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RADAR STUDY OF WADERS

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Complete Paper

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A RADAR STUDY OF WADERS

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SUMMARY

This is a preliminary study of the radar characteristics of two wader species, the dunlin, Calidris alpina, and the oystercatcher, Haematopus ostralegus. Some results are given on the curlew, Numenius arquata, but these are limited because only two were captured. Flight and echo data were obtained by means of a high-resolution auto-following pulse radar from wild birds released from a 90ft tower. A new method of obtaining the multi-aspect dynamic radar echoing area of a target is demonstrated and values are given for the dunlin and the oystercatcher. Bird activity modulation waveforms, spectral diagrams and auto-correlation functions have been analysed for the three wader species.

CONTENTS

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1 INTRODUCTION

During the Nato-Gibraltar Bird Migration Study, the PPI of an S-band (10cm) surveillance radar at Gibraltar revealed in the Autumn broad front movements of large well-spaced echoes at dusk and during the night. Some of the movements came from Europe heading south or south-west into Africa but others from the east could have originated from any part of the Mediterranean and passed into the Iberian Peninsula. A proportion of these targets,many of which consisted of only one or two birds, were sampled by an X-band (3cm) high-resolution automatic-tracking radar and wingbeat spectra were obtained from the echo signal data. The fundamental frequencies of these spectra ranged from 3.5 to 10 Hz and it is possible that the birds producing them could have been waterfowl, especially ducks.

Waterfowl occur throughout the world and many species undertake long migrations. They can be hazardous to aircraft because of their size and numbers. Although their movements in some parts have often been studied by radar, their echoing area and wingbeat spectra for identification purposes have not been extensively investigated. However, a study of the mallard, Anas platyrhynchos, has recently revealed some of their important radar characteristics (1).

Alternatively the echoes in question could have been produced by waders, ie relatively long-legged shore-birds of small to medium size and which also undertake long migrations.

This paper is an interim statement on an investigation to determine the radar characteristics (eg dynamic echoing area and wingbeat spectra) of waders in order to elucidate further the data obtained during the Nato-Gibraltar Bird Migration Study.

2 BIRD SPECIES

There are ten relatively common species of waders or shore-birds in Britain which might be suitable candidates for examination. Waders are not the easiest of birds to catch, however, especially when there is a need to have available freshly-caught birds for release at a radar site at a particular time. During this trial only three species of wader were obtained viz. dunlin, Calidris alpina, curlew, Numenius arquata and oystercatcher, Haematopus ostralegus.

The dunlin is one of the smallest and most numerous waders. Its average weight is only 50 g but the peak winter population in England, Scotland and Wales exceeds 300,000 birds and large compact flocks occur. Dunlin are widely distributed and, despite their small size, have been involved in collisions with aircraft and they are particularly troublesome at Vancouver Airport in Canada.

In Britain the dunlin nests on moors and marshes but it is better known outside the breeding season as a passage migrant and winter visitor when it frequents the seashore and mud-flats of both fresh and salt water. Birds which breed as far north as Greenland in the west and western Siberia in the east frequent our shores and migrants winter as far south as North West Africa. Movements of dunlin may, therefore, be detectable by radar at Gibraltar.

The curlew, in contrast with the dunlin, is the largest wader in Europe (average weight 800 g). As a breeding bird in Britain it is more common than the dunlin, nesting on moors, marshes and meadows, and outside the breeding season it frequents mud-flats and estuaries. The peak annual population in England, Scotland and Wales may exceed 50,000 birds. Although it is not generally seen in large flocks, small parties may occur on some airfields and collisions with aircraft have occurred.

Many of the curlew which winter in Britain come from Scandinavia, with some from the Low Countries and the USSR. Curlew from North and Central Europe winter in South Europe and North Africa and some may therefore be observable by radar from Gibraltar.

The oystercatcher is a medium-sized wader (average weight 550 g) which is very common along coasts and in the breeding season it also occurs locally inland. The peak winter population in England, Scotland and Wales, augmented by birds from the Faroes, Iceland, Scandinavia, the USSR and Holland, is in the order of 150,000 birds. Large flocks frequently occur and oystercatchers often create a strike risk on coastal airfields.

During the winter months the oystercatcher is widespread along the northern shores of the Mediterranean and around the Iberian Peninsula and hence may be detected by radar at Gibraltar.

