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OBSERVATIONS OF WIND WAVES ON A RESERVOIR

BY

K.G. BIRCH AND J.A. EWING

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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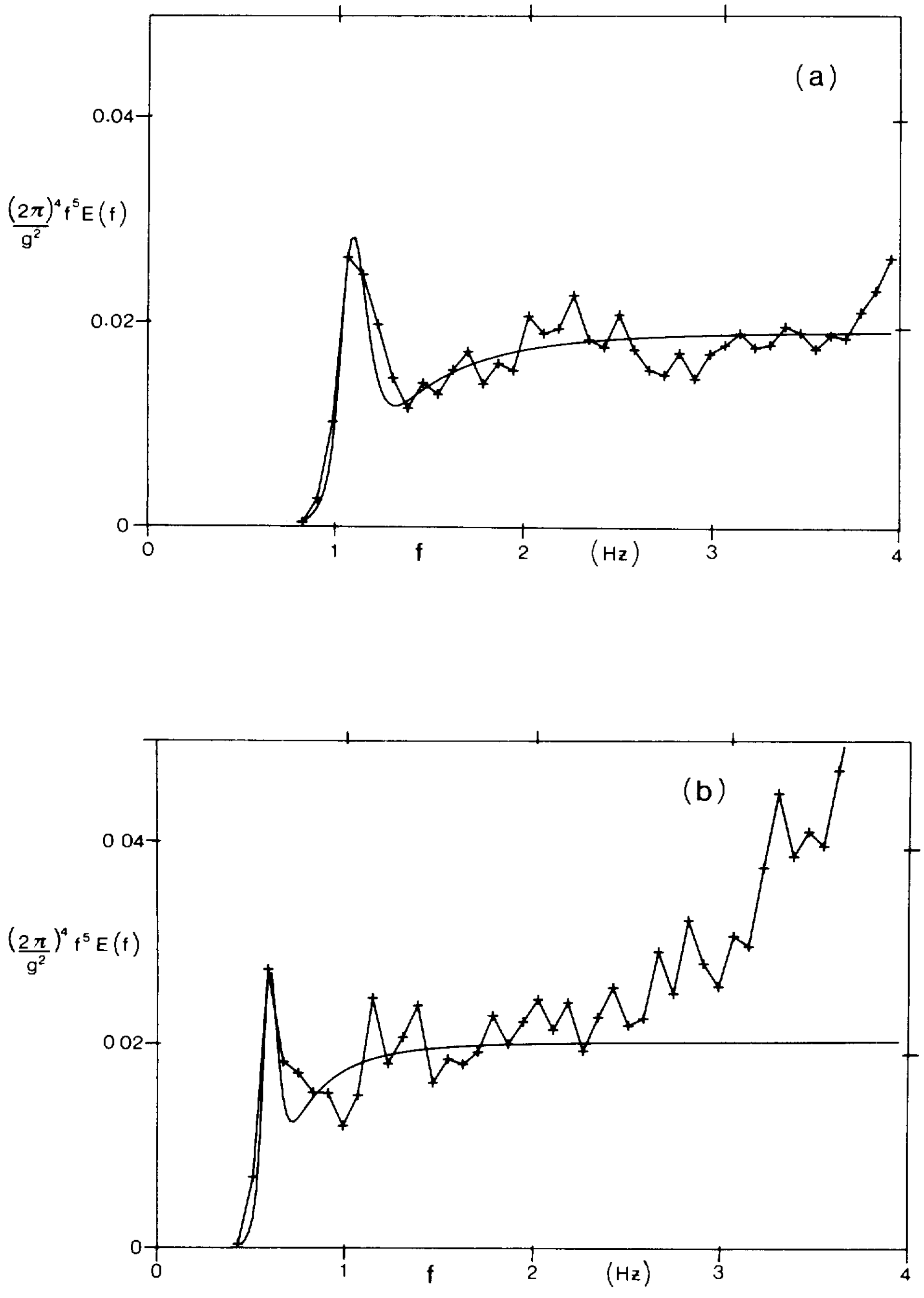
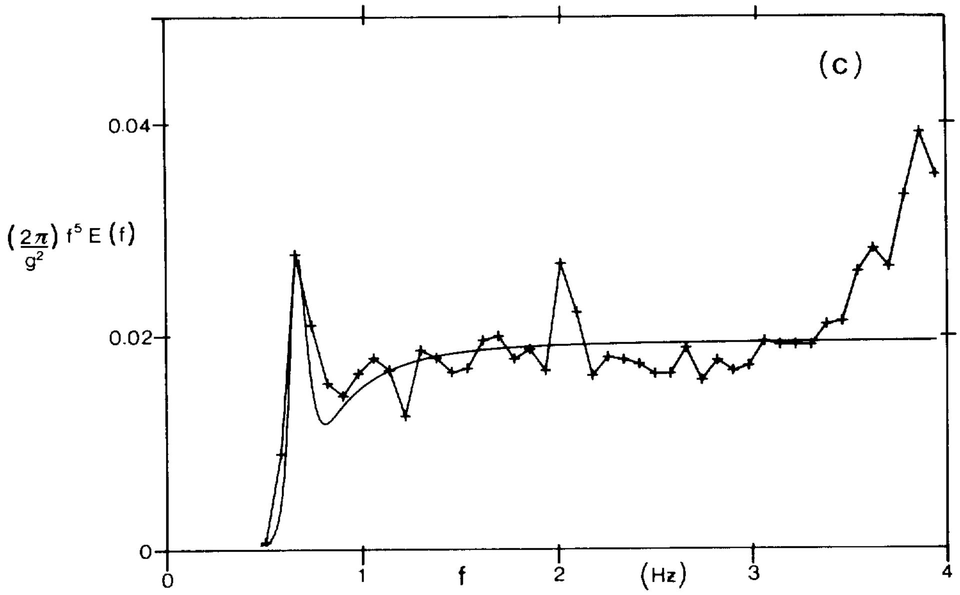


Fig. 8a, b Averaged spectrum prewhitened by f^5.
(a): section 4 of record 5
(b): section 4 of record 20
The continuous curve is the JONSWAP spectrum.



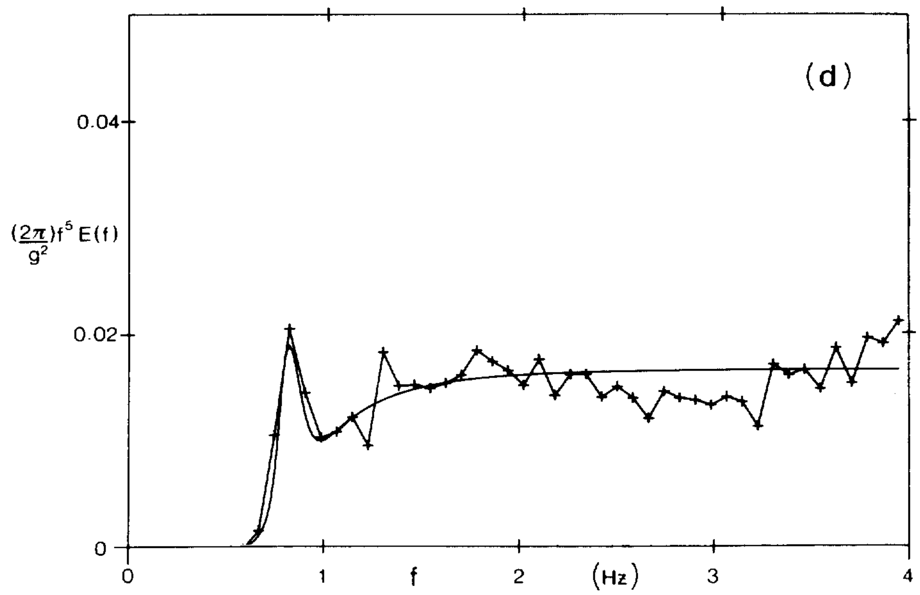


Fig. 8c, d As for Figure 8a, b
(c): section 2 of record 23
(d): section 9 of record 45

INSTITUTE OF OCEANOGRAPHIC SCIENCES

WORMLEY

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SUMMARY

Measurements of wind waves on a reservoir, where the longest fetch is about 1km, have been made using an array of wave staffs and an electromagnetic current meter.

The results show that the scaling laws of Kitaigorodskii (1962) are obeyed on this scale. In particular, the variation of non-dimensional wave energy and non-dimensional peak frequency are functions of non-dimensional fetch in agreement with expressions derived during the Joint North Sea Wave Project (JONSWAP).

The one-dimensional frequency spectra are close to the JONSWAP form with a high frequency tail varying as frequency to the power -5 in accordance with Phillips' (1958) hypothesis. There appears to be a limited region above the spectral peak where a wind speed dependent and a frequency to the power -4 spectral behaviour is observed.

Wave directional spectra obtained from an array of wave staffs and an electromagnetic current meter indicate a narrower angular distribution than measured under fetch limited conditions in the ocean.

1. INTRODUCTION

Most studies of wind generated waves have been carried out under oceanic conditions where the fetch varies from about 20km to 200km and where the presence of swell is a complicating factor. The characteristic features of wave spectra at these intermediate fetches were first discussed in the Joint North Sea Wave Project (Hasselmann et al., 1973). The JONSWAP study showed that the spectrum of fetch-limited waves was more sharply peaked than the Pierson-Moskowitz spectrum. The high frequency tail of the spectrum was found to vary as frequency to the power -5 but with a Phillips (1958) 'constant' dependent on non-dimensional fetch. More recent studies of fetch-limited waves, notably those of Forristall (1981), Kahma (1981) and Donelan et al., (1985), have identified a region above the spectral peak where the energy density E depends on wind speed U and wave frequency f, namely

$$E(f) \sim Uf^{-4}$$

A spectrum of this form was first proposed by Toba (1973) based on wind tunnel data and dimensional arguments. Theoretical evidence for an equilibrium range which is wind speed dependent has recently been given by Kitaigorodskii (1983) and Phillips (1985).

Measurements of wind waves on a reservoir have some advantages over ocean wave measurements. These comprise the absence of swell, a well-defined fetch, a fixed frame of reference for wave and current sensors and, lastly, a facility which is readily accessible and convenient to use.

The purpose of this work is to study the similarity laws of Kitaigorodskii (1962) at fetches intermediate between those of the laboratory and those in the ocean, to investigate the form of the high frequency end of the spectrum and to study wave directional properties at short fetches.

2. EXPERIMENTAL ARRANGEMENT

The site of the experiments was the Queen Elizabeth II Storage Reservoir at Hersham, Surrey. A plan view of the reservoir is shown in Figure 1. The measurements were made from a tower located in the south-east corner of the reservoir. The longest fetch from the tower is 1035m towards the north-east; the shortest fetch of 240m is towards the south-east. The water depth of approximately 20m implies that wind-generated waves are in 'deep-water'. The reservoir has sloping sides, inclined at about 18 degrees to the horizontal, so that reflection at the boundaries is probably small (Moraes, 1970). The reflected waves would be further reduced by an adverse wind.

