Studies of Sound Transmission Fluctuations in Shallow Coastal Waters

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STUDIES OF SOUND TRANSMISSION FLUCTUATIONS IN SHALLOW COASTAL WATERS

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The propagation and fluctuation of sound have been studied in shallow coastal waters off the British Isles. The environment and the special environmental measurements are described. Acoustic measurements were made for various ranges between about 2 and 137 km, with bottom-laid transducers. Frequencies used were mainly 1, 2 and 3 kHz, most often transmitted continuously but sometimes pulsed. The investigations have extended over several years, and amplitude and phase fluctuations have been found with periods ranging from a year to less than a second. The nine fluctuation mechanisms which have been identified may be summarized as: (*a*) seasonal in amplitude, (*b*) seasonal in phase, (*c*) attenuation due to fish which sometimes causes a greatly reduced amplitude at night when the shoals break up, (*d*) storm effects, (*e*) tidal changes in depth which sweep an interference pattern past the receiver, (*f*) tidal changes in the shear flow or the water structure which also affect the interference pattern, (*g*) phase effects due to tidal changes in the mean streaming velocity, (*h*) fluctuations of a few

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minutes period, some due to fish, (*i*) surface wave effects, which depend critically on the position in the tidal interference cycle. The above nine effects are really all subjects in their own right, and here large advances are described for seven of them. Most of the effects are both new and important, to be measured in many tens of decibels and in hundreds of phase cycles, but perhaps special attention should be drawn to the significance of the work on fish.

INTRODUCTION

When a sound wave is transmitted under water the received signal shows fluctuations in amplitude and phase. Thus the propagating medium can cause a tone originally pure to be spread in frequency. The effect can be considerable: a signal that is loud one moment may drop several tens of decibels and become quite inaudible within a few seconds. Fluctuations can occur with a wide range of periods, from less than a second to more than a year, with a correspondingly large number of different causes. Fluctuation is an integral part of the propagation mechanism, so that fluctuations and mean transmission loss should be studied together, the understanding of the one helping the understanding of the other. Fluctuations are of great practical importance because of their nuisance to the transmission of information, and this is involved in most applications of underwater sound, e.g. telemetry, communications, or echo ranging. The nuisance is particularly great for systems which rely on the coherence of the medium.

The investigations to be described here were carried out in the shallow waters off the British Isles, with the object of increasing the understanding of fluctuations in a limited range of conditions. Thus water depths were typical for coastal waters, ranges varied from 1.9 to 137 km (1 to 74 nautical miles), and frequencies were typically 1, 2 or 3 kHz. In all the experiments both source and receiver were fixed, i.e. laid on the sea bed. This has two great advantages. First it avoids the extra fluctuations due to the motion of a transducer, which is inevitable if it is suspended from a ship or a buoy. Such fluctuations should not be regarded as spurious, but they are additional, and an unnecessary complication. Secondly, it allows observations to extend over a long period of time, or to be repeated at intervals. Measurements may be continued in bad weather conditions. Long term measurements have proved very worthwhile in the present studies, since understanding has tended to come for the longer period effects first, and then to work down to those of shorter period. In fact the character of the shorter period fluctuations changes through the longer period cycles.

The present phase of fluctuation studies started in 1961, and is reported here up to 1966. Some fluctuations work at Admiralty Research Laboratory before 1961 will not be covered since it is hoped to report this separately. Some nine different fluctuation mechanisms have been identified, up to the time of writing. Several of the mechanisms interact with one another, and the unravelling of these intertwinings has involved a complicated experimental path, with many pitfalls to be avoided. Because there are so many mechanisms most of the effort has been expended in identifying them and sorting out their interactions, so that this account may be regarded as an introduction to the effects. It is the main account of the research; and the first apart from short papers read at an Acoustical Society of America Meeting (in October 1964) and at two NATO Advanced Study Institutes (Weston 1967*a*; Weston & Horrigan 1967). For reasons of brevity and clarity it has been possible only in part to follow here the chronological approach; it was thought better to arrange the main discussion in sections divided up according to the mechanism responsible. But it is necessary first to describe briefly the area, and the techniques used.

It is not intended to give a general theoretical review, though the mechanisms acting in this particular area are of course discussed in the appropriate section. Neither is it intended to give a general review of experiment here, since the volume of published literature is large. But it is worth pointing out that the current propagation studies across the Straits of Florida have a similar experimental arrangement and philosophy, with fixed source and fixed receiver (Steinberg & Birdsall 1966; Clark, Dann & Yarnell 1966).

2. Environment

The area of the experiments need be described only briefly, some points being taken up later in the appropriate sections. All measurements over the shorter ranges (some up to 23 km) were carried out near one end of a much longer 137 km path (figure 1).

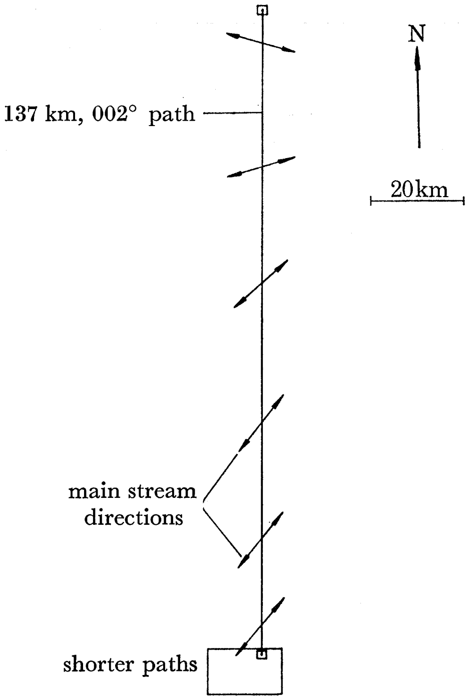

Figure 1. Transmission paths and main tidal streams.

Many measurements of the tidal streams in the area have been made by the Hydrographer, the Lowestoft Fisheries Laboratory and the Admiralty Research Laboratory—in connexion with the present experiments and with others. The tidal flows have velocities of the order of 0.5 m s^{-1} (1 knot).

The transducers are laid in about 33 m of water, but midway along the 137 km track the depth becomes about 70 m as shown in the figure 2 profile. There is a tidal depth range of about 5 m. The bottom material is mainly sand, though rocky outcroppings are common.

The seasonal temperature cycle is illustrated in figure 3. At the start of the measurements no special temperature device was available, so the resistance variations were measured in a disused cable lying on the sea bed, having conductors shorted together at the far end. A correction was made for the short run out of the water, using other cores in the same cable. The measured temperature is an average along the sea bed down to 33 m depth, for a 3.1 km cable length (mean resistance 38 Ω). It was calibrated from separate bathythermograph experiments. The results show large differences from year to year, especially in winter: up to 2 °C at a given time, and up to several weeks in the date of the coldest day.

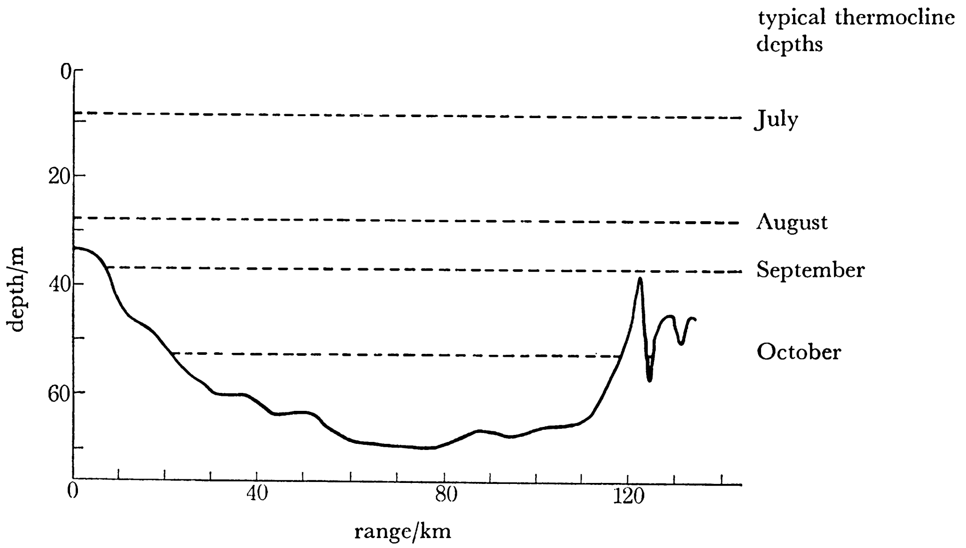

Figure 2. Bottom profile along 137 km path, with typical thermocline depths.

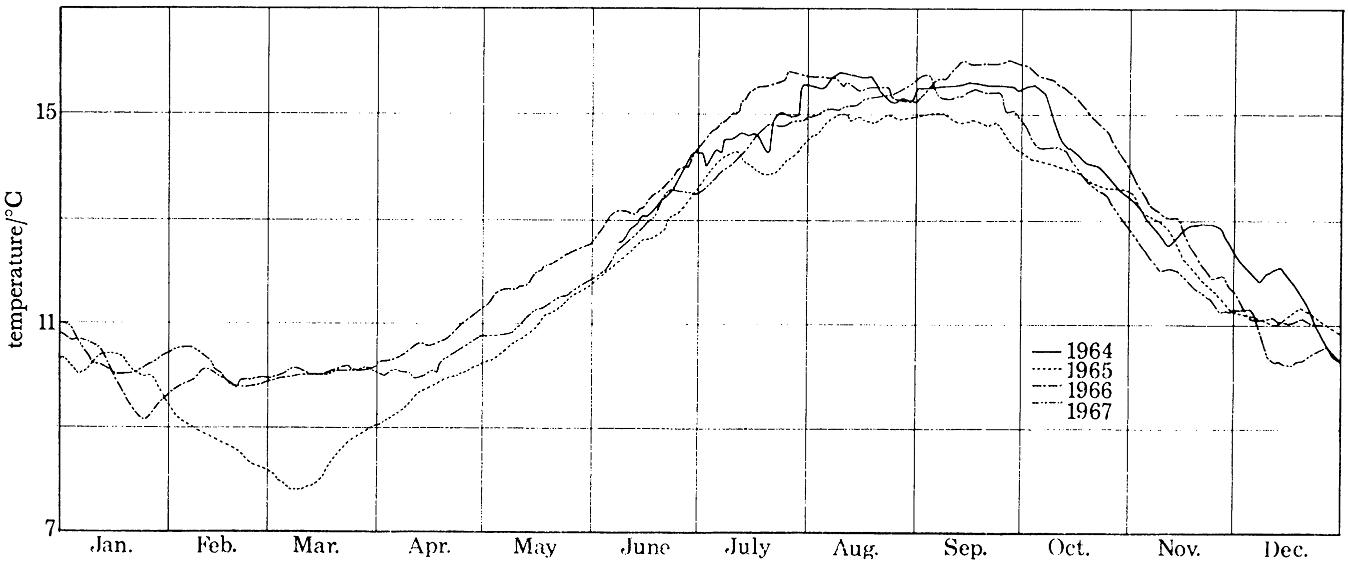

Figure 3. Seasonal variation in water temperature measured by cable resistance.

Surface heating produces a temperature layering of several degrees Celsius in the summer months. But even in the summer the water is often isothermal near the coastline, and in the winter if there is layering at all it is restricted to the very centre of the channel. Information on typical thermocline depths is included in figure 2 though this gives an oversimplified picture.

3. Measurement and analysis methods

3.1. *General*

Practically all the measurements were made with c.w. transmissions, the advantage of a pure tone being that on replay the sampling rate, etc. may be chosen at will. At various times, and with a variety of projectors, frequencies of 1041.7, 2083.3, 2998 and 4167.7 Hz were used. Measurements were sometimes made simultaneously at more than one receiver. Three basic types of record have been produced, which account for the majority of the figures reproduced in this paper. These types are amplitude or level against time, phase against time, and spectral analyses of either amplitude or phase. The three types can of course come with a range of speeds, time constants, resolutions, durations, etc. For example, the duration varies from hours in some cases, up to one virtually continuous 31-day record in 1965 (figure 11).

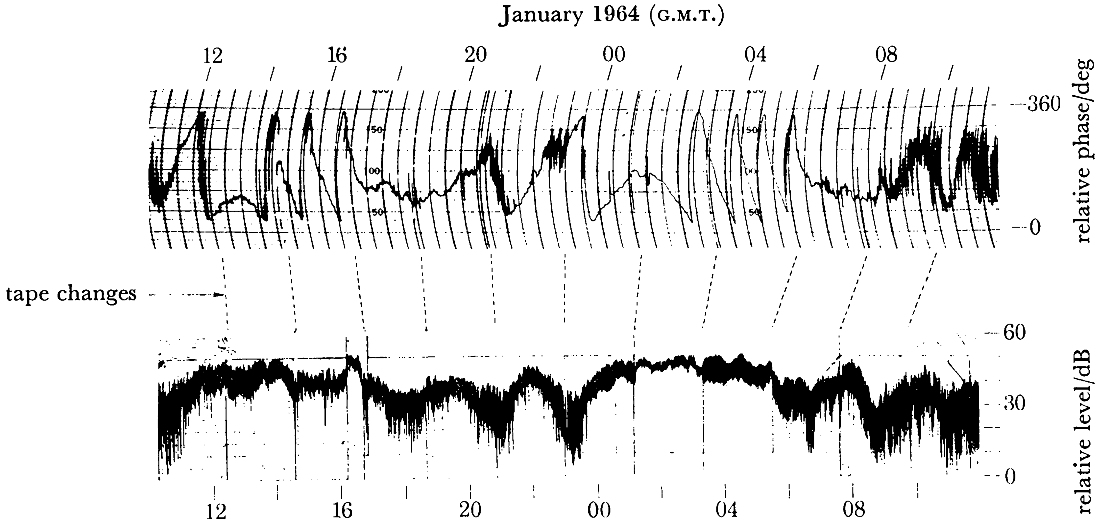

FIGURE 4. Phase and amplitude fluctuation records at 2 kHz, 7.8 km (from magnetic tape, phase record smoothed with 10 s time constant).

3.2. *Amplitude records*

The received signals are first filtered to improve the signal/noise ratio. But the bandwidth must not be less than several hertz, or some of the fluctuations it is desired to study will be smoothed away. In the earlier work the filtered signal was rectified, displayed on a cathode ray oscillograph, and recorded on cine film. In the later work a high speed logarithmic level recorder (Brüel & Kjaer—shortened to B & K in table 1) was normally used, with a second channel displaying a neighbouring frequency band to measure the level of ambient noise. It is worth stressing the advantage of using a very slow paper speed, in order to make visual examinations and comparisons feasible. A magnetic tape recording was made for later replay, and to cover the faster fluctuations. Figure 4 includes a reproduction of a logarithmic level record, this short range example showing fluctuations in excess of 50 dB! Many more examples appear later.

3.3. *Phase records*

The filtered signal was also processed by a Peekel phasemeter, which gives a d.c. output directly proportional to phase, with a time constant of about 0.1 s. The phasemeter of course needs a pure tone reference signal. For the shorter ranges both the power drive and the reference signal were derived at the one location by counting down from a 100 kHz crystal controlled oscillator. But for the 137 km experiments there was the problem of producing the same pure tone signal at either end. Linkage by the normal telephone land-lines could not be guaranteed to have phase stability. Solutions feasible but expensive were a reliable radio link, a special cable link, or matched crystals of high stability. The method adopted was both cheap and simple: receiving the 200 kHz carrier of the B.B.C. Light Programme (radio 2) at both ends. This was divided down to reach the desired frequencies, which explains the odd values of the frequencies 1041.7 and 2083.3 Hz transmitted for the phase work. The Light Programme has the disadvantage that it shuts down for a few hours each night, precluding any very long measurements.

Samples of the various phase displays are shown in figures 4 to 6. In the earlier work the phasemeter output, like the amplitude, was recorded on a cathode ray oscillograph film (figure 5). This has the disadvantage that it is very difficult to follow, especially if there are any complete 360° phase changes. This point is underlined by figure 6, which is a heavily smoothed plot from a film record. It appears to show a 7 min oscillation of 60° peak-to-peak swing. It was not till long after drawing the figure that it was realized that this really shows a steady phase drift with a complete cycle every 7 min. This should appear as a sawtooth with a linear rise followed by a fast fly-back, but becomes sinusoidal due to the 'noise' (mainly real fluctuations at higher frequencies) and smoothing (cf. Sheftelman 1967). Because of these troubles the film was replaced by a heavily damped pen recorder (see figure 4), supplemented

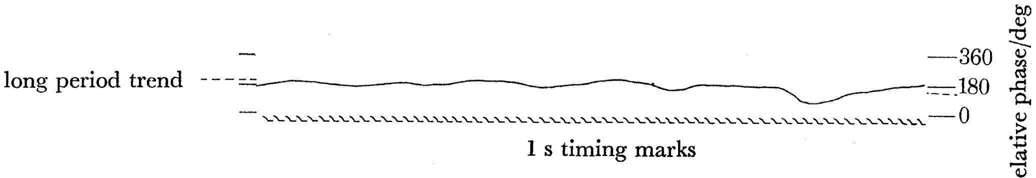

FIGURE 5. Sample of phasemeter output film from June 1961 137 km experiment at 1041.7 Hz.

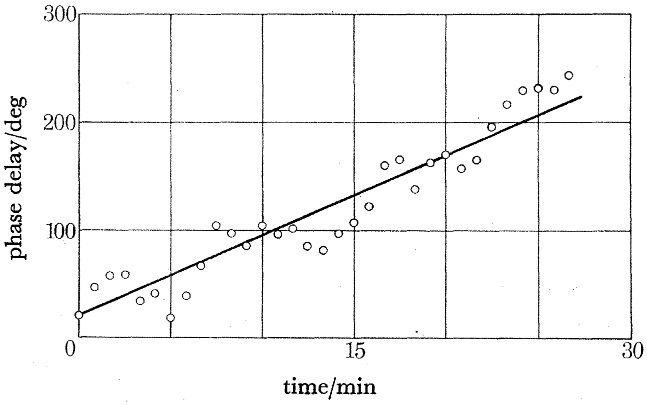

FIGURE 6. Sample phasemeter output (averaged over 50 s) for 1041.7 Hz, 137 km experiment in June 1961. The solid line is the apparent long period trend.

by magnetic tape recording for the faster fluctuations. The sawtooth form is clear in figure 4, perhaps untypically so.

