Institute of
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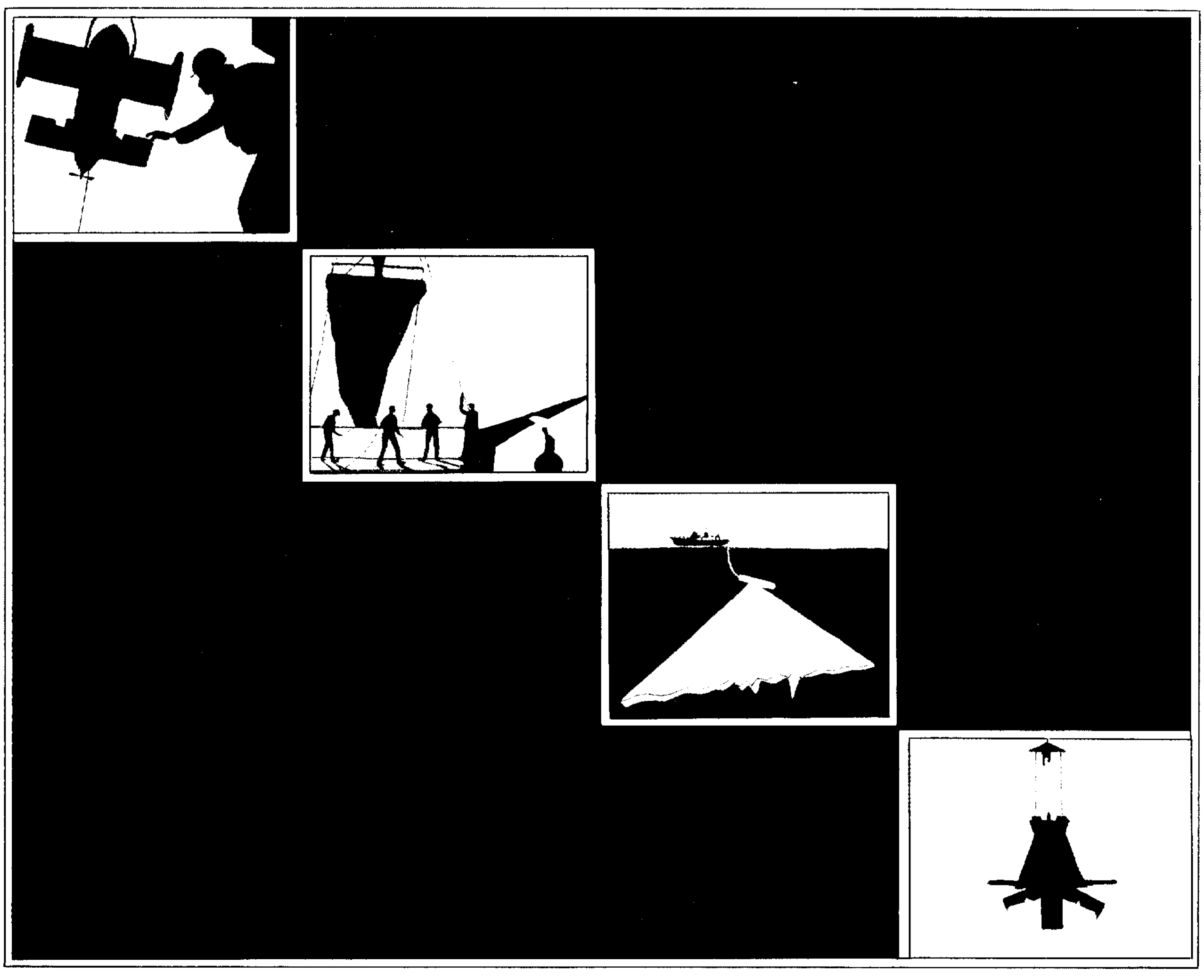
Directional wave data recorded off Flamborough Head

C H Clayson & J A Ewing

Report No 273 1990



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ABSTRACT

A directional wave buoy was deployed 7.7 nm north-east of Flamborough Head, in the southern North Sea during the period from December 1984 to May 1986. The deployments of the Datawell WAVEC buoy were carried out on behalf of the U.K. Department of Energy.

This report summarizes the operational history, analytical techniques and the results obtained during the measurement period. The basic non-directional information consists of measurements of the frequency spectrum from which wave height and period statistics have been computed. In addition to this information, the directional wave buoy provides estimates of the directional spectrum from which the mean wave direction and directional spread are calculated.

The results of this study are contained in a set of tables and figures which, in addition to wave height and period statistics, provide statistics of the joint occurrence of wave height, wave period and wave direction. Information is given for each of four seasons and for the whole data set.

KEYWORDS

DIRECTIONAL WAVE SPECTRA
FLAMBOROUGH HEAD
NORTH SEA(S)
NWEURNORS
WAVE BUOY
WAVE DATA
WAVE HEIGHT

ISSUING ORGANISATION

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CONTENTS

1. INTRODUCTION

This report summarises the techniques used and the results obtained during a 19 month series of deployments of a Datawell Wavec directional wave buoy, 7.7 nm north-east of Flamborough Head, Humberside during the period from December 1984 to May 1986. The deployments were carried out as part of a programme of work, commissioned by the U.K. Department of Energy Petroleum Engineering Department, for Directional Wave Measurements in the Southern North Sea. This report is the second directional wave data report of its type, involving the Wavec equipment, to be produced by the Institute of Oceanographic Sciences Deacon Laboratory (IOSDL). A previous report by Clayson and Ewing (1988) gave extensive information regarding the instrumentation, data collection, calibration and analysis procedures. The current report will not repeat this information in such detail.

The location of the buoy mooring, described in 2 below, was selected following a survey of possible sites by Humphery (1984); these included the Rough and West Sole gas fields. The West Sole area was rejected owing to the presence of a number of sandbanks, which would have complicated the local wave climate. The Rough area was subject to considerable shipping activity, although a buoy moored within the 500 m exclusion zone of a fixed platform should have been relatively safe. There were, at the time, no telemetry facilities available on the site and access would have been difficult to arrange. The Flamborough area was heavily fished but would allow ready access to shore-based receiving equipment and for buoy deployment/recovery, using local vessels from Bridlington or Scarborough. Due to some urgency to establish the equipment in operation in time for the space shuttle SIR-B experiment, the less problematic Flamborough site was adopted.

The activities reported upon include:-

(a) the deployment, recovery, maintenance and calibration of the buoys used. This was carried out initially by the Institute of Oceanographic Sciences, Taunton Laboratory (IOS(T)) and, later, by IOSDL;

(b) the establishment, operation and maintenance of the shore based receiving station and real-time processing and logging equipment. This was carried out mainly by the Institute of Oceanographic Sciences, Bidston Laboratory (now the Proudman Oceanographic Laboratory (POL)), with the assistance of a local builder from Flamborough;

(c) the translation, quality checking and reformatting of the field processed data tapes and the transfer of the data to the IBM mainframe computer at Wallingford (carried out by POL);

(d) the conversion of the data transferred to the IBM to the standard MIAS directional wave data format (carried out by MIAS at POL);

(e) the production of summarised data in graphical and tabular parameterised form from the complete MIAS data set (carried out by IOSDL).

2. LOCATION

The wave measurements were made with a Datawell Wavec buoy moored at 54°14'N, 0° 02' E, 7.7 nm east-north-east of Flamborough Head lighthouse, as shown in Figs. 1(a) and (b). The water depth at the location of the buoy was 51 m.

The bathymetry in the vicinity of the buoy is quite straightforward to the north, but there is a series of banks to the east, culminating in the Dogger Bank.

The mean spring tidal range at the site is 5 m. Tidal currents in the area are predominantly semi-diurnal and are aligned approximately north-west to south-east with a maximum speed of about 0.7 m/sec.

3. INSTRUMENTATION AND DATA COLLECTION

Standard Wavec buoys, manufactured by Datawell bv of Haarlem, Holland, were used for this project. One of these, serial no. 22009, was procured by IOS(T) in March 1984 and was used for the initial deployments. A second buoy, serial no. 22012, was procured in March 1985 for back-up purposes. The deployment history of the buoys is given in Appendix A.1. Details of the buoy and mooring configurations are identical to those described by Clayson and Ewing (1988).

3.1 Receiving station

The digital, frequency shift keyed, transmissions from the buoy were received by a Kathrein 717758 quarter wave antenna with ground plane elements. This was erected on a guyed 2 m length of scaffold pole in the grounds of a bungalow, approximately 1 mile north west of Flamborough Head lighthouse. Space for the receiving equipment (Direc receiver/processor, HP85B microcomputer and Columbia 300C tape cartridge drive) was rented from the owner. Arrangements were made for a local builder to change the tapes, to post them to POL and to report any obvious malfunctions. The receiving station was close to the cliff edge at a height of about 50 m above sea level. Initially, the HP85B was programmed to acquire processed spectral data from the Direc at 3-hourly intervals (determined by reading the real time clock of the Direc). The entire set of 128 spectral estimates, at 0.005 Hz intervals, of the nine possible co- and quadrature spectra of heave, slope north-south and slope east-west, was recorded. This amounted to a total of 13460 bytes per record (including housekeeping data), allowing 20 days' data to be accommodated on each 300 ft tape cartridge. It was subsequently decided that a 3-hourly rate was inadequate to resolve the rapid changes in wave conditions in the area. The software was, therefore, changed to give $1\frac{1}{2}$ - hourly records of sets of 64 spectral estimates, maintaining a comparable data acquisition rate. Although the tapes had a potential storage capacity of 20 days, they were changed at intervals of 10 days to reduce the delay in diagnosing faults from the data.

The 64 spectral estimates consisted of estimate "zero", which contained substituted calculated parameters, together with 63 estimates produced by averaging pairs of estimates from the original set of 128. These estimates consequently have centre frequencies of 0.0075, 0.0175, 0.0275, . ., 0.6175, 0.6275 Hz. In the subsequent reformatting of the data prior to archiving and statistical processing, the early data were converted to the 64 estimate form. Since they were only 3-hourly, allowance for this had to be made in the derived statistical estimates, as noted in section 4.3.

Another change in the processed data resulted from the change from Direc serial no. 23004 to Direc serial no. 23009 on 10th April 1985. It was subsequently found that Datawell had changed the scaling of the slope signals by a factor of 2000 in the processor firmware. Consequently, it was necessary to divide estimates of heave/slope cross spectra by 2.10^3 and to divide estimates of slope/slope cross spectra by 4.10^6.

Detailed descriptions of the Direc processing and of the HP85B control and logging functions were given by Clayson and Ewing (1988). The performance of the Flamborough Head receiving was not as satisfactory as that of the Cromer station, resulting in an overall data return of 60%. This was due to a number of factors, the principal of which were:-

(a) the relatively frequent occurrence of mains power losses at the site, due to its isolated position. The tape drive automatically rewound to load point upon power-up and the HP85B program auto-booted. Since the latter was not capable of determining the position of the end of the last file on the tape, power failures resulted in overwriting of substantial quantities of data;

(b) lightning strikes on the power lines or antenna resulted in errors in the program stored in the HP85B RAM memory, causing program "crashes". These could only be remedied by human intervention since there was no watchdog circuit in the HP85B system;

(c) the Columbia 300C tape drives suffered from a number of hardware faults. The Data Track Technology Tracker 1600 drives used at Cromer proved highly reliable, in contrast;

(d) the accessibility of the site to the local coastal footpath resulted in vandalisation of the receiving antenna, whereas

(e) the Cromer station was daily under the view of coastguard staff and was in a protected compound. However, even this station suffered from a number of mains power failures.