The tower (see Figure 2) carries a small laboratory with mains power. It is supported by four legs of small cross-sectional area and has four platforms or catwalks which extend up to 9m away from the centre of the tower. The instruments were deployed on a boom beneath the platform which points towards the north-west. This allows for measurements to be made of wave direction for the longest fetches by winds from the north-west to the north-east. All the instruments for measuring waves and currents are mounted on a boom below the platform. Seasonal variations in the water level (± 1m) are taken out by adjusting the level of the boom relative to the platform with a winch.

(a) Wind measurements

Wind speed and direction were measured at 10m height above the mean water level using a cup anemometer and vane attached to a mast above the laboratory. The anemometer was calibrated in the small wind-wave flume at the National Maritime Institute (now British Maritime Technology) in Teddington. The calibration was linear over the working range up to 20 m/s. A hand-held anemometer was used for some records when a failure occurred in the data logging of the cup anemometer.

(b) Wave measurements

The wave elevation measurements were made using a PTFE covered wire of 1.4mm diameter. The varying water level produces a change in the capacity of the coated wire which was found to be linear over the calibrated range of ± 35 cms.

The effect of a meniscus on a wave staff is to distort the profile near the crests and troughs. Liu and Lin (1982) have carried out comparisons between a non-intrusive laser displacement gauge and a 1.6mm resistance wave staff. Comparisons of wave spectra from the two systems indicated that above about 6 Hz the response of the resistance staff deviates and lies below the laser displacement gauge. Further tests made by Liu et al., (1982) with 0.13mm and 0.4mm diameter wires gave slightly better results. We therefore consider our measurements with 1.4mm diameter wires to be valid up to 5 Hz.

Six wave staffs were aligned in a linear array of total length 3m along the boom (Figure 3). The spacing of the wave staffs was chosen to derive information on wave direction following the method proposed by Barber (1963).

(c) Electromagnetic current meter

An electromagnetic current meter in the form of a 15 cm diameter annular head (Griffiths and Collar, 1980) was located at the end of the boom. The current meter was calibrated in the wave tank at IOS, Wormley. The head was placed about 30 cms below the mean water level. The two orthogonal components of oscillatory current speed in the horizontal plane measured using this current meter can be used to infer the mean wave direction and directional spread. The mean current speed and direction at a depth of 30 cm can also be determined from this system.

3. DATA ACQUISITION

The analogue sensor signals from the wave staffs and the electromagnetic current meter (emcm) were digitized simultaneously using Dual Slope Convertors, with the pulse outputs of the anemometer and wind vane directly interfaced to a digital logger. To accommodate the size of the sensor suite two ten-channel loggers were used under the control of a single time base. A sampling rate of 8Hz was adopted for all channels, with data stored on two $^1/_4$ inch magnetic tape recorders in NRZ-1 format.

Mains interference in the vicinity of the tower was appreciable necessitating the emcm sampling to be locked to mains frequency, reducing noise due to beats between mains voltage picked up by the head and the sampling frequency. Further reduction of earthing problems and interference of the analogue signals from the emcm was achieved using charge coupling techniques via switched capacitors on the analogue inputs to the logger.

Prior to recording periods the wave staffs and the emcm were cleaned to remove any algae growth, and data quality checks during recording periods were carried out by processing a data subset using an Acorn Model B Microcomputer. A Fast Fourier Transform routine was used to give wave spectral information, (for one sensor only) in near real time. Mean wind speed and standard deviation were evaluated every 30 sec. in real-time throughout each recording period.

Following the data collection periods, the data were translated from $^1/_4$ inch magnetic tape to 9-track computer compatible tape via a CAMAC workstation. The analysis of the data was carried out on a mainframe computer at IOS, Bidston.

4. ANALYSIS

(a) One-dimensional frequency spectra

Wave spectra were computed from the time series of wave elevation from each of the wave staffs using the Fast Fourier Transform (FFT) of 2000 data points, equivalent to a record length of 250 sec. A simple 'box-car' average over 20 consecutive harmonics yielded spectral estimates with a bandwidth of 0.08 Hz and 40 degrees of freedom. The Nyquist frequency was 4 Hz.

(b) Directional wave spectra

(i) Wave staffs

The line array of 6 wave staffs consists of 2 'optimum' arrays each of 4 staffs with fundamental spacings of 0.25m and 0.5m respectively. (See Figure 3). The arrays are optimum in the sense that 4 wave staffs with fundamental separation D give all spacings up to 6 D. The two arrays were chosen to give the best information on directional characteristics for wave spectra whose dominant wavelengths are 1.0m and 2.0m respectively and thus cover most of the conditions likely to be encountered on the reservoir.

Cross-spectra from appropriate pairs of staffs are estimated in an analogous manner to that used for one-dimensional frequency spectra. That is, the analysis is carried out over 2000 data points and cross spectral estimates derived for a bandwidth of 0.08 Hz with 40 degrees of freedom.

The method of analysis is based on a model-fitting procedure (see, for example, Davis and Regier (1977)). The parameters of a model spectrum $G(\theta)$, where θ is the wave direction, are chosen to minimize the squared difference between the measured cross-spectra and the model (theoretical) cross-spectra. (For convenience we suppress the variation with wave frequency).

The unimodal distribution

$$G(\theta) = N \exp\left[-0.25s(\theta-\overline{\theta})^2\right] \qquad (1)$$

was used as a model form. The normalization factor $N = \sqrt{(s/4\pi)}$ is such that $\int_{-\pi}^{\pi} G(\theta)d\theta = 1$. The mean wave direction is $\overline{\theta}$.

This distribution is a simple form of the more general distribution

$$G(\theta) = N_1 \cos^{2s} \tfrac{1}{2}(\theta-\overline{\theta})$$

first proposed by Longuet-Higgins, Cartwright and Smith (1963). Equation (1) is a good approximation to this form when the distribution is narrow, that is s is large.

The directional spread is characterized by s or by $\theta_2 = \sqrt{2/(s+1)}$. The parameter θ_2 is equivalent to the r.m.s. directional spread about the mean wave direction for a narrow distribution.

(ii) Electromagnetic current meter

The theory for the determination of directional information from oscillatory currents is directly analogous to that for a pitch-roll buoy (Longuet-Higgins et al., 1963). If we denote the two components of horizontal current by the subscripts 1 and 2, then we can only determine the 2nd order angular harmonics of the directional distribution, namely

$$A_2 = \frac{C_{11} - C_{22}}{C_{11} + C_{22}} \quad : \quad B_2 = \frac{2C_{12}}{C_{11} + C_{22}}$$

where C_{ij} is the cross-spectrum of series i with series j. The angular harmonics are defined by,

$$A_n + iB_n = \frac{1}{\pi} \int_0^{2\pi} e^{in\theta} G(\theta)d\theta$$

Two useful parameters can be derived from A_2 and B_2, namely, the predominant wave direction $\overline{\theta} = \tfrac{1}{2}\arctan(B_2/A_2)$ and an estimate of the directional spread s. The predominant wave direction determined from the 2nd order Fourier harmonics is ambiguous to 180 degrees, but this is not a problem on the reservoir where the wave direction is always well determined by the wind direction.

5. RESULTS

Table 1 contains a summary of the records considered in this report.

(a) Basic statistics

Each record consists of a number of consecutive 4 min. sections. For each section up to 6 wave staffs were in operation. Using the averaged spectrum for each section we have calculated the following parameters:

total variance,	σ^2
peak frequency	f_m
Phillips "constant",	α
overshoot factor,	γ

These parameters were computed following the method used in 'JONSWAP' as described in Hasselmann et al., (1976). Table 2 shows the results for these parameters and for the non-dimensional standard deviation $\tilde{\sigma} = g\sigma/U^2$ and non-dimensional peak frequency $\tilde{f}_m = Uf_m/g$. U is determined at the 10m level: some values are visually estimated from a hand-held anemometer and are denoted by H. The non-dimensional fetch is defined as $\tilde{x} = gx/U^2$.

Figure 4 compares $\tilde{\sigma}$ for each record (averaged over all sections) with the relations given by JONSWAP and by Kahma (1981), namely,

$$\tilde{\sigma} = \begin{cases} 4 \times 10^{-4}\ \tilde{x} & : \text{JONSWAP} \\ 6 \times 10^{-4}\ \tilde{x} & : \text{Kahma} \end{cases}$$

The values from measurements on the reservoir lie between these two relations. Data for Record 5 are for a wind direction of 050° where the geometric value of the fetch, 500m, is changing rapidly. The effective fetch is longer than this value: if we take a value of 830m, corresponding to a direction of 030°, we obtain the modified value indicated by the displaced symbol in Figure 4.

Values of the non-dimensional peak frequency $\tilde{f}_m$, shown in Figure 5, are close to the relations given by JONSWAP and by Kahma (1981), namely

$$\tilde{f}_m = \begin{cases} 3.5\ \tilde{x}^{-0.333} & : \text{JONSWAP} \\ 3.18\ \tilde{x}^{-0.333} & : \text{Kahma} \end{cases}$$

Figure 6 shows values of α determined from the reservoir data compared to JONSWAP and to a formulation given by Mitsuyasu (1973) based on laboratory experiments:

$$\alpha = \begin{cases} 0.076\ \tilde{x}^{-0.22} & : \text{JONSWAP} \\ 0.081\ \tilde{x}^{-0.308} & : \text{Mitsuyasu} \end{cases}$$

Estimated values of α are approximately constant with fetch: there was a tendency for the results to be closer to the relation of Mitsuyasu than that of JONSWAP for $\tilde{x} < 200$.

Values of γ are very scattered and do not appear to vary systematically with non-dimensional fetch, (as also noted in Hasselmann et al., (1973)). The mean value of γ from all records was 3.6.

(b) One dimensional frequency spectra

The spectra of selected records are shown in Figures 7a-d on logarithmic axes. The spectra from individual wave staffs are plotted in this figure. The straight line indicates the slope of spectrum with high frequency tail varying as frequency to the power -5. Estimates of the exponent n of a power law of the form $E(f) \sim f^{-n}$ are given in Table 2. Values of n, estimated by a least squares regression over the range $2f_m$ to 3.2 Hz, varied from 4.6 to 5.8 with a mean value of 5.25. (An upper frequency limit of 3.2 Hz was chosen to avoid the possibility of contamination from aliassed energy in the spectrum).

To illustrate the high frequency behaviour in greater detail we have pre-whitened the spectra by f^5. If the tail of the spectrum varies as f^{-5}, then the prewhitened spectrum should approach a constant value. Figures 8a-d show the results for the averaged spectrum of records 5, 20,23 and 45 respectively. The curve is that given by the JONSWAP spectrum

$$E(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp \left\{ -\frac{5}{4} \left(\frac{f_m}{f}\right)^4 + \ln(\gamma) . \exp \left(-\frac{(f-f_m)^2}{2\sigma^2 f_m^{\;2}} \right) \right\}$$

with α, f_m and γ determined as described in Hasselmann et al., (1976). the results indicate a f^{-5} behaviour for the wave spectra beyond a frequency of $2f_m$ in accordance with estimates of n, noted above.