To be suitable for later phase as well as amplitude analysis the magnetic tape record had to include either phasemeter output, or original signal plus reference. A recorder with a full width, single track head was used, to minimize 'drop-outs'. The received signal, the reference signal at double frequency and, for convenience, a 50 Hz timing signal were all recorded on this single track. Excellent agreement between live and replay records has been achieved for both amplitude and phase.

3.4. *Spectral analysis*

The spectral analysis of the records has been carried out digitally, using first the Ferranti Pegasus computer and later the English Electric KDF 9 at Admiralty Research Laboratory. The first stage is to put equally spaced amplitude or phase readings on five-hole paper tape, and a mixture of manual and automatic methods has been used for this. For the C.R.O. films an automatic photoelectric film scanner and tape punch designed at A.R.L. (by J. R. Bouffler) could be used. In a later system the intermediate stage of film recording was omitted, the rectified signal or the phasemeter output being connected to a digital voltmeter. Another device due to J. R. Bouffler converted the voltmeter output to a suitable form and punched it out. It continued doing this with a repetition period which could be chosen as low as 0.5 s (but figures 23 to 25, 27 and 28 all use 1 s). This system was normally operated on a signal replayed from tape, so that if desired the sampling rate could effectively be increased by reducing the tape speed.

Since the quantity of data was relatively small the fluctuation spectra were calculated by a straightforward Fourier analysis of the original data, and a running average of five coefficients plotted. This has certain technical advantages over the 'conventional' method which uses an intermediate calculation of the autocovariance (Blackman & Tukey 1959), although some spectra were also calculated in this way. The Fast Fourier Transform technique was not known at the time of this work. The spectra (see figures 23 to 28) are presented in terms of amplitude coefficients reduced to their equivalents in a 1 Hz band. For the amplitude fluctuations the coefficient has been normalized by dividing by mean signal amplitude, to give a coefficient of variation. This was chosen because it was comparable in definition to the phase fluctuation as expressed in radians (see § 13).

Even with this simple Fourier analysis there are points to watch. First there is the well known danger of an aliasing error, which was minimized by a suitable analogue smoothing of the original data before sampling (time constant usually 0.1 to 1.0 s). Where appropriate the Nyquist or folding frequency is shown (figure 26 only), but for most of the spectral plots there is no appreciable aliasing since the frequency extends only halfway to the folding frequency. In the phase work there are two additional troubles. If the phase is passing through the 360° point in a relatively well behaved manner, the phasemeter does not know whether to register 360° or 0°. In fact it may indicate almost any value, so that such regions are quite unsuitable for spectral analysis. Again if the phase fluctuations are very wild and very rapid the phasemeter will compromise on a steady but meaningless 180°. But even with a perfect phasemeter the meaningfulness of phase analysis is questionable under these conditions (see § 13.3).

Spectral analyses of amplitude fluctuations have been published before, e.g. Mackenzie (1962), and these too suggest the importance of surface wave period effects. But a major difference and limitation in his work was the ship-mounting of the transducers. Also we will not follow Mackenzie in interpreting the fluctuation spectrum as equivalent to the half spectrum of the frequency spreading. There is a close relation; but this also involves the phase spectrum, not to mention the phase relations between the two fluctuation spectra and the absolute levels of the two spectra. These various relations should help to identify the mechanisms responsible for fluctuations, and could well be investigated by a cross spectral analysis (compare § 12 and 13.3).

4. RESULTS

A chronological list of the c.w. experiments carried out is included for reference as table 1. There were, in addition, a few experiments with pulsed sound, notably between August and November 1964, and in April 1966, and some with explosion sources in June 1966 (see § 7). The main presentation of the results of the experiments is in figures 7 to 18, 20 to 28 and 31, though figures 4 to 6 already introduced also contain useful information.

A summary of the identified, expected or observed fluctuation mechanisms is given in table 2, and some other possible mechanisms are listed later, in § 12. The mechanisms in table 2 are arranged as far as possible in descending order of their predominant periods. The account in

TABLE 1. CHRONOLOGICAL LIST OF C.W. EXPERIMENTS

date	frequency/Hz	range/km	bearing/degrees	recording
June 1961	1041.7	137	002	film, B & K
July 1961	1041.7	137	002	film, B & K
Feb. 1962	1041.7	1.9	241½	film, B & K
Sept. 1962	1041.7	137	002	tape, B & K
Nov. 1962	1041.7	137	002	tape, B & K
Apr. 1963	1041.7	137	002	tape, B & K, phase pen record
Aug. 1963	1041.7	137	002	tape, B & K, phase pen record
Jan. 1964	2083.3	7.8, 10.0, 16	047, 059½, 269	tape, B & K, phase pen record
May 1964	2083.3	7.8, 10.0	047, 059½	tape, B & K, phase pen record
June 1964	2083.3	7.8, 10.0	047, 059½	tape, B & K, phase pen record
Mar./Apr. 1965	2083.3	3.9	082	tape, B & K, phase pen record
Apr. 1966	1041.7, 2083.3, 2998, 4167.7	137	002	tape, B & K, phase pen record

TABLE 2. SUMMARY LIST OF FLUCTUATION MECHANISMS

mechanism	predominant period	parameter affected	comment
(*a*) seasonal change in conditions–temperature structure, fish population, etc.	one year	mainly amplitude	transmission is best in winter
(*b*) seasonal change in mean temperature	one year	mainly phase	phase delay is greatest in winter
(*c*) fish shoaling	one day	amplitude	the level *changes* often occupy only about 10 min near dusk and dawn
(*d*) storms	several hours	mainly amplitude	transmission is reduced by the extra scattering loss, etc.
(*e*) changes in water depth	tidal	amplitude and phase	the changing mode interference patterns cause fluctuations at the tidal period or its harmonics
(*f*) changes in shear flow or water structure	tidal	amplitude and phase	the mode parameters can be greatly changed (especially above 2 kHz), causing fluctuations as in (*e*)
(*g*) changes in mean streaming velocity	tidal	phase	the phase delay is a direct measure of the resolved velocity component
(*h*) includes fish	a few minutes	amplitude and phase	see § 12 for complete list
(*i*) surface waves	many seconds	amplitude and phase	the magnitude of the effects is largely controlled by mechanisms (*e*) and (*f*)

the following sections is arranged in approximately the same order. This means that the discussion of a particular figure usually has to be split among a number of sections, since many fluctuation types affect the typical record. (This has made both the investigations themselves, and the presentation of results, difficult.) The method of measurement and analysis tends to change as one descends through the table. For a predominant period greater than about 1 h the level records or phasemeter pen records are most useful, the data sometimes being smoothed and replotted by hand as a function of time. For periods between about a second and an hour a digital analysis and presentation of Fourier spectra tends to be the most useful. Periods much shorter than a second are beyond the response of the phasemeter, and other techniques may be better (see § 13.3.).

The table 2 division into nine mechanisms is of course an arbitrary one. Each of the effects can be very large, and in suitable circumstances any one of the mechanisms might appear predominant. The list is by no means complete, since it includes only those mechanisms which have been tentatively identified. Part of the fluctuation energy with periods between a minute and an hour is due to mechanisms (*e*), (*f*) and (*h*), but possibly not all. The rest may be due to long surface waves, internal waves, bodily water movements, turbulence, etc. (see § 12)—but it is extremely difficult to prove any of these hypotheses.

5. SEASONAL AMPLITUDE CHANGES

It has been known for about half a century that shallow water propagation is better in winter than in summer (Aigner 1922). Some more recent demonstrations of this are reported by Macpherson & Fothergill (1962) and Weston (1963). The effect has been obvious in the present 137 km experiments, with a level difference of the order of 20 dB, but it has not been the intention to make this a major part of the investigation. One may speculate as to whether the signal character may also vary with season, due to differences in the number of effective normal modes, and experimental impressions are that this is the case.

Why should transmission be better in winter? It must be due to the seasonal changes in the environmental parameters, and there are many parameters of possible importance. One effect is the attenuation due to the presence of magnesium sulphate, which decreases as the temperature rises (Schulkin & Marsh 1962). This goes the wrong way since the magnesium sulphate attenuation will be greater in the winter, but anyway it amounts to only a few decibels at the frequencies of present interest. Another effect is the varying depth dependence of the temperature or sound velocity structure in the water. This means that in summer there will be full insonification over a restricted depth range, and transmission can go up or down depending on whether or not the transducers are within the given depth range. More important the mode parameters are affected, so that the refraction of the equivalent plane waves causes more frequent boundary reflexions, occurring at steeper angles. Mode attenuation is therefore greater in summer, and this is the explanation most frequently put forward. A third effect is the change in the acoustic properties of the sea bottom in summer, due to the presence of large quantities of gas (see, for example, Weston 1963). A possible fourth effect is due to the greater numbers or different behaviour of fish in the summer (Weston 1967*a*). Fish are known to produce a large attenuation at night during the summer, as discussed in § 7. It is difficult to determine the relative importance of these various effects, and there may be others unlisted. Relative importance will certainly depend on area, but it is thought that refraction and fish together should greatly outweigh the rest.

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6. Seasonal phase changes

The velocity of sound in sea water increases with temperature, and is therefore greatest in the summer. At that season the number of sound wavelengths between two fixed transducers will be least, i.e. the phase delay between the projected and received signal will reach its minimum. It should be possible to observe these seasonal changes in phase delay. In practice the changes or trends may be followed over comparatively short periods only, because count of complete phase cycles is lost if the equipment is switched off.

The first evidence for this is presented in figure 7, for 2 kHz sound propagated over a path of 7.8 km length. The most remarkable thing about this record is that it was possible to monitor phase continuously and on-line over a period as long as $5\frac{1}{2}$ days. In figure 7 (and figure 8) the amplitude record, the predicted phase variation, and the tidal oscillations in the observed

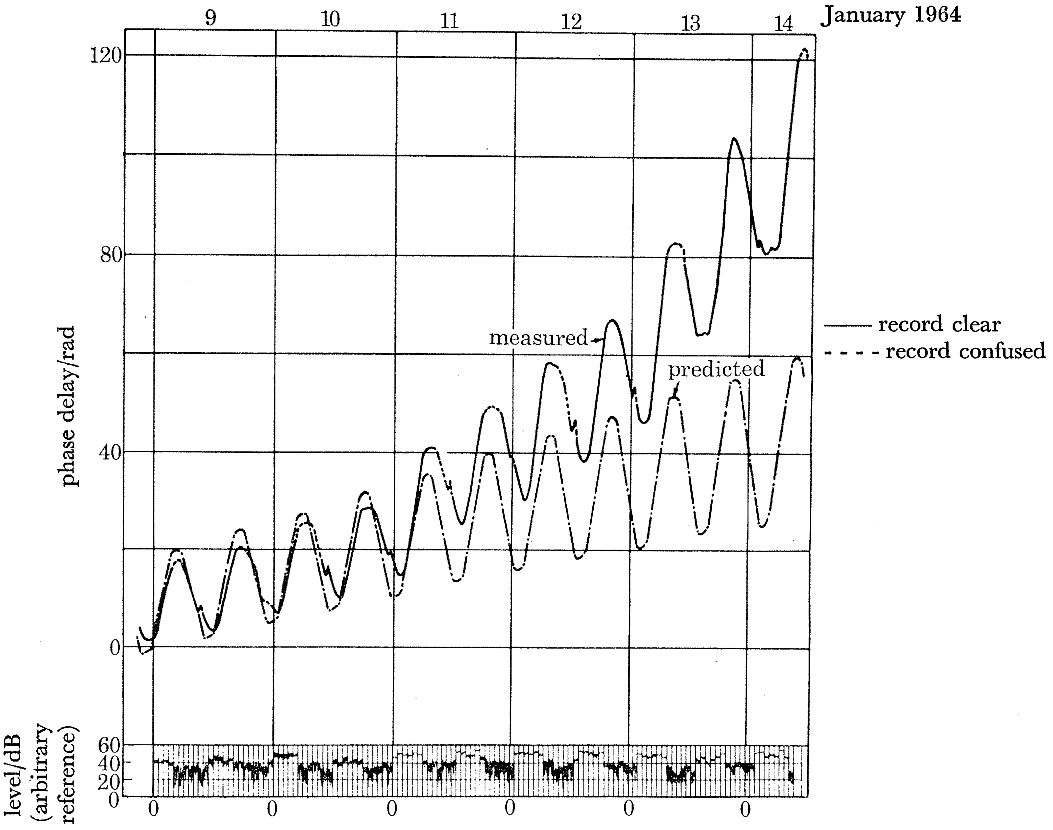

Figure 7. January 1964 fluctuations: measured and predicted phase curves and recorded amplitude samples (2083.3 Hz, 7.8 km, 047°). 1 min samples taken each hour for amplitude record.

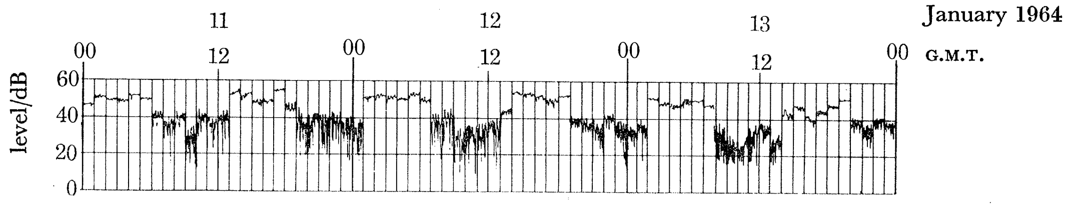

Figure 8. Larger scale version of some of recorded amplitude samples in figure 7 (2083.3 Hz, 7.8 km, 047°). 1 min samples taken each hour.

phase should all be ignored for the time being. There remains the long term trend, a smooth sweeping increase in phase delay, faster towards the end. About 100 rad or seventeen complete phase cycles are covered. The phase delay increases because the record was taken in January 1964, while the water was still cooling.

Three further experiments of this type have been carried out, and the results shown in figures 9 to 11. The duration of monitoring was steadily increased till it reached 31 days in the last experiment, though this did include a few short breaks. Another advance was made in the May and June 1964 measurements, when it was possible to receive and process the signals on two separate hydrophones. The curves for both hydrophones are included in figures 9 and 10,

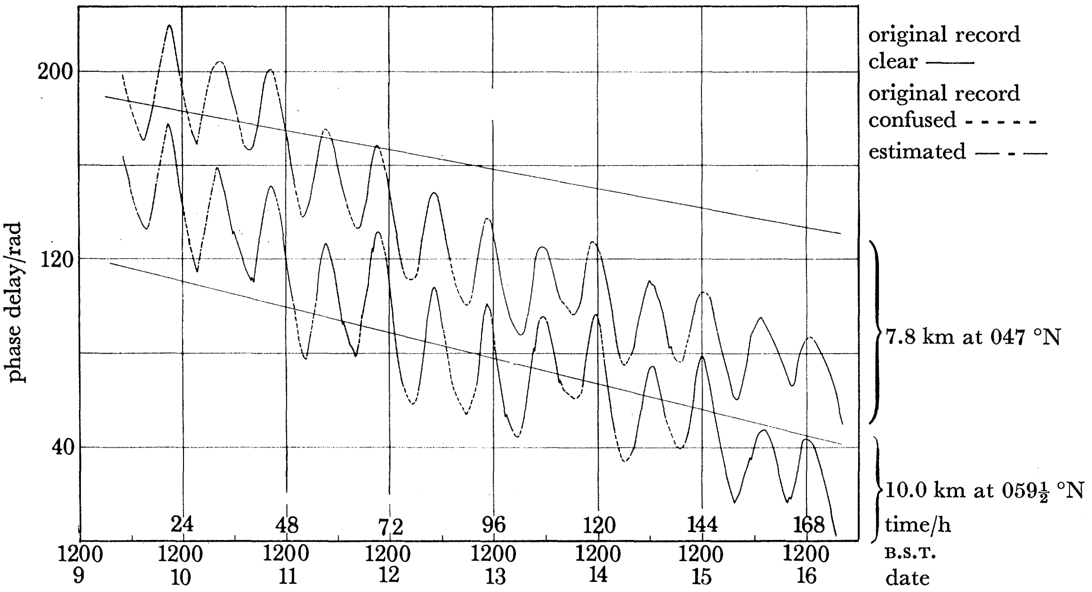

FIGURE 9. Measured (curves) and predicted (straight lines) phase curves in May 1964 (2083.3 Hz, 7.8 km at 047° and 10.0 km at 059½°).

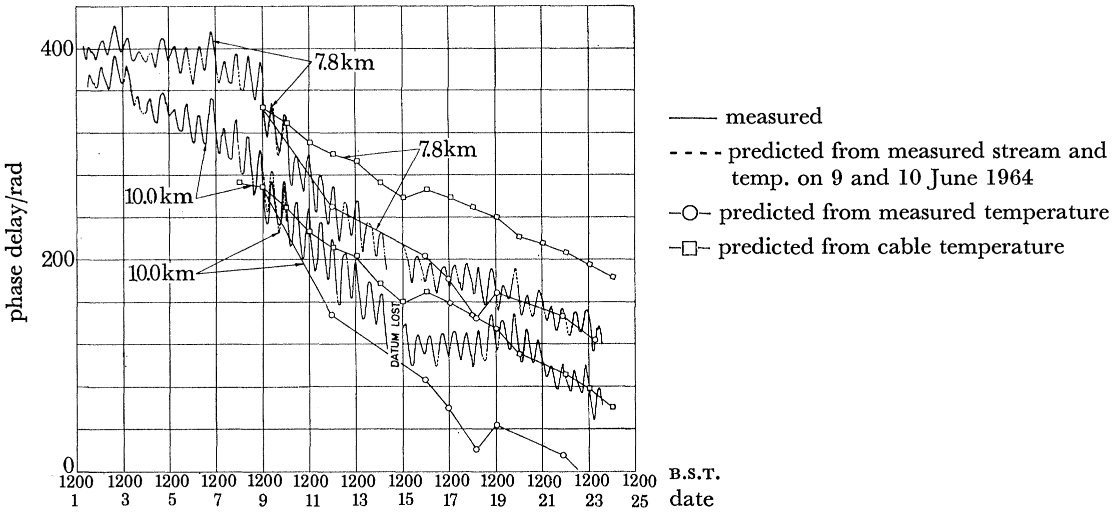

FIGURE 10. Measured and predicted phase curves for 22 days in June 1964 (2083.3 Hz, 7.8 km at 047° and 10.0 km at 059½°).

though regrettably this makes the displays very complicated. Towards the end of the January 1964 experiment a fault caused a loss of about 15 dB in the projector output. This made the phase tracking more difficult in May and June 1964, and reduces the reliability of the results. A repair had been made before March/April 1965. The tidal oscillations are again very evident in figures 9 to 11, but should temporarily be ignored. In the May 1964 experiment (figure 9) the water was warming up, so it was both expected and found that there would be a decreasing phase delay. This was true also for the records in June 1964 (figure 10) and March/April 1965 (figure 11). But the decrease was somewhat irregular on all three occasions. In fact the date of the March/April 1965 experiment was specially chosen to try and include the period of minimum temperature, corresponding to minimum sound velocity and maximum phase delay. The record (figure 11) shows that this occurred somewhere in the first half of the experiment.

