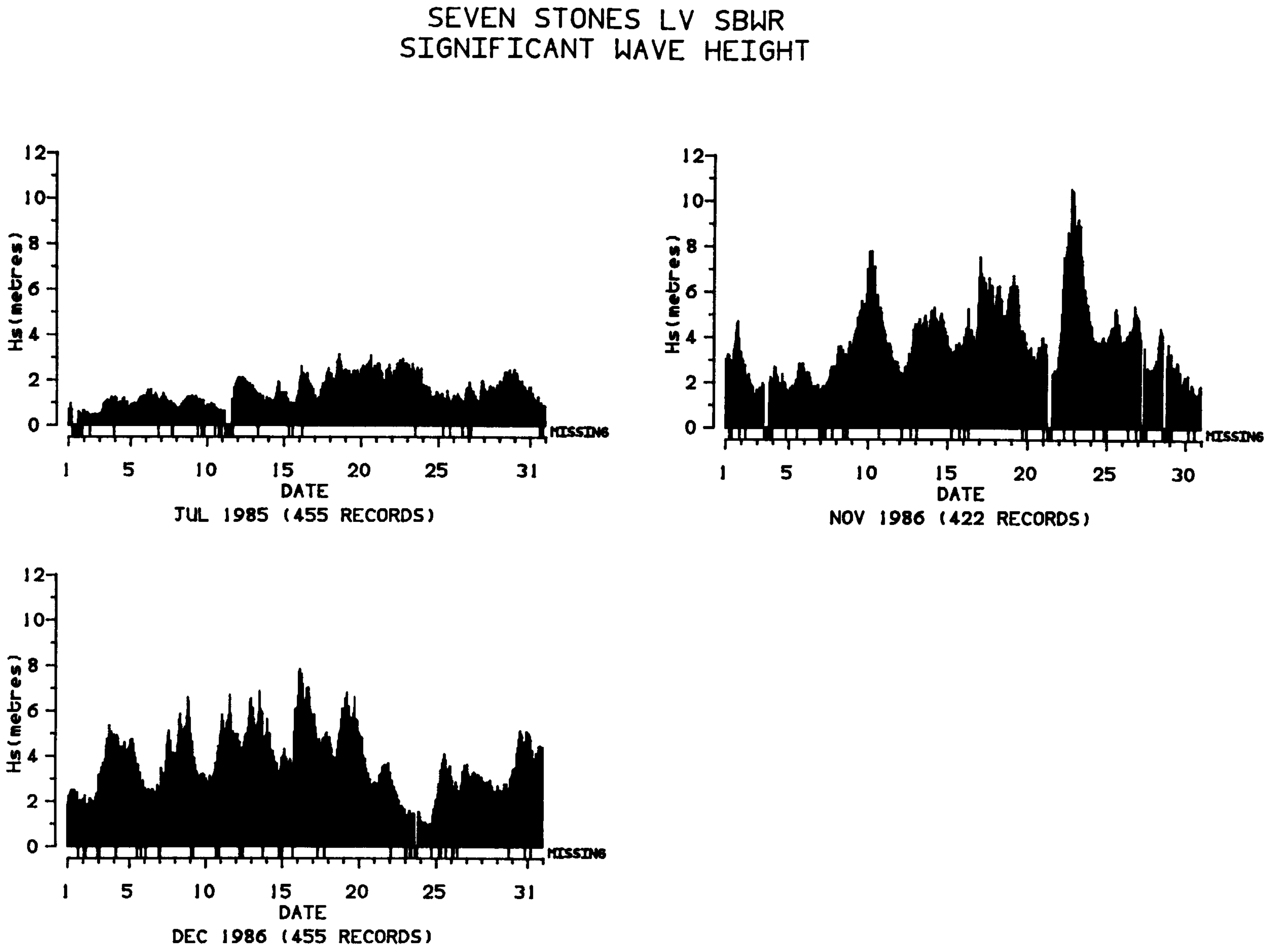

SEVEN STONES LV SBWR
SIGNIFICANT WAVE HEIGHT
Hs(metres)
0
2
4
6
8
10
12
1
5
10
15
20
25
31
DATE
JUL 1985 (455 RECORDS)
MISSING
Hs(metres)
0
2
4
6
8
10
12
1
5
10
15
20
25
30
DATE
NOV 1986 (422 RECORDS)
MISSING
Hs(metres)
0
2
4
6
8
10
12
1
5
10
15
20
25
31
DATE
DEC 1986 (455 RECORDS)
MISSING

Figure 13 (a-c)

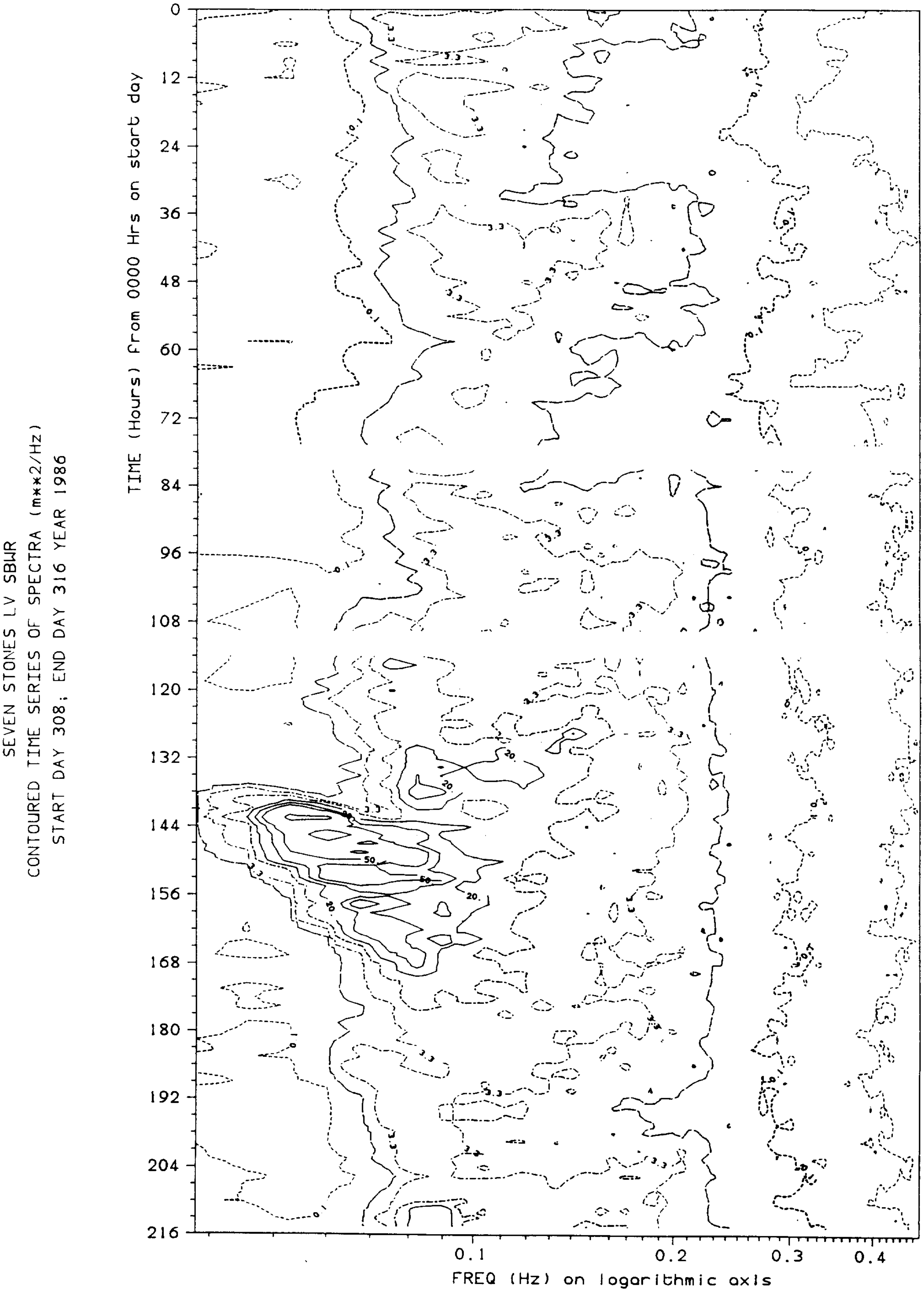

SEVEN STONES LV SBWR
CONTOURED TIME SERIES OF SPECTRA (m**2/Hz)
START DAY 308; END DAY 316 YEAR 1986
TIME (Hours) from 0000 Hrs on start day
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192
204
216
0.1
0.2
0.3
0.4
FREQ (Hz) on logarithmic axis
0.1
3.3
20
50

Figure 14 (a)