3.2 Data translation and transfer to IBM

The tape cartridges and HP85B diagnostic printouts were mailed in standard Jiffy bags to POL where they were copied to 9 track computer-compatible tape, using an HP workstation.

Plots of energy spectra, direction and spread were produced from records at the beginning and end of each field tape, together with tabulated energy, direction, spread and check ratio for each estimate: these were used for quality control in conjunction with the HP85B diagnostic data. Accepted data were finally translated to the MIAS format for directional wave data by BODS at POL, using the nominal magnetic variation for the buoy site for the conversion of the magnetically orientated slope data to true heading referenced data.

3.3 Calibrations

Calibrations were carried out initially using the Datawell rotating arm test rig at Haarlem. This rig was constructed of non-magnetic components and was housed in a special room remote from magnetic disturbances: consequently the complete set of sensor outputs could be used in a directional analysis, giving useful calibration and test data. Later calibrations were carried out using a rotating arm rig of similar design, but with magnetic components in closer proximity, at Hydraulics Research Ltd., Wallingford. Separate pitch, roll and magnetometer calibrations were carried out on appropriate test rigs, as described by Clayson and Ewing (1988).

In all cases, the calibrations agreed with the nominal values to within approximately $\pm 1\%$, or $\pm 1°$ in equivalent orientation. The nominal calibrations were used in banking the data since it is not, in any case, possible to correct the slope data for errors in the pitch, roll and magnetometer calibrations unless the raw data are logged; this would have presented considerable data storage and processing problems (in excess of 1 Mbyte/day).

4. ANALYSIS AND RESULTS

In this report both tabular and graphical information are presented for users. The recommendations proposed by Ewing (1986) for the presentation of directional wave data are followed. Many questions on directionality are comparatively straightforward and can be answered by direct reference to the tables and figures in this report. Other more complicated questions may require access to the full data set held by the Marine Information and Advisory Service (MIAS) on magnetic tape.

4.1 Definition of parameters

The basic non-directional information contained in this report consist of significant wave height, h_s ($=4\sqrt{m_0}$), mean zero-crossing period, T_z ($= \sqrt{(m_o/m_2)}$) and wave period at the peak of the wave spectrum, T_p, where m_n are the moments of the frequency spectrum evaluated over a frequency range from 0.05 Hz to the Nyquist frequency of 0.63 Hz.

The directional characteristics of the waves are described in terms of the mean wave direction, θ_1 and the directional spread θ_2 (see Appendix A.2). If the directional distribution is unimodal then, for a narrow angular distribution, θ_2 is equal to the r.m.s. spread of wave energy about the mean direction. In some situations the directional distribution can be bimodal and more advanced methods are then necessary to resolve the two peak energies (see Long and Hasselmann, 1979, and Lygre and Krogstad, 1986). We do not consider bimodality in this report.

All wave directions in this report are defined as those directions from which the waves are coming; this is in the same sense as the definition of wind direction.

4.2 Sampling variability

Sampling variability in spectral estimates can be calculated following the work of Blackman and Tukey (1959) and, more recently, by Donelan and Pierson (1983). For the variability in the directional parameters we have used Long (1980). Table 1 gives typical values of the standard deviation of significant wave height, peak period, zero-crossing period and for the two directional parameters.

Statistical uncertainties depend on the form and shape of the spectrum and its angular distribution as well as the degrees of freedom of spectral estimates; values given in Table 1 should therefore only be used as a guide to the sampling variability.

4.3 Data return

Wave measurements taken at Flamborough Head cover the 16 month period 6 January 1985 to 5 May 1986; this is less than the overall deployment period due to the operational problems described in Appendix A.1. Wave records of 30 min. duration were taken every 3 hours from 6 January 1985 to 14 May 1985. The sampling strategy was changed on 15 May 1985 to recording every $1\frac{1}{2}$ hours, since it was found that the more frequent recordings were necessary to describe wave conditions at this site in the southern North Sea. In the calculation of the statistics presented below, the probability distributions for Winter and Spring were calculated separately for 1985 and 1986, and then averaged to produce the final results. For the distributions for Summer and Autumn, only one year's data set was available for use.

The data return for each month is shown in Table 2 for complete records where all directional wave information is available (denoted by d.w.s.) and for records where only the significant wave height, h_s, is available. The graphs shown in Figs. 3(a)-(d) give a good visual indication of missing data sequences. Table 3 shows the data return by season and for the whole dataset. The overall data return was 60%.

In the tables and figures which follow the four seasons are defined as:

Winter : December, January, February
Spring : March, April, May
Summer : June, July, August
Autumn : September, October, November

4.4 Distribution and return value of significant wave height

The mean and maximum values of h_s for individual months are shown in Table 2. There is a clearly defined seasonal variation. Figs. 3(a)-(d) show the individual values of h_s throughout each month for the whole period of the measurements. The greatest value of h_s of 6.1m was obtained during January 1986. These figures allow the identification of storm periods and, as discussed above, missing data sequences. The 50-year return value of h_s was obtained by fitting a Fisher-Tippett Type 1 distribution to the values of h_s as shown in Figure 4. The parameters of the Fisher-Tippett 1 distribution were estimated using the method of moments. A value of 9.6 m was obtained for the 50-year return value at the Flamborough Head site. This return value should be used with caution since it is based on a short data base of less than 2 years of wave recordings.

4.5 Joint distribution of wave height and period

Figs. 5(a)-(e) show the joint probability of occurrence of significant wave height, h_s, with mean zero-crossing period, T_z, for all data and for each season. Numerical values are in parts per thousand for bins of 0.5 m in wave height and 0.5 sec in wave period. In the figures and the tables to follow, values in a particular cell are those values which include the lower bound but do not include the upper bound of the cell. For example, in Fig. 5(a) 58.7 parts per thousand in the cell $0.5 \leq h_s < 1$ and $4 \leq T_z < 4.5$. Values of T_z range from 2 sec to 9.5 sec at Flamborough Head. The wave steepness line corresponding to $2\pi h_s/gT_z^2 = 1/15$ is drawn in the figures; the winter and spring seasons have the steepest waves.

4.6 Joint distribution of wave height and direction

Tables 4(a)-(e) give the joint probability of significant waveheight, h_s with mean wave direction, θ_1, at the spectral peak for all data and for each season. Values are in parts per thousand for bins of 0.5 m in wave height and 45° in wave direction centred about values of 0°, 45°, 90°, etc. Most observations, including those for high waves, come from directions between north and south-east, as would be expected for this location. Significantly more observations come from the south-east than from the east.

4.7 Joint distribution of wave period and wave direction

Tables 5(a)-(e) give the joint probability of peak wave period, T_p, with mean wave direction, θ_1 at T_p, for all data and for each season. Values are in parts per thousand with a bin size of 45^o for centred values of wave direction (see section above).

The wave period at the peak of the wave spectrum was obtained from the reciprocal of the peak frequency as determined from spectral analysis at a resolution of 0.01 Hz. At low frequencies the evenly spaced values of frequency become widely spaced values of period. It was therefore decided to group values of T_p as follows:-

Range of T_p	Bin size (sec)
1.5 - 8	0.5
8 - 13	1
13 - 15	2

The longer values of the peak period occur for wave directions from the north to north-east and for winter and autumn. The most commonly occurring values of T_p are in the range 4-9 sec.

4.8 Joint distribution of wave height, period and direction

Fig. 6 shows the joint probability of occurrence for all three parameters h_s, T_p and $\theta_1(T_p)$ for all data. The numbers inside each circle give the probability of occurrence in parts per ten-thousand for a given combination of $h_s$and T_p (in bins of 0.5 m and, as described above, for T_p). For all such observations a directional rose (with values at 45° intervals) gives the direction from which the waves are coming as percentage values. It is important to note the change in the period scale which occurs at 8 sec and 13 sec.

The longer wave periods clearly come from the north. The highest wave heights are for periods in the range 9-14 sec and from directions close to north.

4.9 Distribution of directional spread parameter

In some engineering studies it is important to have information on the directional spread parameter θ_2 as well as statistics of mean wave direction. Tables 6(a)-(c) give the joint probability of occurrence of wave height, wave period and wave direction all with directional spread for the whole data set. The most common values of $\theta_2(T_p)$ are in the range 20°-30° with a tendency for the narrower spreads to be associated with northerly and south-easterly wave directions and long wave periods. High wave heights are associated with narrow directional spread.

5. ACKNOWLEDGEMENTS

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APPENDIX A.1

Deployment history of Flamborough Head Wavecs

4th October 1984	Wavec serial no. 22009 deployed by mfv "Janet M". Position 54°13.7' N, 0°01.7' E. Depth 51 m. Direc receiver serial no. 23004 and associated equipment installed at bungalow near Flamborough Head. Receiver could not achieve frame sync.
10th October 1984	Mr Gerritzen of Datawell visited receiving site and diagnosed fault in buoy. One channel latched up at saturation limit, resulting in two frame sync words per frame.
16th October 1984	Wavec serial no. 22009 recovered.
29th October 1984	Wavec serial no.22009 transported to Datawell,Haarlem, for repair and recalibration.
6th December 1984	Wavec serial no. 22009 deployed.
7th March 1985	Wavec serial no. 22009 found adrift (suspect trawled).
17th March 1985	Wavec serial no. 22009 deployed.
21st March 1985	Wavec serial no. 22009 reported off station (suspect trawled).
28th March 1985	Wavec serial no. 22009 sighted adrift by Belgian trawler in Force 10 - could not pick it up
10th April 1985	Wavec serial no. 22012 deployed. Direc receiver serial no. 23009 installed in place of 23004, due to frequency change.
16th April 1985	Wavec serial no. 22009 recovered by mfv "Grimsby Gladness".
3rd June 1985	Receiving station HP85B locked up following suspected lightning strike.
6th June 1985	Receiving station restored to operational status.
24th June 1985	Wavec serial no. 22009 calibrated at Datawell, Haarlem.
w.e.18th August 1985	Intensive fishing reported in area.
16th October 9185	Wavec serial no. 22012 recovered. Buoy mooring safety line and mooring cross strop found to have been cut. Suspect fishing activities of w.e. 18th August.
22nd October 1985	Wavec serial no. 22009 deployed.
27th November 1985	Reception of signals apparently ceased.
5th December 1985	mfv "Janet M" confirmed buoy still on station.
10th December 1985	Antenna at receiving site found to have been vandalised. Temporary antenna rigged.
9th February 1986	Wavec serial no. 22009 reported 1 nm north of correct position.