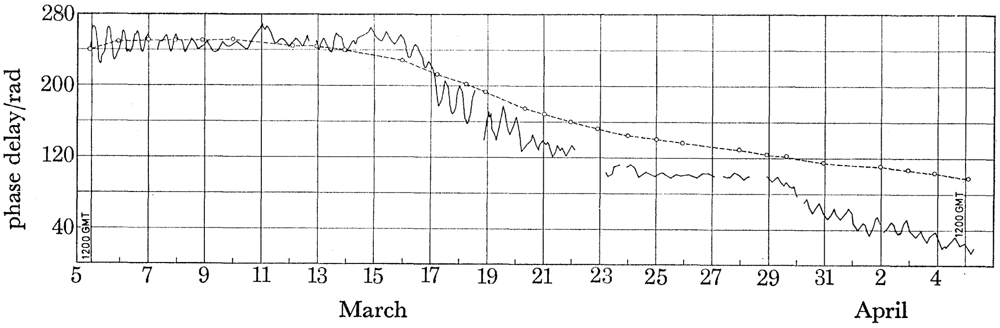

Figure 11. Measured (curve) and predicted (○- - -○) phase curves for 31 days in March/April 1965 (2083.3 Hz, 3.9 km, 082°).

The seasonal trends in all four short range experiments are summarized in table 3. In the last column the total phase change is divided by the range in km and the duration in days, to make intercomparisons easier. The rate of phase change behaves in the expected way through the seasons. The figures and table together show that the rate passes through zero about March, and will do so again after June (temperature maximum is actually in August/September). Numerically the highest rate recorded is 2.3 rad d^{-1} km^{-1} when averaged over $5\frac{1}{2}$ days, for 2 kHz transmission.

Table 3. Seasonal trend in 2 kHz short range phase measurements

figure	date	duration/days	range/km	extra phase delay/rad	rate of phase change/ rad d^{-1} km^{-1}
7	Jan. 1964	$5\frac{1}{2}$	7.8	+100	+2.3
9	May 1964	8	7.8	−140	−2.2
			10.0	−140	−1.7
10	June 1964	22	7.8	−270	−1.6
			10.0	−310	−1.4
11	Mar./Apr. 1965	31	3.9	−230	−1.9

Table 3 merely demonstrates that the behaviour is correct qualitatively. But it is possible to make a quantitative and more detailed check by calculation from the known seasonal temperature variation, assuming that effects due to salinity changes are negligible. It also assumes that the modal phase velocity is equal to the free space sound velocity, and since the waters inshore are usually isothermal this is justified. In figure 7 the seasonal prediction has been combined with the tidal prediction, but in figures 9 to 11 only the seasonal trend is predicted. In all four figures the prediction is based on the temperature as measured by cable resistance (figure 3). In figures 7 and 9 the prediction had to be made from temperature measurements at the right season but the wrong year, so the lack of detailed agreement is not surprising. In figures 10 and 11 the temperature measurements were made at the same time, but detailed agreement is still not there. This is presumably to be explained in part by the small difference in the depths and positions for the acoustic and temperature observations. This may also account for the predicted seasonal effects being in general too small. Figure 10 also shows some independent predictions based on conventional temperature measurements from various ships (H.M.S. *Egeria* and R.V. *Clione*). This time the predicted effect is on average too large.

The measurements above are all for short ranges, where the arriving signal is strong enough not to be blanked out by storms, enabling monitoring to be continuous over long periods. There are no reliable observations of seasonal trends in phase delay for the 137 km path, and it is remarkable enough that any phase results at all could be obtained over this range. But there are two experiments to look at briefly. One in April 1963 (figures 12, 13) lasted for almost

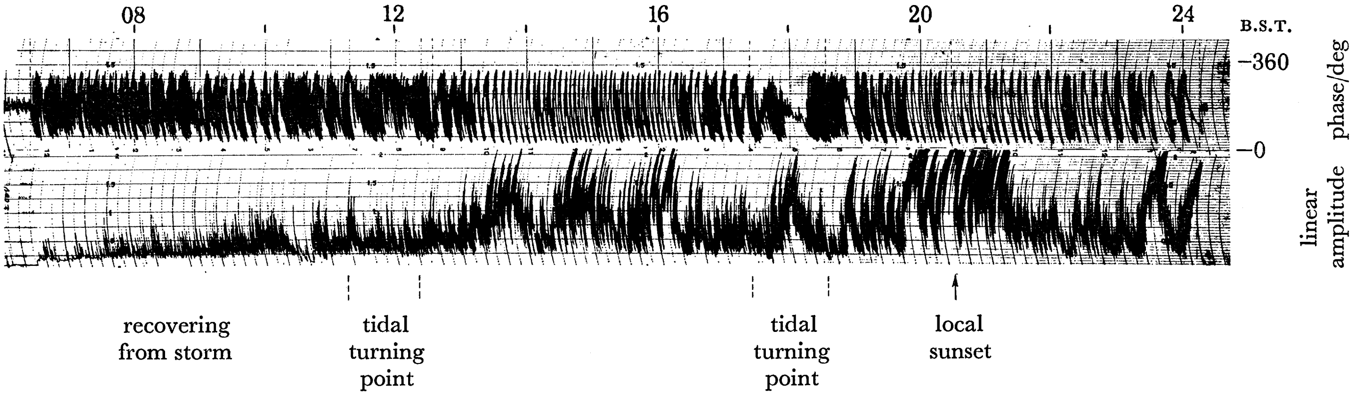

FIGURE 12. Phase and amplitude records in April 1963, 137 km, 1041.7 Hz (live record).

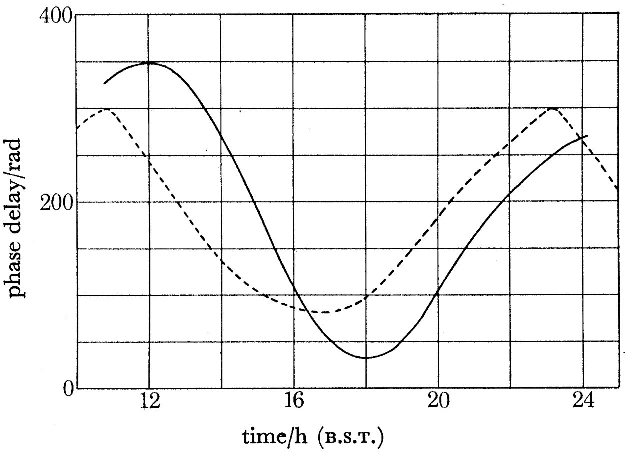

FIGURE 13. Measured phase curve (——) from figure 12 and calculated tidal streaming effect (- - -) (1041.7 Hz, 137 km).

one tidal cycle, with 1 kHz transmission. The major effect is tidal, but the asymmetry suggests there is some energy of a longer period. From the difference in phase delay of the two peaks, and the difference in the numerical value of the maximum upward and downward slopes, the seasonal trend is of the order of 200 rad per day. This gives 1.5 rad $\mathrm{d}^{-1}\,\mathrm{km}^{-1}$, or referring it to 2 kHz it becomes 3.0 rad $\mathrm{d}^{-1}\,\mathrm{km}^{-1}$ which is comparable to the rate over the shorter ranges. Another 137 km experiment in April 1966 (figure 14) showed at 2 kHz no evidence for the seasonal trend. It should be mentioned in passing that any theory for the 137 km phase would have to take into account the temperature structure. Sound tends to travel in a channel near the velocity minimum, and the modal phase velocity is often fairly close to the free space velocity near this minimum (compare § 9).

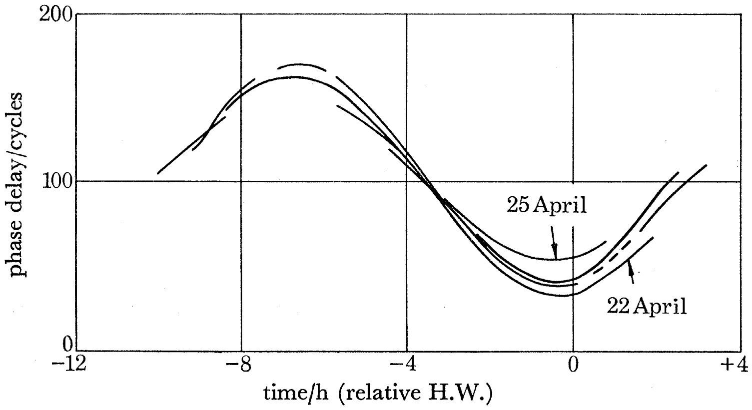

FIGURE 14. Measured phase curves for 21–25 April 1966 showing tidal streaming (137 km, referred to 2083.3 Hz).

7. ATTENUATION DUE TO FISH

7.1. *Longer ranges*

It is perhaps surprising that the underwater acoustics literature does not contain any information or speculation on long range attenuation due to fish. The only exceptions are the recent references based on the present work (Weston 1966, 1967*a*, *b*; Weston & Horrigan 1967). It is suggested that the degree of aggregation of the fish, which changes between day and night, will affect the attenuation.

The first and still one of the best pieces of evidence for the effect is shown in figure 15, which has already been reproduced in Weston (1967*a*). Look first at the top curve, where the mean level is relatively constant until about 40 min after sunset. Then, just as it gets really dark, the level falls about 30 dB in a few minutes. The measurement is limited by the ambient noise level in the 17 Hz wide receiving band, so the full drop may be much greater than this. At the time of this first observation the effect caused some consternation, and the equipment was thoroughly examined to find out what was wrong! Fortunately there was a repetition the next night, as shown in the third curve. Figure 15 also shows the reverse effect near sunrise; where the time scale is plotted backwards, so that for all four curves the horizontal scale is virtually one of light intensity. The morning effects occur about 25 min before sunrise, suggesting that the fish reactions lag 8 min behind the light intensity.

The figure 15 results for August 1963 prompted a re-examination of past records, and table 4 summarizes the information up to 1966 for fish effects over the 137 km path. One April night in 1966 a special pulse experiment was carried out, with three frequencies interleaved. These frequencies were separated when replaying the magnetic tape recording, as shown in figure 16. Observed attenuations were respectively 12 and 8 dB at 1 and 2 kHz, with no definite effect at 3 kHz. This experiment also calls attention to the facts that the 1 kHz attenuation at dusk apparently occurs later than the 2 kHz attenuation; the greatest changes occurred, respectively, about 45 and 20 min after sunset. This is supported by the other observations listed in table 4, mean values 41 and 22 min. But this is just one of the areas on which more information is needed; for example the dusk curve for 29 August in figure 15 suggests the attenuation comes in two stages, at 25 and 45 min after sunset.

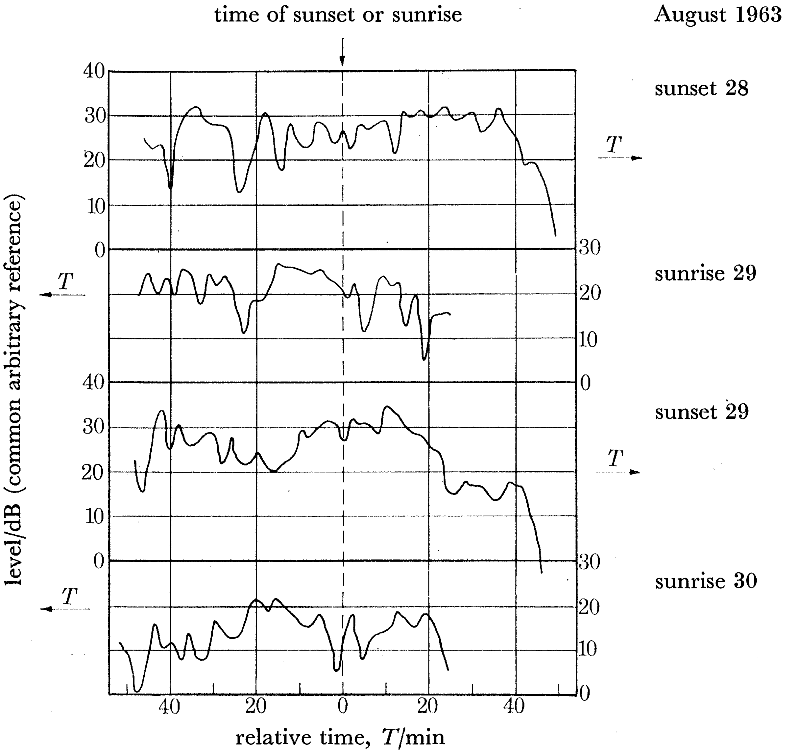

FIGURE 15. Illustration of fish attenuation: 1041.7 Hz c.w. signal level received from a source 137 km distant.

TABLE 4. FISH ATTENUATION OVER THE 137 km PATH

date	frequency/Hz	dawn enhancement/dB	timing rel. to sunrise/min	dusk attenuation/dB	timing rel. to sunset/min
July 1961	1041.7	—	—	no record, but about 20 noted	—
Sept. 1962	1041.7	—	—	about 10	+39
Apr. 1963	1041.7	not signif.	—	not signif.	—
Aug. 1963	1041.7	over 30	−25	over 30	+40
Apr. 1966	1041.7	obscure	—	mean 13	+45
	2083.3	about 15	about +75	mean 11	+22
	2998	—	—	not signif.	—

Some special experiments to extend the frequency coverage were carried out, using as sound sources underwater explosions of 1 lb (0.45 kg) T.N.T. charges fired by A.C.S. *St Margarets*. The shots were fired at 2 min intervals for about an hour on either side of the expected effects. There were three experiments; at 70 km range near sunset on 1 June 1966, at 70 km range near sunrise on 2 June 1966, and at 93 km range near sunset on 6 June 1966. The arrivals were examined wideband and also separately in the three octaves from 400 Hz to 3.2 kHz, there being little received energy outside these limits. No dusk or dawn effects were observed at all, probably due to the time of year.

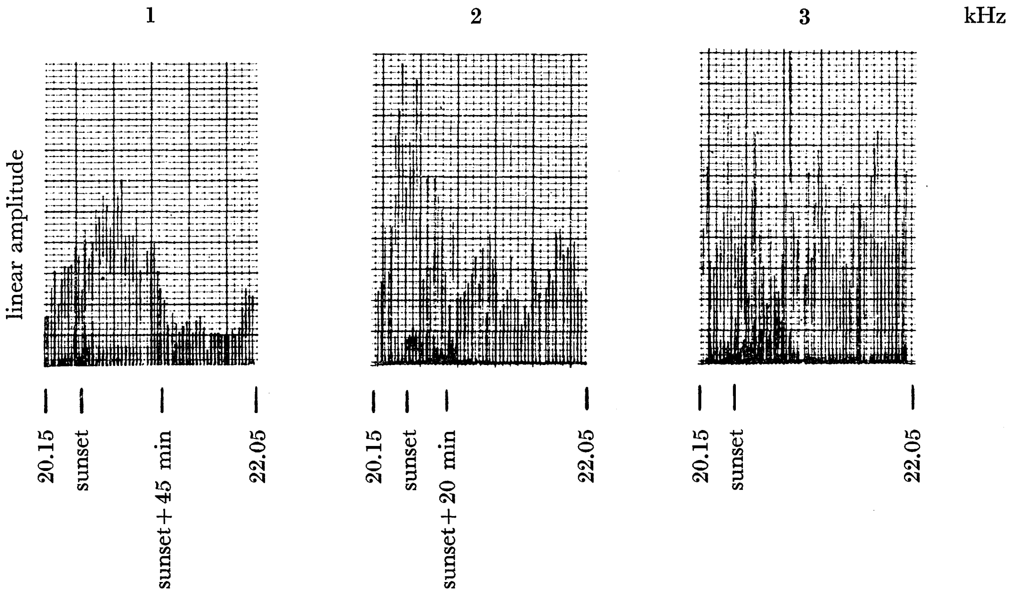

Figure 16. Multifrequency pulsed records over 137 km path, near sunset in April 1966.

7.2. *Shorter ranges*

Some results showing fish attenuation over a 23 km path were obtained using pulses, and are summarized in tables 5 and 6. They are illustrated in figures 17 and 18 with 20 h sections of level records having 50 dB logarithmic scales, and centred on local midnight. The first results (table 5) were at 1 kHz only, and showed no fish attenuation in September 1963 but a

Table 5. Fish attenuation over the 23 km path for wideband 1 kHz pulses

date	dawn enhancement/dB	timing rel. to sunrise/min	dusk attenuation/dB	timing rel. to sunset/min
4 Sept. 1963	—	—	not signif.	—
10 Sept. 1963	—	—	not signif.	—
11 Sept. 1963	not signif.	—	—	—
25 Aug. 1964	—	—	20	+29
26 Aug. 1964	19	−31	12	+39
27 Aug. 1964	24	−29	—	—
1 Sept. 1964	—	—	12	+45
2 Sept. 1964	17	−51	27	+42
3 Sept. 1964	20	−30	27	+37
4 Sept. 1964	17	−47	—	—
mean of 1964 results (i.e all positive results)				
	19.4	−38	19.6	+38

large effect for the same period in 1964. The later results are shown in table 6, the chief difference being that pulses of three different frequencies were transmitted sequentially. As shown the 870 Hz attenuation is about 8 dB up on that at 1 kHz, but apart from this figure 18 shows there is a very close correspondence in shape. The third frequency was 1200 Hz on 14/15 September 1964 and 2 kHz the rest of the time. There is evidence for a real effect, perhaps averaging a few decibels, at the third frequency—but it was generally too obscure for reliable measurement. Taking all 23 km results together, the major effect seems to occur in September, although there is much variability both day-to-day and year-to-year.