Figure 9a,b shows the spectra for records 20 and 45 when prewhitened with f^4. There does not appear to be a f^{-4} behaviour at high frequencies although there is a region obeying this law just above the spectral peak.

(c) Directional spectra

Directional wave information are available both from the array of wave staffs and the electromagnetic current meter (emcm), as discussed in section 4. Figure 10 shows estimates of the spread parameter s for record 8 obtained using these different techniques. There is considerable scatter in the estimates of s from both these methods but the overall agreement is satisfactory. The continuous curve shows estimates of the spread parameter s determined by Hasselmann, Dunckel and Ewing (1980), henceforth abbreviated as HDE, using a pitch-roll buoy in the southern North Sea. It appears that at the short fetches of the reservoir s is always larger, that is the r.m.s. directional spread is narrower, than measured in the ocean. For record 8 the ratio of wind speed to phase velocity at the spectral peak, $U/c_m \sim 3.3$. The relation proposed by Mitsuyasu et al., (1975) predicts a value of $s<1$ for this range of U/c_m.

The spread parameter s is very sensitive to noise in the measured cross-spectra (Long, 1980). An alternative, more stable parameter is the r.m.s. directional spread θ_2. Results for this parameter, determined from an analysis of the wave staffs of record 8 (with 160 degrees of freedom), are shown in Figure 11. The continuous line is the relation of HDE. A better fit to the data is given by the empirical line

$$\theta_2 = \theta_2^{m} \, (f/f_m)^{1.5}, \text{ where } \theta_2^{m} = 20.1 \text{ deg.}$$

The behaviour of s versus f/f_m is qualitatively similar for other records taken on the reservoir.

Table 3 tabulates values of the average of the two largest values of s_m (at the spectral peak) from the electromagnetic current meter. It is clear that these values exceed the estimate $s_m = 9.77$ given by HDE for oceanic conditions.

6. CONCLUSIONS

Measurements of wind-wave spectra on the reservoir have shown the following features.

(a) Basic statistics

The scaling laws of Kitaigorodskii (1962) are obeyed by wind waves on the reservoir. In particular, the non-dimensional peak frequency $\tilde{f}_m$ and the non-dimensional standard deviation $\tilde{\sigma}$ are functions of the dimensionless fetch $\tilde{x} = gx/U^2$. Values of $\tilde{f}_m$ and $\tilde{\sigma}$ lie between the relations given by JONSWAP and Kahma (1981).

The Phillips "constant", corresponding to a f^{-5} tail, was found to be approximately constant over the range of observed fetches. There was a tendency for the results to be closer to the relation of Mitsuyasu (1973) than that of JONSWAP for $\tilde{x}$ <200m.

Values of the 'overshoot parameter' γ do not appear to vary systematically with fetch and take an overall mean value of 3.6.

(b) One dimensional frequency spectra

Estimates of the frequency spectra obtained are close to the empirical spectral relation of JONSWAP in accordance with the conclusions of the previous section. The exponent of the power law for the saturation range beyond twice the peak frequency varied from -4.6 to -5.8 with an average value of -5.25, compared with the -5 power law proposed by Phillips (1958).

However there does appear to be a limited region in the measured spectra between the spectral peak, f_m, and $2f_m$ where a f^{-4} behaviour is observed. (Kitaigorodskii (1983) has given theoretical evidence for th existence of two spectral ranges as shown schematically in Figure 12.) Kahma (1981) has described such a region by the expression

$$E(f) = (2\pi)^{-3} \alpha_u gUf^{-4}$$

Estimates of α_u from the prewhitened spectra (of Figure 9) are given in Table 4. At the lowest wind speeds U ~5 m/s, values of $\alpha_u \sim 0.0038$ which is fairly close to the values of $\alpha_u = 0.0044$ given by Kahma (1981) and $\alpha_u = 0.0045$ given by Forristall (1981). However, at the highest wind speeds observations on the reservoir indicate a value $\alpha_u \sim 0.002$ which is less than predicted by Kahma and Forristall. Donelan et al. (1985) give a value of $\alpha_u \sim 0.0032$ using their equation (5.2) with $U/c_m = 4$. Our values of α_u lie below this value.

It is possible some observations in the ocean did not extend to high enough frequencies to observe region II where the energy density varies as f^{-5}. Kahma (1981) has suggested that the frequency f_l (see Figure 12) which separates the two sub-ranges is given by $f_l = 2g/\pi U$. For wind speeds less than 10 m/s, f_l is greater than 0.62 Hz which exceeds the useful frequency range of most accelerometer buoys used in making wave measurements.

(c) Directional spectra

Directional wave spectra, estimated from an array of wave staffs and an electromagnetic current meter, indicate a narrower directional distribution than previously obtained with a wave buoy under fetch-limited situations in the southern North Sea (Hasselmann et al., 1980). In particular, the spread parameter s takes values from about 13 to 20 at the peak of the wave spectrum. An equivalent parameter, the r.m.s. spread θ_2, varied from about 17° to 22° at the spectral peak. Above the spectral peak s varied as $(f/f_m)^{1.5}$, less rapidly than given by Hasselmann et al., (1980).

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TABLE 1

Summary of records

Record No.	Date	Time at start	Average wind speed and direction m/s, degree		Fetch (m)
5	21.4.82	1308	3.9	050	500
8	21.7.82	1343	7.1	020	1035
9	27.7.82	1106	6.9	020	1035
19	22.3.83	1210	14.9	270	770
20	22.3.83	1310	12.4	270	770
21	22.3.83	1410	15.5	270	770
23	24.3.83	1229	10.8	0	920
27	24.3.83	1440	11.3	0	920
37	7.10.83	1030	7.8	220	480
44	16.4.84	1247	6.3	310	910
45	16.4.84	1330	7.6	310	910

TABLE 2

Details of individual records

Record no.	Section no.	U (m/s)	f_m (Hz)	α	γ	σ^2 (cm^2)	$\tilde{x}$	$\tilde{\sigma}$ ($\times 10^{-2}$)	$\tilde{f}_m$	n
5	1	4.5	1.01	0.0204	3.2	3.5	242	0.906	0.463	5.8
	2	3.7	1.02	0.0180	2.8	3.2	328	1.298	0.385	5.3
	3	3.6	1.09	0.0194	4.9	3.5	378	1.418	0.400	5.4
8	1	7.4	0.77	0.0224	2.8	11.8	185	0.615	0.581	5.4
	2	7.6	0.76	0.0203	3.4	14.1	176	0.639	0.588	5.1
	3	6.8	0.70	0.0197	2.6	13.8	220	0.789	0.485	5.0
	4	6.7	0.72	0.0215	2.4	14.2	226	0.826	0.492	5.2
9	1	7.0	0.78	0.0176	4.8	12.0	205	0.687	0.556	4.6
	2	6.4	0.77	0.0187	4.3	12.5	246	0.843	0.502	4.8
	3	7.0	0.76	0.0203	3.2	11.0	205	0.660	0.547	5.1
	4	7.0	0.78	0.0220	4.1	14.6	203	0.773	0.551	5.0
19	1	14.9(H)	0.61	0.0231	4.5	43.9	34	0.292	0.921	4.8
	2	"	0.59	0.0201	2.8	36.4	34	0.267	0.893	4.7
	3	"	0.61	0.0251	4.3	49.2	34	0.310	0.923	4.8
20	1	12.4(H)	0.60	0.0254	4.7	49.5	49	0.449	0.763	4.8
	2	"	0.60	0.0243	4.0	43.1	49	0.419	0.757	4.7
	3	"	0.55	0.0236	2.8	55.1	49	0.474	0.699	4.7
	4	"	0.60	0.0238	4.5	45.1	49	0.428	0.753	4.6
21	1	15.5(H)	0.56	0.0211	2.9	53.4	31	0.298	0.883	4.6
	2	"	0.58	0.0239	3.7	50.6	31	0.290	0.924	4.7
	3	"	0.56	0.0223	2.3	46.4	31	0.278	0.878	4.9
	4	"	0.60	0.0218	4.3	46.0	31	0.277	0.950	4.8
23	1	10.8(H)	0.67	0.0200	3.5	24.8	77	0.418	0.743	5.1
	2	"	0.67	0.0196	4.7	26.9	77	0.436	0.742	5.1
	3	"	0.63	0.0180	4.1	31.5	77	0.472	0.698	5.0
	4	"	0.62	0.0199	3.1	27.8	77	0.443	0.680	5.0
27	1	11.3(H)	0.64	0.0166	4.7	31.5	71	0.430	0.740	5.0
37	1	7.6	0.97	0.0188	3.5	5.3	82	0.391	0.755	4.9
	2	8.1	0.95	0.0187	3.4	6.3	72	0.374	0.781	5.3
	3	8.1	0.87	0.0195	3.4	7.6	72	0.413	0.717	5.3
	4	8.1	0.90	0.0190	3.2	6.4	72	0.377	0.746	4.9
	5	7.2	0.93	0.0189	4.4	5.9	91	0.458	0.682	5.1
	6	7.4	0.91	0.0208	4.2	6.9	86	0.472	0.694	4.9
44	1	6.4	0.79	0.0146	2.4	7.3	218	0.649	0.518	5.4
	2	6.8	0.85	0.0159	3.4	6.6	194	0.546	0.585	5.5
	3	6.0	0.88	0.0150	3.0	5.4	247	0.631	0.540	5.4
	4	6.5	0.87	0.0162	3.1	6.1	212	0.574	0.573	5.6
	5	5.5	0.92	0.0147	3.5	4.5	292	0.679	0.519	5.7
	6	4.6	0.92	0.0157	2.9	4.2	416	0.938	0.437	5.6
	7	7.6	0.93	0.0141	5.3	4.9	157	0.379	0.716	5.6
	8	6.9	0.89	0.0153	3.2	5.1	186	0.463	0.630	5.5

TABLE 2 (Continued)

Details of individual records

Record no.	Section no.	U (m/s)	f_m (Hz)	α	γ	σ^2 (cm^2)	$\tilde{x}$	$\tilde{\sigma}$ ($\times 10^{-2}$)	$\tilde{f}_m$	n
45	1	8.4	0.82	0.0190	3.8	8.8	127	0.412	0.705	5.4
	2	8.4	0.78	0.0174	4.0	11.0	127	0.464	0.664	5.4
	3	7.5	0.77	0.0173	4.1	11.3	160	0.589	0.585	5.4
	4	7.5	0.78	0.0171	3.6	10.7	158	0.567	0.591	5.3
	5	8.2	0.82	0.0170	3.7	11.9	134	0.509	0.680	5.3
	6	7.5	0.82	0.0160	4.4	12.9	158	0.623	0.628	5.4
	7	6.6	0.81	0.0158	3.0	11.0	206	0.750	0.547	5.3
	8	7.3	0.85	0.0158	2.6	9.5	168	0.569	0.634	5.4
	9	6.7	0.88	0.0152	3.7	9.9	196	0.679	0.605	5.5