14th February 1986	Wavec serial no. 22009 recovered by Whitby lifeboat near rocks at Whitby.
7th March 1986	Wavec serial no. 22012 deployed.
10th May 1986	Wavec serial no. 22009 reported missing.
2nd June 1986	Wavec serial no. 22009 recovered by fishing vessel off Lemvig, Denmark.
25th June 1986	Wavec serial no. 22009 calibrated at HR Ltd.

APPENDIX A.2

Method of analysis and definition of directional parameters

The cross-spectra obtained from the Wavec buoy system are measured with reference to magnetic coordinates using a fluxgate compass. These cross-spectra were first transformed to true North-East axes using a value of 5.3°(W) for the magnetic variation at the buoy location.

The transformed cross-spectra were banked on magnetic tape in the GF3 format recommended by the Intergovernmental Oceanographic Commission (1987). All analysed data in the report have been derived from this data base.

Information contained in the MIAS data base of directional spectra consists of the vertical acceleration and surface slopes referred to true North-East axes. If we denote the vertical acceleration (in units of "g") by the subscript 1 and the slopes in the North and East directions by subscripts 2 and 3 respectively, then it can be shown (Longuet-Higgins et al., 1963) that the six cross-spectra derived from a pitch-roll buoy system are given by

$$C_{11}(f) = \int_0^{2\pi} (2\pi f)^4/g^2 \; F(f,\theta)d\theta, \qquad Q_{12}(f) = \int_0^{2\pi} k(2\pi f)^2/g \cos\theta \; F(f,\theta)d\theta,$$

$$C_{22}(f) = \int_0^{2\pi} k^2 \cos^2\theta \; F(f,\theta)d\theta, \qquad Q_{13}(f) = \int_0^{2\pi} k(2\pi f)^2/g \cos\theta \; F(f,\theta)d\theta,$$

$$C_{33}(f) = \int_0^{2\pi} k^2 \sin^2\theta \; F(f,\theta)d\theta, \qquad C_{23}(f) = \int_0^{2\pi} k^2 \sin\theta \cos\theta \; F(f,\theta)d\theta,$$

where C_{ij} and Q_{ij} are the co- and quadrature spectra of series i with j. $F(f,\theta)$ is the directional wave spectrum with respect to frequency f and direction of propagation θ. k is the wave number. Only five of the cross-spectra are independent. This allows estimation of the five Fourier coefficients in the expansion of $F(f,\theta)$, namely,

$$a_n + ib_n = \frac{1}{\pi} \int_0^{2\pi} e^{in\theta} \; F(f,\theta)d\theta, \qquad n=0,1,2.$$

In the calculations it is convenient to compute the normalised angular harmonics $A_1 = a_1/a_0$ etc. where πa_0 is the one-dimensional spectrum obtained by integrating $F(f,\theta)$ over all directions. Thus

$$A_1 = \frac{Q_{12}}{\sqrt{C_{11}(C_{22} + C_{33})}}, \qquad B_1 = \frac{Q_{13}}{\sqrt{C_{11}(C_{22} + C_{33})}},$$

$$A_2 = \frac{C_{22} - C_{33}}{C_{22} + C_{33}} \qquad B_2 = \frac{2C_{23}}{C_{22} + C_{33}}$$

The angular harmonics A_n, B_n, and the check ratio (see below) are functions of wave frequency but, for convenience, we suppress this variation.

In the above we make use of the relation

$$C_{11}/(C_{22} + C_{33}) = (2\pi f)^4/g^2k^2 = \tanh^2 kh$$

which is, in effect, the dispersion relation for waves of small amplitude in water of depth h. The quantity $R = \frac{1}{\tanh kh}\left(\frac{C_{11}}{C_{22} + C_{33}}\right)^{1/2}$ provides a check on the functioning of the wave buoy system and on the analysis, since R should be unity (surface currents can influence the check ratio. For a discussion of this effect see Clayson and Ewing (1988), Appendix A.4 and Figure 7.

The mean wave direction, θ_1 and directional spread, θ_2 are obtained from the first-order angular harmonics, namely

$$\theta_1 = \arctan(B_1/A_1)$$

$$\theta_2 = [2/(s + 1)]^{1/2} \text{ where } s = C_1/(1 - C_1)$$

and $C_1^2 = A_1^2 + B_1^2$.

For a narrow directional distribution θ_2 is the r.m.s. spread about the mean wave direction.

TABLE 1

Uncertainties associated with sampling variability

Degrees of freedom = 36

Variable	Standard deviation
h_s	3%-5% of h_s
Tp, Tz	approx. 5% of Tp, Tz
θ_1(Tp)	3°-7°
θ_2(Tp)	3°-6°
R(Tp)	±0.07

TABLE 2

Flamborough Head WAVEC Buoy

Data return and mean and maximum h_s by month

Month	% data return		h_s (m)	
	hs	d.w.s.	mean	max.
Jan. 1985	68	68	1.85	4.12
Feb. 1985	49	49	0.74	4.15
Mar. 1985	21	21	0.80	1.89
Apr. 1985	41	41	1.61	4.05
May 1985	64	64	0.87	1.90
June 1985	75	75	0.90	2.98
July 1985	83	83	0.69	2.42
Aug. 1985	42	42	1.27	3.87
Sept. 1985	84	83	1.02	2.88
Oct. 1985	79	79	0.99	2.07
Nov. 1985	69	68	2.33	5.80
Dec. 1985	50	49	1.37	4.74
Jan. 1986	89	88	2.15	6.08
Feb. 1986	0	0	-	-
Mar. 1986	75	75	1.02	4.50
Apr. 1986	92	92	1.38	6.05
May 1986	14	14	0.75	1.42
All data	60	60		

TABLE 3
Flamborough Head WAVEC Buoy
Data return by season and year

Season	Number of records h_s	Number of records d.w.s.	% data return h_s	% data return d.w.s.
Winter (Dec-Feb)	965	954	50	50
Spring (Mar-May)	1258	1258	54	54
Summer (June-Aug)	979	976	67	67
Autumn (Sept-Nov)	1124	1117	77	77
All data	4326	4305	60	60

Table 4(a) : All Data
Wave height, h_s (m)

Wave direction, θ_1 (T_p): deg; central value	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	Totals
0	68.6	159.1	90.3	66.6	32.8	17.1	9.3	7.3	6.1	4.8	4.7	3.2	0.1	470.0
45	10.2	18.8	20.8	21.7	13.7	12.1	3.7	2.9	2.0	0.3	-	-	-	106.2
90	20.7	25.1	20.8	10.2	4.7	4.4	3.0	0.2	0.5	-	-	-	-	89.6
135	24.1	71.9	49.9	18.7	6.6	4.1	2.6	0.2	-	-	-	-	-	178.1
180	5.6	24.1	19.2	4.2	1.5	0.5	-	-	-	-	-	-	-	55.1
225	3.7	9.9	2.1	-	0.3	-	-	-	-	-	-	-	-	16.0
270	1.0	17.8	6.6	4.4	0.3	0.2	-	-	-	-	-	-	-	30.3
315	2.6	24.6	13.5	6.3	2.0	1.6	2.1	0.8	-	0.2	-	-	-	53.7
Totals	136.5	351.5	223.2	132.1	61.9	40.0	20.7	11.4	8.6	5.3	4.7	3.2	0.1	1000

Table 4(b) : Winter
Wave height, h_s (m)

Wave direction, θ_1 (T_p): deg; central value

	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	Totals
0	39.7	96.5	92.4	65.9	38.9	29.9	14.3	6.9	11.4	8.1	4.4	5.1	-	413.5
45	-	14.6	26.6	56.1	23.5	15.3	9.8	9.8	3.3	-	-	-	-	159.1
90	9.1	5.8	7.3	17.1	9.9	13.1	2.9	-	1.8	-	-	-	-	67.0
135	21.6	55.1	48.4	25.0	17.9	16.5	10.5	0.8	-	-	-	-	-	195.8
180	12.7	11.3	34.2	8.1	4.1	2.2	-	-	-	-	-	-	-	72.6
225	-	4.8	6.5	-	0.8	-	-	-	-	-	-	-	-	12.1
270	-	7.6	12.4	14.8	0.8	0.8	-	-	-	-	-	-	-	36.4
315	-	8.1	5.1	14.8	6.9	2.9	2.2	1.5	-	0.8	-	-	-	42.3
Totals	83.1	203.9	233.1	201.9	103.3	80.8	14.3	19.0	16.5	8.8	4.4	5.1	-	1000

Table 4(c) : Spring
Wave height, h_s (m)

Wave direction, θ_1 (T_p): deg; central value

	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	Totals
0	93.5	98.1	84.2	43.5	18.0	14.8	11.1	12.9	5.8	2.3	1.1	2.3	0.6	388.2
45	28.4	32.6	45.2	20.0	3.5	9.7	5.1	1.7	4.6	1.1	-	-	-	151.9
90	38.8	56.7	12.8	8.2	5.1	1.1	-	-	-	-	-	-	-	122.7
135	22.6	106.4	67.6	21.1	5.8	-	-	-	-	-	-	-	-	223.5
180	0.6	18.5	8.5	0.6	0.6	-	-	-	-	-	-	-	-	28.8
225	0.6	7.6	1.1	-	0.6	-	-	-	-	-	-	-	-	9.9
270	-	11.8	6.3	2.8	0.6	-	-	-	-	-	-	-	-	21.5
315	1.8	13.8	22.1	5.2	-	3.6	5.3	1.8	-	-	-	-	-	53.6
Totals	186.2	345.6	247.8	101.3	34.1	29.1	21.6	16.5	10.3	3.4	1.1	2.3	0.6	1000

Table 4(d) : Summer
Wave height, h_s (m)

Wave direction, θ_1 (T_p): deg; central value

	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	Totals
0	103.5	245.9	88.1	58.4	22.5	10.2	7.2	3.1	-	-	-	-	-	538.9
45	7.2	8.2	-	-	-	-	-	-	-	-	-	-	-	15.4
90	34.8	25.6	12.3	3.1	1.0	-	-	-	-	-	-	-	-	76.8
135	43.0	64.5	37.9	14.3	2.0	-	-	-	-	-	-	-	-	161.7
180	9.2	46.1	15.4	-	1.0	-	-	-	-	-	-	-	-	71.7
225	14.3	17.4	-	-	-	-	-	-	-	-	-	-	-	31.7
270	4.1	34.8	5.1	-	-	-	-	-	-	-	-	-	-	44.0
315	6.1	40.0	7.2	5.1	1.0	-	-	-	-	-	-	-	-	59.4
Totals	103.5	482.6	166.0	80.9	27.7	10.2	7.2	3.1	-	-	-	-	-	1000

Table 4(e) : Autumn
Wave height, h_s (m)