The 1964 results also tend to show a progressive change in character (figures 17, 18). The earlier records show a dip in level near dawn and dusk, perhaps lasting only about half an hour

Table 6. Fish attenuation over the 23 km path for tone pulses

	dawn/dB		dusk/dB	
date	870 Hz	1 kHz	870 Hz	1 kHz
14 Sept. 1964	—	—	20	15
15 Sept. 1964	25	20	—	—
21 Sept. 1964	—	—	30	15
22 Sept. 1964	25	17	25	20
23 Sept. 1964	12	12	—	—
5 Oct. 1964	—	—	15	10
6 Oct. 1964	20	not signif.	—	—
mean	20.5	12.3	22.5	15

No significant attenuations were found on 4, 5, 18, 19, 20 November 1964.

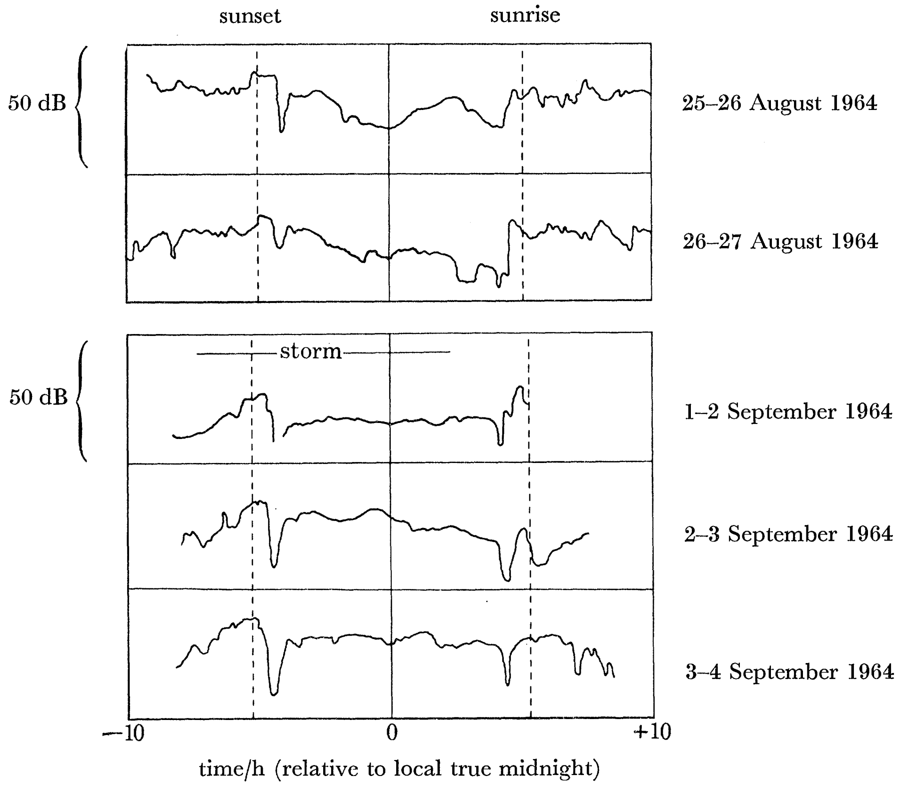

Figure 17. Amplitude records through the night for wideband 1 kHz pulses over a 23 km path, showing fish attenuation.

During most of the night the level recovers practically to its daytime value. The later records show a single great bowl-shaped depression lasting the whole night, and typically reaching its lowest level only in the middle of the night. The changes are gradual and timing ill-defined, hence the omission of times in table 6.

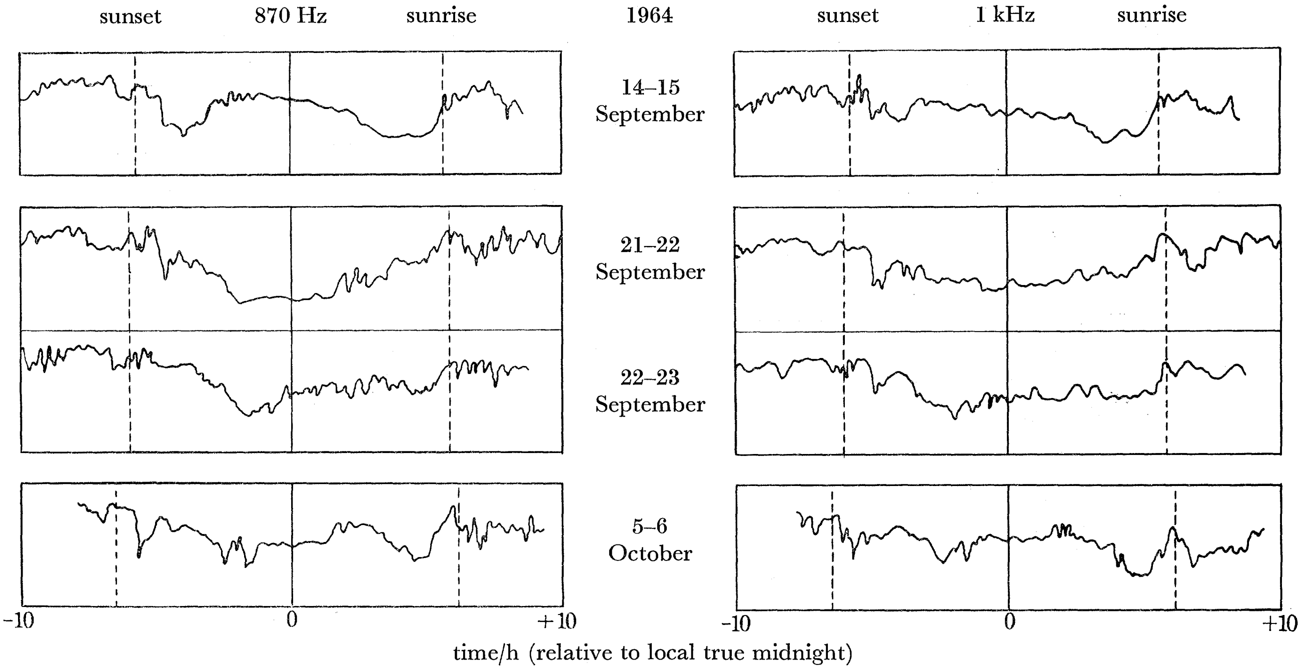

Figure 18. Amplitude records through the night for various tone pulses over a 23 km path, showing fish attenuation.

Some June 1964 results over 7.8 and 10.0 km paths (figures 20, 22) are discussed in § 11. There appears to be a small attenuation in the *daytime*. The other interesting point is of a different nature since there are diurnal changes in character, with greater fluctuation in daytime.

On very many occasions the outputs of up to three very close hydrophones have been monitored, for ranges between 1 and 2 km. Results have always been negative. This is not to deny the possibility of fish attenuations up to say 2 dB, but such effects cannot normally be measured. In particular this monitoring has included the period 26 August to 4 September 1964 (corresponding to some of the 23 km data in table 5) and April 1966 (corresponding to some of the 137 km measurements in table 4). These negative results are important since they rule out the possibility that the positive results at other ranges are due to the clustering of fish round the projector, thus decoupling it from the medium. The positive results could admittedly be due to clustering round the receiver, but it is unlikely the fish would always pick the distant hydrophones and never the close ones. It is not intended to imply that local effects can never occur nor that attenuation will always increase in a linear manner with range, since the concentration of fish is also likely to vary along the propagation path.

7.3. *Discussion*

It has been assumed throughout that fish are the cause of the large attenuations observed. The chief justification for this is the timing of the effects, which implies organisms sensitive to the light intensity. The timing of the break-up of fish shoals at night and the morning formation of shoals is known to be similar. Further justification comes from the numerical agreement obtained in the next paragraph. Accepting that fish are responsible, what are the details of the mechanism? Since decoupling of the transducers is ruled out, an effect along the sound path must be looked for. The obvious and favoured mechanism is due to those pelagic fish having swim bladders, which swim in shoals by day and as individuals at night. The swim bladder gives the fish an acoustic resonance at a surprisingly low frequency, and a high target strength over a wide frequency range. During the night the propagation of sound may be likened to looking through a mist, each fish both scatters and absorbs sound to produce in total a high attenuation. During the day the fish are close together in the shoals, and the scatterers interfere with one another (Weston 1967*a*). This is like the mist droplets coalescing into rain droplets, when one can see much further. A rival explanation refers to the bottom living fish, which may temporarily swim upwards in the water column near dusk and dawn. Even if this is not the chief cause it may sometimes contribute. Whatever the cause the effects are very large, since attenuations in excess of 1 dB km^{-1} have been measured. Although the changes are particularly large near dawn and dusk, the records show that the effects are not restricted to these times. All this has led to the suggestion that fish may be at least partially responsible for other propagation phenomena: the normal attenuation in shallow water (Weston 1967*a*, *b*), but not in deep water (Weston 1966, 1967*a*), seasonal effects (§ 5 and Weston 1967*a*), and the fluctuations of a few minutes period (§§ 11 and 12).

To make a quantitative calculation of numbers of fish from the observed attenuation it is necessary to know the size of fish, resonant frequency and depth. Knowledge of any two of these parameters is sufficient to determine the third, within narrow limits. In practice each of the parameters will show a range of values rather than a single value. There is insufficient information for a reliable calculation, but since the basic calculation is so simple it is worth proceeding a certain way. The methods will follow Weston (1967*a*), and the errors will be considered at the end. For a plane wave, attenuation in dB m^{-1} is

$$\alpha = (10 \lg e) N\sigma_e$$

where N is concentration (number of fish per unit volume) and σ_e is extinction cross section of a single fish. This extinction cross section is the sum of the scattering and absorption cross sections. For an attenuation of 1.08 dB km^{-1} (2 dB per nautical mile) which is appropriate at 870 Hz

$$N\sigma_e = 2.5 \times 10^{-4}\ \mathrm{m^{-1}}.$$

A cautious figure for N is obtained by assuming resonance, when a suitable formula for σ_e is

$$\sigma_e = \frac{\lambda^2}{\pi}\frac{Q}{Q_r} = 0.19\ \mathrm{m^2}.$$

Here Q is the overall Q factor and Q_r the Q factor for radiation damping alone, and the assumed values of 5 and 25 respectively are guesses appropriate to a fish fairly near the bottom in the water depth of 33 m. We can now calculate N, and also N' the number of fish per unit area of sea, in a variety of forms

$$N = 1.3 \times 10^{-3}\ \mathrm{m^{-3}},$$

$$N' = 4.6 \times 10^{-2}\ \mathrm{m^{-2}}\ (190 \text{ per acre; } 1.6 \times 10^{5} \text{ per square nautical mile}).$$

One of the commonest swim bladder fish in the area is the pilchard, and in some trawling carried out by R.V. *Clione* in June 1964 the mean length of the pilchards caught was 23 cm (private communication from F. R. H. Jones of Lowestoft Fisheries Laboratory). Guess the mean fish weight as 100 g (0.22 lb). Assume temporarily that similar fish were responsible for the observed attenuation, despite the fact that the calculated resonance frequency is slightly too low. N' values above may be converted to a mass concentration or weight of fish per unit area M'

$$M' = 4.6\ \text{g m}^{-2}\ (42\ \text{lb/acre};\ 16\ \text{ton/square nautical mile}).$$

The above figures seem reasonable, especially if it is remembered that they refer only to that part of the fish population within about 10% of the size specified. But different assumptions can change the figures drastically, so consider two further possibilities. In the first the resonant fish are taken to be swimming relatively near to the surface, where the calculated fish length is 9 cm. The Q_r/Q ratio is now probably nearer 10 than 5, so σ_e is halved. In addition, the Lloyds Mirror effect near the sea surface reduces the acoustic pressure, and thereby also reduces the effectiveness of the fish as agents of attenuation. The 3 dB point will come at a depth of a few metres, and the effect must be balanced by postulating more fish. The above N and N' values must be multiplied by at least 4, perhaps much more. But the weight per fish is down by a factor 16, so the M' values could move either way.

The second possibility is to abandon the resonance hypothesis. Well above resonance the extinction coefficient is less by the approximate factor QQ_r, or about 125. Thus for 23 cm pilchards swimming within a few metres of the surface the above N, N' and M' figures must all be multiplied by 250, or perhaps much more. In addition, away from resonance the attenuation with the fish dispersed is not necessarily greater than that with the fish in shoals.

The biggest uncertainty in our measurements is what happens below 870 Hz. This is pointed up by the calculations, which are not worth refining till better information is obtained as a function of frequency. Experimental studies of this type are in fact in progress.

8. Storms

It is well known that storms can raise the level of ambient noise, and also raise the surface reverberation. There is rather less information on the effect of surface conditions on sound transmission (see Weston 1963; Marsh, Schulkin & Kneale 1961). The transmission loss can grow very rapidly as the wind and waves build up, reaching dramatic proportions, so it is justifiable to refer to storm rather than wind. When observations are made for some period over a fixed range the effects of storms become qualitatively very obvious, and have been noticed on a large number of occasions in the present work. But quantitative records for the storms are not always good, much better ones have been obtained since the end of the reporting period in 1966, and so the present account will be relatively short.

The only record published here, which includes a storm effect, is figure 12. The early part corresponds to a period of recovery from a severe storm which had raged for the two previous days. The recovery is visible on both the phase and amplitude records, the latter showing a rise in level which approaches 20 dB. But note that storms can cause level changes which are much greater than this, a considerable factor greater even if changes are expressed logarithmically. The most rapid changes in shallow water propagation are seen for wind speeds of about 15 m s^{-1} (30 knots). Wind strength is a convenient measure for storm effects, but is obviously not the immediate cause of the acoustic attenuation. It is in fact observed that the acoustic effects lag behind the wind conditions, and the tail of the effect may persist long after the storm has gone. Some particularly interesting evidence on storms was collected in April 1966: as the wind strength increased the 3 kHz signal was lost first, followed by the 2 kHz signal and last the 1 kHz signal.

What secondary effect or effects, lagging behind the wind, can cause the acoustic loss? The most obvious is the mean height of the surface waves, with wave period and direction also playing some part. These waves scatter the acoustic energy into steeper angles, and it is eventually lost into the bottom. One might also expect some effect with a swell coming from a distant source, unaccompanied by wind, though in this case the wave slopes are very low compared to those for a local storm. A second possibility is the entrainment of air bubbles, which both scatter and absorb the propagating sound. A third mechanism is the breaking up of the fish shoals in storms, which is known to occur. The dispersal of the fish can raise the attenuation, as studied in § 7. It is also known that after a storm the fish may be quite slow to re-form into tight shoals. The fish mechanism in storms might not be so important in the winter, nor at night. The fourth mechanism is of a different type; the wave induced turbulence can erode the isothermal or surface layer into the underlying thermocline. Leaving aside the possibility of effects due to the turbulence itself, there is an irreversible deepening of the wind mixed layer. This mechanism is described as different because it produces a permanent change which can either improve or worsen the sound transmission. It is thought that all four of these mechanisms can be important.

9. Introduction to tidal effects in sound propagation

There are several different aspects to the tidal phenomena, which it is worthwhile introducing before the reader is confused by data. The phenomena may be summarized by saying that there are four different mechanisms which together produce three types of acoustic effect. The mechanisms are the tidal changes in water depth, the tidal streaming, the depth dependence of the tidal streaming, and the tidal changes in water structure. The effects concern signal amplitude, phase, and character.

Water depth is important because it controls the modal interference pattern. This pattern arises because effective propagation in shallow water is limited to a small number of travelling normal modes or waveguide modes. These modes beat together in space to form a spatial interference pattern. The phase velocities of the modes depend on the water depth, so for a given mode the arrival phase also depends on the water depth. More important, the scale of the interference pattern also depends on water depth. As the depth is reduced the pattern is compressed, as depth is increased the pattern is expanded. With transmission between fixed transducers the pattern is swept past the receiver by the tidal changes in water depth, and the spatial variation is converted to a temporal variation. The effect produces related fluctuations in the amplitude and phase of the signal. For the shorter ranges the result should be simple, perhaps one would be swept from an interference peak to the neighbouring trough and back. The basic acoustic fluctuation would then have the same period as the water depth changes, i.e. the period of the semi-diurnal tide. But for the longer ranges the sweeping might be through several interference peaks, so that the period of the typical acoustic fluctuation would be much less than the tidal period. In practice this range dependence is counter balanced by the increasing simplicity of the acoustic field at the longer ranges, since the number of effective modes is reduced. The interference effects are quite simply calculable for two modes in isovelocity water (see Weston 1960), but become more complicated for larger numbers of modes and for layered water (Weston 1969). For the closer ranges and higher frequencies it is convenient to describe propagation in terms of rays rather than modes, but an almost identical argument holds for the ray interference patterns.

The character of the signal is greatly influenced by the fluctuations of several seconds period, which in turn are caused by the sea surface waves. The relative magnitude of these fluctuations depends critically upon the position in the above interference pattern, it is small when at a peak and large at a trough. Conversely, these faster fluctuations can help to fill in a deep interference trough, as discussed in § 13.

Next consider the tidal streaming. As far as the sound is concerned one merely adds to the local sound velocity the component of tidal flow resolved in the propagation direction. The mean streaming motion should not affect signal amplitude, but should produce a sinusoidal variation in phase which can be of very large amplitude. One should be careful to use the appropriate value for the streaming velocity, e.g. when there is temperature layering the acoustic energy may be virtually restricted to the lower half of the water column. The gross phase change due to the mean streaming is usually much greater than the gross change caused by the other variations in the phase velocity of the predominant mode. But in other circumstances, e.g. at much lower frequencies, the tidal depth changes might cause the greater effect.