TABLE 3

Spread parameter at spectral peak

Record no.	U/c_m	s_m
8	3.3	17.7
9	3.4	20.1
23	4.6	13.3
27	4.6	14.3
44	3.5	15.9

TABLE 4

Estimates of α_u

Record no	U (m/s)	α_u
5	3.9	0.0038
20	12.4	0.0025
21	15.5	0.0020
23	10.8	0.0022
45	7.6	0.0021

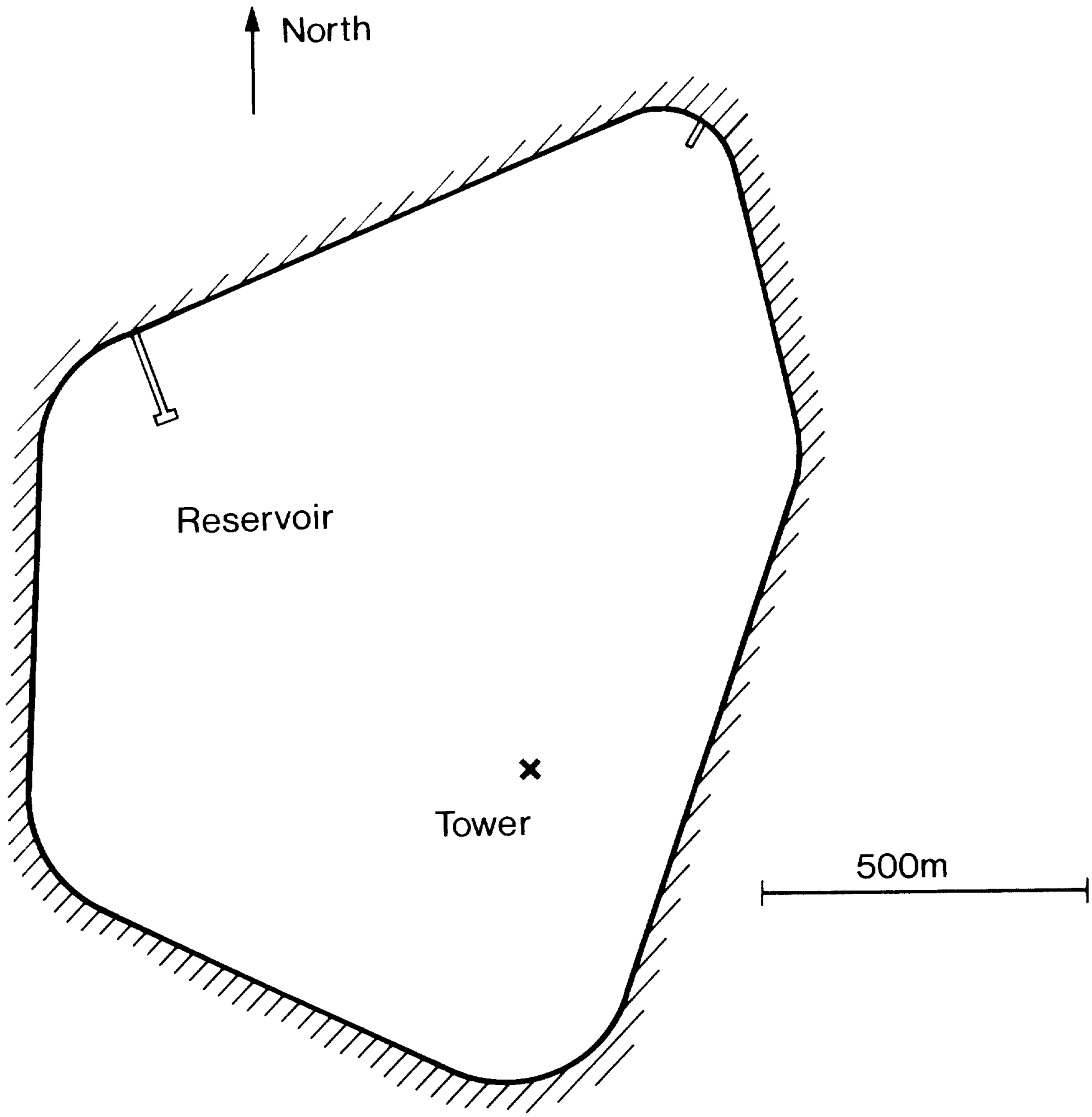


Fig. 1 Plan view of Queen Elizabeth II Storage Reservoir, Hersham, Surrey.

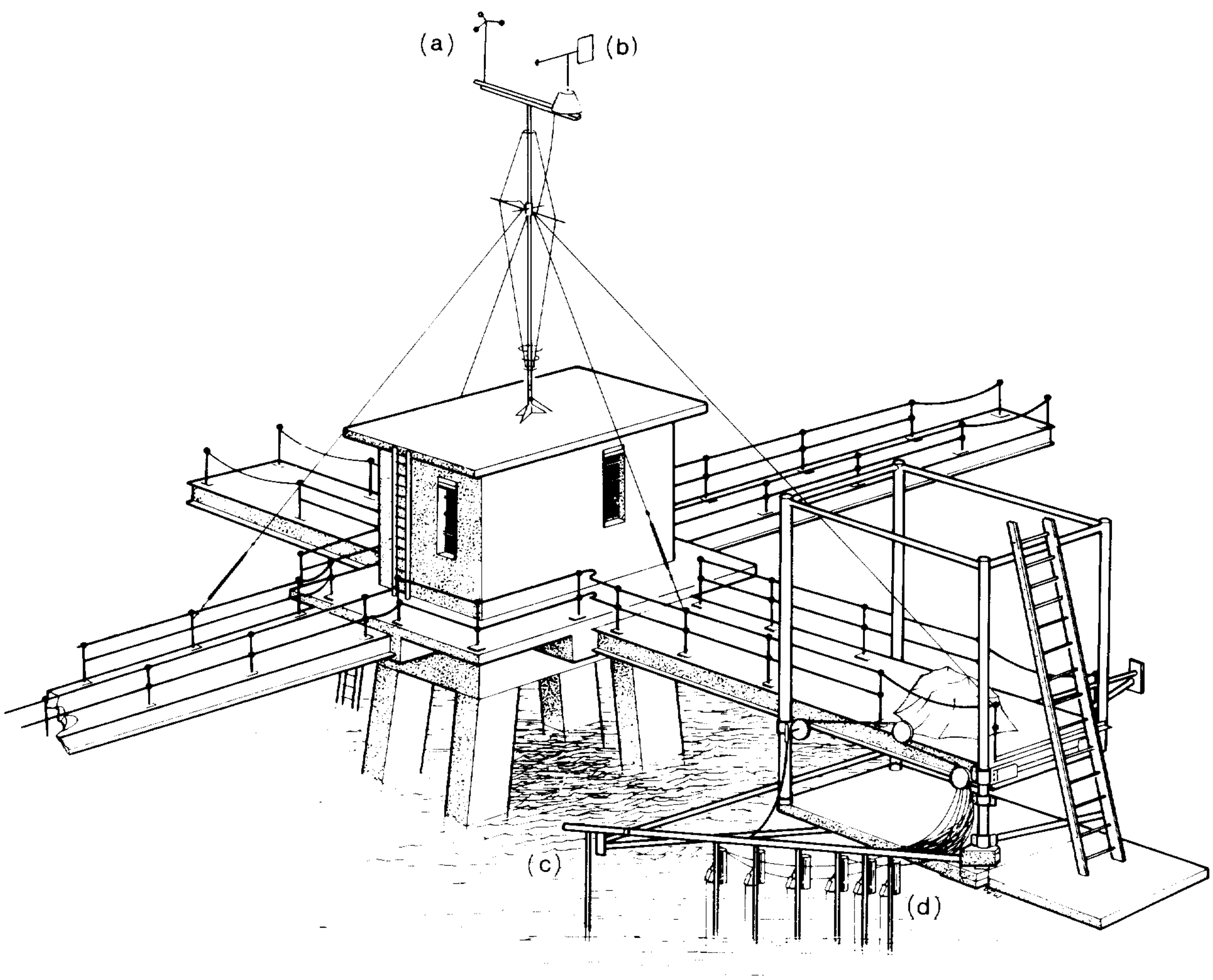


Fig. 2 Schematic diagram of tower showing (a) anemometer (b) wind vane (c) electromagnetic current meter and (d) array of wave staffs.

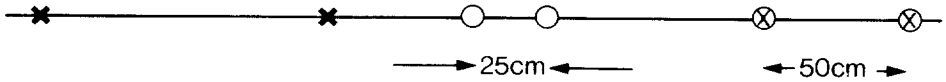


Fig. 3 Arrangement of wave staffs in two 'optimum' arrays with fundamental spacings 25cm (O) and 50cm (X).

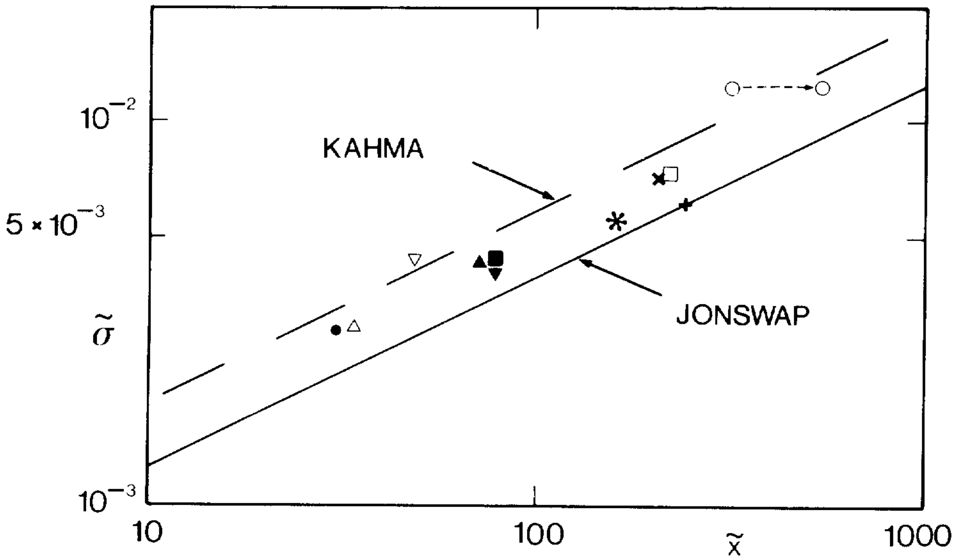


Fig. 4 Non-dimensional standard deviation $\tilde{\sigma}$ as a function of non-dimensional fetch $\tilde{x}$.