Wave direction, θ_1 (T_p): deg; central value

	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	Totals
0	37.6	196.1	96.7	98.5	51.9	13.4	4.5	6.3	7.2	9.0	13.4	5.4	-	540.0
45	5.4	19.7	11.6	10.7	27.8	23.3	-	-	-	-	-	-	-	98.5
90	-	12.5	51.0	12.5	2.7	3.6	9.0	0.9	-	-	-	-	-	92.2
135	9.0	61.8	45.7	14.3	0.9	-	-	-	-	-	-	-	-	131.7
180	-	20.6	18.8	8.1	-	-	-	-	-	-	-	-	-	47.5
225	-	9.8	0.9	-	-	-	-	-	-	-	-	-	-	10.7
270	-	17.0	2.7	-	-	-	-	-	-	-	-	-	-	19.7
315	2.7	36.7	19.7	-	-	-	0.9		-	-	-	-	-	60.0
Totals	54.6	374.2	247.1	144.1	83.3	40.3	14.3	7.2	7.2	9.0	13.4	5.4	-	1000

Table 5(a) : All data
Wave direction, θ_1 (T_p): deg; central value

Wave period, T_p (sec)	0	45	90	135	180	225	270	315	Totals
1.5-2.0	-	-	0.1	-	-	-	-	-	0.1
2.0-2.5	-	-	-	0.1	0.5	0.8	0.5	-	1.9
2.5-3.0	-	-	-	1.2	2.9	4.3	1.4	0.1	10.0
3.0-3.5	0.1	-	1.1	8.1	7.1	5.7	6.4	0.9	29.3
3.5-4.0	0.1	0.4	1.8	14.8	8.6	4.0	11.1	6.3	47.2
4.0-4.5	2.5	1.5	9.7	27.6	11.1	0.8	7.2	8.7	69.1
4.5-5.0	5.1	1.9	8.2	25.4	10.7	-	2.0	10.8	64.1
5.0-5.5	12.2	5.5	15.7	32.7	9.7	0.5	1.5	9.1	86.9
5.5-6.0	14.5	6.6	6.2	18.5	1.8	-	0.2	3.7	51.6
6.0-6.5	30.3	17.3	19.8	26.4	2.3	-	-	6.4	102.5
6.5-7.0	25.8	9.5	10.5	10.1	0.5	-	-	2.9	59.3
7.0-7.5	35.4	16.9	6.5	5.7	-	-	-	2.0	66.7
7.5-8.0	42.2	23.7	4.9	6.5	-	-	-	1.8	79.1
8 - 9	75.8	15.2	3.5	0.9	-	-	-	0.6	96.1
9 - 10	80.0	5.9	1.5	-	-	-	-	0.4	87.9
10 - 11	71.8	1.7	-	-	-	-	-	-	73.5
11 - 12	45.4	-	-	-	-	0.1	-	-	45.5
12 - 13	21.9	-	-	-	-	-	-	-	21.9
13 - 15	7.1	-	-	-	-	-	-	-	7.1
Totals	470.2	106.1	89.5	178.0	55.2	16.2	30.3	53.7	1000

Table 5(b) : Winter
Wave direction, θ_1 (T_p): deg; central value

Wave period, T_p (sec)	0	45	90	135	180	225	270	315	Totals
1.5-2.0	-	-	-	-	-	-	-	-	-
2.0-2.5	-	-	-	-	-	-	-	-	-
2.5-3.0	-	-	-	1.8	2.6	-	-	-	4.3
3.0-3.5	-	-	-	12.7	13.8	3.7	3.3	-	33.3
3.5-4.0	-	-	-	3.6	6.9	5.1	8.3	-	23.9
4.0-4.5	-	1.8	-	14.2	8.4	2.6	14.3	0.8	42.1
4.5-5.0	-	1.8	0.8	9.8	15.1	-	5.9	0.8	34.1
5.0-5.5	13.0	-	11.6	33.6	14.3	0.8	3.7	10.3	87.4
5.5-6.0	6.1	4.3	5.8	21.9	2.9	-	0.8	5.1	47.2
6.0-6.5	9.5	10.6	4.3	35.6	6.6	-	-	6.9	73.6
6.5-7.0	12.8	14.8	9.8	21.6	2.2	-	-	8.8	70.1
7.0-7.5	15.3	27.2	8.4	13.9	-	-	-	3.7	68.7
7.5-8.0	24.4	48.8	17.9	24.1	-	-	-	3.7	119.1
8 - 9	46.3	31.9	7.6	2.9	-	-	-	0.8	46.3
9 - 10	67.2	11.6	0.8	-	-	-	-	1.5	81.0
10 - 11	111.5	6.1	-	-	-	-	-	-	117.7
11 - 12	80.3	-	-	-	-	-	-	-	80.3
12 - 13	20.0	-	-	-	-	-	-	-	20.0
13 - 15	7.2	-	-	-	-	-	-	-	7.2
Totals	413.6	158.9	67.0	195.7	72.8	12.2	36.3	42.4	1000

Table 5(c) : Spring
Wave direction, θ_1 (T_p): deg; central value

Wave period, T_p (sec)	0	45	90	135	180	225	270	315	Totals
1.5-2.0	-	-	0.6	-	-	-	-	-	0.6
2.0-2.5	-	-	-	0.6	-	-	-	-	0.6
2.5-3.0	-	-	-	-	1.1	1.8	-	0.6	3.5
3.0-3.5	0.6	-	3.5	13.8	4.6	5.3	3.6	0.6	31.9
3.5-4.0	0.6	0.6	6.4	28.9	7.6	0.6	8.6	2.9	56.1
4.0-4.5	4.0	2.4	20.5	46.6	5.8	0.6	4.6	6.4	90.8
4.5-5.0	5.2	1.7	17.7	40.9	5.7	-	2.3	11.0	84.5
5.0-5.5	13.5	9.9	25.1	34.5	2.8	1.1	2.3	11.0	100.4
5.5-6.0	18.1	12.9	9.3	20.3	0.6	-	-	4.1	65.3
6.0-6.5	48.1	36.0	22.8	32.1	0.6	-	-	6.4	145.9
6.5-7.0	36.0	18.6	11.5	2.3	-	-	-	1.8	70.3
7.0-7.5	26.5	21.4	5.2	1.1	-	-	-	3.6	57.8
7.5-8.0	26.7	23.4	-	1.8	-	-	-	3.6	55.4
8 - 9	47.9	13.8	-	0.6	-	-	-	1.8	64.2
9 - 10	41.6	10.3	-	-	-	-	-	-	52.1
10 - 11	52.2	0.6	-	-	-	-	-	-	52.8
11 - 12	51.0	-	-	-	-	0.6	-	-	51.6
12 - 13	15.6	-	-	-	-	-	-	-	15.6
13 - 15	0.6	-	-	-	-	-	-	-	0.6
Totals	388.2	151.6	122.6	223.5	28.8	10.0	21.4	53.8	1000

Table 5(d) : Summer
Wave direction, θ_1 (T_p): deg; central value

Wave period, T_p (sec)	0	45	90	135	180	225	270	315	Totals
1.5-2.0	-	-	-	-	-	-	-	-	-
2.0-2.5	-	-	-	-	2.0	3.1	2.0	-	7.2
2.5-3.0	-	-	-	3.1	6.1	15.4	3.1	-	27.7
3.0-3.5	-	-	1.0	4.1	7.2	9.2	12.3	3.1	36.9
3.5-4.0	-	1.0	1.0	12.3	15.4	4.1	19.5	13.3	66.6
4.0-4.5	6.1	1.0	17.4	31.8	19.5	-	7.2	13.3	96.3
4.5-5.0	13.3	3.1	13.3	27.7	12.3	-	-	15.4	85.0
5.0-5.5	20.5	5.1	21.5	35.9	8.2	-	-	6.1	97.3
5.5-6.0	24.6	1.0	7.2	12.3	-	-	-	2.0	47.1
6.0-6.5	42.0	1.0	15.4	18.4	1.0	-	-	6.1	84.0
6.5-7.0	32.8	-	-	11.3	-	-	-	-	44.1
7.0-7.5	74.8	2.0	-	5.1	-	-	-	-	82.0
7.5-8.0	80.9	1.0	-	-	-	-	-	-	82.0
8 - 9	109.6	-	-	-	-	-	-	-	109.6
9 - 10	92.2	-	-	-	-	-	-	-	92.2
10 - 11	41.0	-	-	-	-	-	-	-	41.0
11 - 12	1.0	-	-	-	-	-	-	-	1.0
12 - 13	-	-	-	-	-	-	-	-	-
13 - 15	-	-	-	-	-	-	-	-	-
Totals	538.8	15.2	76.8	162.0	71.7	31.8	44.1	59.3	1000

Table 5(e) : Autumn
Wave direction, θ_1 (T_p): deg; central value

Wave period, T_p (sec)	0	45	90	135	180	225	270	315	Totals
1.5-2.0	-	-	-	-	-	-	-	-	-
2.0-2.5	-	-	-	-	-	-	-	-	-
2.5-3.0	-	-	-	-	1.8	-	2.7	-	4.5
3.0-3.5	-	-	-	1.8	2.7	4.5	6.3	-	15.2
3.5-4.0	-	-	-	14.3	4.5	6.3	8.1	9.0	42.1
4.0-4.5	-	0.9	0.9	17.9	10.7	-	2.7	14.3	47.4
4.5-5.0	1.8	0.9	0.9	23.3	9.8	-	-	16.1	52.8
5.0-5.5	1.8	7.2	4.5	26.9	13.4	-	-	9.0	62.7
5.5-6.0	9.0	8.1	2.7	19.7	3.6	-	-	3.6	46.6
6.0-6.5	21.5	21.5	36.7	19.7	0.9	-	-	6.3	106.5
6.5-7.0	21.5	4.5	20.6	5.4	-	-	-	0.9	52.8
7.0-7.5	25.1	17.0	12.5	2.7	-	-	-	0.9	58.2
7.5-8.0	36.7	21.5	1.8	-	-	-	-	-	60.0
8 - 9	99.4	15.2	6.3	-	-	-	-	-	120.9
9 - 10	119.1	1.8	5.4	-	-	-	-	-	126.2
10 - 11	82.4	-	-	-	-	-	-	-	82.4
11 - 12	49.2	-	-	-	-	-	-	-	49.2
12 - 13	51.9	-	-	-	-	-	-	-	51.9
13 - 15	20.6	-	-	-	-	-	-	-	20.6
Totals	540.0	98.6	92.3	131.7	47.4	10.8	19.8	60.1	1000

Table 6(a)
Spread parameter, θ_2 (T_p): deg

Wave height, h_s (m)	10-20	20-30	30-40	40-50	50-60	60-70	70-80	Totals
0 - 0.5	18.1	55.7	37.9	13.2	3.9	1.2	-	130.0
0.5-1.0	81.1	167.7	74.1	19.5	8.6	3.5	0.2	354.7
1.0-1.5	68.8	116.6	30.4	10.2	2.8	0.7	-	229.5
1.5-2.0	44.1	65.0	16.5	3.0	0.7	-	-	129.3
2.0-2.5	21.6	33.0	6.3	0.2	-	-	-	61.1
2.5-3.0	8.8	25.6	4.2	-	-	-	-	38.6
3.0-3.5	6.5	13.0	1.4	-	-	-	-	20.9
3.5-4.0	4.4	4.9	1.2	-	-	-	-	10.5
4.0-4.5	4.4	4.6	0.2	-	-	-	-	9.2
4.5-5.0	3.5	3.0	-	-	-	-	-	6.5
5.0-5.5	3.0	2.3	-	-	-	-	-	5.3
5.5-6.0	2.3	1.4	0.2	-	-	-	-	3.9
6.0-6.5	0.2	-	-	-	-	-	-	0.2
Totals	266.9	492.9	172.4	46.2	16.0	5.3	0.2	1000