At a given time and place the tidal streaming is not a constant, but varies considerably with depth, giving a shear flow. This depth dependence produces a refraction, which for sound travelling nearly horizontally may be computed with good accuracy by adding to the local sound velocity the resolved component of tidal flow. A more general theory is given by Keller (1955), but is unnecessary here. The idea of refraction due to a variable streaming velocity is not new, but seems to have been neglected in considering long distance propagation. It is of interest here for shallow water, but should be of significance in deep water too. Various measurements of the depth dependence of the streaming have been reported in the literature, e.g. Bowden, Fairbairn & Hughes (1959). The magnitude of the effect is summarized in a book compiled by Warburg (1945). For water depths less than 20 m the effect is negligible, but for water depths between about 40 and 100 m the approximate and empirical relation shown in figure 19 may be used round the British Isles. The shape is virtually the same for all depths between 40 and 100 m, the curve in figure 19 being stopped at the appropriate depth, except that for the last few metres above the bottom there is a rapid and logarithmic fall in velocity to zero. The general variation as in figure 19 is not contradicted by current measurements in our working area made by H.M.S. *Egeria*, R.V. *Clione* and other vessels; but it has become obvious that the complete picture is much more complicated. Any rapid changes near surface and bottom will be unimportant in acoustics, except at the higher frequencies. But a large effect remains, for a 0.5 m s^{-1} surface current there is a 0.2 m s^{-1} depth variation. A sound velocity difference of 0.2 m s^{-1} would be produced by a pressure difference equivalent to 11 m head of water, or a temperature difference of 0.06 °C, and will cause refraction through 55 min arc. These figures show that the effect might not be important in the presence of strong thermal layering, but could be of great significance under near-isothermal conditions. In the deep water application, where the streaming velocity variations are comparable to those in shallow water, this implies importance in surface duct propagation. The interesting point about streaming depth dependence is its tidal modulation, the *whole* effect is reversed every 6 h approximately.

What are the acoustic implications in shallow water? At the lower frequencies the ray angles associated with the normal modes are much greater than the above 55 min arc, and the streaming depth dependence is not noticed so much. The effect on the mode parameters becomes more important for frequencies of about 2 kHz and above (Weston 1969), and qualitatively may be split into two parts. First the gross depth dependence of the sound intensity can be affected, together with the boundary losses and the mean attenuation rate. Secondly, the interference between the various modes will be changed, and one must consider the sum of the depth change and streaming change effects. The depth change effect taken alone should produce interference patterns symmetrical about high and low water; whereas the streaming effect, if symmetrical at all, will have a different point of symmetry. Acting together the effects should in general produce asymmetrical patterns, repeating at the tidal period. Besides causing both the mean level and the interference to vary through the tidal cycle, the presence of the tidal streaming means that at any given time the propagation will not obey the reciprocity law.

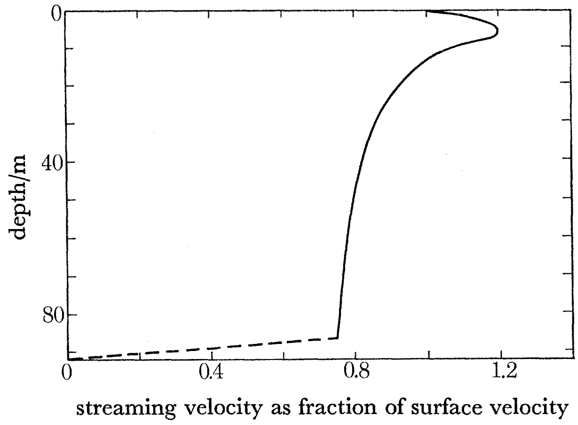

FIGURE 19. Typical depth dependence of tidal streaming velocity in shallow water. (For water depths of 40 to 100 m.)

A third streaming effect can be to introduce water masses of different acoustic properties into the sound path, and this effect is related to the possibility of having tidal-period internal waves. This introduction could produce gross changes in phase delay through the tidal cycle, to be added to the phase effects produced directly by the mean streaming motion. But perhaps more important, the varying refraction will affect the interference pattern, and this will have to be added to the depth change and shear flow effects. All these phenomena may have points of symmetry at different times in the tidal cycle.

The experimental data on these phenomena are presented in §§ 10, 11 and 13, together with further discussion.

10. TIDAL STREAMING EFFECTS

10.1 *Long range*

In this section the gross effect of the mean tidal streaming on the phase will be treated. Attempts to measure the long period effect were made from June 1961 onwards, but the phenomenon was not positively observed and identified until April 1963, for 1041.7 Hz transmission over the 137 km path. The original pen recording has been reproduced in figure 12, and the deduced phase variation as figure 13. Over one tidal period the peak-to-peak variation is through 317 rad or about 50 complete cycles! The smooth sinusoidal form of the curve points to one advantage of long range measurements: any interference effects should produce fluctuation through less than one cycle (2% of the total swing), and anyway at this range most of the 1041.7 Hz energy arrives in the first mode. A disadvantage of the 137 km path is that it tends to lie across the main direction of tidal streaming (figure 1). Thus only a small component of the stream is effective, and components at either end of the acoustic track may sometimes oppose one another (±25 cycles corresponds to $\pm 0.4\ \mathrm{m\ s^{-1}}$ stream). Considering these uncertainties, the curve predicted in figure 13, from published information on streaming, is in good agreement with experiment. The amplitude agreement is close and the timing is out by 1 h (after allowing for the seasonal trend). The magnitudes of the effects from the brief successful measurements at 1041.7 Hz in June 1961 (figure 6) and September 1962 agree with the figure 13 curve.

Chronologically the next work was at the shorter ranges, but it is convenient to pass first to the experiments across the 137 km path for several days in April 1966, usually at 2083.3 Hz but sometimes at 1041.7 Hz. Phase monitoring was possible only part of the time for a number of reasons, including the strong one of insufficient signal. Figure 14 shows the result, the measurements on separate days being patched together (i.e vertically shifted to give the best fit) to define a clear sinusoid. The amplitude differences between the sinusoids are real, since spring tides occurred on 22 April. A typical value for the peak-to-peak variation during this period is 110 complete cycles, corresponding to $\pm 0.43\ \mathrm{m\ s^{-1}}$. The degree of agreement with prediction (not shown) is similar to that in 1963, with timing error again one hour.

10.2. *Short range*

The short range measurements in figures 7, 9, 10 and 11 have already been introduced and their long term trends discussed, so we are now ready to examine the tidal streaming sinusoidal curves. It is much easier to organize measurements over a short path, with a signal/noise ratio generally good and all transducers cabled back to the same place. This is why the short range measurements could be extended to 31 days (figure 11). The first measurements, in January 1964 (figure 7), are still some of the cleanest. There is extraordinarily good agreement between the measured and predicted tidal curves, for both the amplitude and timing of the sinusoidal curves. When there are minor differences there is no reason to disbelieve the measurement, since small variations from the predicted tide are quite common. Figure 7 shows clearly the change in amplitude from neaps at the beginning of the record nearly to springs at the end. The experiments indicate a gradual change in streaming velocity from ±0.18 to $\pm 0.36\ \mathrm{m\ s^{-1}}$, the direction being almost parallel to the tidal stream. These effects are also shown in figures 9, 10 and 11; note especially the cycle of neaps and springs in the longer records. In June 1964 some measurements of temperature and current (as a function of depth) were made near the acoustic path during the experiment, by H.M.S. *Egeria* and R.V. *Clione*. The detailed predictions for 9–10 June in figure 10 agree very well with the experimental curves.

Some of the curves (e.g. figure 7) show irregularities which are due to interference effects as discussed in the next section. The remaining discrepancies or distortions (see, for example, figure 11) may be due to the tidal introduction of hotter or colder water.

Both the long and short range results reported here show very clearly the influence of the semi-diurnal tide, as expected. But this is in contrast to results obtained in the Straits of Florida, where in admittedly different environmental conditions the predominant tidal effect was diurnal (Steinberg & Birdsall 1966; Clark *et al.* 1966). Visual examination of the present records does not show up a diurnal tidal component, but a Fourier analytical approach for the most suitable record (January 1964, figure 7) does show a significant component. Its amplitude is about 5% of that of the semi-diurnal component, which is of the order to be expected from the reported tidal height variations.

11. Interference effects and the tidal influence

11.1. *Amplitude patterns*

Definite interference patterns have been seen at short ranges and presumed patterns at the long 137 km range. There is comparatively little to say on the 137 km range because both the records and the situation are confused, but we will say this little bit first. The confusion arises partly because with c.w., as opposed to pulses, it is not easy to distinguish artifacts such as shipping noise from the true signal. The remainder of the confusion is due to the complicated behaviour of the signal itself. Calculations (Weston 1960, 1969) make it appear that, in the 1 to 2 kHz region over the 137 km path, one should be swept through some half dozen cycles of the first mode/second mode interaction pattern between high and low water. This suggests the typical interference period should be of the order of an hour. This much is supported by the amplitude results: see, for example, figures 12 and 15 at 1 kHz and Weston & Horrigan (1967) for 2 kHz. The best display is obtained with a level recorder running at a very slow paper speed. At 1 kHz the effects seem more obvious in the winter than in the summer, possibly because the relative level of the second mode is very low in summer. The 2 kHz amplitude fluctuations seem faster than those at 1 kHz. Similar fluctuations should be present in the phase at 137 km, but are difficult to see because of the drift due to the tidal streaming. It is not worth pursuing the various long range problems at this stage, since more useful experimental results are currently (1967) being obtained.

For all the shorter range work the tidal changes should sweep through less than one cycle of the first mode/second mode interaction pattern, despite the fact that the depth variation can reach 7 m in water of mean depth only about 33 m. But the result is still quite complicated because of the presence of higher modes. Without knowing the precise levels of excitation of these modes it is impossible to predict the details of the patterns. Patterns were observed in an earlier 4 kHz experiment in the same area (Weston, Smith & Wearden 1969). A good example of an amplitude pattern has already appeared in figure 4 for January 1964, where if one neglects the faster (seconds period) fluctuations there is still a variation through about 25 dB. On simple theory, neglecting effects due to depth dependence of tidal streaming, there should be a symmetrical pattern about the times of high and low water. The relevant times in figure 4 are at approximately 14.00 (high), 20.00 (low), 03.00 (high) and 07.00 (low). Out of these four possibilities the pattern centred on 03.00 may readily be seen, and this pattern is very striking. Symmetry extends to about ± 8 h. On inspection, patterns of very imperfect symmetry may be seen for the other central times, and in addition there is a degree of matching between the two high water patterns and between the two low water patterns. The number of peaks in the overall pattern shows that there are contributions from more than two modes, probably three or four effective modes are taking part at this range.

The more complete amplitude pattern for the January 1964 experiment is included in figure 7, and part is shown on a larger scale in figure 8. This record is synthesized by putting together hourly samples of the level record, each lasting 1 min. This produces a record of manageable length, but at the same time preserves the short period character. The display brings out clearly the tendency for there to be just two amplitude régimes at this range, a high level interference maximum followed by a low level interference minimum of similar duration. They are separated by some 20 dB in level, not to mention changes in character of the faster fluctuations to be discussed in § 13.

The amplitude interference patterns may be seen in all the close range results. There are real differences in behaviour at different ranges, with both a systematic and an irregular dependence on range. For example, if results at 3.9, 7.8, 10.0 and 16 km are compared over a period, the behaviour is found to be simplest at 16 km. But at extremely close range, fractions of a kilometre, there may again be comparatively little variation since one ray arrival may predominate.

11.2. *The June 1964 amplitude patterns*

Figure 20 shows a further collection of short range level records, covering the same two ranges and the same period in June 1964 as the smoothed phase record reproduced in figure 10. Each record is displayed on a 50 dB logarithmic scale. For both the 10.0 and 7.8 km ranges the originally continuous record has been cut up into $12\frac{1}{2}$ h tidal cycle segments, each centred on the time of high water. When stacked one below the other several periods of fluctuation may be seen, some not having been observed previously. The grey shading visible in parts of figure 20 (and figures 21 and 22) is an artifact.

Perhaps the most obvious feature is again the symmetry within the tidal segments. At 10.0 km eight out of the 39 complete segments show some symmetry, and of these four show it clearly. At 7.8 km 20 show some symmetry, and 11 of these show it clearly. If there is symmetry for the one range it also tends to occur for the other, and is specially likely to occur for the period midway between neaps and springs. A particularly good example at both ranges appears in the record labelled a.m. 7 June. As shown by the above numbers, symmetry is more common at the 7.8 km range, and in addition always tends to have the same form. The central part is a high flat plateau, and this is surrounded by a low region of rough appearance (due to the wave period fluctuations). The repetition of this form shows that there is also an obvious symmetry about the time of low water.

A second feature of figure 20 is the slow change in the pattern for both ranges through the cycle from neaps to springs. This is seen most clearly for the 7.8 km results, the smooth central plateau disappearing for several tidal segments at and before each period of neaps. In passing it may be noted that the mean levels seem particularly high near the second period of neaps around 18 June.

The third feature contradicts the first. Following the discussion in § 9, it was expected that the tidal changes in shear flow and water structure would destroy the pattern symmetry, and replace it by a repeating but asymmetrical pattern. This does not usually happen, as already described. But on searching for this effect strong evidence for it was found, for the 10.0 km

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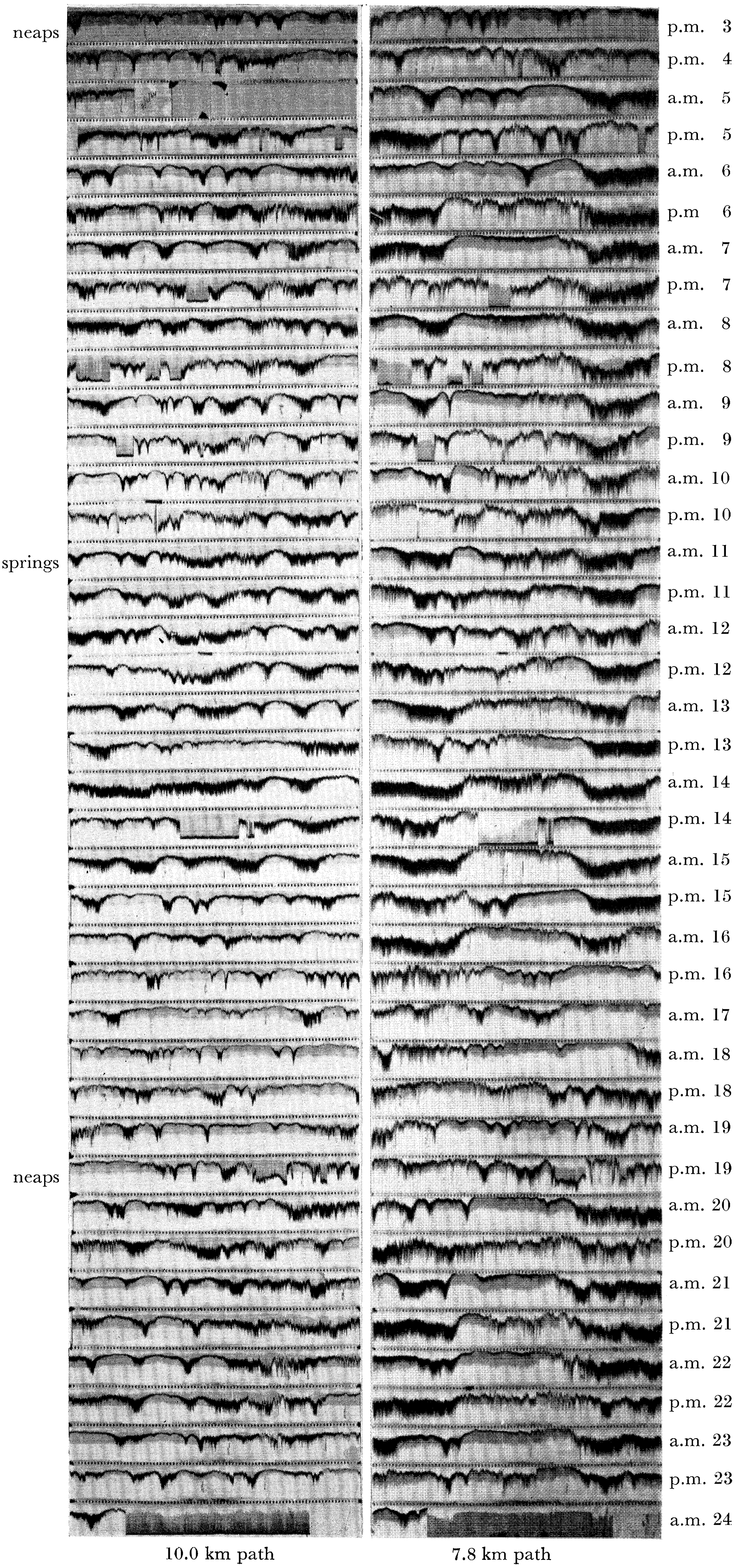
Description of plate 17

Figure 20. Twenty day amplitude records for 2083.3 Hz propagation, 3 to 24 June 1964 (arranged in $12\frac{1}{2}$ h tidal periods with high water at the centre of each record).


neaps
springs
neaps
p.m. 3
p.m. 4
a.m. 5
p.m. 5
a.m. 6
p.m 6
a.m. 7
p.m. 7
a.m. 8
p.m. 8
a.m. 9
p.m. 9
a.m. 10
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p.m. 20
a.m. 21
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a.m. 22
p.m. 22
a.m. 23
p.m. 23
a.m. 24
10.0 km path
7.8 km path

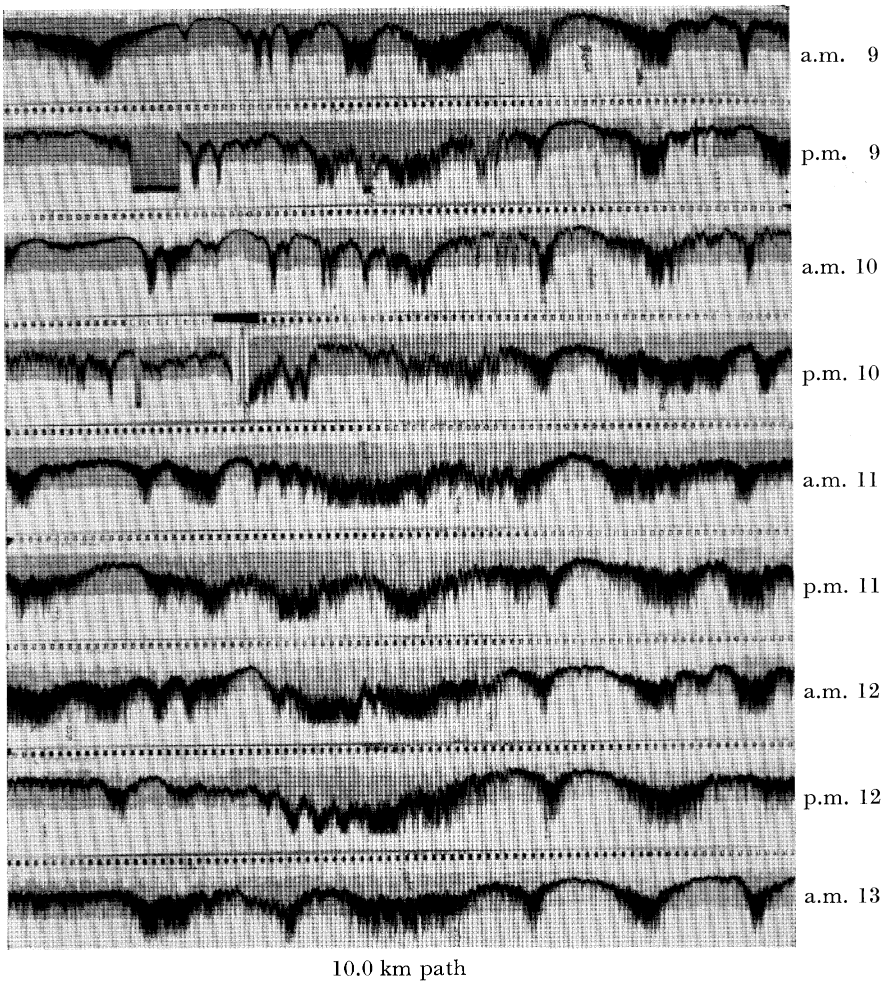


FIGURE 21. Larger scale version of some of the 12½ h amplitude records from figure 20 (2083.3 Hz, June 1964), showing repeating asymmetry near springs. High water occurs at the centre of each record.