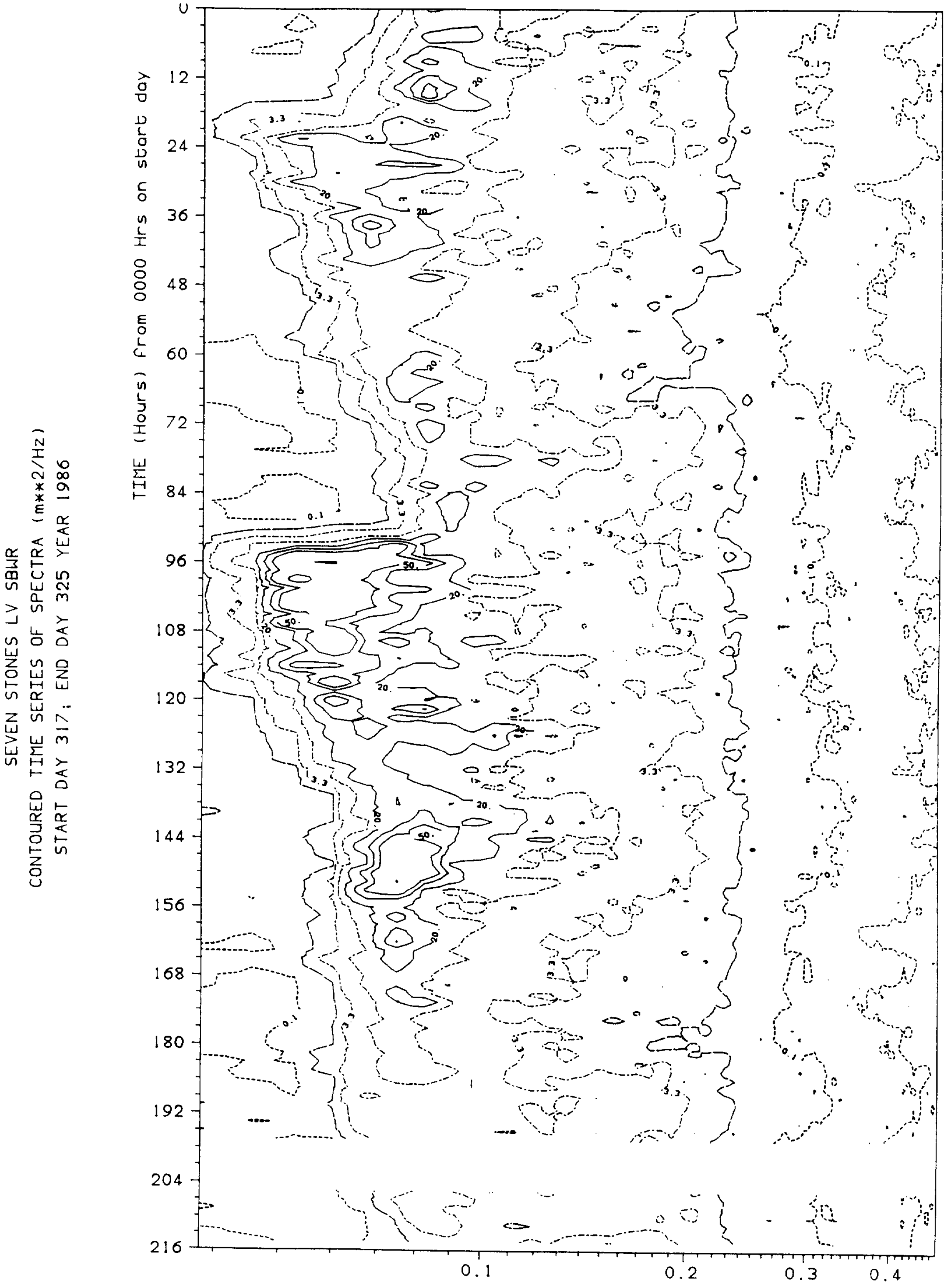

SEVEN STONES LV SBWR
CONTOURED TIME SERIES OF SPECTRA (m**2/Hz)
START DAY 317; END DAY 325 YEAR 1986
TIME (Hours) from 0000 Hrs on start day
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192
204
216
0.1
0.2
0.3
0.4
FREQ (Hz) on logarithmic axis
0.1
3.3
20.
50.

Figure 14 (b)

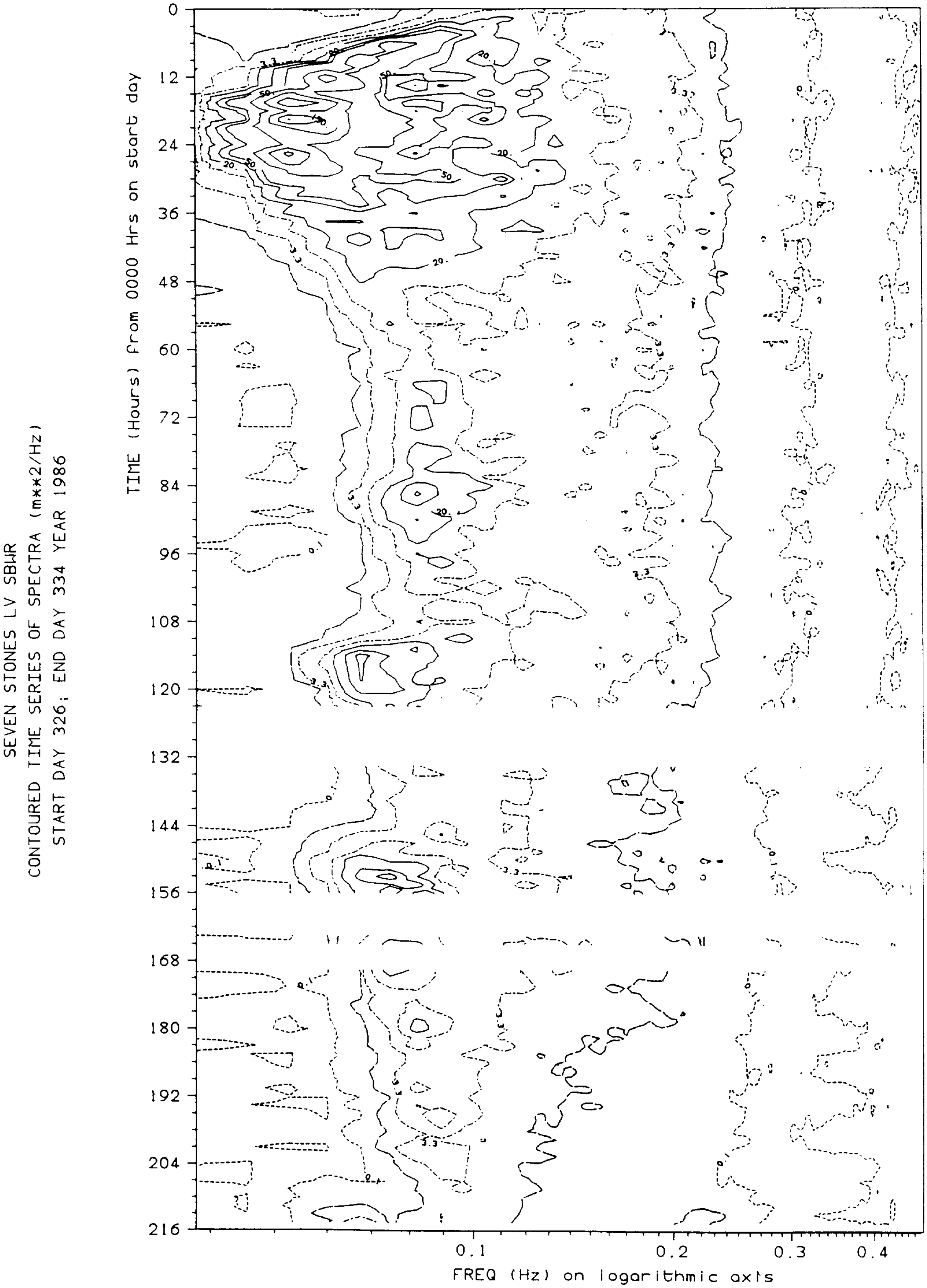

SEVEN STONES LV SBWR
CONTOURED TIME SERIES OF SPECTRA (m**2/Hz)
START DAY 326; END DAY 334 YEAR 1986
TIME (Hours) from 0000 Hrs on start day
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192
204
216
0.1
0.2
0.3
0.4
FREQ (Hz) on logarithmic axis
0.1
3.3
20
50

Figure 14 (c)

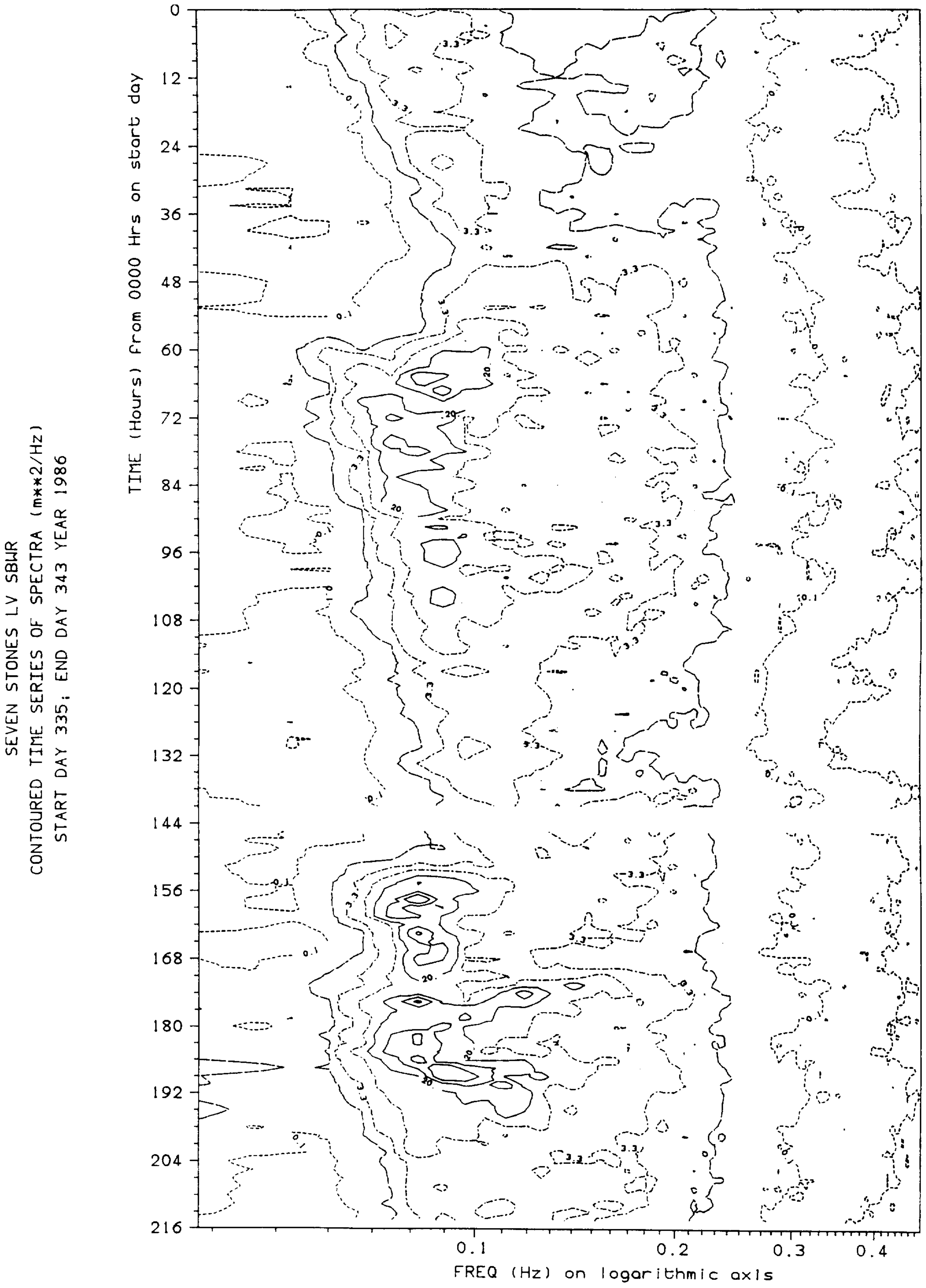

SEVEN STONES LV SBWR
CONTOURED TIME SERIES OF SPECTRA (m**2/Hz)
START DAY 335; END DAY 343 YEAR 1986
TIME (Hours) from 0000 Hrs on start day
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192
204
216
0.1
0.2
0.3
0.4
FREQ (Hz) on logarithmic axis
0.1
3.3
20.