3 EXPERIMENTAL WORK

3.1 Capture, Transport and Release of Birds

The birds used in the trial were all caught either in cannon nets or mist nets under a licence granted by the Nature Conservancy Council. They were taken in the late evening or early morning as they were forced up the beach by rising tides at the high tide roosting places on the Dovey Estuary, Dyfed. As soon as possible after capture they were put into boxes or pigeon baskets in which they had plenty of room to stand and move about and were taken by road 65 Km to the radar site at Aberporth. Over a number of days, 2 curlews, 23 dunlins and 25 oystercatchers were transported in this way and all flew strongly on release. Most of the birds were released within eight hours of capture but some caught after nightfall were retained longer than this for release the following morning.

The birds were released individually from a wooden box at the top of a 90ft (27.4m) metal tower using a technique which had been perfected the previous year with feral pigeons Columba livia var. The box used (Fig 1) was originally intended for carrying rabbits and was slightly wider at the base than at the top so that when a number of such boxes were stacked together the ventilation holes could not be cut off. Any such box of similar proportion would satisfy the present requirement. A metal ring was attached to the base of the box so that it could be hauled upside down up the tower. The hinged lid, then forming the floor of the release box, was fitted with a sliding pin catch which could be actuated from the ground. The pull cord for this release catch passed through a number of simple wire loops bound with tape onto the main rope to prevent it from twisting around the main rope or from being blown by the wind and fouling on the tower. When the box was at the top of the tower and all was ready, a sharp tug on the pull cord withdrew the peg and the bottom of the box swung open on its hinge and the bird dropped out.

By attaching the tail end of the rope used to pull the box up the tower to the base of the box some control could be exerted over the box to prevent it from swinging too much in the wind.

Generally two people were required to handle the birds, pull up the box, take care of slack in the rope, operate the telephone link with the radar, pull the release cord and lower the box again.

3.2 Radar, Recording and Computing Facilities

The C-band (5.5 - 5.6 cm wavelength) instrumentation pulse radar used for these experiments has a range precision of 8 feet and an angular precision of 0.15 military mils (0.0084 degrees). The diameter of the radar resolution cell at a range of 10,000feet is approximately 140 feet.

The radar can track automatically a small target and generate 3 dimension positional data in polar coordinates, and an amplitude-time record of the echo signal. Flight and radar echo signal data together with time (GMT or ZT) code and voice description of each radar target were recorded on multi-track magnetic tape for subsequent analysis.

Target trajectory data were fed into the RAE data and computing centre on site, where polar coordinates were transformed into cartesian coordinates and velocity and acceleration information were obtained by means of mathematical curve-fitting procedures.The quantized mean signal levels were also converted to (S/N) ratios and range data pairs.

Wind velocities at appropriate altitudes and times were obtained by using one of the instrumentation radars to track balloon-borne reflectors.

3.3 Visual Acquisition and Putting-on Operations

The acquisition and putting-on problems encountered when dealing with a low level moving target were described in some detail in a previous paper (1). As a result of lessons learnt in the mallard trials great improvements were made in the acquisition and putting-on operations for this study.

The difficult problem of where to release the bird was solved by putting it into a box and hoisting it up a 90ft tower. The top of the tower was fully illuminated by the radar beam and at a known distance from the radar. A television camera with a telephoto lens, fixed to the radar aerial, enabled the radar operator to put the radar on to the bird box visually. A telephone line to the tower solved the communication problems. Thus the radar could be set up in all three coordinates and be ready for acquisition immediately the bird was released. Furthermore the radar operator was able to watch the release of the bird on the tv viewer and follow its movements during the initial tracking operation. He also had a limited warning of ground clutter situations by watching the bird's attitude and picture background.

From the roof of the radar building, angular data from special binoculars was used to redirect the radar in those cases when it lost the bird after release (the field of view of the tv viewer was generally too limited for reacquisition).

4 RESULTS

The results of the trial held on the 19th, 20th and 21st November 1975 were highly successful with 22 out of 23 dunlins, 12 out of 14 oystercatchers and both curlews being tracked.

Not only did this show a great improvement in the numbers of released birds auto-followed by radar compared with the earlier mallard trial, but there was an improvement in track duration. Whereas the longest mallard track lasted for 100 seconds, the average wader track was 240 seconds duration. The longest track during these wader trials was of a dunlin which was followed for 595 seconds.

4.1 Flight Characteristics

A map of the operational area was given in a previous paper (1). With a few exceptions all the waders flew towards the sea and followed the coast line and, unlike the mallard, none dived immediately towards the sea. Most were lost by the radar when they flew behind the cliff edge or into a region generating heavy ground clutter. The waders flew in level flight much longer and more slowly than the mallards and about 100-500 ft higher.