Table 6(b)
Spread parameter, θ_2 (T_p): deg

Wave period, T_p (sec)	10-20	20-30	30-40	40-50	50-60	60-70	70-80	Totals
1.5-2.0	-	-	0.2	-	-	-	-	0.2
2.0-2.5	-	0.7	0.9	0.2	-	-	-	1.8
2.5-3.0	-	3.0	4.4	1.6	-	-	-	9.0
3.0-3.5	0.5	11.1	10.0	4.2	1.2	0.2	-	27.2
3.5-4.0	1.2	23.0	18.1	4.4	1.6	0.7	-	49.0
4.0-4.5	8.6	33.2	20.9	7.4	1.9	1.4	0.2	73.6
4.5-5.0	9.8	35.8	14.9	3.9	2.6	0.9	-	67.9
5.0-5.5	14.6	47.4	21.6	6.7	2.1	0.7	-	93.1
5.5-6.0	9.1	26.7	9.1	4.9	1.4	0.5	-	51.7
6.0-6.5	20.9	52.0	21.8	5.6	3.9	0.2	-	104.4
6.5-7.0	16.0	33.0	9.5	0.9	0.7	0.5	-	60.6
7.0-7.5	20.0	39.3	7.2	0.9	0.5	-	-	67.9
7.5-8.0	21.8	44.4	7.0	1.6	0.2	-	-	75.0
8 - 9	39.0	46.5	6.5	0.9	-	-	-	92.9
9 - 10	46.7	35.5	4.6	0.2	-	-	-	87.0
10 - 11	30.9	29.7	6.0	0.7	-	-	-	67.3
11 - 12	19.7	18.1	3.7	0.5	-	-	-	42.0
12 - 13	7.2	10.0	3.7	1.4	-	-	-	22.3
13 - 15	0.9	3.5	2.1	-	-	-	-	6.5
Totals	266.9	492.9	172.4	46.2	16.0	5.3	0.2	1000

Table 6(c)
Spread parameter, θ_2 (T_p): deg

Wave direction, $\theta_1(T_p)$: deg; central value	10-20	20-30	30-40	40-50	50-60	60-70	70-80	Totals
0	179.6	214.2	51.3	8.6	2.3	0.5	-	456.5
45	5.3	56.4	27.2	8.8	2.1	1.2	-	101.0
90	7.0	55.5	24.4	6.7	3.7	0.9	-	98.2
135	46.0	101.5	30.0	5.3	1.2	-	-	184.0
180	15.8	30.9	5.8	3.3	0.7	0.9	-	57.4
225	-	1.6	8.4	3.3	0.9	0.9	0.2	15.3
270	-	9.3	15.6	4.6	1.9	0.2	-	31.6
315	13.2	23.5	9.8	5.6	3.3	0.7	-	56.1
Totals	266.9	492.9	172.4	46.2	16.0	5.3	0.2	1000

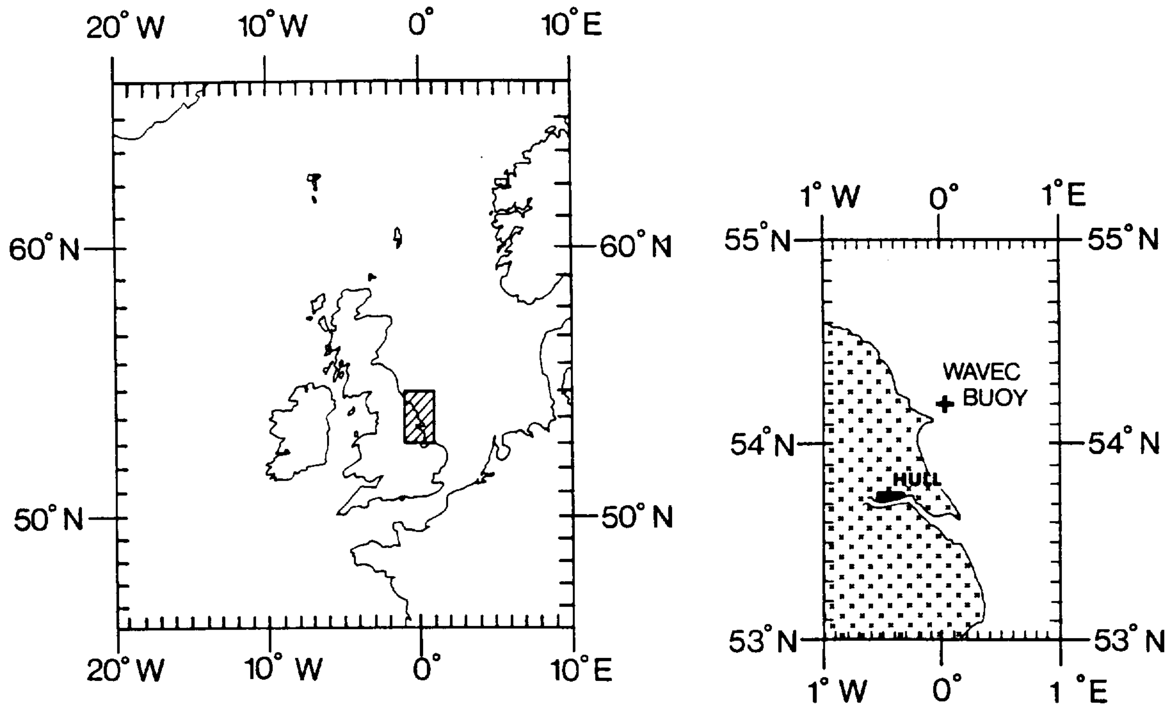


Fig. 1: Location of WAVEC directional wave buoy off Flamborough Head

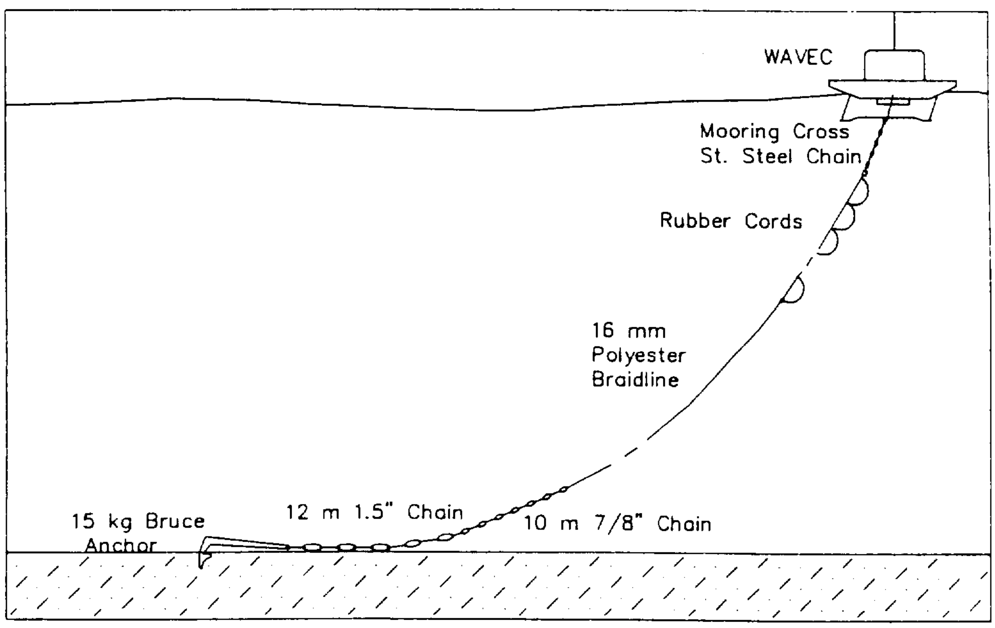


Fig. 2: Schematic of WAVEC mooring (not to scale)

Fig. 3(a)

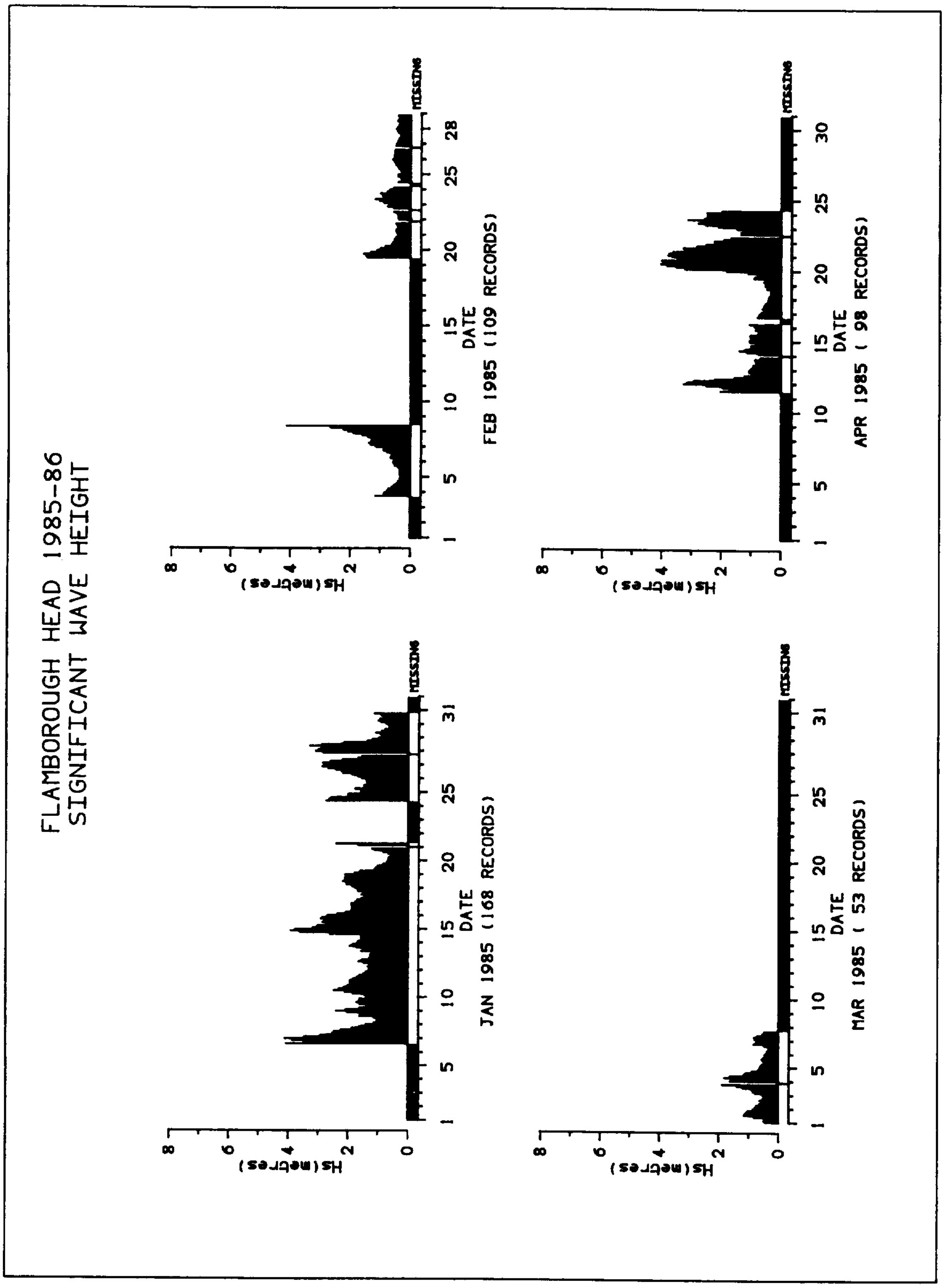

FLAMBOROUGH HEAD 1985-86
SIGNIFICANT WAVE HEIGHT
Hs(metres)
DATE
MISSING
JAN 1985 (168 RECORDS)
FEB 1985 (109 RECORDS)
MAR 1985 (53 RECORDS)
APR 1985 (98 RECORDS)