Figure 14 (d)

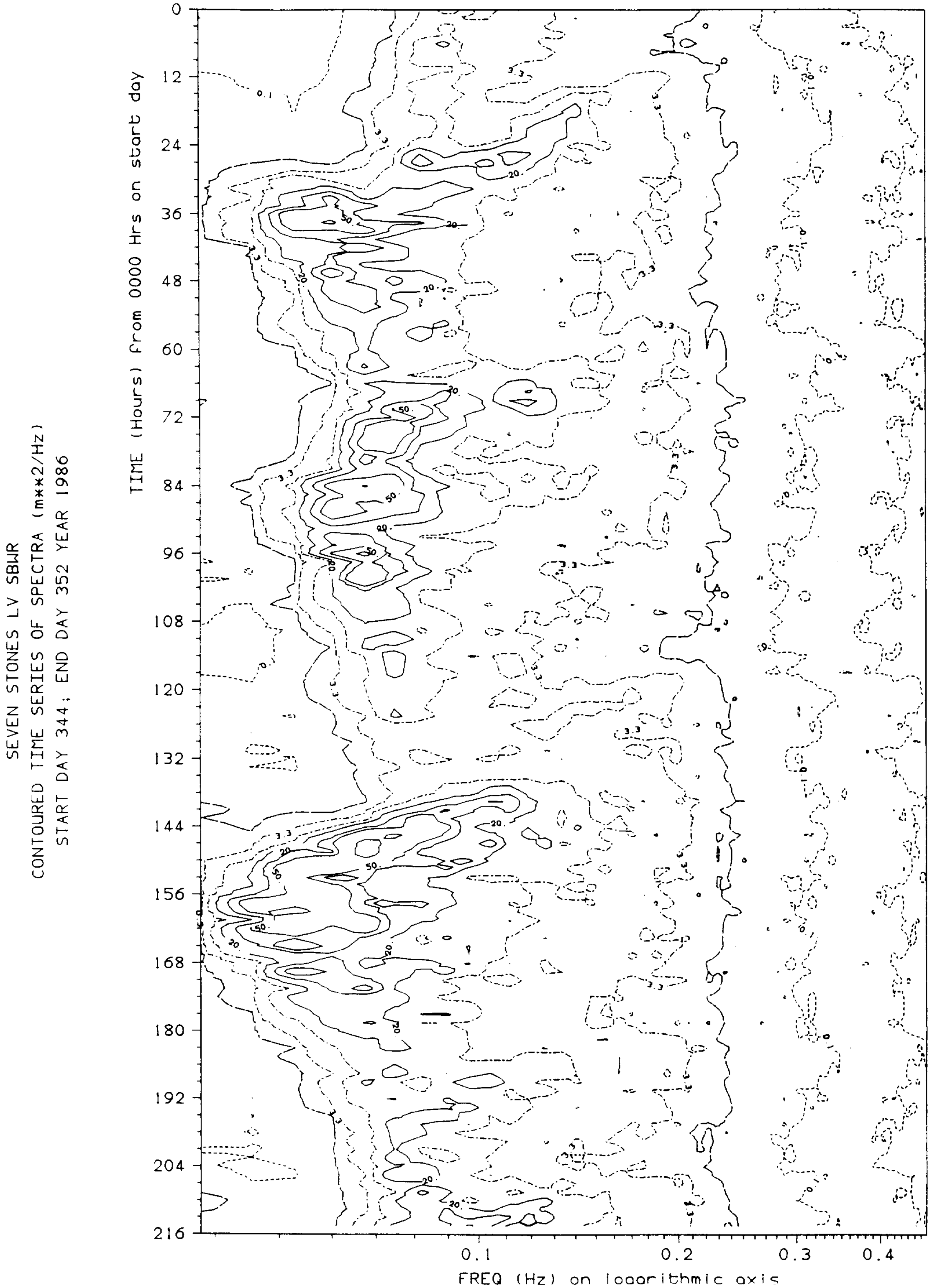

SEVEN STONES LV SBWR
CONTOURED TIME SERIES OF SPECTRA (m**2/Hz)
START DAY 344; END DAY 352 YEAR 1986
TIME (Hours) from 0000 Hrs on start day
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192
204
216
0.1
0.2
0.3
0.4
FREQ (Hz) on logarithmic axis
0.1
3.3
20
50

Figure 14 (e)

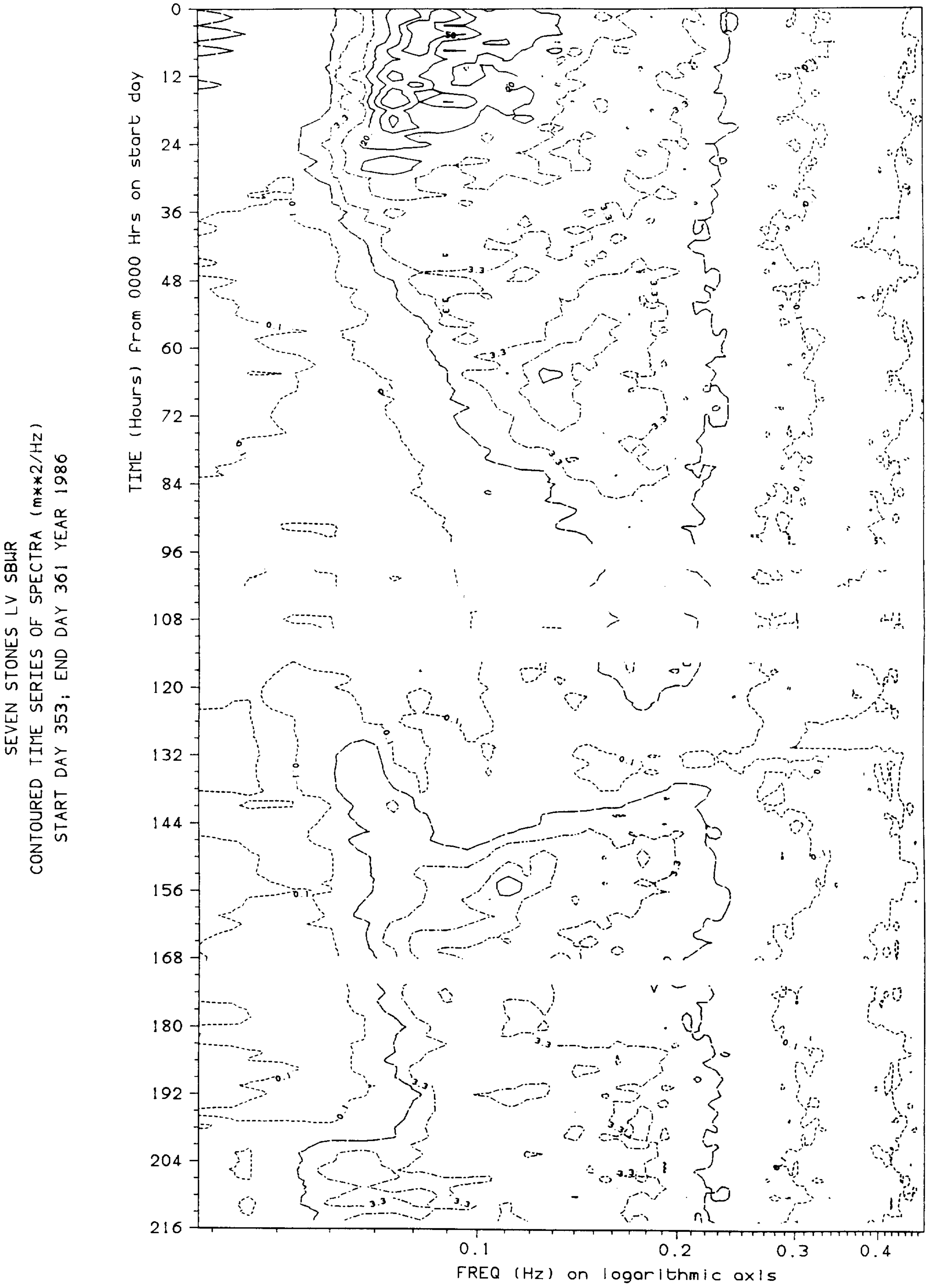

SEVEN STONES LV SBWR
CONTOURED TIME SERIES OF SPECTRA (m**2/Hz)
START DAY 353; END DAY 361 YEAR 1986
TIME (Hours) from 0000 Hrs on start day
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192
204
216
0.1
0.2
0.3
0.4
FREQ (Hz) on logarithmic axis
50
20
3.3
1.0
0.1

Figure 14 (f)