The altitude of dunlin flights ranged from 600 to 1000 feet above sea level. The altitudes of oystercatcher flights ranged from 400 to 700 feet ASL. In general the dunlins flew higher than the oystercatchers.

Air speeds obtained from 10 runs ranged from 20 to 29 knots for the dunlins, and 25 to 36 knots for the oystercatchers, when head and tail winds were less than 8 knots.

4.2.1 Dynamic Radar Echoing Areas

We need to know the echoing area characteristics of birds in order to estimate the maximum distances they can be detected and tracked by radar. The echoing area of any moving target made of heterogenous material and complicated in shape is very difficult to measure and specify, because its echoing area is a multi-valued quantity which varies with target aspect and radar parameters.

In the past we have made static radar echoing area measurements on freshly killed birds "set" with their wings close to their bodies or outstretched in flight. The birds were rotated in azimuth and their echoing areas were measured at every azimuth aspect. Echoing area diagrams were plotted in azimuth over 180 degrees from head-on through broadside-on to tail-on aspect. Each diagram was plotted for a single value of radar frequency, radar aerial polarisation and aerial elevatic angle.

However, birds flap their wings and their body shape changes in flight, and so it is desirable to measure their echoing areas under dynamic conditions of flight. Opportunities have occurred to make dynamic echo area measurement of birds in flight at suitable vertical and horizontal aspects. Static and dynamic broadside-on aspect echoing area results agree fairly well, but in all cases dynamic values have been found to be smaller than static values (2).

Recently new recording apparatus has been fitted to the Aberporth FPS16 radars, which has made it possible to record continuously target signal to noise ratio and radar range. With these facilities it has been possible to measure and record the relative signal to noise (S/N) ratio versus range of a reference sphere of known echoing area and shortly afterwards of flying birds of a known species. The echoin areas of the birds can then be calculated in terms of the echoing area of the sphere By exploiting the erratic flight of a released wild bird and using many birds of the same species, a multi-aspect value of dynamic echoing area is created, which can be specified as a mean value with limits of one or two standard deviations from the mea In Appendix A it is shown that the fluctuations about the mean value are fairly symmetrical.

In practice there are limits to the number of birds which can be captured and released, and the number of days the radar can be obtained. Consequently the resul given here are tentative and may be updated in the future. Basically the method is a good one, because for the first time the echoing area is obtained from many birds in a great variety of aspects in full flight. Furthermore the value is a practical quantity because it has been obtained by a radar during normal operation.

The experimental procedure and calculation of results are given in Appendix A. A summary of this work is given here:-

Radar wavelength: 5.6 cms; Aerial Polarisation: Vertical

The signal to noise (S/N) ratio obtained at the output of a radar receiver system from a moving target of echoing area (σ) is given by the radar range inverse fourth power law equation:

$$10 \log (S/N) = 10 \log (K)(\sigma) - 4(10 \log R/R_o) \quad \text{......... (1)}$$

where K is a constant for a known set of radar and propagation parameters.

R is the radar (slant) range and R_o is the normalizing range, which for the FPS16 operating on small birds is conveniently made 1 nautical mile.

The logarithms are to the base 10.

If all the quantities are measured or expressed in decibels (dB) we can write equation (1) as a linear equation with negative slope:

$$Y(dB) = b(dB) - mX(dB) \quad \text{.......... (2)}$$

Radar echoing area of 12 inch dia metal reference sphere

At the radar operating wavelength of 5.6 cm, the radar echoing area of the sphere is approximately 700 sq cm.

Dynamic radar echoing area of a dunlin

The dynamic radar echoing area of a dunlin was calculated by making use of the (S/N) ratio versus normalized range (R/R_o) ratio data obtained from the reference sphere and a number of dunlins, and equations (1) and (2).

Dynamic REA of a dunlin = 4 sq cm $\pm$13 dB

where 4 sq cm is the average value and 13 dB is twice the standard deviation from the mean.

The (S/N) ratio and range data for the sphere and the dunlins were measured on the same day. Over three hundred pairs of data points obtained from fourteen dunlin flights were used to compute the mean value and standard deviation.

Dynamic radar echoing area of an oystercatcher

The dynamic radar echoing of an oystercatcher was calculated in the same way as that of the dunlin:

Dynamic REA of an oystercatcher = 13 sq cm $\pm$15 dB

where 13 sq cm is the average value and 15 dB is twice the standard deviation from the mean.