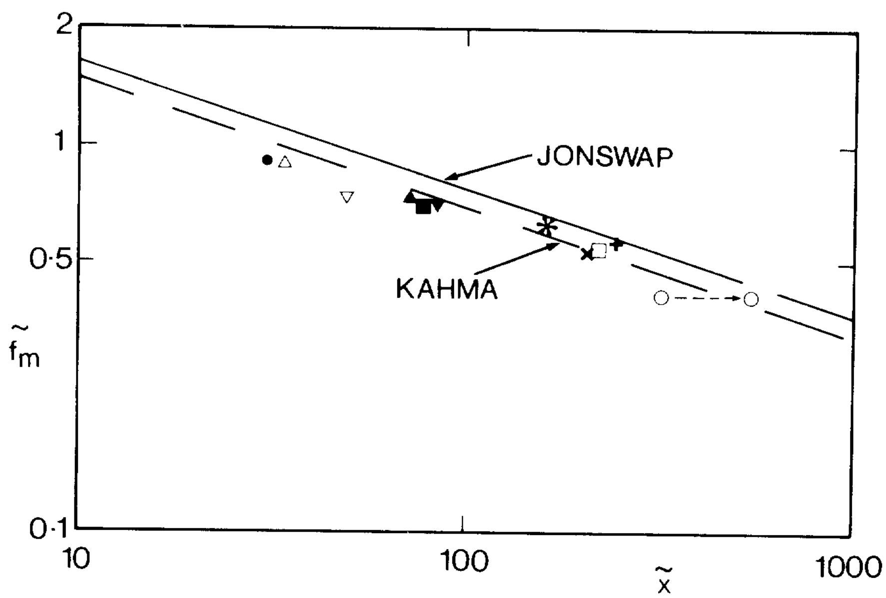


Fig. 5 Non-dimensional peak frequency $\tilde{f}_m$ as a function of non-dimensional fetch $\tilde{x}$.

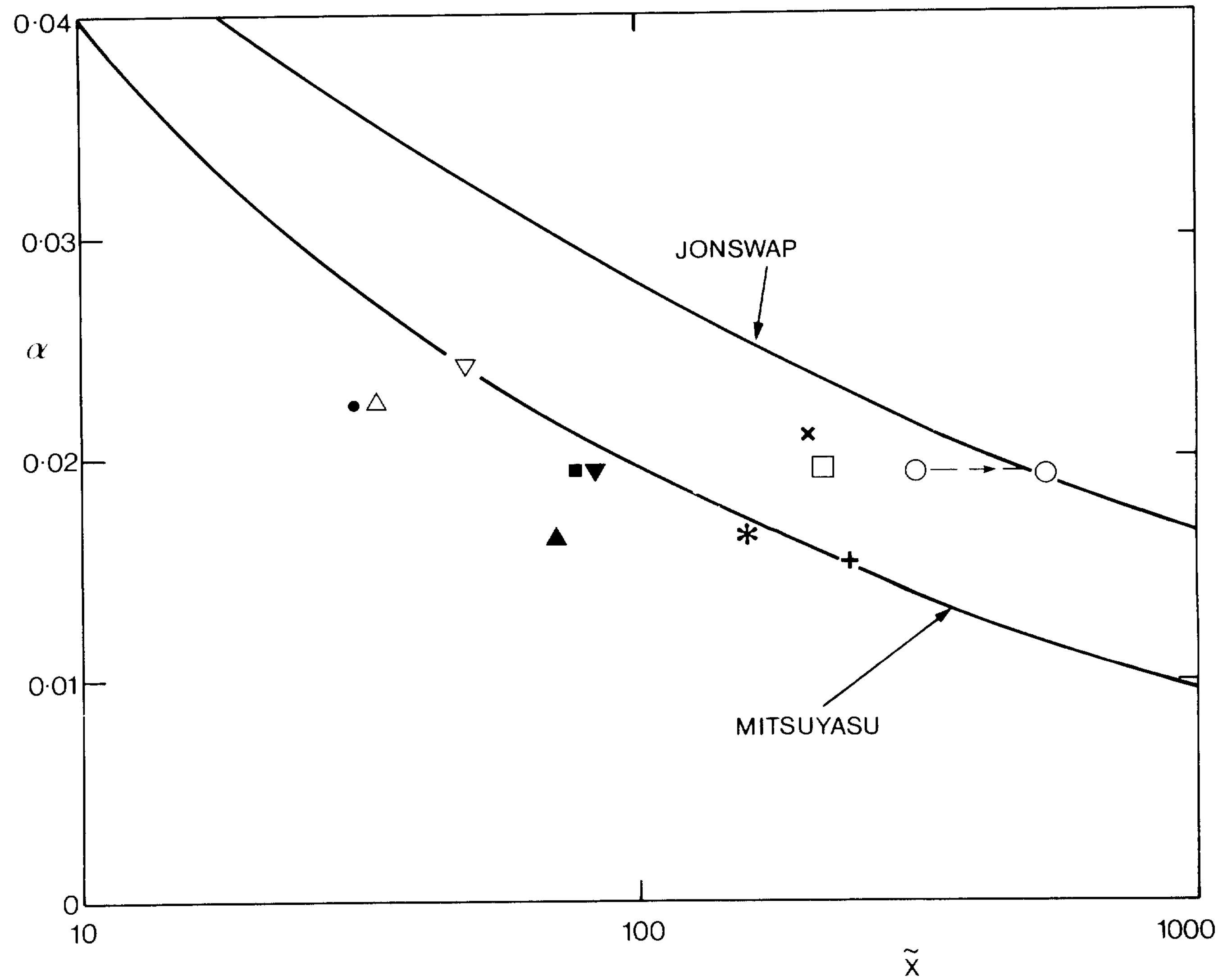


Fig. 6 α as a function of non-dimensional fetch $\tilde{x}$.

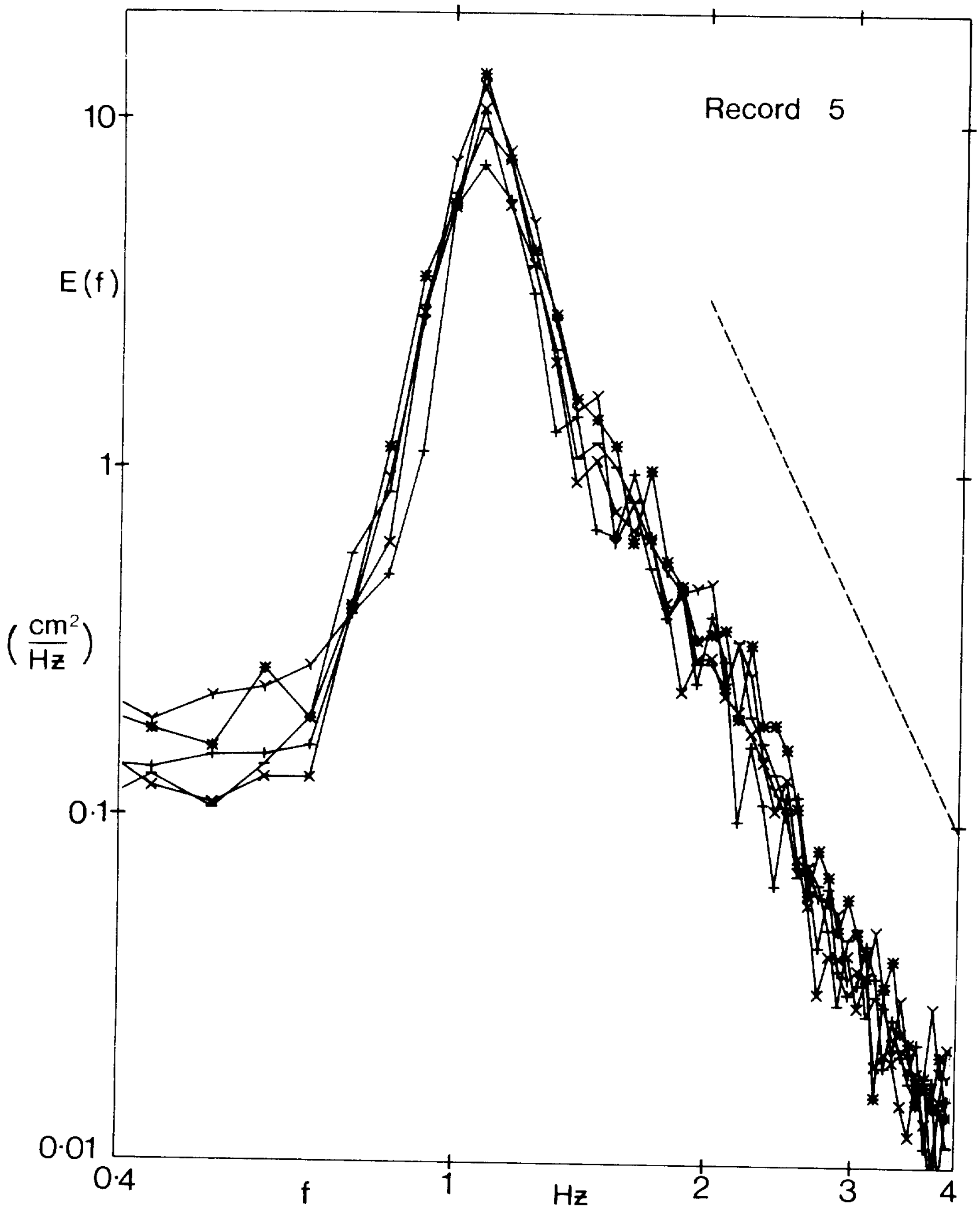


Fig. 7a One dimensional frequency spectra for section 4 of record 5.