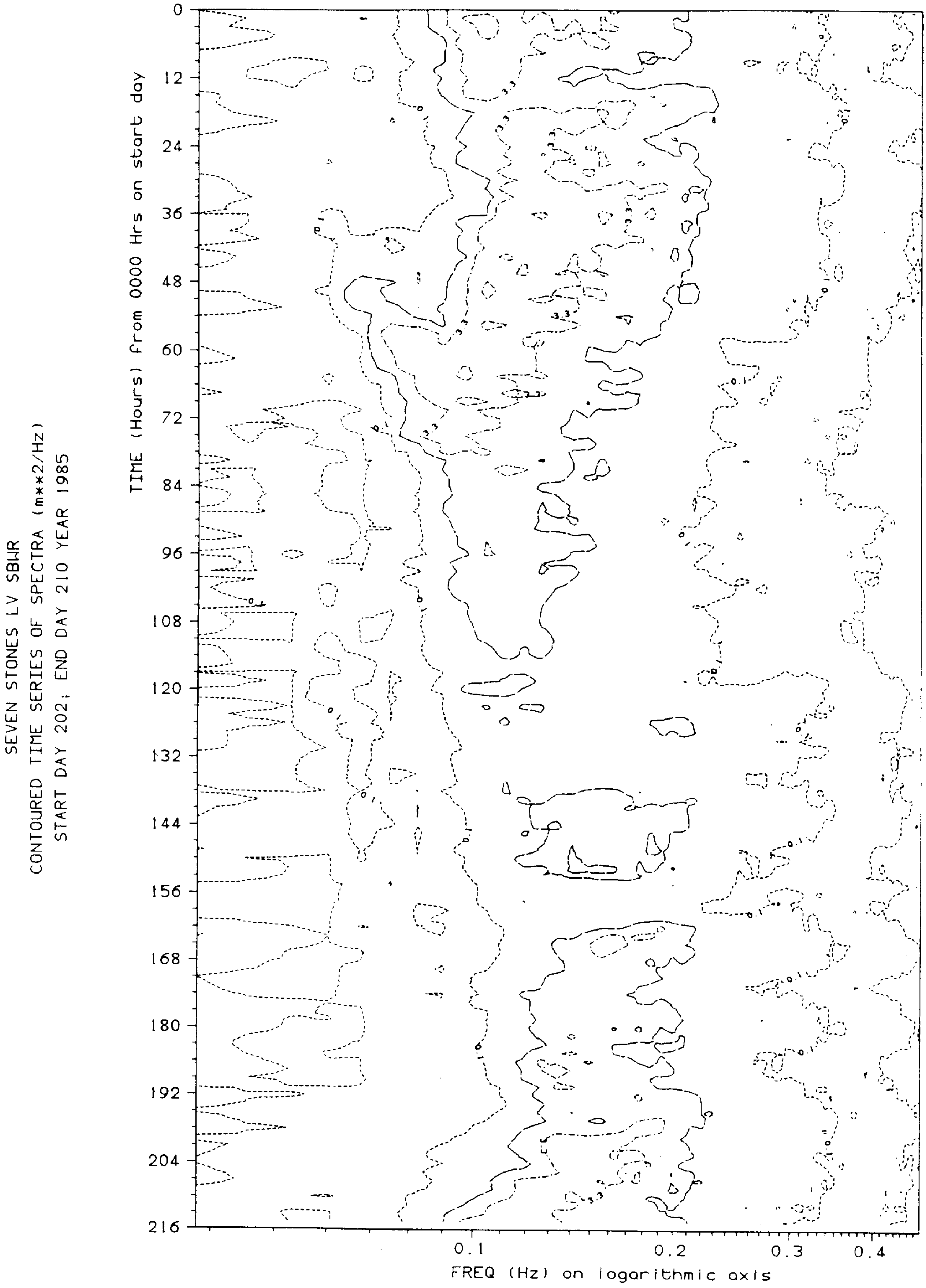

SEVEN STONES LV SBWR
CONTOURED TIME SERIES OF SPECTRA (m**2/Hz)
START DAY 202; END DAY 210 YEAR 1985
TIME (Hours) from 0000 Hrs on start day
0
12
24
36
48
60
72
84
96
108
120
132
144
156
168
180
192
204
216
0.1
3.3
0.1
0.2
0.3
0.4
FREQ (Hz) on logarithmic axis

Figure 14 (g)

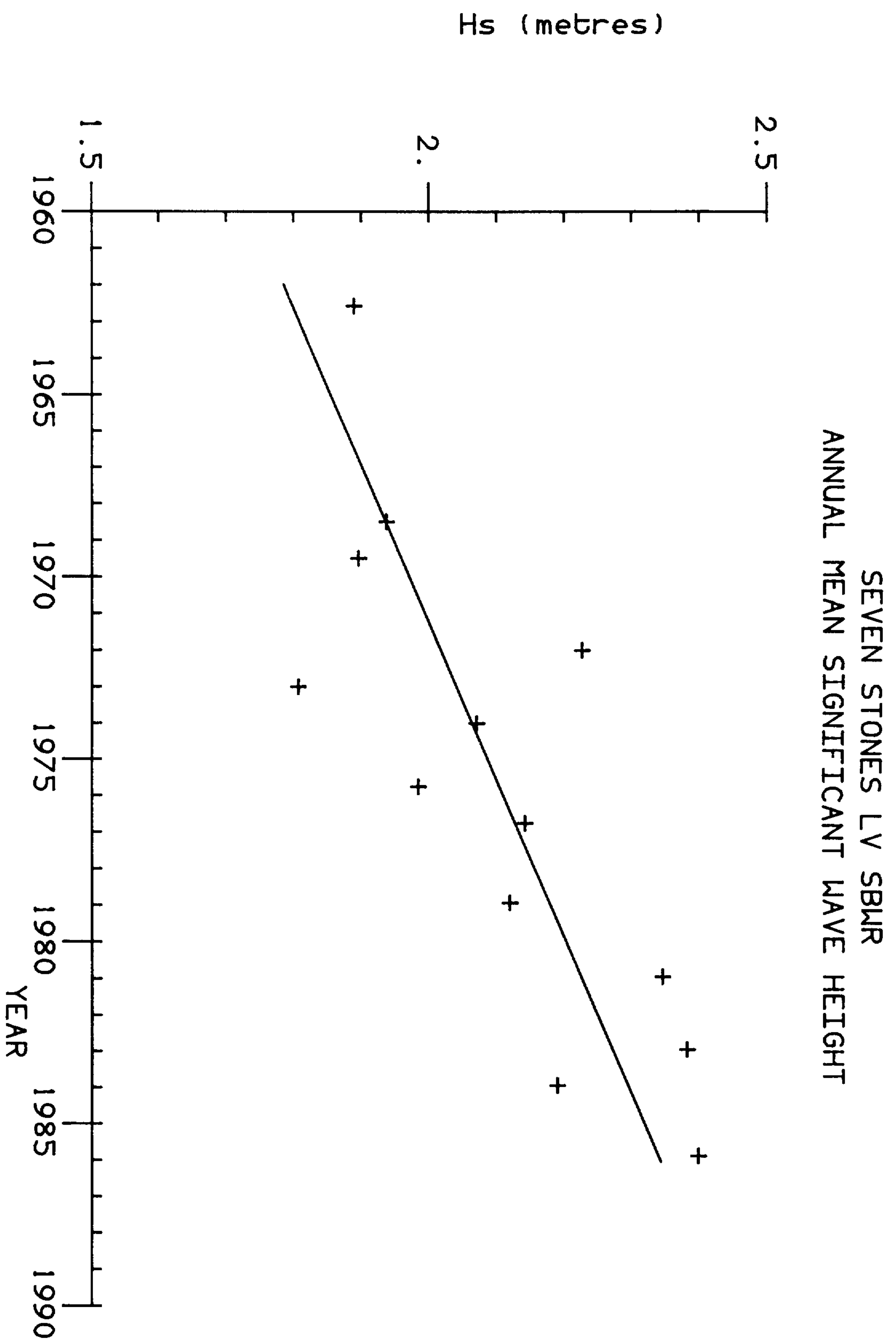

SEVEN STONES LV SBWR
ANNUAL MEAN SIGNIFICANT WAVE HEIGHT
Hs (metres)
1.5
2.
2.5
1960
1965
1970
1975
1980
1985
1990
YEAR

Figure 15

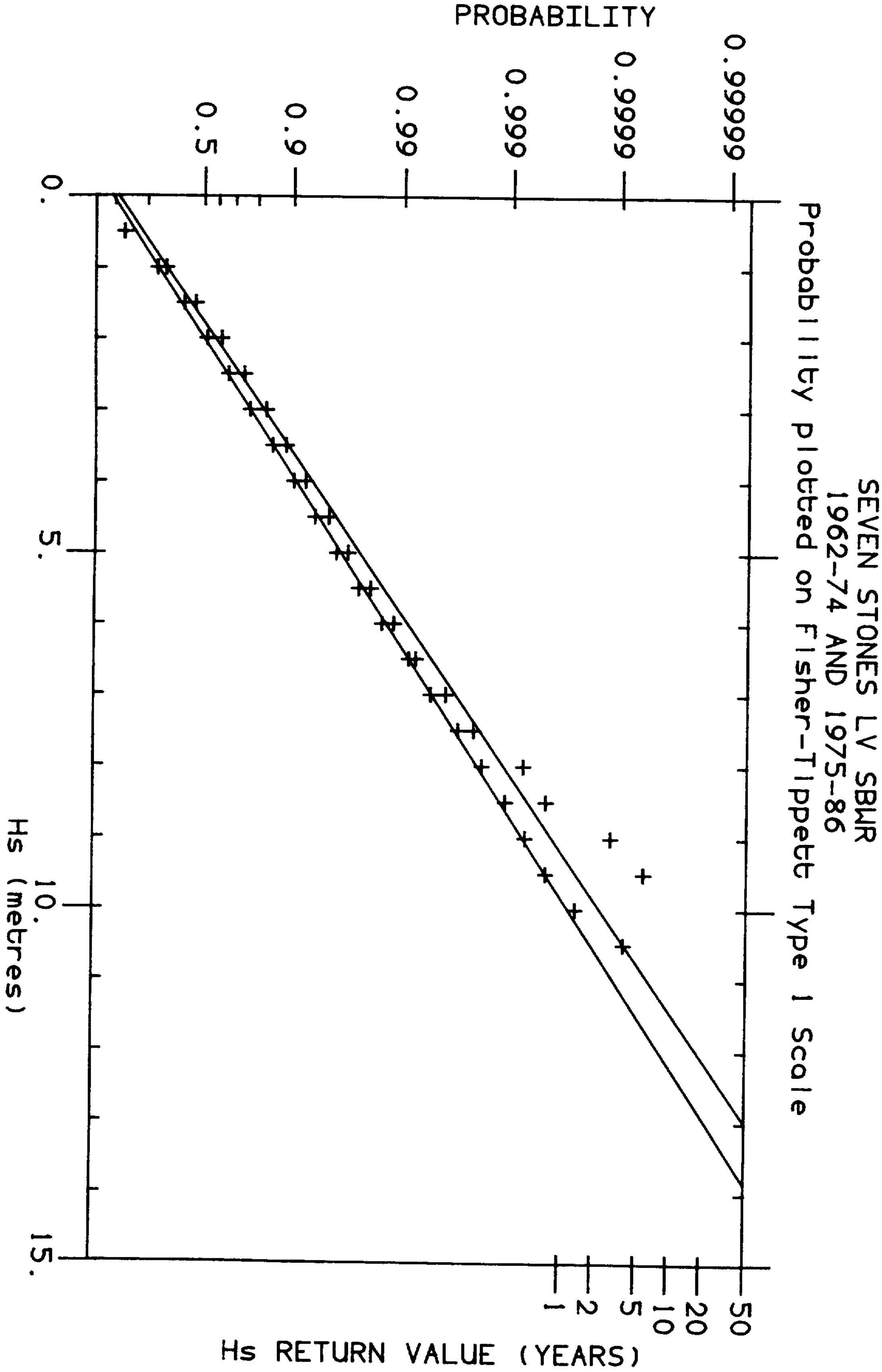

SEVEN STONES LV SBWR
1962-74 AND 1975-86
Probability plotted on Fisher-Tippett Type 1 Scale
PROBABILITY
0.5
0.9
0.99
0.999
0.9999
0.99999
0.
5.
10.
15.
Hs (metres)
1
2
5
10
20
50
Hs RETURN VALUE (YEARS)

Figure 16 (a)