The (S/N) ratio and range data for two sphere runs and two sets of oystercatcher runs were made on different days. Over 180 pairs of data points obtained from eleven oystercatcher flights were used to compute the mean value and standard deviation.

4.2.2 Bird Activity Modulation Waveforms

If the relatively slowly changing average current component of the bird echo signal is removed there is left a rapidly varying alternating current component called bird activity modulation (BAM). The BAM waveform is generated by periodic wing flapping and transient changes in body shape and movement.

Generally, birds whose physical dimensions are less than the radar wavelength usually produce simple periodic BAM waveforms, while birds whose dimensions are larger than the radar wavelength produce complex BAM waveforms. Usually these BAM waveforms, simple or complex, can be assessed by using an electronic analyzer to extract the Fourier components of the waveform which are displayed as a spectrum diagram. This is true for steady flight such as during migration, but erratic flight, such as occurs when a wild bird is released, affects the cyclic pattern of the waveform.

The spectrum of an "erratic" BAM waveform can suffer in two ways: the components of the periodic spectrum can be reduced or lost and additional unwanted fluctuating components can be introduced. The consequences of additional components can be mitigated by filtering or, better still if they are caused by stationary pseudo-random effects, by using correlation techniques in place of or before spectrum analysis.

The BAM Waveforms of Waders

The BAM waveforms of two dunlins taken from runs 04D and 04I are shown in Fig 2. These waveforms are made by a species which continuously flaps its wings. Both records were taken after the birds had been in flight for about 1 minute. In both waveforms, although there are strong periodic amplitude components, the overall pattern changes from second to second. Furthermore although there are some toothlike pattern similarities they are not clearly similar.

The BAM waveforms of two oystercatchers are shown in Fig 2b. Again there are cyclic components, the overall pattern of which changes throughout. Comparison of the waveforms reveals superficial pattern similarities of a weak kind.

The BAM waveforms of two curlews are shown in Fig 2c. Again there are pattern change throughout each record. Comparison of the waveforms reveals pattern similarities of a weak kind.

The striking short and long term waveform pattern similarities which are a feature of the BAM waveforms generated by small birds on migration, like the swift, *Apus apus*, are almost entirely absent in these wader BAM waveforms.

There is no doubt in the case of these released birds that flight tends to be errati even some minutes after release. Furthermore the physical dimensions of these waders are comparable to or greater than the radar wavelength in use. It seems possi that both these effects are responsible for these very complex fluctuating BAM waveforms which in the form of amplitude waveforms are not easy to interpret.

4.2.3 The Spectra of Waders

The BAM waveforms of all the wader flights were analyzed by means of an electronic spectrum analyser. A moving "strobe" on the spectrum display coupled to an interpolation oscillator, permitted the response peaks to be calibrated accurately.

The dunlin

The spectral diagrams obtained from a dunlin, run 04I, are shown in Fig 3a. The top diagram is the analysis of a 40 second portion of the BAM waveform obtained after the bird had been flying about 1 minute. The Fourier analysis was performed on all amplitude levels of the BAM waveform and then the resultant coefficients of the analysis were summed. The bottom diagram is a Fourier analysis of the same BAM waveform, but in this case only the peak values were averaged.

Both diagrams have prominent fundamental responses whose peak values occur at 5.5 Hz for the summed Fourier coefficients and 5.6 Hz for the peak value analysis. Broad second, third and fourth harmonic responses occur at very much lower amplitud than the fundamental in both sum and peak spectrum diagrams.

Spectral diagrams obtained from eight dunlins are shown in Fig 3b. These are 40 second sum analyses such as mentioned above but taken after 1 or 2 minutes of fligh time. This is the reason for the fundamental spectral response of run 04I being 5.6 Hz rather than 5.5 Hz as in Fig 3a. Runs 04D, 04H, 04I, 05B and 05E have similar overall diagrams, while runs 04C, 04F, and 05G have spectra with strong broad harmonic responses. Often the peak values of these harmonic responses are not simple multiples of the peak value of the fundamental frequency, although they are multiples of some element of the fundamental response.

Note that there are a wide range of fundamental component peaks from 5.5 to 7.7 Hz.

The oystercatcher

The sum and peak spectral diagrams obtained from the oystercatcher, run 03G, are shown in Fig 4a. Both diagrams have strong fundamental frequency components which peak at 4.9 Hz. Harmonic response occurs in both examples, but the second harmonic response is more prominent in the peak evaluation.