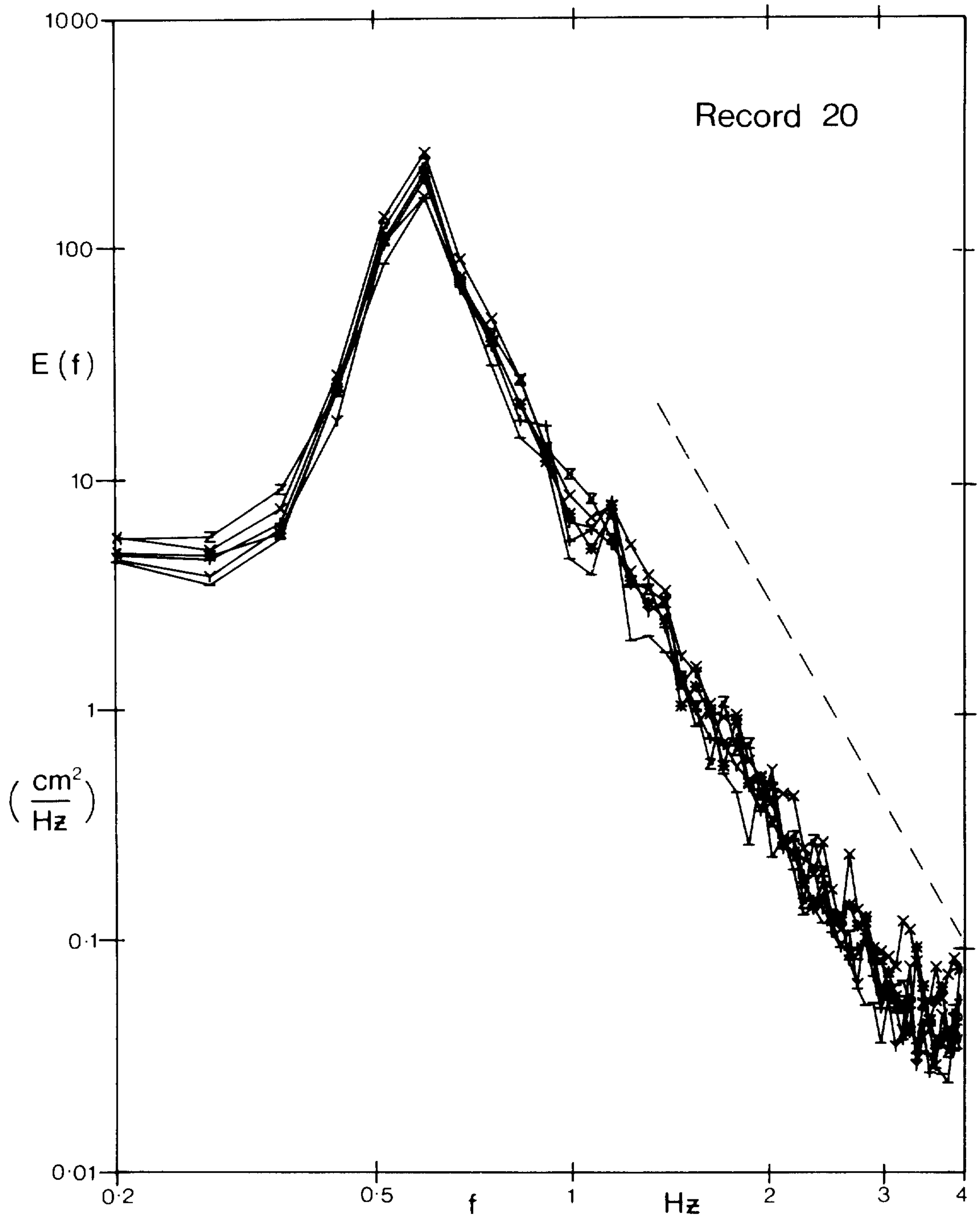


Fig. 7b One dimensional frequency spectra for section 4 of record 20.

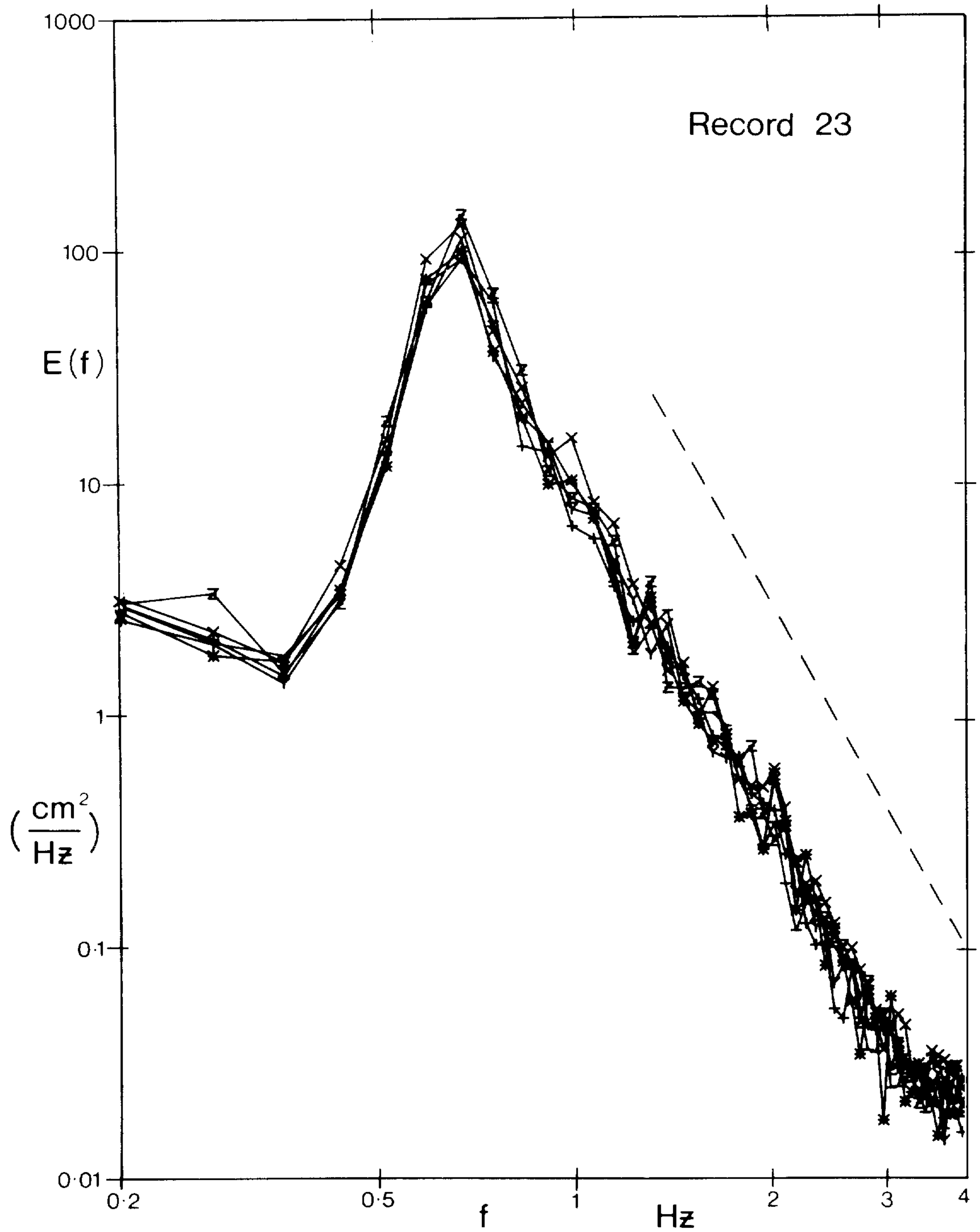


Fig. 7c One dimensional frequency spectra for section 2 record 23.

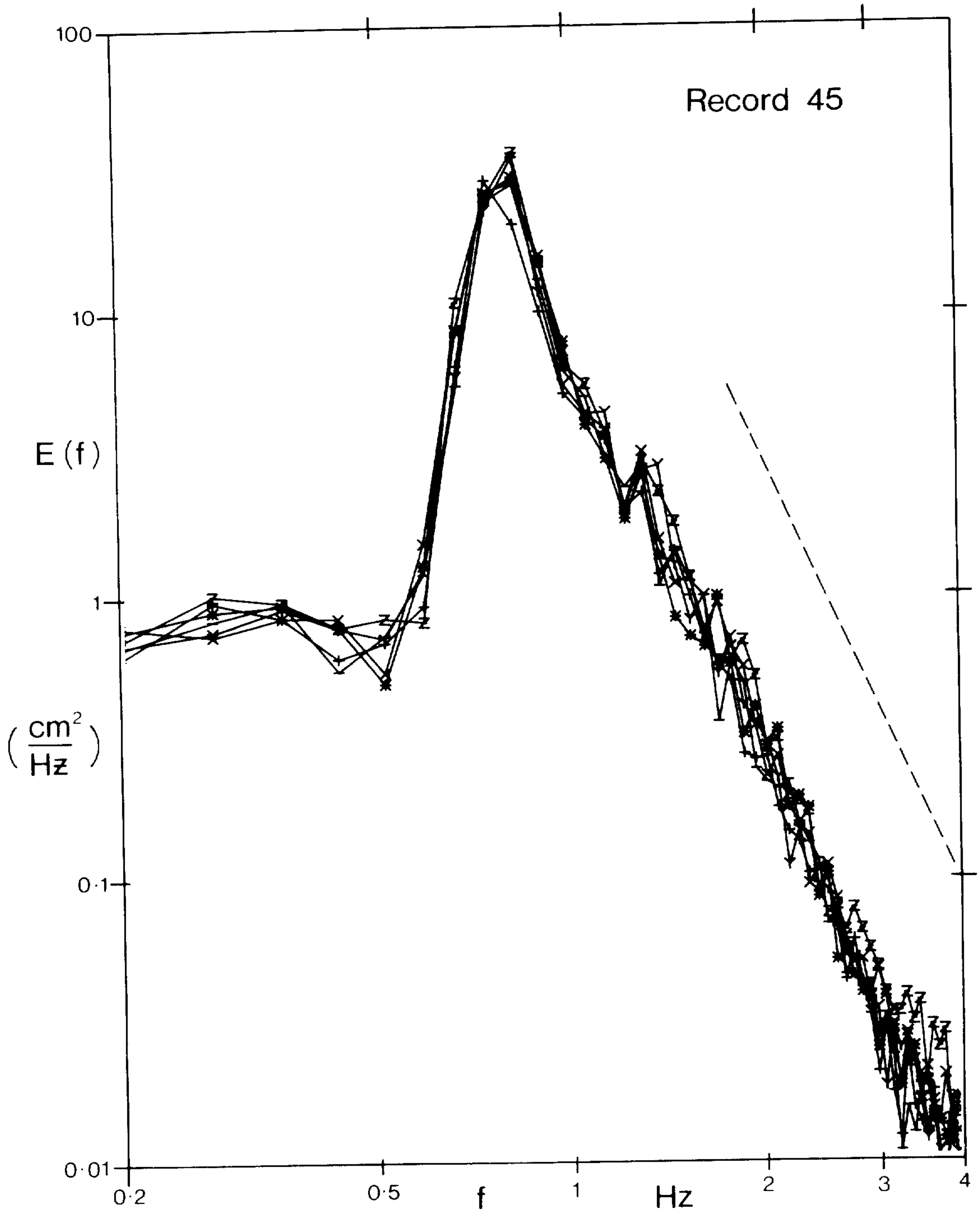


Fig. 7d One dimensional frequency spectra for section 9 record 45.