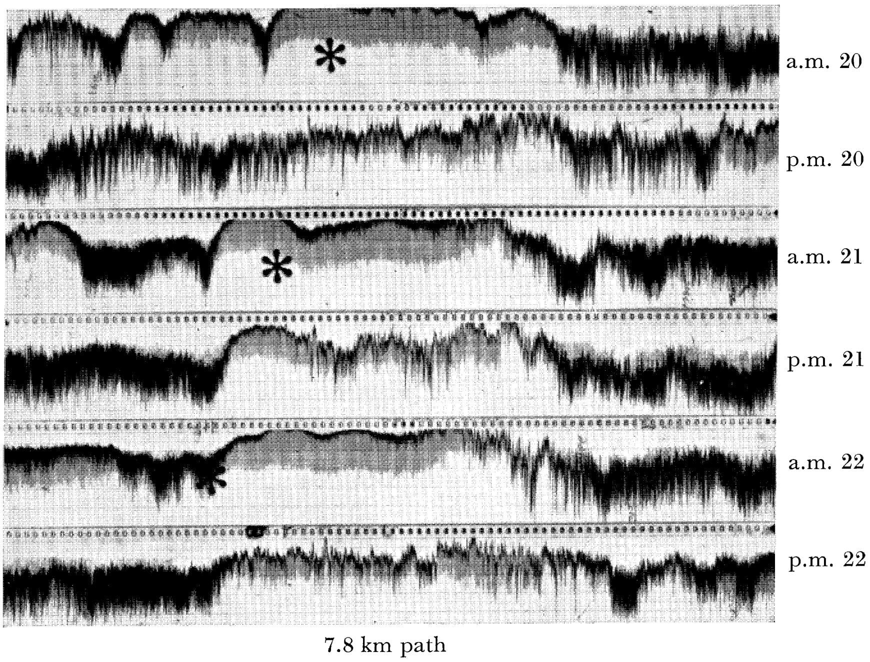


FIGURE 22. Larger scale version of some of the 12½ h amplitude records from figure 20 (2083.3 Hz, June 1964), showing day–night differences due to fish. High water occurs at the centre of each record, and the asterisks indicate local true midnight.

range between 9 and 13 June. This part of figure 20 is reproduced on a larger scale as figure 21. There is a similar but much less obvious effect for the same period at 7.8 km, and also for other times at 10.0 km. Why should the asymmetry effect occur on some occasions and not on others? The clue is that the major evidence for asymmetry, from 9 to 13 June, coincided with spring tides. It is shown below that a fast running tide acts in a number of distinct ways, which reinforce one another.

Consider first the conditions at neaps. The depth change effect should be symmetrical about high water, when the interference distance for any two modes will be maximized. The shear flow effect should be symmetrical about a different time, perhaps the time of maximum streaming, which is only 1 h before high water. At this time the streaming is to the northeast, in approximately the same direction as the sound propagation, so that the shear flow will contribute a negative sound velocity gradient. This will modify an existing gradient which is also negative, since at extreme neaps the measured temperature depth differential of 0.7 °C will produce a negative gradient which is numerically about five times greater than the positive gradient due to pressure. There are also weak salinity gradients, but these will not be considered further. The shear flow will therefore enhance the negative gradient and reduce the interference distance (Weston 1969), the latter being in opposition to the depth effect. At neap tides all these effects are relatively small, especially the fractional changes in gradient, so that the relations among depth change, gradient change and interference distance are all approximately linear. Depth and shear flow effects can be linearly superposed and symmetry will not be destroyed, but the depth change interference effects will be slightly reduced and delayed.

At springs the flow rate is fast enough for turbulence to extend through the whole water column and thoroughly mix it, in fact isothermal water was observed on 11 June. The existing gradient is positive, and due to the pressure effect alone. The shear flow will now try to enhance and advance the depth patterns. A couple of days on either side of 11 June the temperature differential of about 0.15 °C is enough to make the water roughly isovelocity. The balance is thus quite fine during springs, i.e. the existing gradient is less and in addition the shear effect itself is greater. Numerical values show that all three contributions to the gradient (pressure, temperature and shear) are of the same order, so the non-linearity becomes important (Weston 1969) and produces the asymmetrical patterns.

It is more difficult to be quantitative about the alternative explanation for asymmetry, in terms of the tidal advection of different water structures. But obviously the greater horizontal streaming at springs is more likely to produce significant changes. Structure changes due to tidal period internal waves should not be ruled out, but are less likely because the high shear flows often make the water dynamically unstable.

We have now presented two completely different types of symmetrical amplitude pattern: those in § 7 due to fish which are centred about midnight (alternatively midday could have been chosen), and the interference patterns which are centred about high or low water. The separation of these effects is possible partly by selection of range and season: at 23 km fish effects are sometimes large and interference is small, at the closer ranges it is the other way round. But luck still comes into it, and it is necessary to take many records. This leads in to the question as to whether or not a fourth feature of significant fish effects can be seen in the present record. Since one day occupies approximately two tidal periods, one should look for a difference in every other record segment in figure 20. At 10.0 km it was possible on 12 occasions to estimate the daytime level in comparison with the two neighbouring night time levels at the same positions in the interference cycle. The daytime level was slightly but significantly lower, mean difference 2.5 ± 2.9 dB. Sixteen estimates for 7.8 km gave a daytime relative attenuation of mean value 4.4 ± 4.2 dB, again significant. It should be stressed that having an attenuation in the daytime is the opposite to the night time effect ascribed to fish in § 7, though it is possible to construct theories to explain both as due to fish.

Upon examining the diurnal level differences a fifth feature was noticed: diurnal changes in record character. These may be seen for both ranges, especially for the interference maxima where they are not confused by the wave period fluctuations. Level fluctuations up to 15 dB, with periods between about 1 and 30 min are present in the daytime only. They are probably due to changes in the positions and perhaps the degrees of aggregation of fish, since appearance and disappearance of the effect occur at dawn and dusk respectively. It is not known how much of this effect may be local to source or receivers. The effect is particularly clear for the 7.8 km range and the period 20 to 22 June, and these results are reproduced on a larger scale as figure 22. The cental plateau in figure 22 is steady during every night, but every other tidal segment shows the daytime fluctuations.

The weather was stormy on 6/7, 12 and 14 June but there are no obvious effects in the record of figure 20.

There is one additional and important comment to be made on the June 1964 level experiments. Leave aside the faster and random fluctuations, due to both wave effects and fish. There are still many occasions in the record when the amplitude behaves in an unpredictable way. This is not however a complete mystery, it could for example be due to the ubiquitous fish. But there are many other occasions when symmetry or repeatability is good, and the behaviour is obviously completely determined by known mechanisms and at least in principle predictable. It is concluded that for these times, lasting many hours or even days, all the causes of fluctuations are known and understood.

11.3. *Phase effects*

The interference effects may also be seen in the phase; let us look first at the January 1964 results in figure 7. The main streaming effect has already been discussed in § 10, the maximum phase excursions occurring about $1\frac{1}{2}$ h before high and low water. This time difference has no importance, and depends on the locality. The interference shows up as a distortion of the phase sinusoid, which tends to be most marked at the top and the downswing of the sinusoid. Comparison with the amplitude record shows that this corresponds to the period of interference minimum. A particularly extreme form of distortion occurs in the middle of the first eight downswings of phase, and appears as a kink in the record lasting about an hour. If the trends on either side of the kink are extrapolated, they form parallel lines with a phase difference of about 180° between them. In fact for the seven occasions when it could be estimated, albeit with difficulty, the mean was 210° and the standard deviation about 60°. During some parts of the period the signal was also monitored over a 10.0 km range, and four further clear examples of phase reversal were seen with mean value 230°.

The explanation of this phase reversal follows by considering an Argand diagram (vector or phasor diagram), in which a point representing the vector sum of all modes will move about in time. A sharp minimum in the interference pattern corresponds to the point moving slowly past the origin. As it moves past there will be a phase flip through 180°, the speed of the change corresponding to the closeness of approach. If the phase measurement system were being used as a 'thermometer' (§ 6) or a 'flowmeter' (§ 10) these phase flips would be a nuisance, and should be corrected for in the record. In theory the corrections should not accumulate, since flips should always occur in pairs if the interference patterns are symmetrical. In figure 7 it is thought that a second set of phase flips are hidden in the distorted and confused part of the record near the top of the phase sinusoids.

The interference distortions are also very evident in the other phase records (figures 9 to 13). These results show how the magnitude of the distortions depends on range, in particular they are very bad in figure 11 for the 3.9 km range.

12. Fluctuations of a few minutes period

It is convenient now to discuss the fluctuations with periods of minutes, since these come next in order of fluctuation frequency. As listed below, there are many possible mechanisms.

Start with the long range propagation, for which there is direct evidence of these fluctuations in figure 15 (see also Weston & Horrigan 1967). A measure of the effect for the 137 km path comes from the Fourier spectra (figures 23 to 25), which show a rise in the 20 to 200 s range of periods. (Spectral analysis methods are described in § 3.4, note that all spectra presented except those in figure 26 use sampling rate one per second and sampling duration several minutes.) This information is obviously incomplete, since the shape for the region with periods of above 200 s is not defined. But there is a suggestion (especially for the amplitude data) that there is a peak, sometimes near 200 s and sometimes at a greater period. The levels for the 200 s region

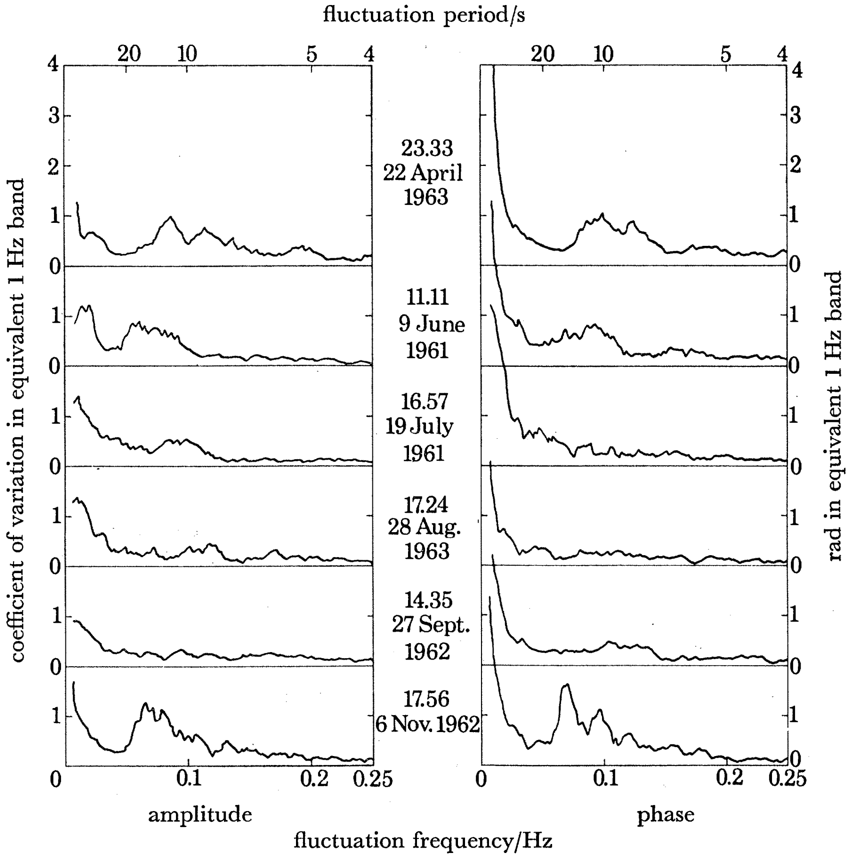


Figure 23. Sample spectra through the seasons for 1 kHz and 137 km, with simultaneous amplitude and phase analyses.

may not always be reliable, because of a breakthrough from even longer periods. In particular this is thought to explain the apparent high levels of 200 s phase fluctuation, which may be affected by the tidal streaming phase variation. For these low frequency phase fluctuations the spectral level is appreciably lower in the summer months, just like the surface effects to be discussed in § 13. If level differences are allowed for, the amplitude and phase spectral shapes are reasonably alike in this frequency range.

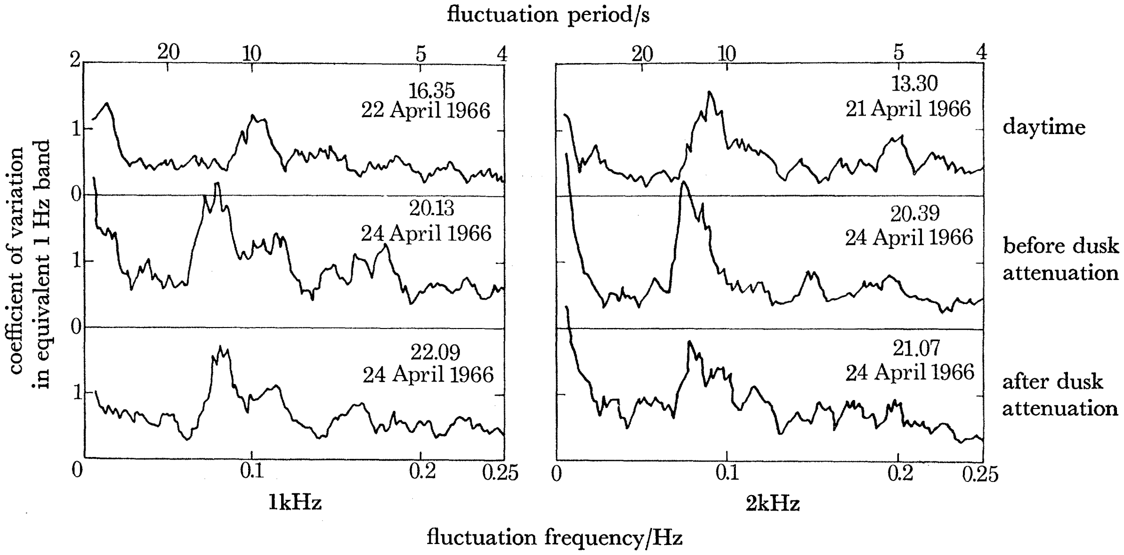


FIGURE 24. Short term variations in amplitude spectra at 137 km, April 1966.

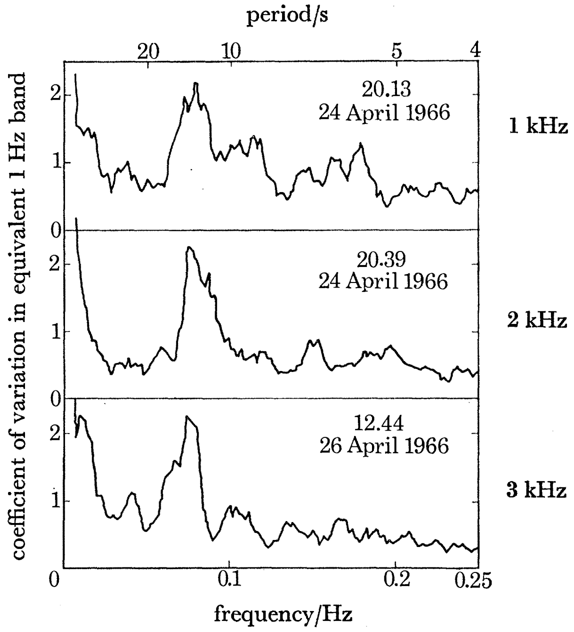


FIGURE 25. Amplitude spectra for different carrier frequencies at 137 km.