Spectral diagrams obtained from nine oystercatchers are shown in Fig 4b. In the case of the oystercatcher although the spectral diagrams of flight 03G are different in Fig 4a and 4b the peak value of the fundamental response occurs at the same frequency 4.9 Hz. Some of the diagrams like 03G have low harmonic response, whereas others like 03C, 03E, 06C and 06H have very strong harmonic responses. The fundamental responses of the nine oystercatchers ranges from 4.9 to 5.7 Hz.

The curlew

The spectral diagrams for summed and peak values of a curlew, run 06D, are given in Fig 5a. Both diagrams have prominent fundamental responses and relatively strong harmonic responses. They are quite different patterns and the peak values of the sum diagram and peak diagram are 4.1 and 3.9 Hz respectively.

The spectral responses of curlews, runs 06D and 06E, are shown in Fig 5b. These are sum diagrams averaged over 10 seconds rather than 40 seconds. The top diagrams were analyzed first, then the second diagrams and so on. This method of analysis enables changes in the spectral pattern to be detected. The fundamental component peak value of 4.0 Hz remains constant throughout this short analysis for curlew, flight 06D, but changes slightly for curlew, flight 06E, from 3.7 to 3.8 Hz.

4.2.4 The Correlation Functions of Waders

The theory and use of correlation techniques for comparing complex BAM waveforms or for searching for the relatively weak periodic wing beat component in a BAM waveform mutilated by severe fluctuations have been given in a previous paper (1). Obviously it is not easy to deal with complex BAM waveforms such as is shown in Fig 2, but the use of spectral analysis usually enables the principle frequency responses to be identified. Auto-correlation and cross-correlation are methods which can be relied upon to deal with the most awkward cases of randomly fluctuating waveforms and they only fail if the signal is absent or very badly distorted.

The wader waveforms were not so seriously mutilated to need correlation techniques, but it seemed worthwhile to look at them with a correlator in order to simplify them and so improve measuring accuracy. An electronic correlator was used to obtain autocorrelation functions.

The dunlin

The bottom waveform in Fig 6 is the autocorrelation function of dunlin run 04I after the BAM waveform had been passed through a 20 Hz low pass filter. Most of the randomly fluctuating components of the BAM are confined to the central peak, which is at delay time zero, and the adjacent sidelobes. Although the periodic components which appear at both sides of the central response are distorted and relatively small in amplitude, they are much easier to interpret than the original BAM waveform (also passed through a 20 Hz low pass filter) in Fig 2a. The chief periodic components of this autocorrelation function is 5.7 Hz, and this is most clearly shown in the top autocorrelation function for dunlin 04I, where the 20 Hz filter was replaced by a 9 Hz bandpass filter. Again the fluctuating components of the BAM waveform are confined to the centre of the pattern and adjacent sidelobes, with the periodic components of low amplitude at each side. The 5.7 Hz sinusoidal timing waveform in the centre of the figure is for comparison purposes. Note there is a small difference in the estimates of the fundamental correlation periodic waveform frequency and the fundamental frequency found by spectral analysis.

The oystercatcher

The autocorrelation function for the oystercatcher, run 03C, is shown in Fig 7. The very pronounced central and 3 adjacent sidelobes contain most of the complex randomly fluctuating components of the BAM waveform. Again we find there is a smal difference between the value of 5 Hz given here for the periodic fundamental component and the peak response of 4.9 Hz given in the spectral diagram of Fig 4a.

The curlew

The autocorrelation function for the curlew, run 06D, is shown in Fig 8. The fluctuating frequency components are again prominent in the centre of the diagram. In this case the estimated fundamental periodic waveform is 4.2 Hz as compared to 4.0 Hz obtained by spectral analysis.

5 COMMENTS AND CONCLUSIONS

1 36 birds were tracked successfully out of 39, and the average track lasted for a duration of 4minutes. This remarkable improvement in results over those of the mallard trials was due to

(a) a more imaginative response and greater flexibility in trial planning.
and
(b) better release, acquisition and putting-on facilities

Although these advances gave successful trials with three species of wader and the herring gull, Larus argentatus, it is not possible to guarantee what will happen with other species. Duck, for example, tend to seek the nearest water, but the better arrangements should still result in longer useful records.

2 The waders usually circled the release point and then climbed in altitude before settling down to a period of fairly straight and level flight. Even in the periods of fairly uniform trajectory there were continuous aspect fluctuations.

3 Air speeds ranged from 20 to 29 knots for dunlins flying at altitudes 600 - 1000 feet, and 25 to 36 knots for oystercatchers flying at altitudes 400 - 700 fee These speeds were measured when head and tail winds were less than 8 knots.