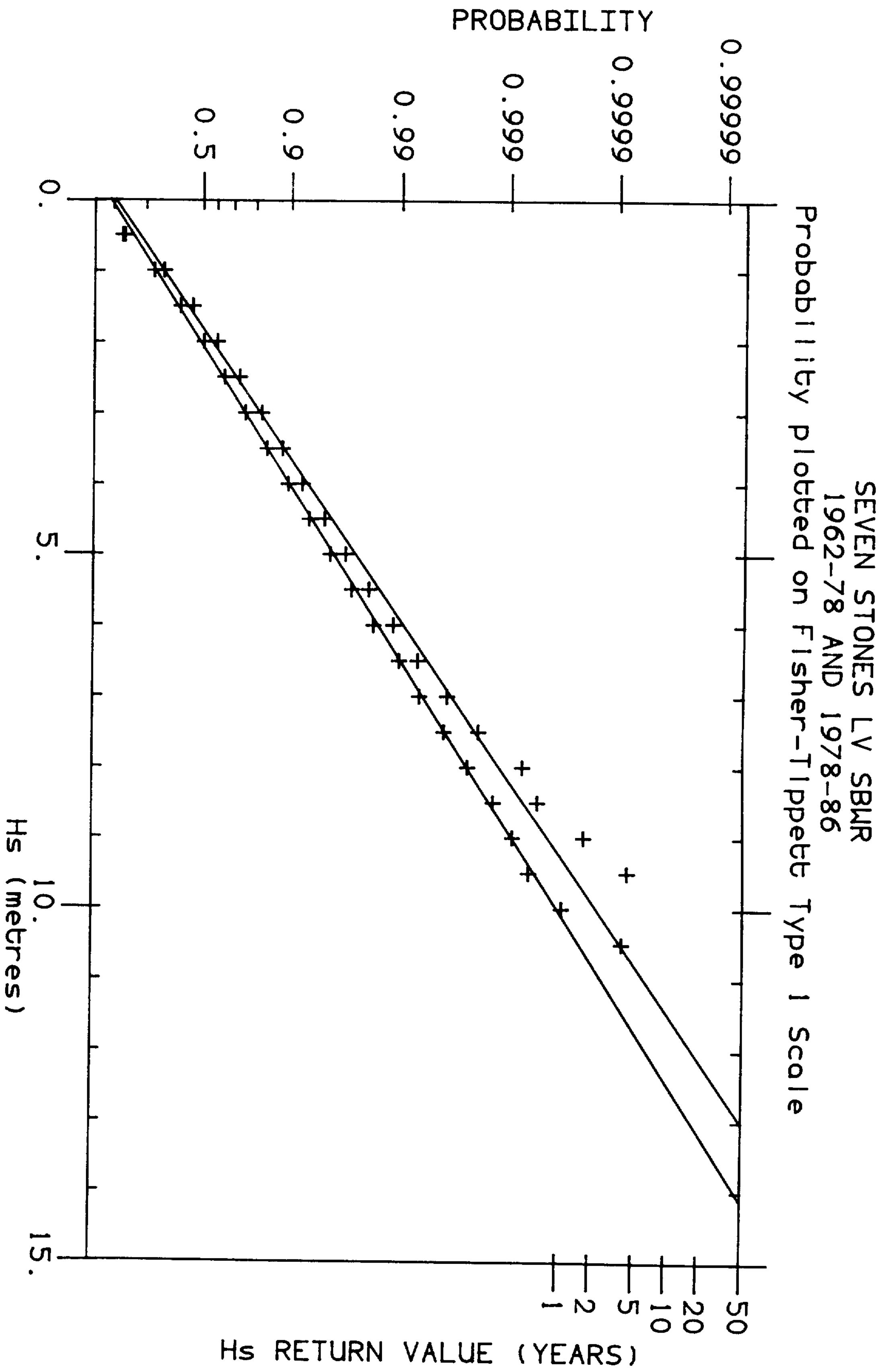

SEVEN STONES LV SBWR
1962-78 AND 1978-86
Probability plotted on Fisher-Tippett Type 1 Scale
PROBABILITY
0.5
0.9
0.99
0.999
0.9999
0.99999
0.
5.
10.
15.
Hs (metres)
1
2
5
10
20
50
Hs RETURN VALUE (YEARS)

Figure 16 (b)

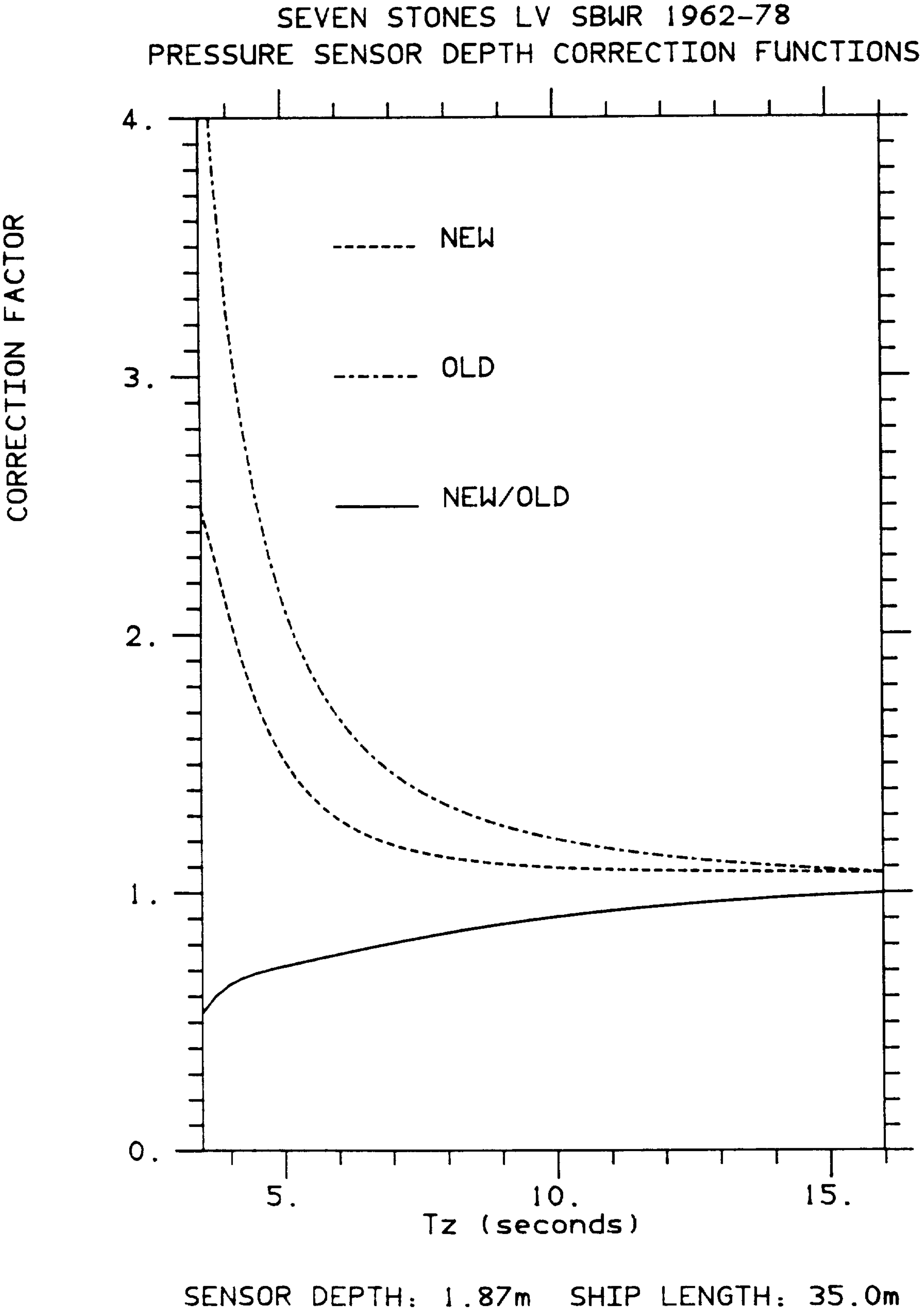

SEVEN STONES LV SBWR 1962-78
PRESSURE SENSOR DEPTH CORRECTION FUNCTIONS
CORRECTION FACTOR
4.
3.
2.
1.
0.
NEW
OLD
NEW/OLD
5.
10.
15.
Tz (seconds)
SENSOR DEPTH: 1.87m SHIP LENGTH: 35.0m

Figure 17 (a)

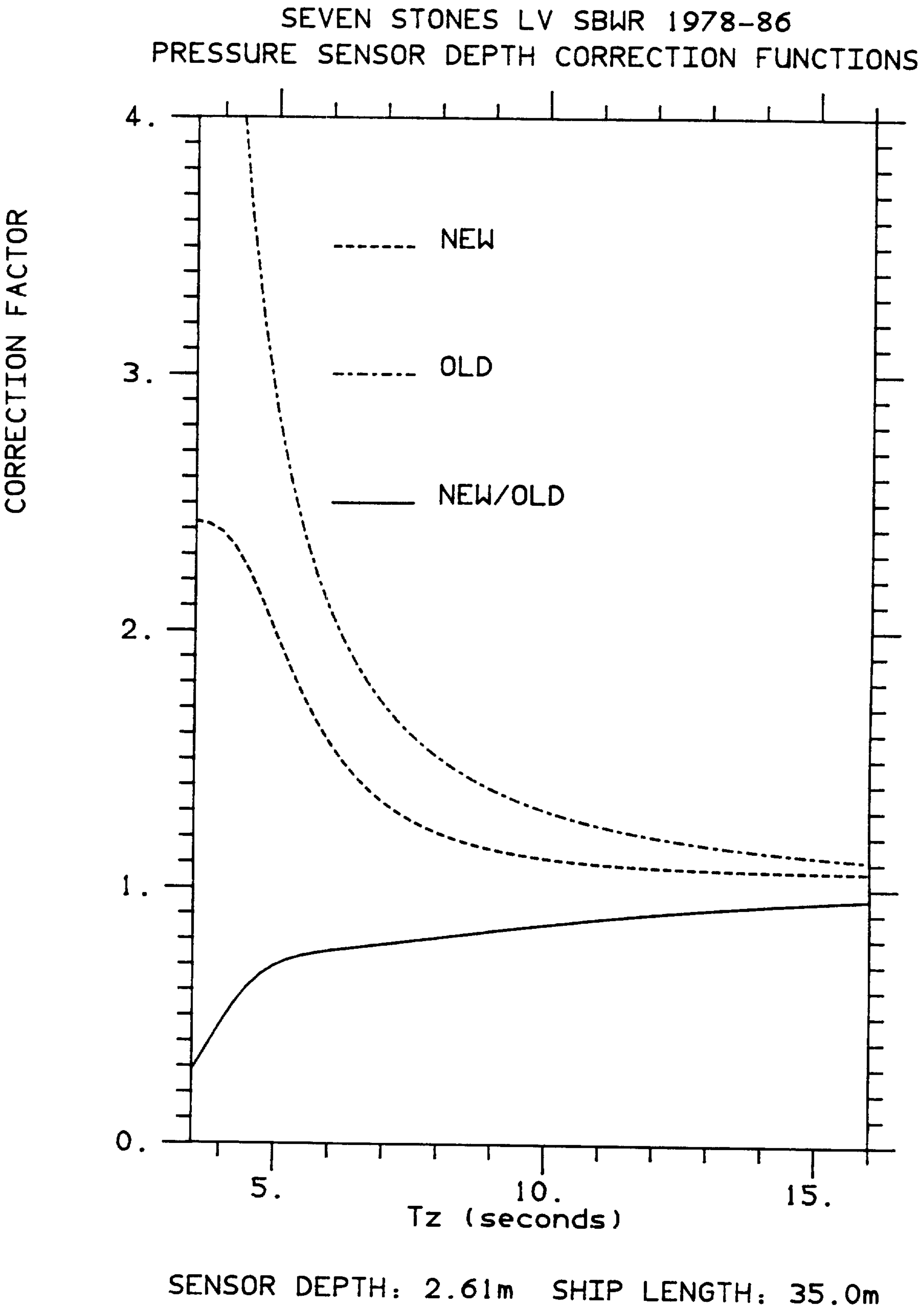

SEVEN STONES LV SBWR 1978-86
PRESSURE SENSOR DEPTH CORRECTION FUNCTIONS
CORRECTION FACTOR
4.
3.
2.
1.
0.
NEW
OLD
NEW/OLD
5.
10.
15.
Tz (seconds)
SENSOR DEPTH: 2.61m SHIP LENGTH: 35.0m