Significant point is the lack of a similar low frequency rise for most of the short range spectra (figures 27 and 28), although rises sometimes occur they are different in character. The June

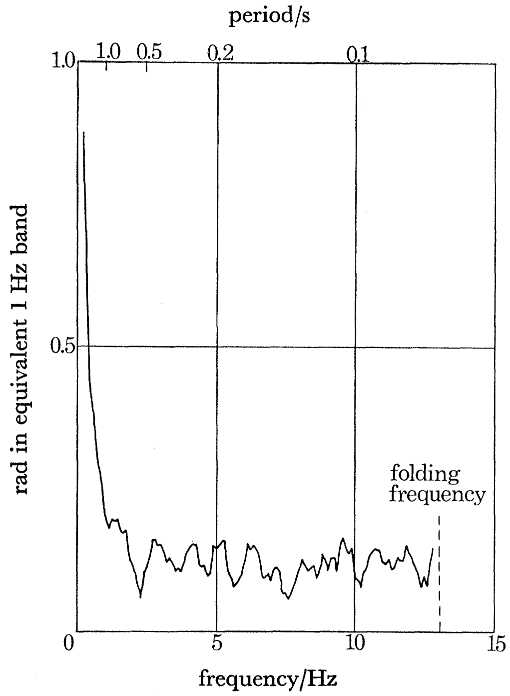


FIGURE 26. Spectrum for faster fluctuations in phase, 1 kHz and 137 km. (20.20, 22 April 1963; sample rate 26.1 s^{-1}; number of samples 251; total period 9.6 s; averaging over 5 Fourier coefficients.)

1964 data in § 11.2 do include examples of short range propagation showing large fluctuations with periods of a few minutes, in daytime only, and ascribed to fish. This suggested looking for differences between day and night in the long range spectra, but a null result was obtained since most but not all of these spectra were taken in daylight hours.

For these longer periods a preliminary look has been taken at the relative timing of the fluctuations in amplitude and in phase delay, by comparing the 'phase' of the amplitude and phase delay Fourier components. Thus for the February 1962 1 kHz 1.9 km experiment the amplitude and phase components tended to be 180° apart for the first six harmonics of a 950 s sample (i.e. periods 950 to 160 s), the random relation for the higher harmonics probably being due to the statistics of the analysis method. Similarly for the June 1961 1 kHz 137 km experiments the first few harmonics (350 to 120 s) showed on average a relation close to 0°. Obviously there is useful information here, pointing to the need for a proper cross spectral analysis covering many more data. The tendency for the relation to be in phase or out of phase, as opposed to being in quadrature, also appears in the swell period fluctuations, as shown by the quite different approach in § 13.3.

Let us list all the possible fluctuation mechanisms for periods of the order of minutes, though completeness cannot be guaranteed. The mechanisms are not necessarily limited to periods of minutes, they may well operate at much longer periods too.

(*a*) Short term random changes in the positioning or degree of aggregation of the fish, to be distinguished from the regular diurnal effects discussed in § 7. The fact that this mechanism is operative at least part of the time is supported generally by the results in § 7, and particularly by those in § 11.2 for daylight hours (figures 20, 22). The present short term effects might concern both amplitude and phase, though the relative importance to phase fluctuations is not yet clear.

(*b*) Short term changes in the mean surface roughness, affecting mainly the amplitude. These may be distinguished, somewhat arbitrarily from the swell at one extreme and storms at the other. The duration of typical wave trains is of the right order (compare (*g*) below), and besides causing modulation of the wave effects such trains may temporarily reduce the mean signal level.

(*c*) Interference effects governed by the regular tidal changes, which will commonly peak at much longer periods than those under discussion (§ 10).

(*d*) Large scale turbulent motion.

(*e*) The tidal introduction of water masses of different properties, especially if there is random inhomogeneity (compare §§ 9 and 11.2).

(*f*) Internal waves, a very fashionable choice these days for most oceanographic problems. Since the first draft of this paper internal wave effects have been identified in the short range propagation results near slack water (paper in preparation), and this brings the total number of identified fluctuation causes to ten.

(*g*) Long surface waves, which are admittedly of very low amplitude. Such waves when of period around a minute are commonly due to 'surf beats', and are correlated with fluctuations in the mean height of the incoming swell (compare (*b*) above and see Tucker 1950, 1963).

Out of all these possibilities there is direct evidence only for the fish aggregation (*a*) and internal waves (*f*), but it is still doubtful whether these are sufficient to explain all the effects. Although random inhomogeneities (*d*), (*e*) could be significant it is considered that the literature puts too much emphasis on these mechanisms.

13. SURFACE WAVE EFFECTS AND THE TIDAL INFLUENCE

13.1. *Long range*

Finally we arrive at a consideration of those fluctuations, peaking in the 10 to 15 s range of periods, which are due to the predominant surface waves on the sea. These are the best known fluctuations, and will be noticed, with good reason, even by the casual observer. On most of the amplitude records in this paper they appear as a broadening of the trace, with the diffuse lower edge characteristic of deeply modulated signals on a logarithmic display (figures 4, 12, 20, 21, 22). But they may just be resolved in figure 8. They may also be seen in the figure 5 sample phase record. These fluctuations have been studied mainly by Fourier analysis, and it must be confessed that it is often necessary to be selective in choosing a length of record suitable for analysis. This is particularly true of the phase analysis, which cannot easily cope with 360° changes, so the possibility of some systematic bias should be borne in mind.

It is again convenient to start with the longer range, since the results there are generally simpler. A large part of the data is presented in figure 23, arranged to show seasonal dependence for the 137 km 1 kHz transmission. Periods greater than about 20 s have already been discussed in § 12, and the main feature in the rest of the curve is commonly a peak in the 10 to 15 s region. This period agrees well with the predominant period for typical ocean swell. The shapes and levels of the curves (for periods below 20 s) are generally very similar for the amplitude and phase spectra. It is possible to see a systematic change through the seasons: the swell peak is strong in winter and spring, but very poorly defined in July, August and September. The obvious reason for this is the greater chance of a high swell during the winter. An alternative explanation follows from the temperature layering in the summer, which produces a sound channel near the bottom for most of the track, and insulates the sound from the wave influence. But arguing against this is the belief that the fluctuations are due mainly to the surface waves in the locality of source and receiver, where the water is shallower and usually isothermal.

Figure 24 shows the shorter-term variability for spectra at 1 and 2 kHz in April 1966. It is also possible to compare the 1 kHz curves with those for the same month in 1963 (figure 23). Over periods of a few days there are real changes, similar to the changes that might occur in the swell spectra. The two results an hour or so apart near sunset are for a day when a large fish attenuation was observed. The curves are for times just before and just after the attenuation, and the shape differences are of very doubtful significance. Some of the 2 kHz information has been discussed at greater length by Weston & Horrigan (1967).

Figure 25 compares 137 km spectra at 1, 2 and 3 kHz. Again the observed differences are not thought to be important.

For figures 23 to 25 the sampling interval was 1 s, and the spectra are displayed to only half the Nyquist frequency. Figure 26 shows the result of a short experiment with a much higher sampling rate, designed to find the upper frequency limit of the fluctuations. Although one cannot be certain that the real limit has been attained, the spectral curve reaches the noise level at very roughly 2 Hz. For the fluctuations due to surface waves there is a very simple theory which predicts the limit. At 1041.7 Hz the sound wavelength is 1.4 m. According to Rayleigh any surface wavelengths of less than half this value, i.e. 0.7 m, will be ineffective as scatterers. And this limiting wavelength will be effective in back scattering only, for sound incident virtually horizontally. The limiting fluctuation frequency should therefore be given by the frequency F of this surface wave. The wavelength of a gravity wave in relatively deep water is $g/2\pi F^2$, so the general equation is

$$\frac{c}{2f} = \frac{g}{2\pi F^2},$$

or $$F = \sqrt{(gf/\pi c)} = 1.47\ \text{Hz} \quad \text{for} \quad f = 1041.7\ \text{Hz}.$$

This is in fair agreement with the 2 Hz already quoted, which applied to winter conditions over the 137 km path. But there is an impression, which has not yet been checked quantitatively, that appreciably faster fluctuations may occur over short ranges near an interference minimum and also over long ranges in the summer. High spectral components of amplitude and phase might well be expected in the short range case, since it is shown below that the relation of fluctuation cause to effect is decidedly non-linear, but there is no theory for the possible long range summer effect.

13.2. *Short range*

Let us now move on to look at the closer range data, sample spectra being shown in figures 27 and 28. Start with the four spectra labelled 'stable', which were taken near the maximum of the temporal interference pattern. The amplitude spectra again resemble the phase spectra, in both level and shape, though the agreement is not so good as for the long range spectra. The February 1962 1.6 km amplitude spectrum also looks like the January 1964 7.8 km amplitude spectrum, despite the differences in range, time and technique. There is a difference in level between the two phase spectra, but the significance of this one result should not be over-emphasized. In turn they all resemble generally the long range summer spectra, though of lower level, and lacking the strong 10 to 15 s peak of the long range winter results (the lack of a very low frequency rise has already been discussed). The weakness of the 10 to 15 s peak is presumably associated with the shortness of range, though direction could play a part.

Figure 28 includes a wave spectrum computed from readings of an inverted echo sounder, which were taken close in time to the acoustic results. The original record suggested there was swell with predominant period 15 s and peak-to-peak amplitude about 0.8 m. The spectral analysis methods were the same as those for the acoustic results. But little effort has been put into such measurements so far, partly because, as demonstrated below, the position in the interference cycle can be even more important than the wave height. The major point about the short range fluctuations is brought out by comparing the 'stable' and 'unstable' amplitude spectra in figure 28. The unstable conditions are those occurring near the minimum of an interference pattern. There is considerable confusion and the spectral levels are greater by a factor of about 5, or perhaps more at the higher fluctuation frequencies. There has previously

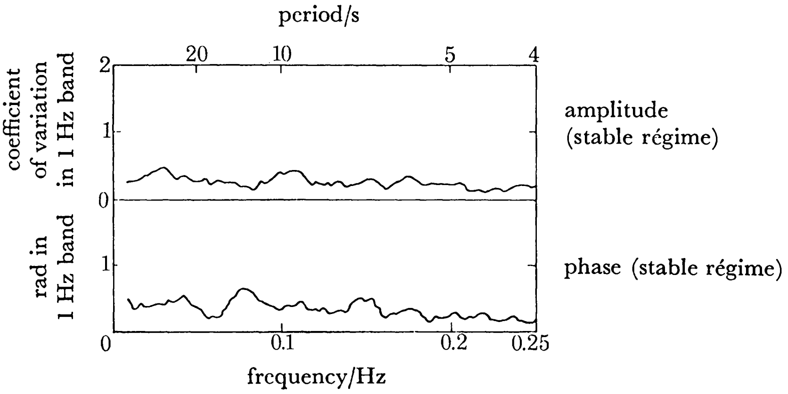


FIGURE 27. Sample spectra for 1 kHz and 1.9 km, with simultaneous amplitude and phase analyses. Both spectra were recorded 8 February 1962 at 19.55.

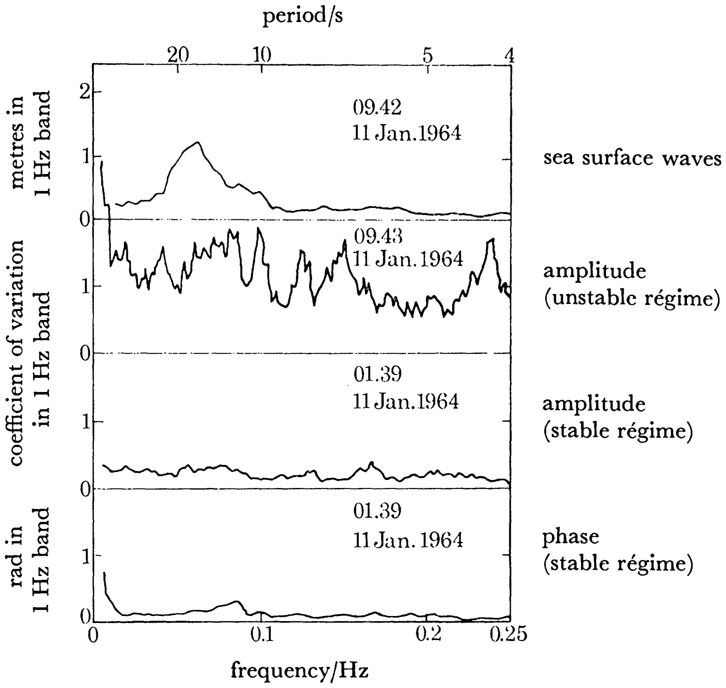
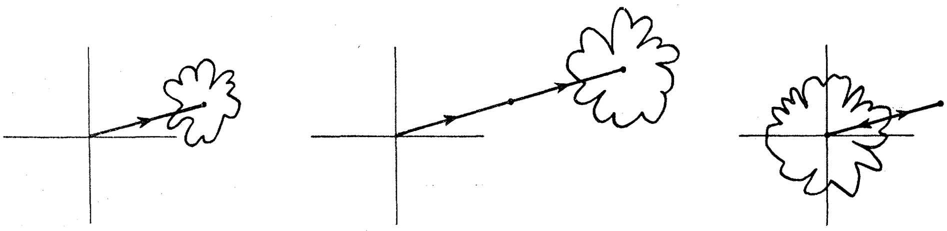


FIGURE 28. Spectra for 2 kHz and 7.8 km, showing in particular the large differences between the stable and unstable régimes.

in this paper been more than a hint that the character of the signal, as shown in the magnitude of the wave period fluctuations of amplitude and phase, varies through the tidal interference cycle. There is further evidence and obvious demonstration of this in most of the amplitude records (e.g. figure 4). When the level is low the relative fluctuation is high and the trace drawn out is very thick. This is shown for the phase record in figure 7: the amplitude is low at the time of the downswing on the phase curve, where the curve is marked as being 'confused'.

The presence of the stable and unstable régimes provides an object lesson in the importance of making measurements over an extended period. One measurement which happened to hit a stable period would cause unfounded optimism on the acoustic coherence of the medium. A single measurement at an unstable period would lead to undue pessimism. Many measurements are necessary to provide both a balanced picture and an explanation.



(*a*) single mode (*b*) Two modes: interference maximum relative fluctuation minimum (*c*) Two modes: interference minimum relative fluctuation maximum

FIGURE 29. Argand diagram schematic showing mean and fluctuation through the interference cycle.

The mechanism for this tidal variation in character is suggested in figure 29. Let there be only two modes effective in carrying the sound energy, and let these have equal mean amplitude with an equal and relatively small fluctuation. For each mode let the fluctuation be regarded as due to the addition of a small extra vector to the mean vector, with random phase relation. In the diagram the resultant vector should trace out a pattern which is symmetrical about the mean. Thus the amplitude fluctuation expressed as a coefficient of variation should equal the phase fluctuation expressed in radians, which is confirmed by the similarity of the present amplitude and phase spectra. Now consider the addition of the two modes in phase, as at the maximum of an interference pattern. The mean amplitude is doubled, and if the fluctuations add incoherently the resultant fluctuation will be even smaller in comparison with the mean. The other case occurs when the two modes have opposing phases, to give the minimum of the interference pattern. In the extreme case illustrated the mean vectors cancel to give a resultant mean of zero. But the resultant fluctuation has the same absolute value as before, and is now large compared to the mean. This model for the mechanism of changes in relative fluctuation level has specified two modes, for clarity, but the restriction is unnecessary. The ideas apply however many modes, or rays, are considered, provided that at some stage in the tidal cycle the resultant vector is small enough to give a good amplitude minimum. It is also unnecessary to associate components of the total fluctuation with the separate modes, provided the magnitude of the total fluctuation as displayed in the diagram (or as measured in x, y coordinates) does not depend greatly on the magnitude of the main vector.

The above model leads to some interesting predictions regarding dependence on swell height, set out in figure 30. On simple theory the mean level for an interference maximum will not depend on swell height. This may not be completely true, as described in § 8 on storm effects, but may be approximately so because storm attenuation probably depends more on the local wind and sea than on the swell. But the fluctuation should be directly proportional to the wave height, since all relations are linear. Consider now the extreme case of the interference minimum where the mean position of the resultant vector is at the origin, for both low and high seas. But the r.m.s. value of the vector is finite, and is proportional to the fluctuation. The absolute value of the fluctuation is indeed once more proportional to wave height, but the fluctuation relative to the r.m.s. amplitude is automatically *independent* of wave height. In general we see that relative fluctuation depends on both wave height and position in the interference cycle, and the latter is the more important.

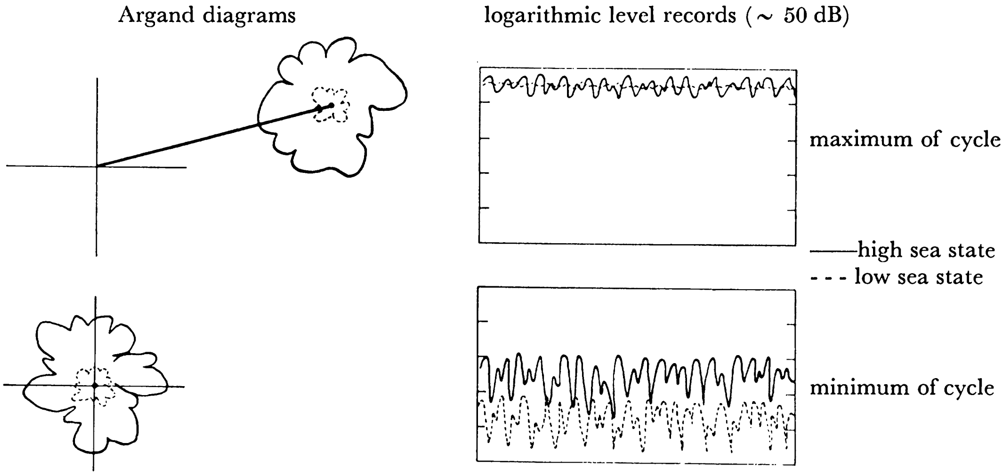


FIGURE 30. Dependence of mean and fluctuation on sea state, shown schematically through the interference cycle.