4 A new method of measuring, calculating and specifying a multi-aspect value of dynamic radar echoing area has been demonstrated. The dynamic REA of a dunlin is 4 sq cm ± 13 dB and the dynamic REA of an oystercatcher is 13 sq cm ± 15 dB. The new method has also been used to obtain the dynamic REA of the herring gull. This bird has been employed as a reference in the past in other ways of determining radar echoing area. A comparison of the different REA results on the herring gull showing the advantages of the new specification will be reported later.

5 Released waders like released mallards generate very complicated BAM waveform which are difficult to interpret. Usually spectral analysis enables the periodic components to be extracted, but in some cases and at low echo signals it may be necessary to use correlation techniques. Perhaps surprisingly for birds that flap along strongly and continuously some of the waders stopped flapping for relatively long periods.

The fundamental frequency components from 9 oystercatcher BAM waveform records measured 1 minute after release had an average value of 5.1 Hz, a standard deviation of 5% and a range of 4.9 - 5.7 Hz. The inflight frequency variations in terms of the average fundamental were 3 to 4% for durations of 40 seconds for any bird (total length of flight about 4 minutes). The two curlew BAM records gave an average value of 4 Hz and a range of 3.9 - 4.1 Hz. 8 dunlin BAM records gave an components of low amplitude at each side. The 5.7 Hz sinusoidal timing waveform in the centre of the figure is for comparison purposes. Note there is a small difference in the estimates of the fundamental correlation periodic waveform frequency and the fundamental frequency found by spectral analysis.

The oystercatcher

The autocorrelation function for the oystercatcher, run 03G, is shown in Fig 7. The very pronounced central and 3 adjacent sidelobes contain most of the complex randomly fluctuating components of the BAM waveform. Again we find there is a small difference between the value of 5 Hz given here for the periodic fundamental component and the peak response of 4.9 Hz given in the spectral diagram of Fig 4a.

The curlew

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From cine film, Griffiths (3) found the average wing beat frequency of 8 oystercatchers was 5.95 Hz with a standard deviation of 9% and a range of 5.3 - 6.3 Hz. Five curlews gave an average of 4.64 Hz and a range of 4.5 - 4.9 Hz. 13 dunlins gave an average of 11.91 Hz, a standard deviation of 9% and a range of 10.7 to 13 Hz.

Comparison of the radar and cine-camera results for the oystercatchers and curlews show reasonable agreement, but the dunlin results are markedly different. Griffith's results have often been higher than any radar results and differences up to 20% have been found, but these do not explain the differences in the dunlin results given here.

A possible explanation lies in work done by Vaughn (5). He shows in Fig 11a of his paper the BAM fundamental frequency component of a semi-palmated sandpiper, Calidris pusillus, falling from 11.3 Hz to 7.1 Hz in about 60 seconds after release. 20 seconds after release the BAM fundamental was still above 10 Hz. Griffiths specifically states that several species of small birds were filmed after being released by hand. Almost all the film records were short possibly only 5 seconds or so. Consequently if dunlin behaved like the sandpiper (they have already been shown to be more variable than the oystercatcher) and were hand released the average value obtained by the cine-camera could be much higher than the radar value obtained a minute after release. A convincing explanation of the differences will probably have to await the simultaneous radar and cine-camera recording of another batch of dunlins.

6 Serious departures from the periodic BAM waveform generated by wing flapping do affect measurement accuracy. Indeed the relatively large rapid aspect changes characteristic of released mallard and the waders used in this exercise produced distorted BAM waveforms which could not be measured accurately using the spectrum analyser. Correlation techniques were used to improve these measurements and they yielded slightly higher values than the spectrum results.

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APPENDIX A

DYNAMIC RADAR ECHOING AREAS OF BIRDS

By exploiting the erratic flight of a released wild bird and by using many birds of the same species, a fluctuating (multi-aspect) distribution of the echoing area is created. The echoing area of each species is given as a mean value, plus and minus two standard deviations from the mean. We show that the distributions of (S/N) ratios about the mean values are approximately gaussian, and consequently two standard deviations about the average value are a measure of 95% of the echoing area fluctuations.

Note that all values are rounded off to two decimal places, but six places of decimals were used in the calculations.

The method and calculations are as follows:-

12 inch diameter metal reference sphere

Twelve inch diameter metal spheres carried by balloons were tracked and their relative (S/N) ratios and radar ranges were recorded at 5 second intervals. A graph of a typical sphere run, 03A, made during the wader trials is shown in Fig 9. The vertical scale is the relative signal to noise ratio in dB, and the horizontal scale is the normalised radar range ratio in dB.