Fig. 3(b)

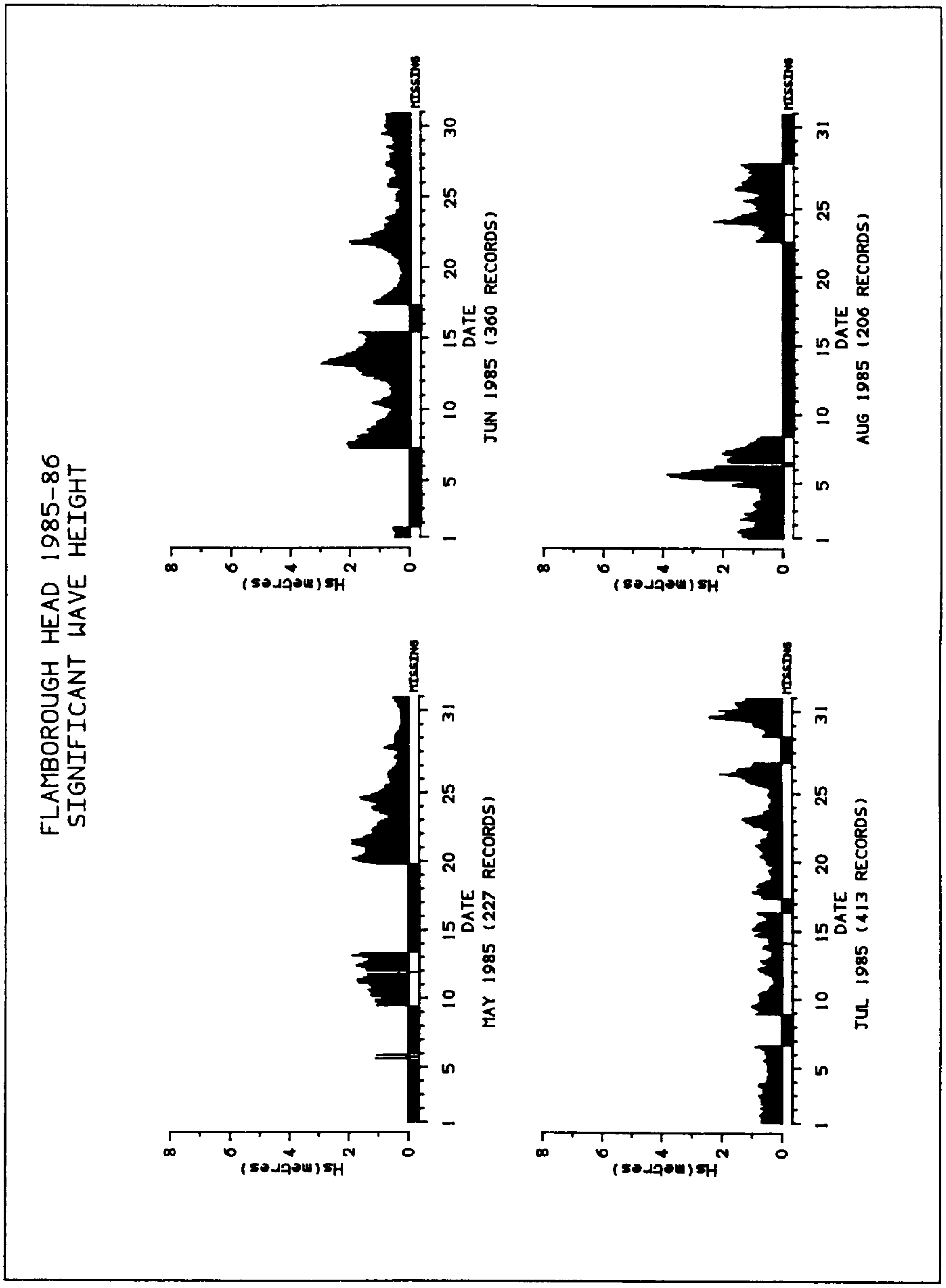

FLAMBOROUGH HEAD 1985-86
SIGNIFICANT WAVE HEIGHT
Hs(metres)
DATE
MISSING
MAY 1985 (227 RECORDS)
JUN 1985 (360 RECORDS)
JUL 1985 (413 RECORDS)
AUG 1985 (206 RECORDS)

Fig. 3(c)

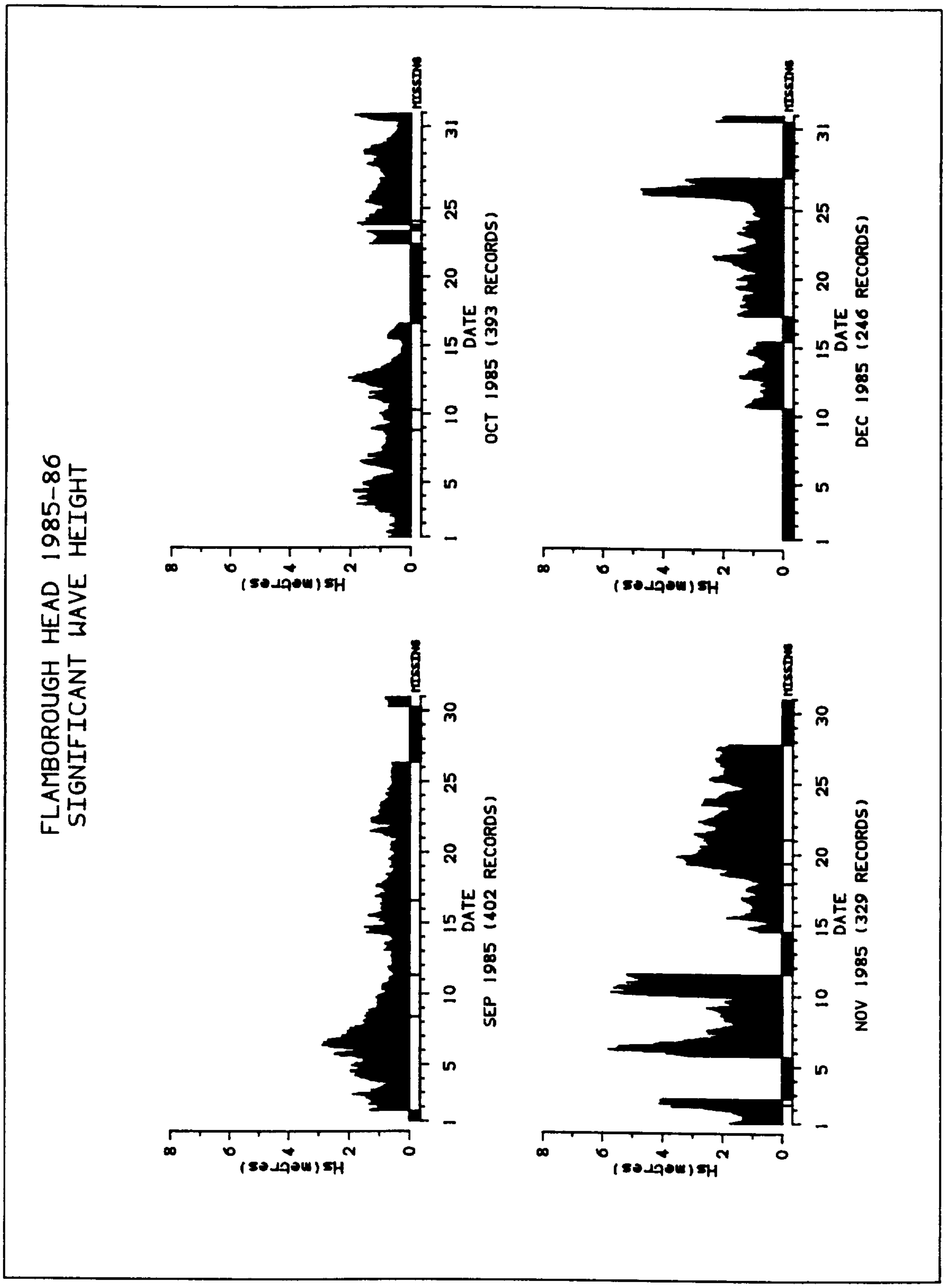

FLAMBOROUGH HEAD 1985-86
SIGNIFICANT WAVE HEIGHT
Hs(metres)
DATE
SEP 1985 (402 RECORDS)
OCT 1985 (393 RECORDS)
NOV 1985 (329 RECORDS)
DEC 1985 (246 RECORDS)
MISSING

Fig. 3(d)