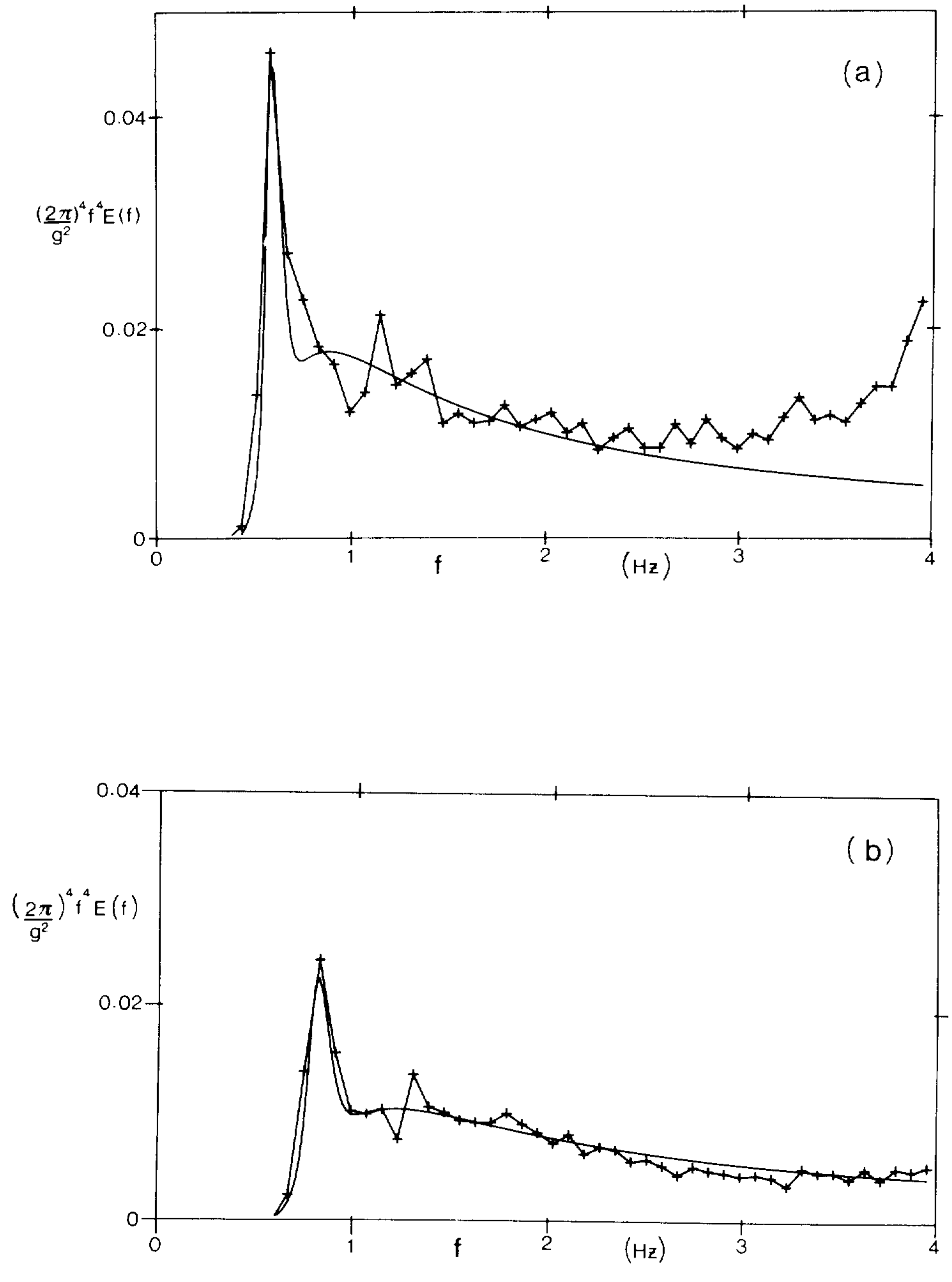


Fig. 8a, b Averaged spectrum prewhitened by f^5.
(a): section 4 of record 5
(b): section 4 of record 20
The continuous curve is the JONSWAP spectrum.

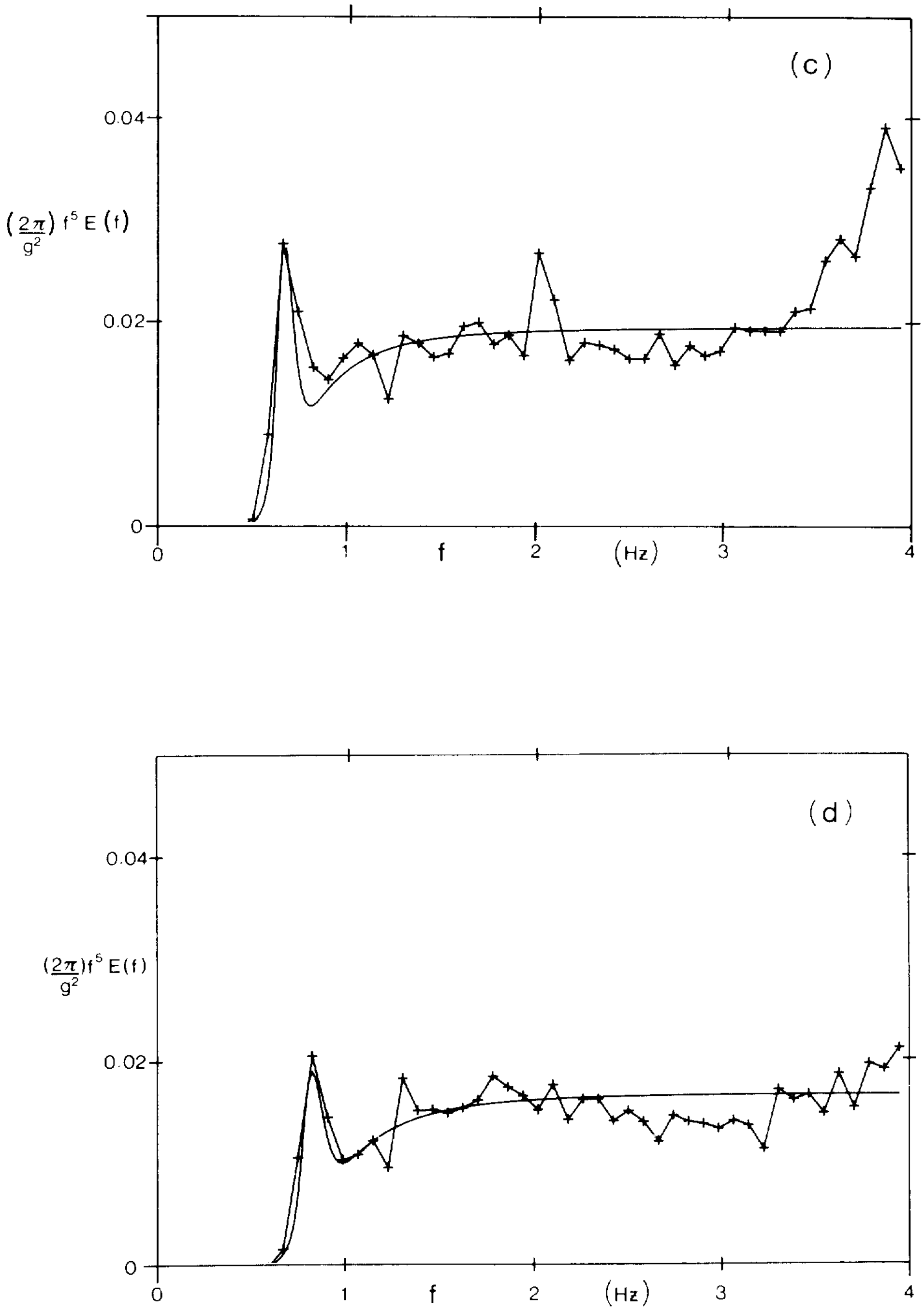
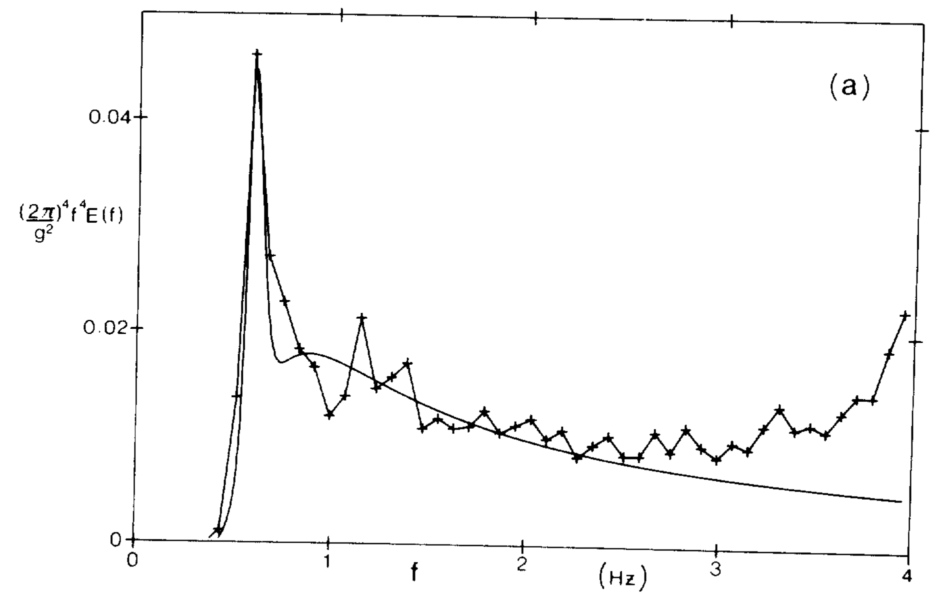


Fig. 8c, d As for Figure 8a,b
(a): section 2 of record 23
(b): section 9 of record 45



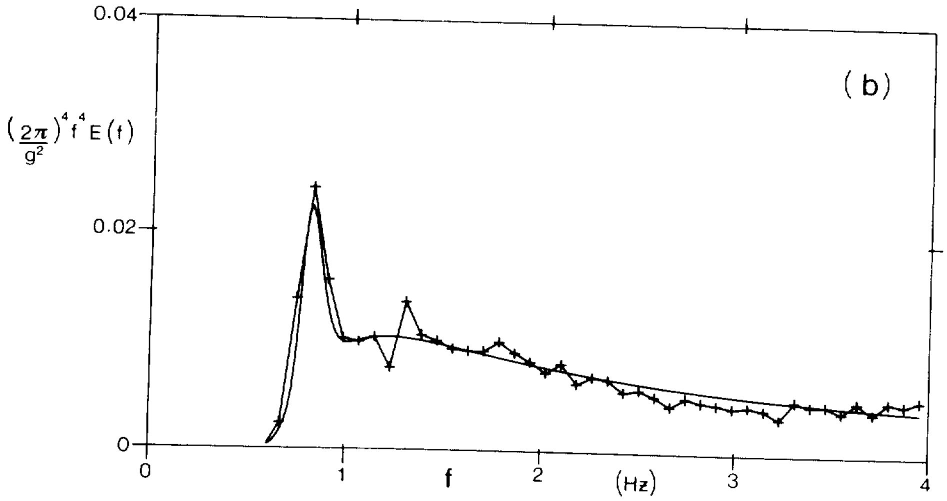


Fig. 9a, b Averaged spectrum prewhitened by f^4.
(a): section 4 of record 20
(b): section 9 of record 45
The continuous curve is the JONSWAP spectrum.