Note that when the radar (slant) range R is 1 nautical mile, the normalised range (R/Ro) ratio in dB = 0, and when R is 0.5 nautical miles and 2 nautical miles respectively, the normalised range ratios are -3 dB and +3 dB. Each value of the sphere (S/N) ratio has been plotted at the appropriate value of normalised range ratio. Using a programme to compute the least-square fit and correlation coefficient of 76 pairs of data points a first degree function was sought. A straight line equation of the form:-

$$(S/N)\ dB = 55.34\ dB - 3.95\ (R/Ro)\ dB \qquad \text{.............. (1A)}$$

was found to give the best fit with a sample correlation coefficient $r = -0.99$ (the negative correlation coefficient occurs because the (S/N) ratio decreases as range increases). With such an excellent fit the population correlation coefficient $p = -0.98$ to -0.99 at 95% confidence level. The linear equation (1A) has been drawn through the data points in Fig 9. Ideally one might expect the slope of equation (1A) to be -4 and identical to that of the functional equation (1) in chapter 4, but equation (1A) is best described as an S1 equation (the description given by NBS (4) to an equation with a statistical distribution in the vertical y plane only) because the measured values of the (S/N) ratio fluctuate about the mean value. There are also uncertainties in the value of the (R/Ro) ratio, but in this project they were very small and can be neglected.

The chief reason for scatter on the (S/N) ratio results is because the echoing area of the sphere includes fluctuating echoing area contributions from the shrouds and the balloon, which although small are not negligible.

The dunlin

A graph of the results taken from 14 dunlin flights shown in Fig 10. The radar parameters were identical with those used during the sphere run. As might be expected with birds showing all aspects from head-on through broadside-on to tail-on positions there is a wide scatter on the (S/N) ratio data.

Using the least-square fit programme on 305 pairs of data points, two regression equations were obtained:-

(S/N) dB = 33.00 dB - 3.85 (R/Ro) dB .... (2A)

(R/Ro) dB = 1.89 dB - 0.11 (S/N) dB .... (2B)

sample correlation coefficient r = -0.65

population correlation coefficient p = -0.57 to -0.71 at 95% confidence level

The straight line obtained from equation (2A) is shown plotted over the experimental scatter diagram in Fig 10 (two different equations are generated because estimating y from x is not just the reverse of estimating x from y except when the correlation coefficient r = ± 1).

The dynamic radar echoing area of the dunlin is computed by first finding the centre of scatter diagram, using the cross-over of straight lines given by equations (2A) and (2B). This occurs at a relative (S/N) ratio of 44.02 dB and when the normalised range ratio is -2.86 dB. Inserting this range ratio into equation (1A) we obtain the relative (S/N) ratio for the 700 sq cm reference sphere as 66.68 dB. As the sphere and dunlin results were obtained at close range with identical radar parameters we can write:-

Average dynamic REA of a dunlin (over a large number of different aspects) is (66.68 - 44.02 = 22.66 dB below 700 sq cm) = 4 sq cm approx.

A measure of the fluctuating characteristics of the dunlin's echoing area as its aspect changes can be obtained by drawing a straight line, using the functional equation (1), chapter 4, through the cross-over point of the (S/N) data and then calculating the standard deviation of all data points from this mean value line. The distribution of (S/N) ratio fluctuations about the mean is shown in the histogram, Fig 11, for 305 data points. Superimposed on the (S/N) ratio distribution is the equivalent gaussian distribution and by comparison we note the fluctuations are fairly symmetrical about the mean, and the standard deviation is approximately 6.6 dB.

The oystercatcher

A graph of results taken from 11 oystercatcher flights is shown in Fig 10. The radar parameters of trial 03 were identical with those of sphere run 03A, while those of 06 with those of sphere run 07A (not shown) made on different days. The radar parameters of trial 06 results have been adjusted to permit them to be used with those of trial 03. Using the least-square fit programme on 181 pairs of data points, two regression equations were obtained:-

(S/N) dB = 38.89 dB - 3.89 (R/Ro) dB .... (3A)

(R/Ro) dB = 4.61 dB - 0.15 (S/N) dB .... (3B)

sample correlation coefficient r = -0.72

population correlation coefficient p = -0.64 to -0.77 at 95% confidence level

The straight line obtained from equation (3A) is shown plotted over the experimental scatter diagram in Fig 10. The dynamic echoing area of the oystercatcher is computed in the same way as for the dunlin. The cross-over of lines given by equations (3A) and (3B) is at a (S/N) ratio of 46.52 dB and at the normalised range ratio of -2.13 dB The (S/N) ratio for the 700 sq cm reference sphere is 63.75 dB at that range ratio.