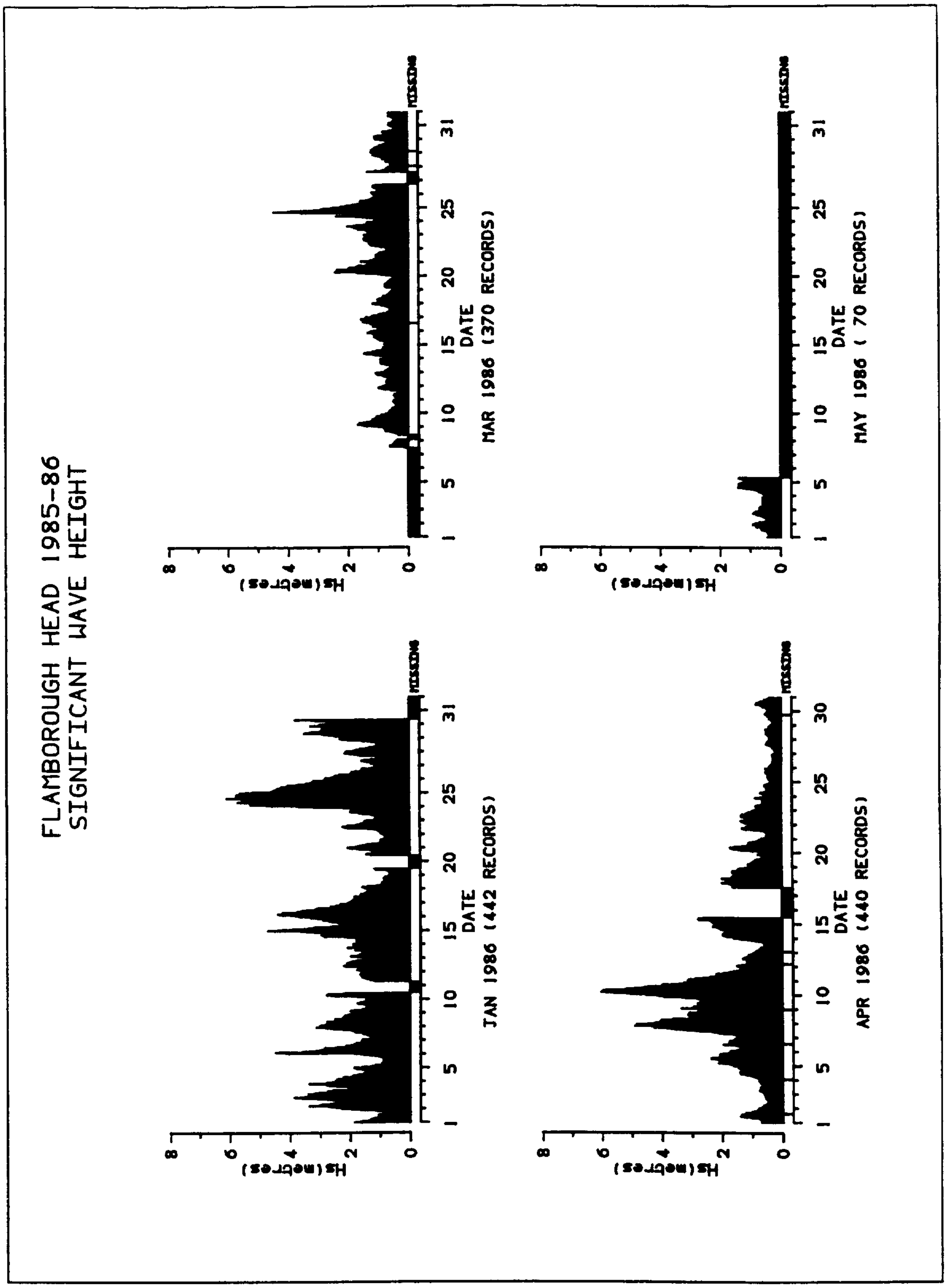
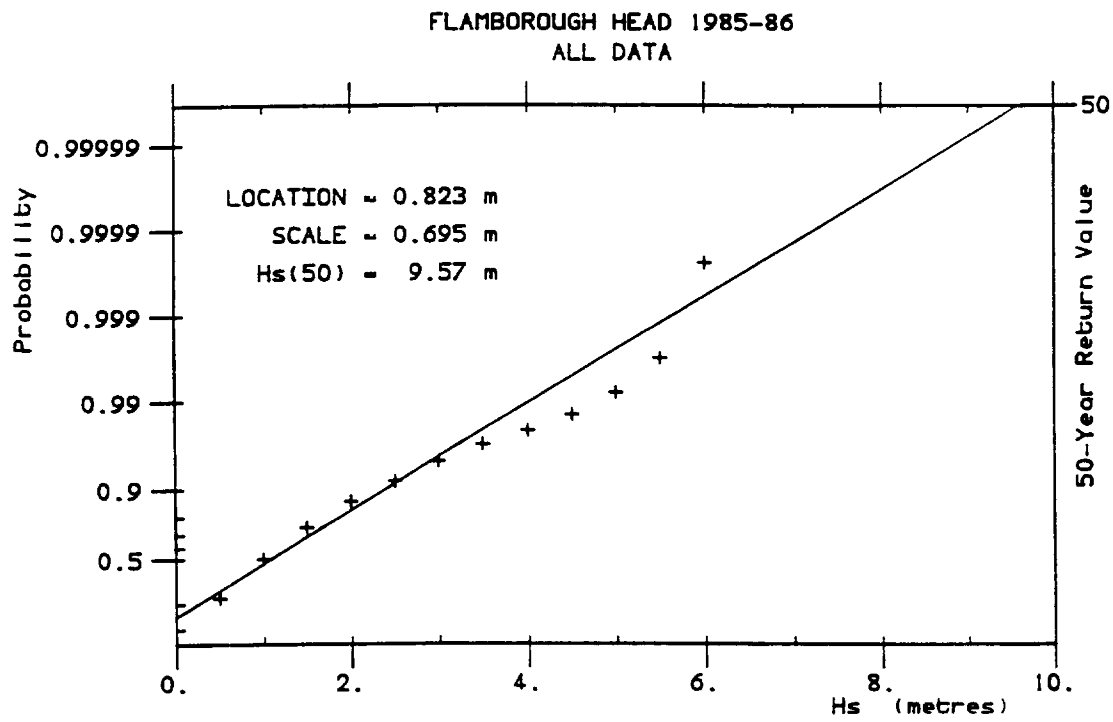

FLAMBOROUGH HEAD 1985-86
SIGNIFICANT WAVE HEIGHT
Hs(metres)
DATE
JAN 1986 (442 RECORDS)
MAR 1986 (370 RECORDS)
APR 1986 (440 RECORDS)
MAY 1986 (70 RECORDS)
MISSING

Fig. 4



CUMULATIVE HS PROBABILITY on FT-1 SCALE

Fig. 5(a)

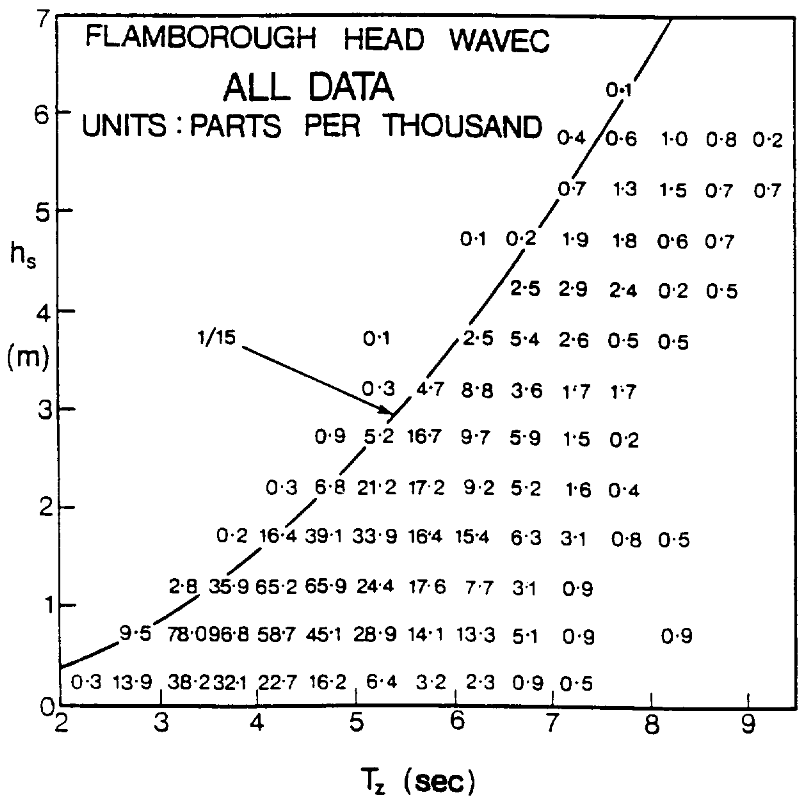


Fig. 5(b)

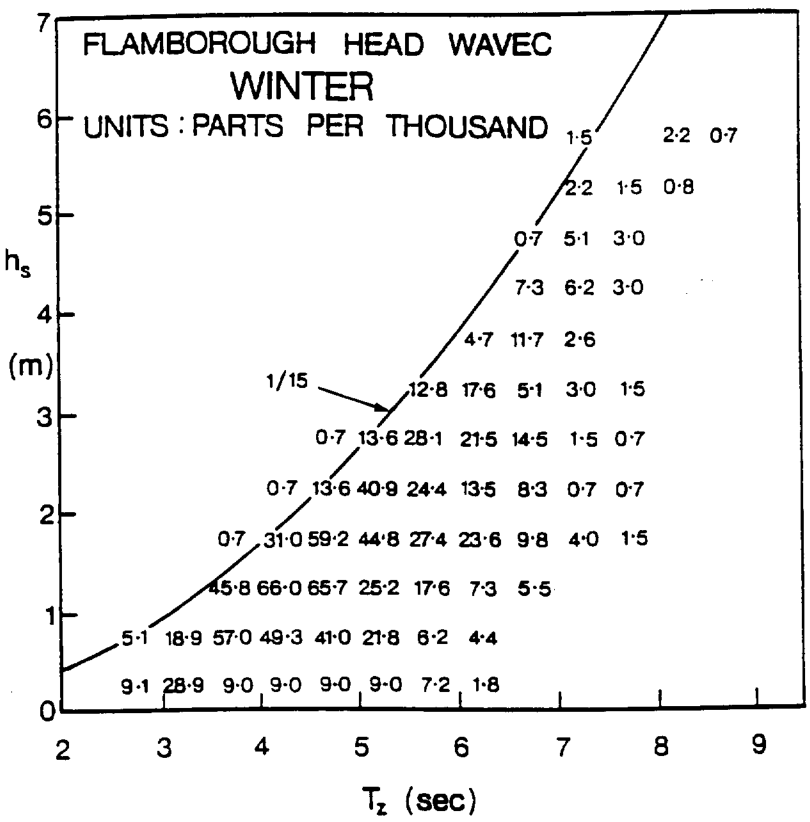

FLAMBOROUGH HEAD WAVEC
WINTER
UNITS : PARTS PER THOUSAND
1/15
h_s (m)
T_z (sec)

Fig. 5(c)