Figure 17 (b)

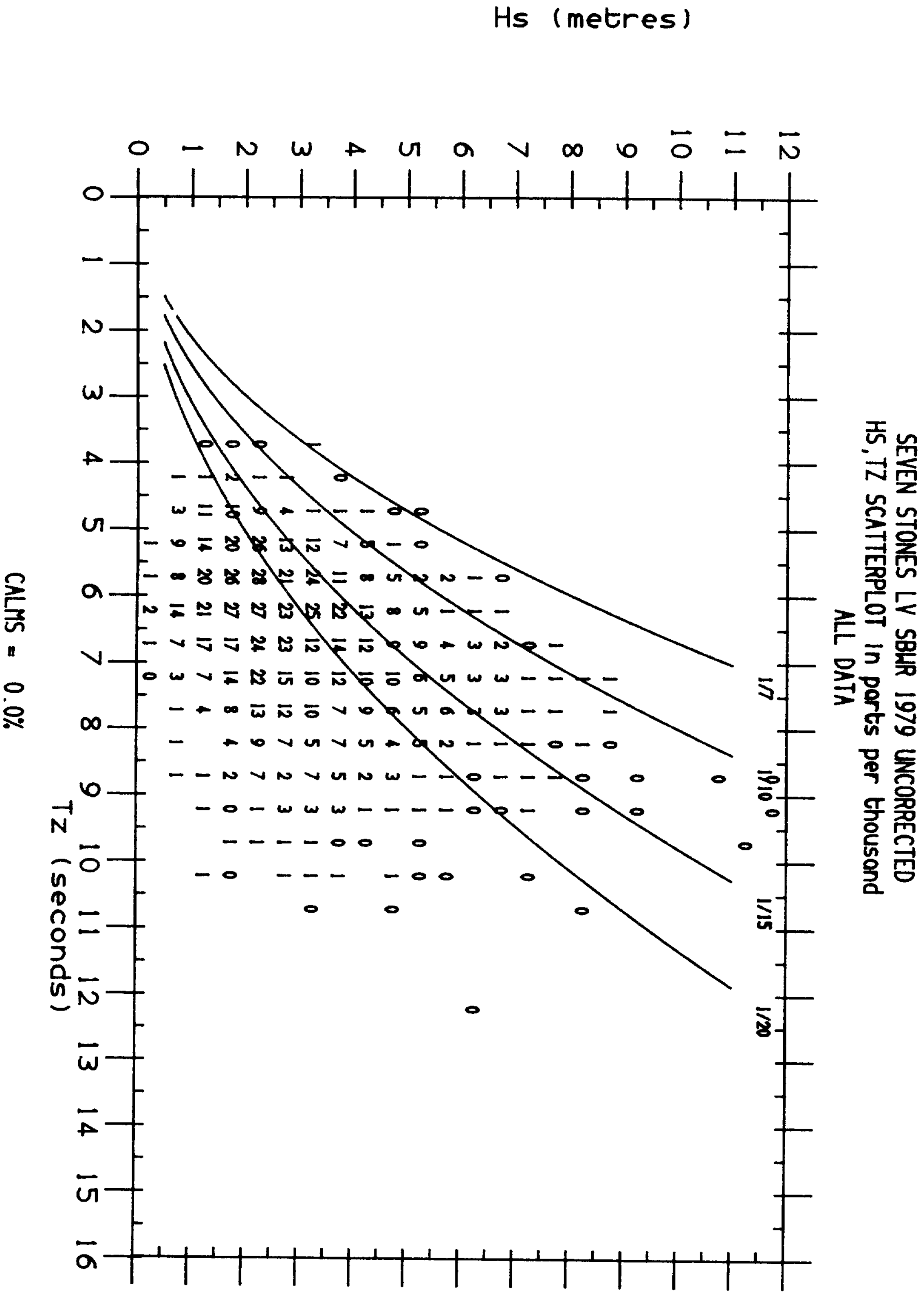

SEVEN STONES LV SBWR 1979 UNCORRECTED
HS,TZ SCATTERPLOT in parts per thousand
ALL DATA
Hs (metres)
Tz (seconds)
CALMS = 0.0%
1/7
1/10
1/15
1/20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Figure 18

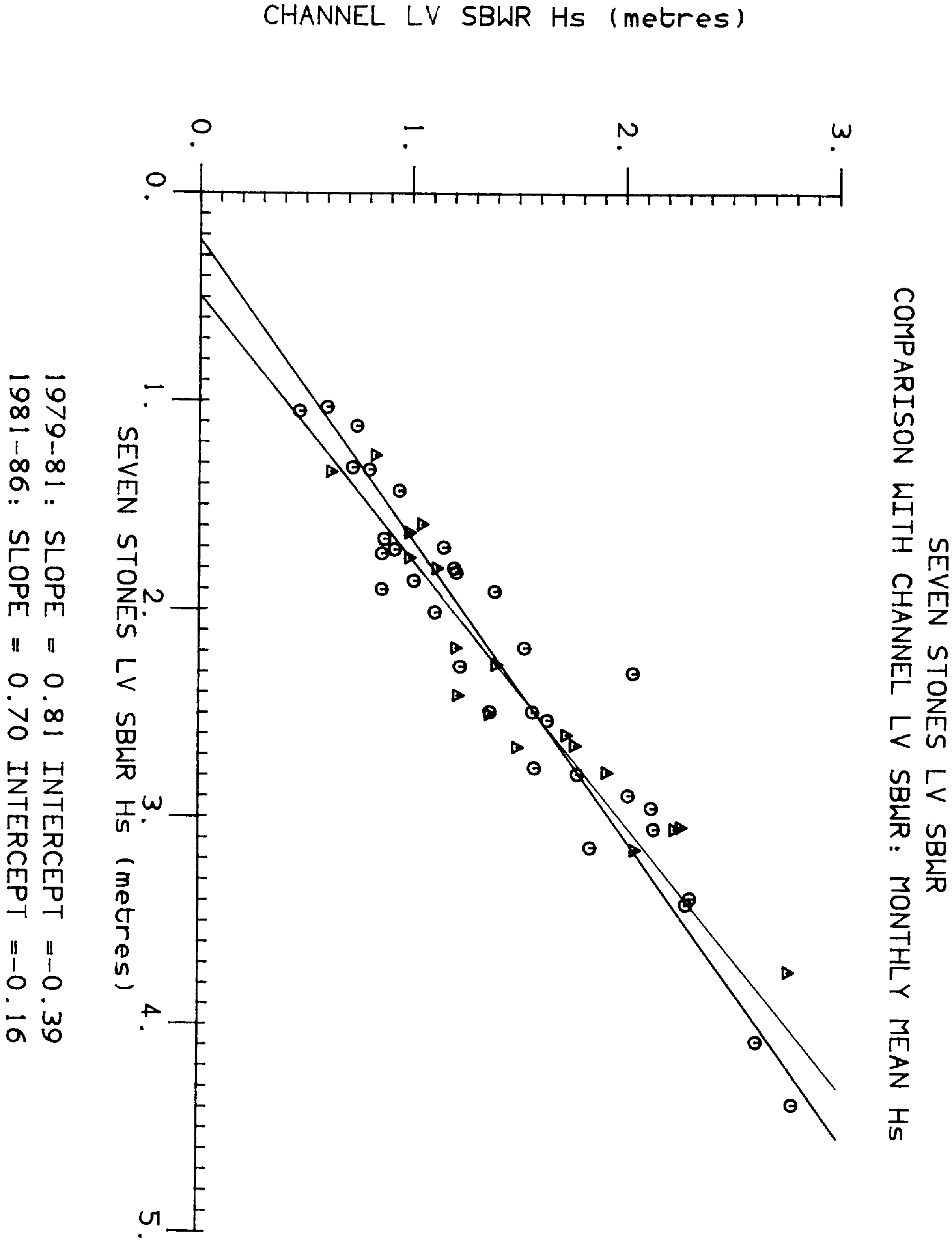

SEVEN STONES LV SBWR
COMPARISON WITH CHANNEL LV SBWR: MONTHLY MEAN Hs
CHANNEL LV SBWR Hs (metres)
0.
1.
2.
3.
SEVEN STONES LV SBWR Hs (metres)
0.
1.
2.
3.
4.
5.
1979-81: SLOPE = 0.81 INTERCEPT =-0.39
1981-86: SLOPE = 0.70 INTERCEPT =-0.16

Figure 19

APPENDIX I: ANALOGUE AND SPECTRAL DATA ANALYSIS AND CORRECTION

Analogue Data Analysis Method

The technique used to analyse the wave data was that proposed by Tucker (1961) and Draper (1963). A twelve minute record of sea surface elevation is taken once every three hours, and from this record are derived estimates of T_Z, the mean zero-up-crossing period, and of H_S, the significant wave height. The former is defined as the duration of the record divided by the number of zero-up-crossings; the latter is defined as 4σ, where σ is the standard deviation of the record, which is estimated from the number of zero-up-crossings and from the size of the two highest crests and the two lowest troughs on the record. H_S as estimated by this method has a standard error of about 6%. The estimate of T_Z is a filtered over-estimate of the true T_Z and is close to the first moment period T_1 ($=m_0/m_1$); workers tend systematically to miss the smallest zero-up-cross waves on chart records.