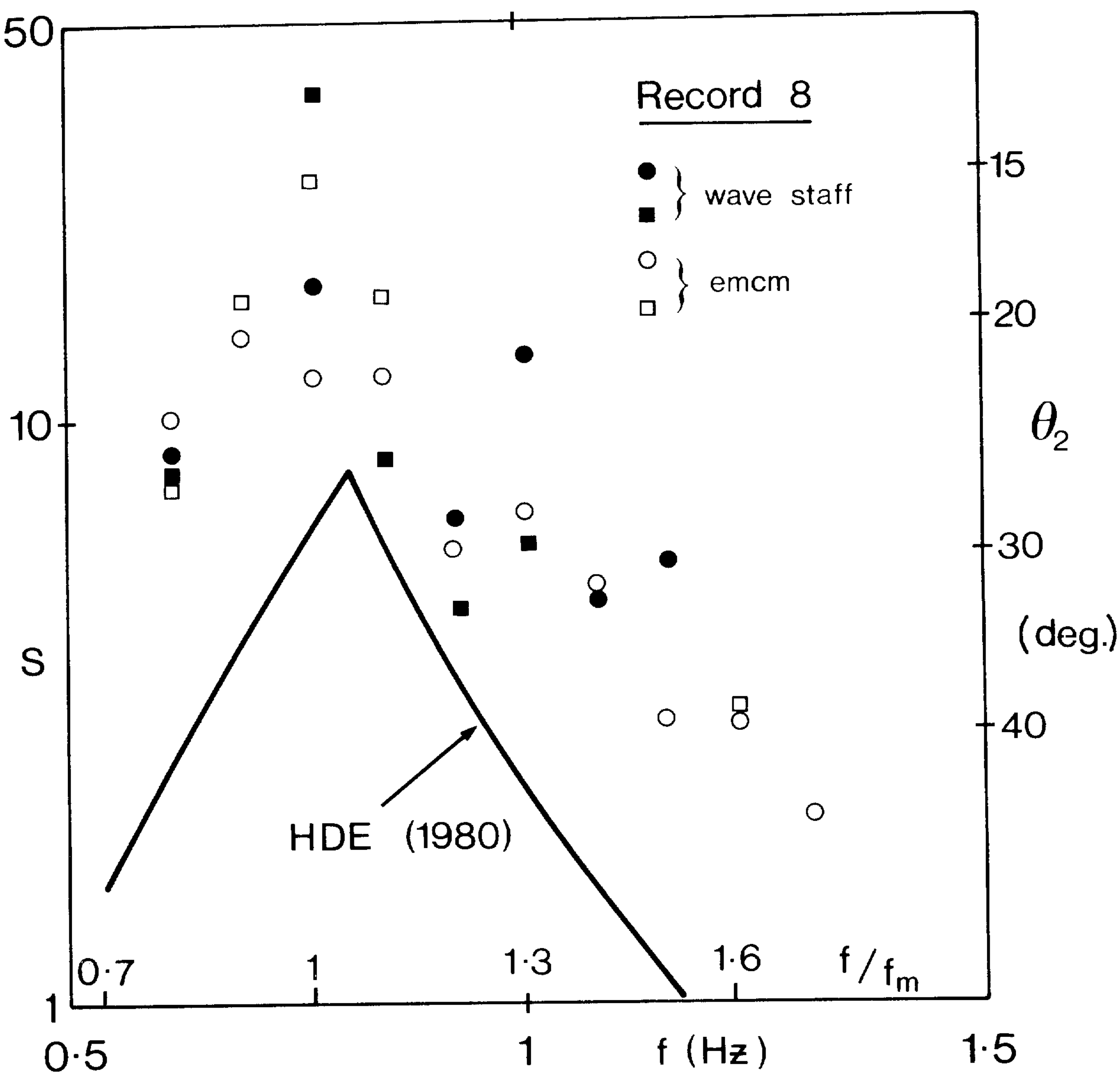


Fig. 10 Directional spread parameter s , estimated from wave staffs and electromagnetic current meter, compared with Hasselmann et al., (1980).

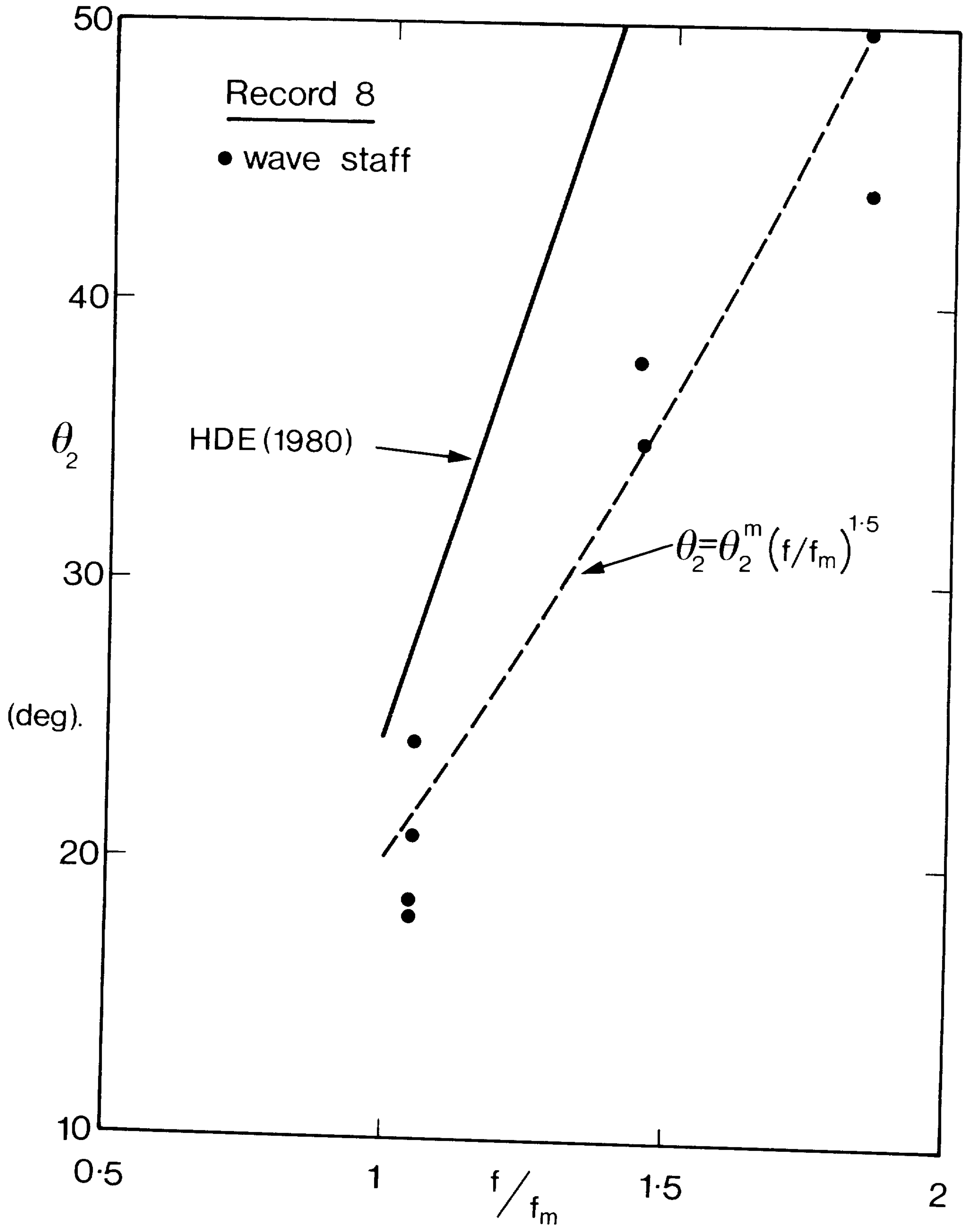


Fig. 11 R.m.s. spread parameter θ_2 as a function of (f/f_m) compared with Hasselmann et al. (1980).

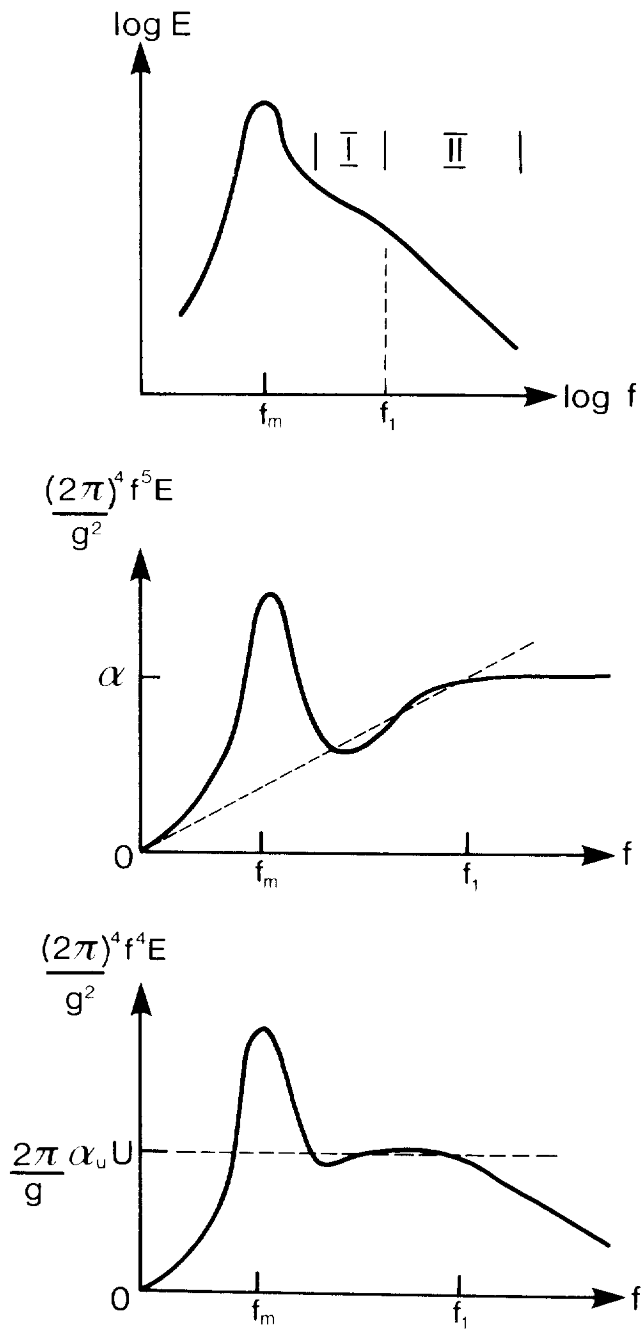


Fig. 12 Schematic diagram to illustrate the existence of two spectral ranges varying as f^{-4} and f^{-5}.