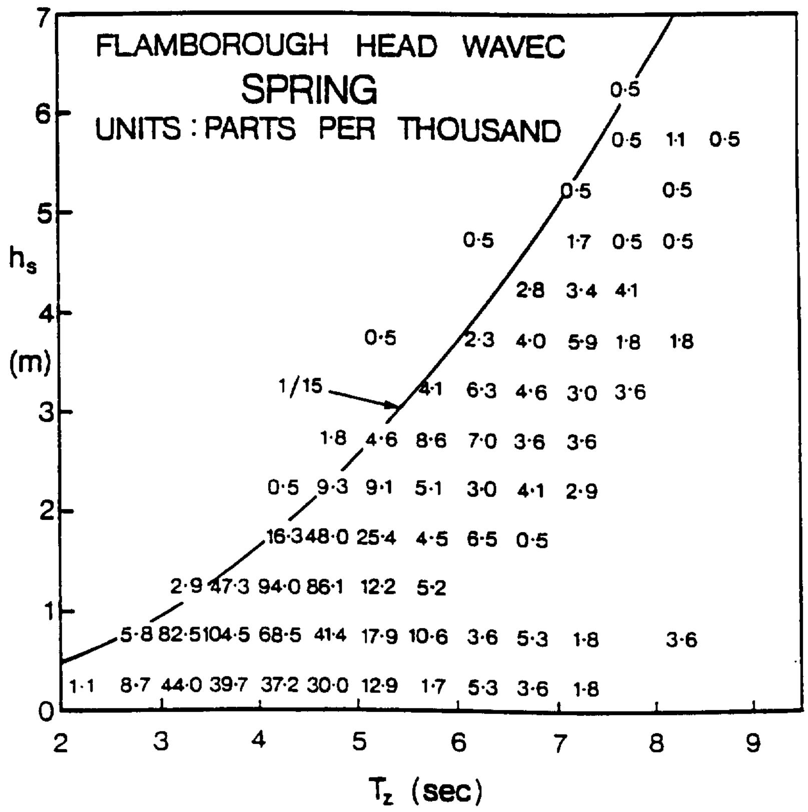

FLAMBOROUGH HEAD WAVEC
SPRING
UNITS : PARTS PER THOUSAND
1/15
h_s (m)
T_z (sec)

Fig. 5(d)

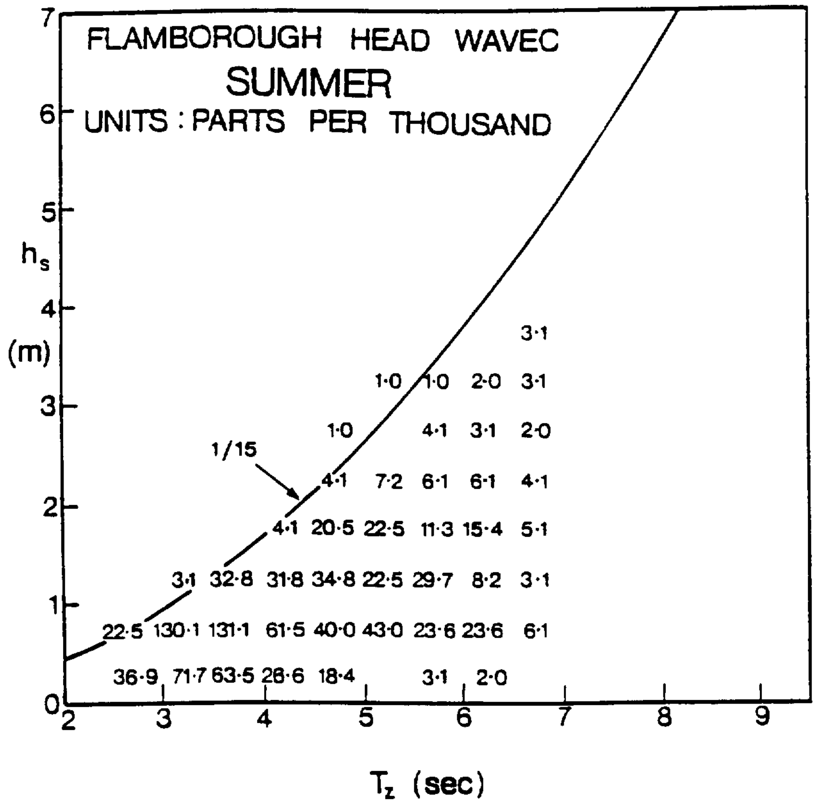

FLAMBOROUGH HEAD WAVEC
SUMMER
UNITS : PARTS PER THOUSAND
1/15
3·1
1·0 1·0 2·0 3·1
1·0 4·1 3·1 2·0
4·1 7·2 6·1 6·1 4·1
4·1 20·5 22·5 11·3 15·4 5·1
3·1 32·8 31·8 34·8 22·5 29·7 8·2 3·1
22·5 130·1 131·1 61·5 40·0 43·0 23·6 23·6 6·1
36·9 71·7 63·5 28·6 18·4 3·1 2·0
h_s
(m)
T_z (sec)

Fig. 5(e)

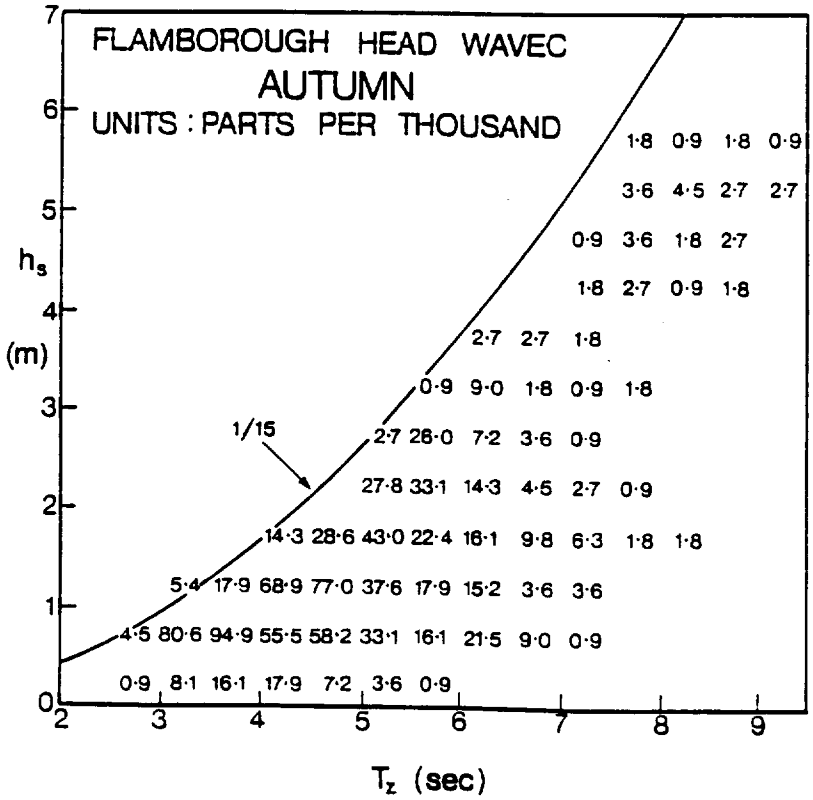
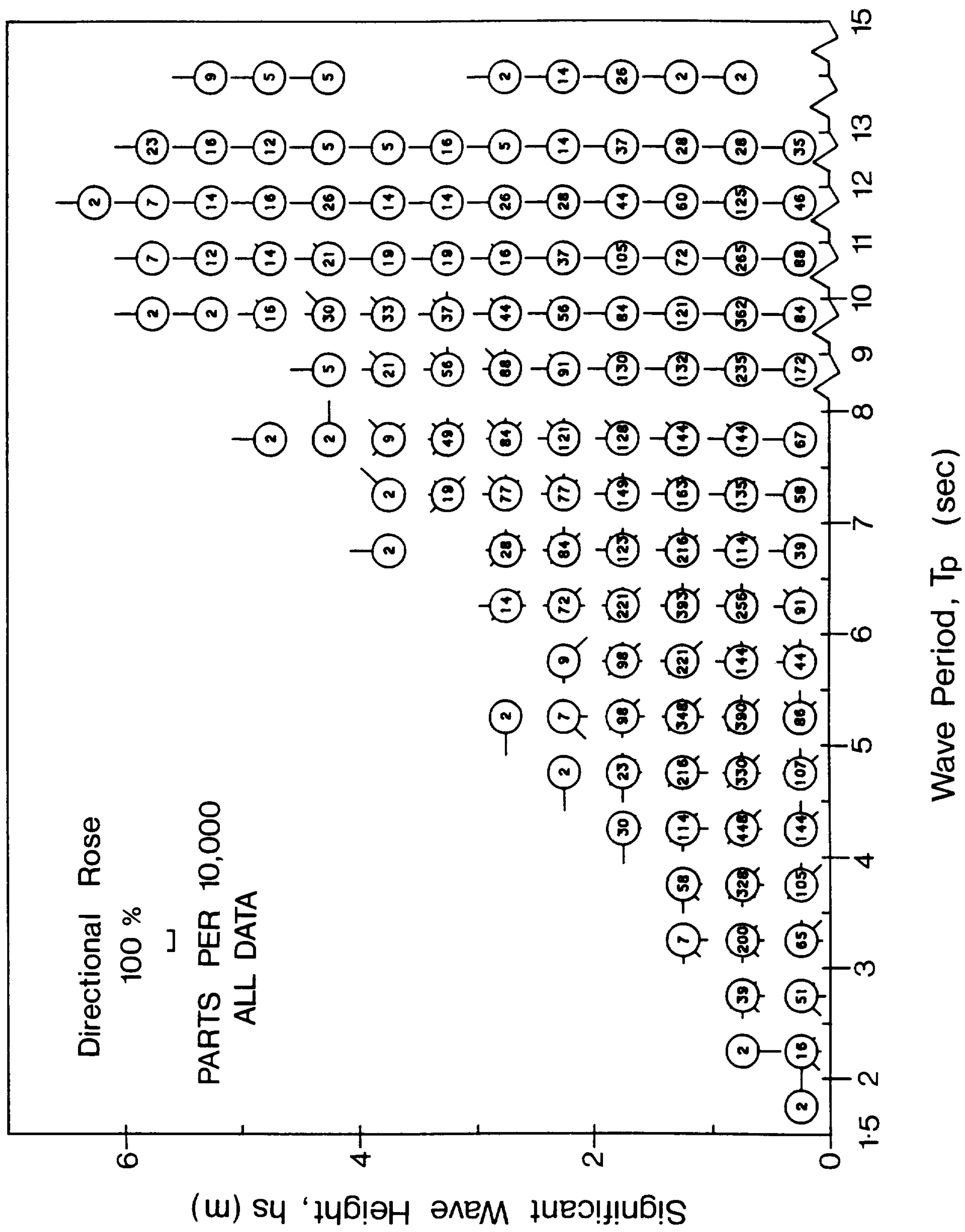

FLAMBOROUGH HEAD WAVEC
AUTUMN
UNITS : PARTS PER THOUSAND
1/15
1·8 0·9 1·8 0·9
3·6 4·5 2·7 2·7
0·9 3·6 1·8 2·7
1·8 2·7 0·9 1·8
2·7 2·7 1·8
0·9 9·0 1·8 0·9 1·8
2·7 28·0 7·2 3·6 0·9
27·8 33·1 14·3 4·5 2·7 0·9
14·3 28·6 43·0 22·4 16·1 9·8 6·3 1·8 1·8
5·4 17·9 68·9 77·0 37·6 17·9 15·2 3·6 3·6
4·5 80·6 94·9 55·5 58·2 33·1 16·1 21·5 9·0 0·9
0·9 8·1 16·1 17·9 7·2 3·6 0·9
h_s
(m)
T_z (sec)

Fig. 6


Directional Rose
100 %
PARTS PER 10,000
ALL DATA
Significant Wave Height, hs (m)
Wave Period, Tp (sec)