The estimate of H_S obtained in this way must be corrected for the frequency response of the electronics of the system, and for the hydrodynamic attenuation of the pressure fluctuations, due to the pressure sensors being mounted in ports in the ship's hull some depth below the mean sea surface level. These corrections are discussed below.

Digital Data Analysis Method

The digital data described in this report are derived from time series containing 4096 values of sea surface elevation sampled at 0.5 second intervals producing 34-minute records. The spectrum produced from the time series is considered to be representative of the 1.5-hour period of which it is a sample. An outline of the method of spectral analysis is given below.

Using the Fourier theorem, the elevation of the sea surface above its mean level at time t is given by

$$h(t) = \sum_{i=1}^{\infty}\left(a_i \cos\left(\frac{2\pi i}{T}\right) + b_i \sin\left(\frac{2\pi i}{T}\right)\right), \text{ where}$$

$$a_i = \frac{2}{T}\int_0^T h(t) \cos\left(\frac{2\pi i}{T}\right) dt \text{ , and}$$

$$b_i = \frac{2}{T}\int_0^T h(t) \sin\left(\frac{2\pi i}{T}\right) dt \text{ ,}$$

and T is the record length.

The Fast Fourier Transform, based on the above relationships, is used to compute the pairs of coefficients (a_i,b_i) at the fundamental frequency $f_0 = 1/T$ and at integral multiples of this frequency up to the Nyquist frequency $f_{max} = 1/2\Delta T$ where ΔT is the sampling interval. The sample estimate of the spectrum at the i^{th} frequency, Φ_i, is then computed as

$$\Phi_i = \frac{1}{2f_0}\left(a_i^2 + b_i^2\right)$$

Variance of the wave record which is not located at one of the harmonic frequencies appears in the spectral estimates not only at the harmonic adjacent to to the true frequency but in a band of harmonics. This leakage leads to biased estimates in that on balance a small proportion of the variance which should appear in the neighbourhood of the spectral peaks leaks towards higher and lower frequencies. The effect can be reduced by tapering the ends of the time series data smoothly to zero before performing the Fast Fourier Transform; a cosine taper applied to 12.5% of the record at each end has been used on the data described in this report. This leads to a small increase in the sampling error of the spectral estimates.

The spectral estimates Φ_i have a standard error of 100%. This may be reduced by taking the average of consecutive spectral estimates, and assigning to it the mid-frequency of the band of estimates used. The smoothed spectral estimates, S_j, have been averaged in blocks of 15:

$$S_j = \frac{1}{15} \sum_{i=15j-14}^{15j} \Phi_i, \text{ and}$$

$$f_j = (15j-7)f_0$$

Sixty-four smoothed estimates of spectral density are output, at the following frequencies:

$f_1 = 0.0381$ Hz, $f_{64} = 0.4688$ Hz, $\Delta f = 0.00684$ Hz.

Moments of order -2 to 4 were calculated from the smoothed spectral estimates as

$$m_n = \frac{1}{T} \sum_{j=1}^{64} f_j^n S(f_j)$$

Application of Corrections to the Data

The first correction, that for the frequency response of the system electronics, has different forms for the SBWR Marks I and II; the Mark II has an improved high-pass filter. The forms of the responses are given below; for further information see Tucker (1956): Mark I and Crisp (1987): Mark II.

$$C_E(\text{Mk.I}) \quad = \quad 0.83\left(1 + (8.8\omega)^{-2}\right)^{3/2}$$

$$C_E(\text{Mk.II}) \quad = \quad \left(\left(\left(\omega_1 - \omega^2\right)^2 + \alpha_1^2\omega_1^2\omega^2\right)\left(\left(\omega_2^2 - \omega^2\right)^2 + \alpha_2^2\omega_2^2\omega^2\right)\right)^{1/2}\omega^{-4}$$

where

ω_1 = 0.09498

ω_2 = 0.10650

α_1 = 1.916

α_2 = 1.241

The second correction, that for the hydrodynamic attenuation of the pressure fluctuations, has in the past been modelled as a simple depth-dependent exponential, i.e.

$$C_H = \exp\left(\frac{2.5\omega^2 d}{g}\right)$$

However, Pitt (1988) reports a new and much more satisfactory empirical form for C_H, which is described below, and has been applied to the data presented in this report. It was found possible to reconcile the different response functions returned from calibrations of SBWR's fitted to various ships of widely differing sizes by employing a Froude-type frequency scaling as

$$F = \left(\frac{2\pi}{g}\right)^{1/2}(Ld)^{1/4}f$$

where F is the scaled frequency variable based on frequency f (=T_Z^{-1} for analogue data), and L and d are the ship length and SBWR pressure sensor depth respectively. The empirical form found to give the most satisfactory fit to all measured response functions was a fourth-order polynomial in F, formulated as

$$R_H^2 = 1 - A_0\left(1 - \exp\left(-A_1F - A_2F^2 - A_3F^3\right)\right)$$

where the four 'A' parameters were found for the general (mean) case, and also for Channel LV in particular. Since the pressure sensor depth on Seven Stones LV changed from 1.9m to 2.6m and the pressure sensor depth of Channel LV was 2.0m, nearly equal to the early Seven Stones LV value, the Channel values of the 'A' parameters, and also of the two further parameters described below, were used for the early data sets. These values are given below. Note that the LV lengths were the same.

This is the form of the new correction as applied to spectral estimates of H_S, so that the corrected spectral estimates at frequency f, S(f), are related to the uncorrected esimates S'(f) by

$$S(f) = S'(f)\, C_E(f) \,/\, R_H^2(f).$$

When correcting Tucker-Draper estimates of H_S however, only one period parameter (T_Z) is available, which necessitates the application of a scalar correction, i.e. one evaluated at a single characteristic frequency (f_c), rather than a full correction separately evaluated at individual frequencies, as is possible with spectral data.

Pitt (1988) finds that the following form is necessary:

$$H_S = H_S'\, C_E \left(\frac{1}{S_{SF} \times R_H^2(f_c)}\right)^{1/2}$$

where the characteristic frequency f_c is no longer T_Z^{-1}, but

$$f_c = \frac{1}{T_z S_{T'T_z}}$$

where $S_{T'T_z}$ is an empirically determined constant relating the observed T_z to the value of T_1 (the first moment period), found by Pitt to be the appropriate f_c to use in these circumstances. H_s and H_s' are the corrected and uncorrected values of H_s, respectively. A further empirical constant, S_{SF}, relates to the use of scalar rather than full correction, and is a factor based on comparison between scalar corrected spectral variance and fully corrected spectral variance. As before, values of these two parameters as estimated for Channel LV were used for the early Seven Stones data sets; however, Seven Stones LV specific values were estimated for, and applied to, the later data rather than general values.

H_s Correction Parameters (Analogue Data)

	Channel LV (used for Seven Stones 1962-78)	**Seven Stones LV (1978-86)**
Pressure Sensor Depth (m)	2.0 (Channel LV) 1.9 (Seven Stones LV)	2.6
A_0	0.8468	0.81027
A_1	0.4876	0.50723
A_2	-6.4058	-8.1996
A_3	26.691	35.790
$S_{T'T_z}$	1.1262	1.0518
S_{SF}	0.8741	0.8929

Figure 17 shows the old and new hydrodynamic correction factors, and the ratio of new to old, plotted as functions of T_z for pressure sensor depths of 1.9m and 2.6m. It can be seen that, for Seven Stones L.V., there are significant changes in the new scheme over the old, particularly for records with T_z between 3 and 5 seconds where H_s is decreased by between 25 and 45%.

APPENDIX II METHOD OF SYSTEM CALIBRATION

Since there are two types of transducer in the Shipborne Wave Recorder system, it is necessary to divide the calibration procedure into two sections. First the accelerometers are removed from the ship mountings and each is inserted into a rig which allows the transducer to be driven through a vertical circle of diameter 1 metre. The transducer is mounted in gimbals and maintains a vertical attitude during rotation. Two rotation rates are applied: 12 and 18 second periods which are derived from a crystal oscillator. The transducer is connected to the electronics unit in the usual way, and the calibration signal is displayed on the chart recorder. However, because a 1 metre 'heave' is small compared with the wave-heights usually experienced at sea, a precision amplifier (contained in the electronics) is switched into the circuit, converting the 1 metre into an apparent 10 metre signal. The output signal can then be read from the chart record and any corrections to instrument sensitivity made.

The pressure units cannot be easily subjected to a dynamic test since this requires the application of a sinusoidally-varying pressure. Therefore for routine re-calibration a static test is applied. Each pressure unit is fixed to the test rig and a series of discrete pressure levels is applied from a reservoir via a regulator valve. Each pressure level is set manually with the valve by reference to a precise pressure transducer contained within the calibrator unit. The output voltage of the transducer is monitored in the SBWR electronics unit and compared to the original laboratory calibration. Any changes in sensitivity are then compensated for by adjustment of the input amplifier gain.

Full calibrations are usually only possible when the ship comes into dock for its 3-yearly refit.

Monthly checks are made at sea by the lightvessel crews, who are asked to drain water through the valve assemblies to ensure that no blockage prevents the water pressure being transmitted to the pressure sensors, and then to take a test record, on a monthly basis. The test record consists of a short length of pen-trace with all transducers turned off (electrically), followed by a few minutes recording with each transducer on its own. The record thus produced shows two heave records (one from each accelerometer) which should look broadly similar; and also the pressure traces, which may not agree so well, but when compared with other monthly test records should exhibit no systematic error. These tests are not direct checks on calibration accuracy but are often good indicators of a fault condition developing.

APPENDIX III DETAILS OF METHODS USED FOR CALCULATING 50-YEAR RETURN VALUES

H_S is used as a measure of the "sea-state", (i.e., the intensity of wave activity) and is sampled every 3 hours. It is assumed that a set of H_S data for one year or more is representative of the wave climate.

For each binned data value of H_S, the probability that this value will not be exceeded is calculated; this probability is then plotted against H_S. The axes are scaled according to an appropriate distribution, so that data with a perfect fit would appear as a straight line on the diagram. In practice, the class of functions known as extreme-value distributions are often found to give a close fit to the data. It should be noted that these functions are used only as 'templates' and not strictly as extreme-value distributions.

Formulae

(i) Weibull (3-parameter)

$$\mathrm{Prob}(H_S \leq h) = \begin{cases} 1 - \exp\left(-\left(\frac{h-A}{B}\right)^C\right), & \text{for } h>A \\ 0, & \text{for } h \leq A \end{cases}$$

(ii) Weibull (2-parameter)

$$\mathrm{Prob}(H_S \leq h) = \begin{cases} 1 - \exp\left(-\left(\frac{h}{B}\right)^C\right), & \text{for } h>0 \\ 0, & \text{for } h \leq 0 \end{cases}$$

(iii) Fisher-Tippett I

$$\mathrm{Prob}(H_S \leq h) = \exp\left(-\exp\left(-\left(\frac{h-A}{B}\right)\right)\right), \quad \text{where } B>0$$

In each case, A is the location parameter, B is the scale parameter, C is the shape parameter. The Weibull 2-parameter distribution is the Weibull 3-parameter distribution with $A = 0$.