13.3. *Specification and display methods for fluctuations*

How should fluctuations be measured or specified? So far we have used a division into amplitude and phase, i.e. polar or r, θ coordinates. The r coordinate obviously makes sense if we are dealing with a range dependent attenuation due to seasonal changes, fish or storms. The θ coordinate makes sense for the seasonal temperature cycle or the tidal streaming. The r, θ approach is still convenient for the small wave period fluctuations at an interference maximum. But for the interference phenomena themselves, or for wave period effects near an interference minimum, the r, θ description behaves badly. The perfectly smooth movement of the resultant vector past or through the origin produces a steady fall in r which suddenly changes to a steady rise, and is accompanied by a discontinuity of π in θ. Thus there can be an extremely nonlinear relation between the surface wave disturbance and the resulting changes in r and θ. The r and θ fluctuation spectra at an interference minimum will not be a good reflexion of the surface wave spectrum, in particular there may be energy beyond the frequency limit calculated above. Thus the amplitude spectrum for the unstable region in figure 28 may not be very meaningful scientifically, but provides a dramatic illustration of the change in character. Unfortunately a companion phase spectrum could not be produced because the particular phasemeter used became completely confused in the unstable region.

For the interference and wave effects the use of Cartesian or x, y coordinates restores good behaviour. There is the added advantage that the magnitude of the x and y wave period fluctuations should equal one another, and should not change through the interference cycle.

Some preliminary experiments have been made with a system that displays the vector or phasor diagram as in figures 29 and 30. The arriving signal is used to generate a circular time base on a cathode ray oscillograph, and the brightness is modulated to give a single spot each revolution at the same phase of the reference or transmitted signal. The result may be photographed on still or cine film. The example in figure 31 shows the locus of the tip of the vector over a 1 min period, with origin offset below the bottom of the picture. It is for the stable régime of short range 1 kHz propagation, and demonstrates that over a period the fluctuations tend to be symmetrical about the mean vector position. But for any single excursion from the mean position the outward and return paths appear to lie close together (see remarks on cross-spectral analysis in § 12). In this technique the x and y plate voltages at the time of spot brightening automatically give the x and y vector coordinates.

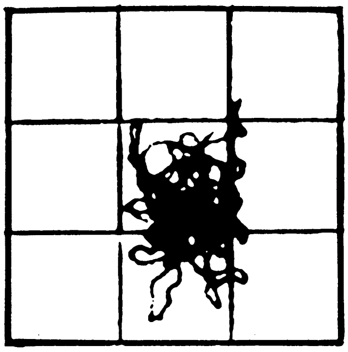


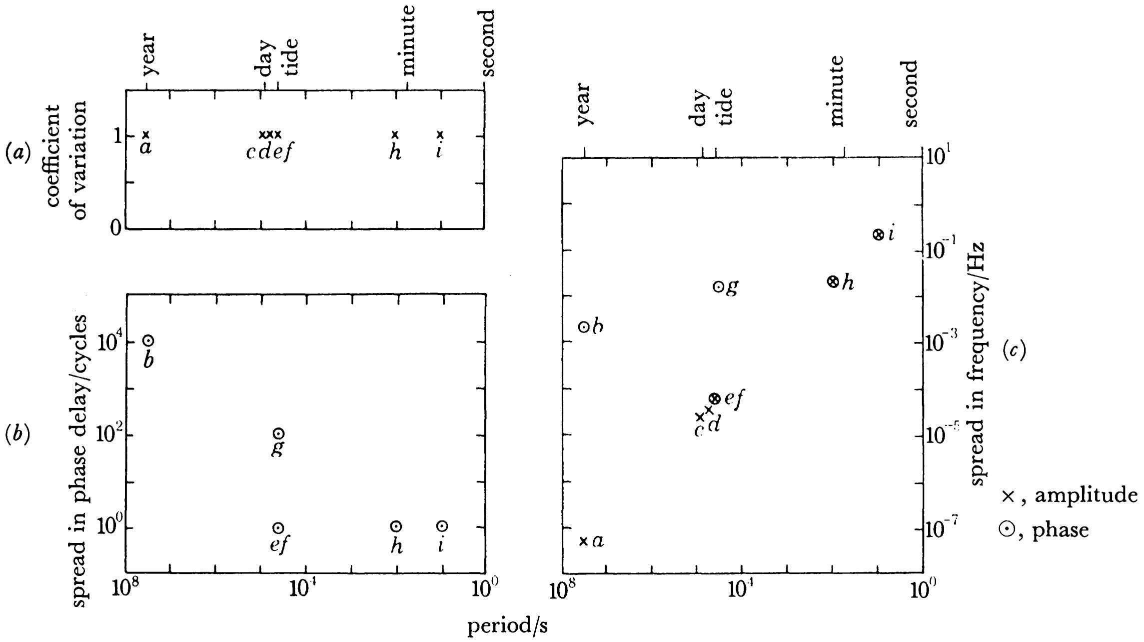
FIGURE 31. Argand display of short range fluctuations during 1 min (1041.7 Hz, 5 February 1965).

So far the detailed mechanism of the swell period fluctuations has not been discussed, though in calculating the limiting fluctuation frequency the idea of surface roughness as a diffraction grating was introduced. There has been a great deal of work on single reflexions from a rough surface, but here we are dealing with normal mode propagation in which there is a selection or reinforcement of certain angles. The best way of tackling this problem is not settled, and is a subject for future work.

14. STATUS OF THE INVESTIGATIONS

It is intended now to summarize where we have got to, to consider the significance of the results, and to mention future intentions and hopes or recommendations for further work. This section is a half way stage in the summing up, coming just before the Conclusions section, which is reserved for a summary of the more specific points where there have been advances.

In table 2 a list of nine fluctuation mechanisms was presented, having varying degrees of novelty. It is admitted that the evidence for the changing of the interference patterns by the depth dependence of the tidal streaming is not so strong as for some, since it is difficult to separate from the effects due to the tidal changes in water structure. Similarly, the attribution of all the fluctuations with periods of minutes is still uncertain. Major advances have been made in the understanding of seven of the mechanisms, and for the other two (seasonal attenuation, storm attenuation) it is hoped to report more information later. Apart from the nine identified mechanisms there are many others which *might* produce significant effects, and some of these are listed in § 12. Indeed the internal wave effect has been confirmed recently, as discussed in a separate paper. But for certain times all the operative mechanisms have been identified and at least partially understood (§ 11.2)! The general propagation or fluctuations problem involves a multiplicity of effects, and the present sorting out has been achieved only by concentrating on one geographical area for several years. It has also been useful to have had a variety of ranges, since the long and short ranges are essential to different parts of the investigation. But more detailed knowledge is still needed to tie up the innumerable loose ends, and more apposite theory is needed in some cases.



(*a*) amplitude and
(*b*) phase effects

(*c*) frequency spreading
due to combined effects

FIGURE 32. Orders of magnitude for the various amplitude and phase fluctuations and frequency spreadings (lettering corresponds to table 2: *ab*, seasonal; *c*, fish; *d*, storm; *ef*, interference; *g*, streaming; *h*, minute period; *i*, wave).

The magnitudes of the different effects are summarized very roughly in the figure 32 schematics, for an undefined but longish range comparable to our 137 km path. All the mechanisms controlling amplitude can produce a relative change of the order unity. But the longer period phase effects tend to be greater than those of shorter period. The resulting frequency spreads tend, nevertheless, to be much greater for the faster fluctuations, which is not surprising.

What special points of significance emerge from this work? One is the possibility of applying some of the phenomena in other fields. For example, the long term phase measurement system works as a combined thermometer and flowmeter. The fish attenuation studies provide information on fish behaviour and fish population. Another point is that one can use the knowledge in the planning of acoustic experiments, in some of which large fluctuations are a great embarrassment. The fluctuations observed fall into two groups: the predictable such as the tidal interference effects, and the unpredictable such as the storms. Not much can be done about the latter group, but for the former one can choose one's time, e.g. avoid the unstable régimes of very high wave period fluctuations.

The most important phenomenon discovered during these studies is the occasional large attenuation due to fish. Further work has started (1967) in which a series of pulses covering several different frequencies are transmitted successively for a period of days. By repeating the experiment at regular intervals during the seasons, light should be thrown on seasonal attenuation, storm effects and interference, as well as on fish.

15. Conclusions

(*a*) There are seasonal variations in amplitude, long range transmission being worse in summer by some tens of decibels.

(*b*) The first known observations are presented for seasonal variations in phase delay, in which the equipment acts as a thermometer. Phase delay is least in summer due to the higher water temperature and sound velocity, and seasonal changes up to 3 rad d^{-1} km^{-1} (at 2 kHz) have been measured.

(*c*) There is an important new phenomenon in which fish cause an attenuation of sound, which is generally greatest at night when the shoals break up and the fish can scatter sound independently. The changes near dawn and dusk can be very rapid, and various amplitude patterns are produced which tend to be symmetrical about midnight. The attenuations are greatest in September, and can be of the order of 1 dB km^{-1}.

(*d*) Storms may cause a dramatic reduction in signal amplitude. The attenuation depends critically on wind speed, and even at short ranges may be many tens of decibels.

(*e*) The spatial pattern of normal mode interference depends on the water depth, and a new effect is reported in which the tidal changes in water depth effectively sweep this pattern past the fixed receiver. The short range effects sometimes show the expected symmetry about high or low water, and there are amplitude variations of up to 30 dB. The number of interference peaks swept through increases with range, so the mean fluctuation period at the longer ranges is much shorter than the tidal period.

(*f*) The water structure and the depth dependence of the streaming velocity can also vary through the tide, and should affect the interference pattern. As evidence for this the perfect symmetry of the pattern is often spoilt, to give an asymmetrical pattern repeating at the tidal period.

(*g*) The first known observations are presented in which the phase delay follows the tidal changes in the mean streaming velocity, and acts as a flowmeter. The variation tends to be sinusoidal, though the change from neaps to springs may be followed, as in the other tidal fluctuations. At long range the phase varies through as much as 100 cycles (at 2 kHz).

(*h*) Large amplitude and phase fluctuations of period around and above one minute are found, particularly at long range. Short term variability in the daytime positioning and aggregation of the fish appears to play a part in this at short range, but there is no lack of other explanations.

(*i*) Surface wave effects produce large amplitude and phase fluctuations, peaking at the predominant swell period of 10 to 15 s, but extending to periods less than 1 s. The most significant discovery here is the critical dependence on position in the tidal interference cycle, the relative fluctuations being several times greater near an interference minimum.

(*j*) The writers have become convinced of the tremendous advantages of having a site with fixed transducers, and of making long term studies. Because of the various interactions it has been possible to understand the faster fluctuations only by starting with the slowest fluctuations (seasonal) and working downwards in period.

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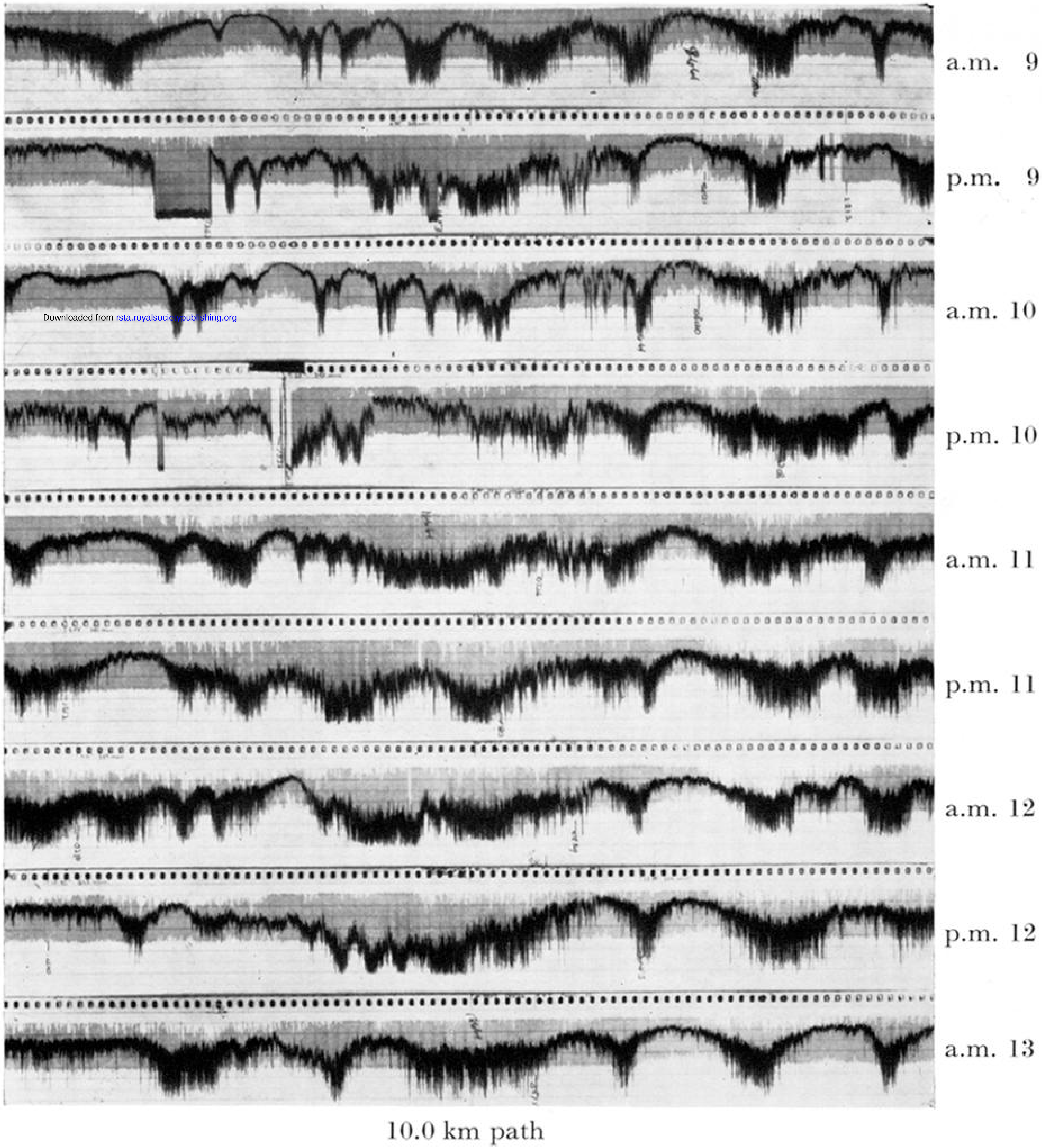
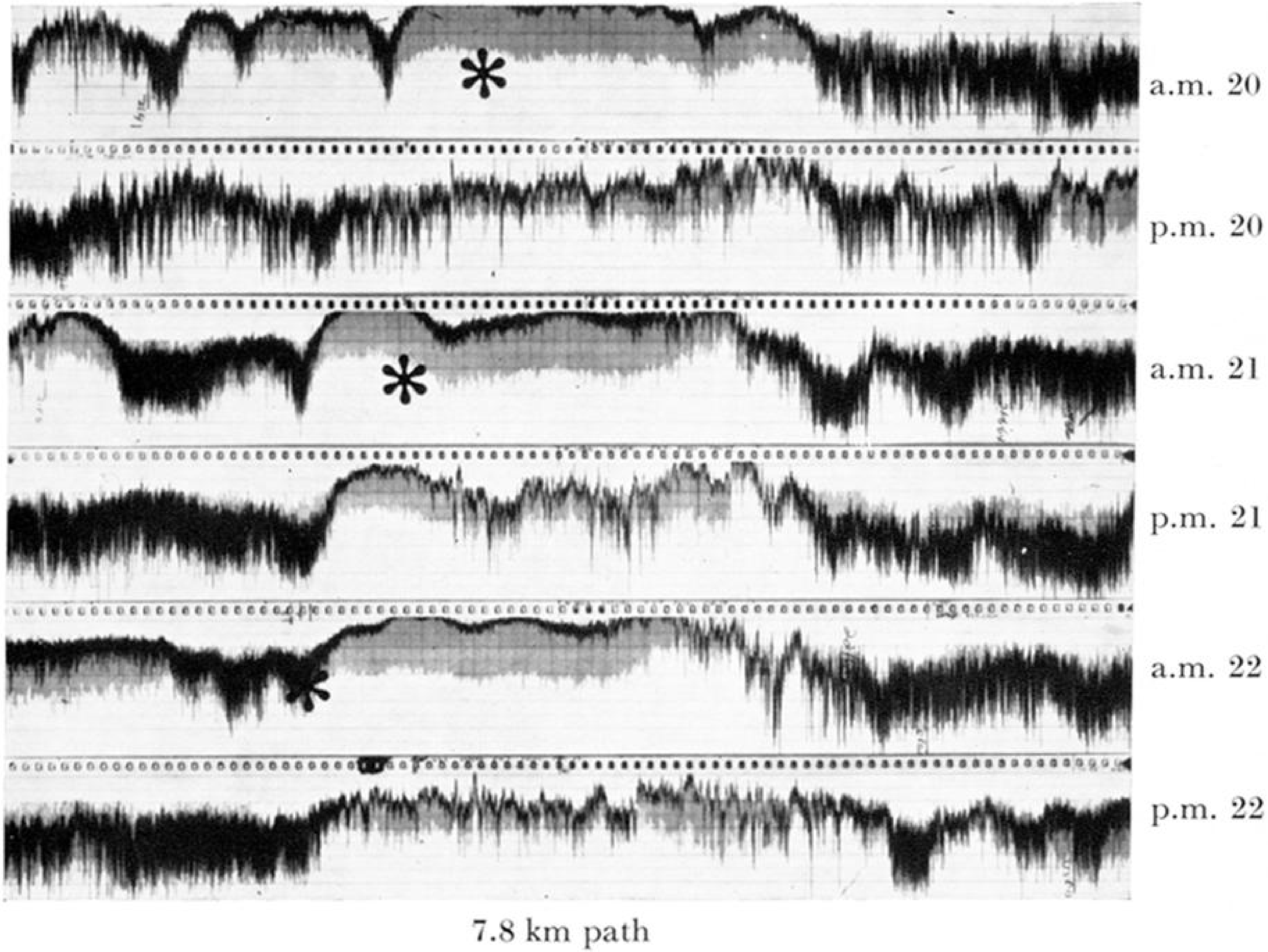


IGURE 21. Larger scale version of some of the $12\frac{1}{2}$ h amplitude records from figure 20 (2083.3 Hz, June 1964), showing repeating asymmetry near springs. High water occurs at the centre of each record.



IGURE 22. Larger scale version of some of the $12\frac{1}{2}$ h amplitude records from figure 20 (2083.3 Hz, June 1964), showing day–night differences due to fish. High water occurs at the centre of each record, and the asterisks indicate local true midnight.