For each distribution, the best fit straight line is drawn, then extrapolated to some desired probability and the corresponding value of H_S read off as the "design sea-state"

Fitting of Distributions by the Method of Moments

Fitting the Fisher-Tippett Type I Distribution

The mean and variance of this distribution are $A + \gamma B$ and $\pi^2 B^2/6$ respectively, where γ (Euler's constant) = 0.5772...; so the moments estimators given data x_i, $1 \leq i \leq n$, are given by

$$A = \bar{x} - \gamma B \quad \text{and} \quad B = \frac{\sqrt{6}s}{\pi}\text{ , where}$$

$$\bar{x} = \frac{\Sigma x_i}{n} \quad \text{and} \quad s^2 = \frac{\Sigma(x_i - \bar{x})^2}{n-1}$$

Values of x and s^2 may be estimated from grouped data.

Fitting the Weibull 2-parameter Distribution

The probability distribution function for the 2-parameter Weibull distribution is

$$p(x) = \frac{C}{B}\left(\frac{x}{B}\right)^{C-1}\exp\left(-\left(\frac{x}{B}\right)^{C}\right) \tag{1}$$

This usually is fitted only to the upper tail of the data, above some specified level x_0; this can be done by defining 'partial' moments v about the origin of values above x_0 such that

$$v_\gamma = \int_{x_0}^{\infty} x^\gamma p(x)dx \tag{2}$$

and substituting for $P_X(x)$ from equation (1) for γ=1 and 2 leads to

$$v_1 = \frac{x_0}{Z^Y}\Gamma(1+Y,Z) \tag{3}$$

$$v_2 = \frac{x_0}{Z^Y}\Gamma(1+2Y,Z) \tag{4}$$

$$\text{where } Y = \frac{1}{C} \text{ , } Z = \left(\frac{x_0}{B}\right)^C \text{ and } \Gamma(p,D) = \int_D^\infty y^{p-1}e^y dy$$

Therefore given estimates of v_1 and v_2 from data using equation (2) and a value for the lower limit of data to be fitted x_0, then estimates of Y and Z, and hence of B and C can be obtained by numerical solution of equations (3) and (4).

Fitting the Weibull 3-parameter Distribution

The Weibull 3-parameter distribution can be converted to the 2-parameter by the transformation $y = x - A$. The mean and variance of the 2-parameter distribution are given by

$$x = B\Gamma\left(1+\frac{1}{C}\right) \tag{5}$$

$$s^2 = B^2\left(\Gamma\left(1+\frac{2}{C}\right) - \Gamma^2\left(1+\frac{1}{C}\right)\right)$$

$$= x^2\left(\frac{\Gamma\left(1+\frac{2}{C}\right)}{\Gamma^2\left(1+\frac{1}{C}\right)} - 1\right) \tag{6}$$

Values of x and s^2 may be estimated from grouped data; the moments estimator for C can be found by numerical solution of (6); C can then be substituted into (5) to provide B. An initial guess is entered first for A, and the best solution for all parameters is found by iteration to obtain the minimum χ^2 distribution.

Fitting of FT-1 Distribution by Maximum Likelihood

The FT-1 distribution is fitted by maximum likelihood to monthly and annual maxima. For data x_i, $1 \le i \le n$, the maximum likelihood estimators for A and B are found from

$$A = -B \log\left(\frac{1}{n}\sum_{i=1}^{n} \exp\left(-\frac{x_i}{B}\right)\right)$$

$$B = \frac{1}{n}\sum_{i=1}^{n} (x_i - A)\left(1 - \exp\left(-\frac{x_i - A}{B}\right)\right)$$

See Johnson & Kotz (1970); these equations are solved by iteration, with initial estimates for A and B provided by their moments estimators.

Monthly maxima were fitted in calendar months to FT-1 distributions to obtain the fifty-year value of H_S. The annual probability distribution P_{ANN} was found by combining the individual calendar monthly distributions P_M as

$$P_{ANN}(H_S \le h) = \prod_{M=1}^{12} P_M(H_S \le h)$$

where

$$P_M(H_S \le h) = \exp\left(-\exp\left(-\frac{h - A_M}{B_M}\right)\right)$$

The fifty-year return value of H_S was found by solving for h with $P_{ANN} = 0.98$.

Calculation of 50-Year Return Value

The 50-year return value of H_S is defined as that value of H_S which is exceeded on average once in 50 years. In each case this has been determined by extrapolating the relevant distribution to the required probability of exceedance which is determined by assuming some frequency of observation (taken in this report to be 3-hourly).

The 50-year return value of H_S, $H_S(50)$ is then given by

$$\mathrm{Prob}(h<H_S(50)) = 1 - \frac{1}{50 \times 365.25 \times 8}$$

$$= 0.99999316$$

Fitting to seasonal or monthly data reduces the number of days observation per year from 365.25 to 365.25/4 or 365.25/12 respectively, and reduces the relevant probabilities to 0.99997262 and 0.99991786 respectively.

For fitting to invidiual calendar monthly maxima, and annual maxima,

$$\mathrm{Prob}(h<H_S(50)) = 1 - \frac{1}{50} = 0.98$$

APPENDIX IV: CORRECTION OF 1978-81 DATA

Figure 18 illustrates the problems associated with the data from this particular operational period. Note that the scatterplot is of data corrected for hydrodynamic pressure response by the old scheme. It had been known that the SBWR calibration showed an error at the end of this period, but such an error would only affect H_S, and the extreme steepnesses indicated on the scatterplot together with there only being one value of T_Z>11s, even given the old correction scheme, suggested that something was 'wrong' with the measurements of T_Z (which would also affect H_S) as well. It was realised therefore that a correction for T_Z would have to be developed first, and the correction to H_S applied and checked afterwards.

Correction of T_Z

The error in T_Z was tackled by comparing the Seven Stones LV SBWR data with such simultaneous data as was available from the Scilly Isles Waverider (W/R) buoy. These data are decribed in Bacon (1987), and run from 1979 to 1985 so that the 1978 Seven Stones data could not be included in the analysis. The Seven Stones LV and the Scilly Isles W/R were nearly 24n.m. apart, the former being sited between the Scilly Isles and Cornwall in about 60m water depth, the latter to the SSW of the Scilly Isles in about 100m water depth: see Figure 1. Since an error in the SBWR T_Z affects the estimate of H_S, it was decided to compare the simultaneous measurements from the two instruments by value of the SBWR T_Z. The table below gives the means of the ratios of the SBWR T_Z to the W/R T_Z for one second bands of T_Z. A few questionable values in the data sets were revealed by examining those for which the ratio of the wave periods were greater than 3.0; consequently, all such 'outliers' were omitted from the analysis. Also given are the total number and percentage of data in each SBWR T_Z band, and the results of the correction process, described below.

Means of Ratios of SBWR T_Z: W/R T_Z

SBWR T_Z (s)	Uncorrected values of SBWR T_Z:W/R T_Z				Corrected Values of SBWR T_Z:W/R T_Z	
	1979-7:1981		8:1981-1985		1979-7:1981	
	%	Mean	%	Mean	%	Mean
<5	10.3	1.07	1.7	1.12	0.8	1.27
5-6	33.3	1.09	6.7	1.22	11.5	1.27
6-7	30.3	1.08	19.4	1.27	28.0	1.29
7-8	16.4	1.08	26.4	1.30	28.6	1.29
8-9	6.8	1.06	23.3	1.29	16.6	1.28
9-10	2.3	1.05	13.5	1.28	9.2	1.24
>10	0.3	1.03	9.0	1.27	5.4	1.24
All	100.0	1.082	100.0	1.280	100.0	1.280
(number of records)	2738		7060			

Obviously one cannot require that the two measurement systems should produce identical results, but one can, given the quantity of data available, require that the ratios of the T_Z's are consistent during and after the period in question. The table shows that the ratios of SBWR to W/R T_Z was about 15% lower in 1979-81 than 1981-85; and they appear not to vary with SBWR T_Z. The SBWR T_Z values prior to 1981 are considerably closer to the W/R values than the post-1981 ones, but good agreement of this sort would not be expected, because of the different frequency responses of the two instruments and measurement processes. Table 1 in Carter and Tucker (1986) shows that for a Pierson-Moskowitz spectrum with T_Z=5.19s, the effect of high-frequency cutoff leads to a SBWR T_Z of 6.39s compared to a value from an instrument with a sharp cutoff at 0.5Hz (more severe than the W/R) of 5.43s, a ratio of 1.18.

Thus the analysis supports the contention that there was an error in the SBWR T_Z for 1979 (and presumably 1978) to 1981. One may speculate that the error arose from the instrument's time scaling which was based on the LV's internal AC supply frequency, which was dependent in turn on the LV's generated DC voltage which may not have been achieved as intended. Instruments fitted after 1981 had their own inbuilt timing devices. Assuming an approximately constant supply voltage throughout the period of operation in question, the T_Z values measured during this time should be corrected by a factor of 1.280/1.082 = 1.18, so that the mean ratio with the W/R T_Z is the same before and after 1981. This has been applied to the data presented here, with results described in the final column of the table above.

Correction of H_S

In order to check that the new corrected values of H_S obtained through the application of the above correction to T_Z, combined with the changing of H_S to account for the reported error in calibration of the SBWR were sensible, the data between 1979 and 1986 were compared with records from the Channel LV SBWR. The monthly mean values of H_S from Channel LV were plotted against those from Seven Stones LV in two groups, 1979-81 and 1981-86, with only those months of ≥80% data return from both sites included. A best-fit straight line was drawn through each set; this showed that there were no significant differences between them. The results are shown in Figure 19, and the plotted values are those in Table 3 for Seven Stones and from Table 8 in Bacon (1989), together with more recently available 1986 values. Note that on Figure 19 the triangles are the pre-1981 values and the circles post-1981.

Quite apart from the indication that the alterations to the Seven Stones data are made to seem reasonable by this comparison, it is interesting that there there is such good correlation with little scatter. The figures show a relationship between monthly mean H_S at Seven Stones LV and Channel LV of a simple linear form implying H_S at Seven Stones when H_S=0 at Channel of 0.25-0.5m, which could be a reasonable figure assuming some swell at the more exposed site; and that H_S(Channel) = (0.7-0.8) H_S(Seven Stones), with some consistency.