Hence we can write:-

Average dynamic REA of an oystercatcher (over a large number of different aspects) is (63.75 - 46.52 = 17.23 dB below 700 sq cm) = 13 sq cm approx.

The distribution of (S/N) ratio fluctuations about the mean is shown in the histogram, Fig 11 for 181 data points. As with the dunlin results, the fluctuations are fairly symmetrical about the mean, and the standard deviation is approximately 7.4 dB.

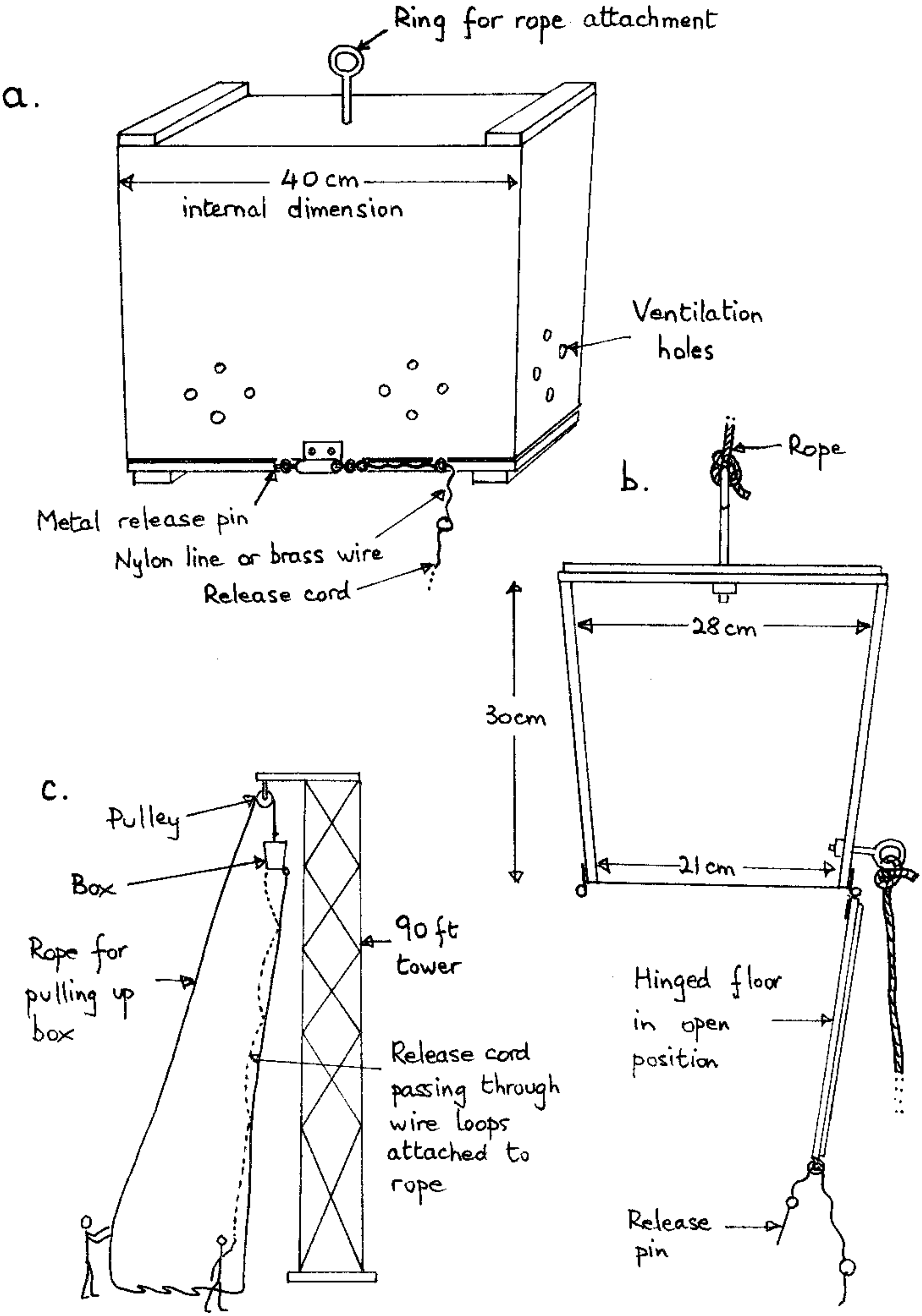
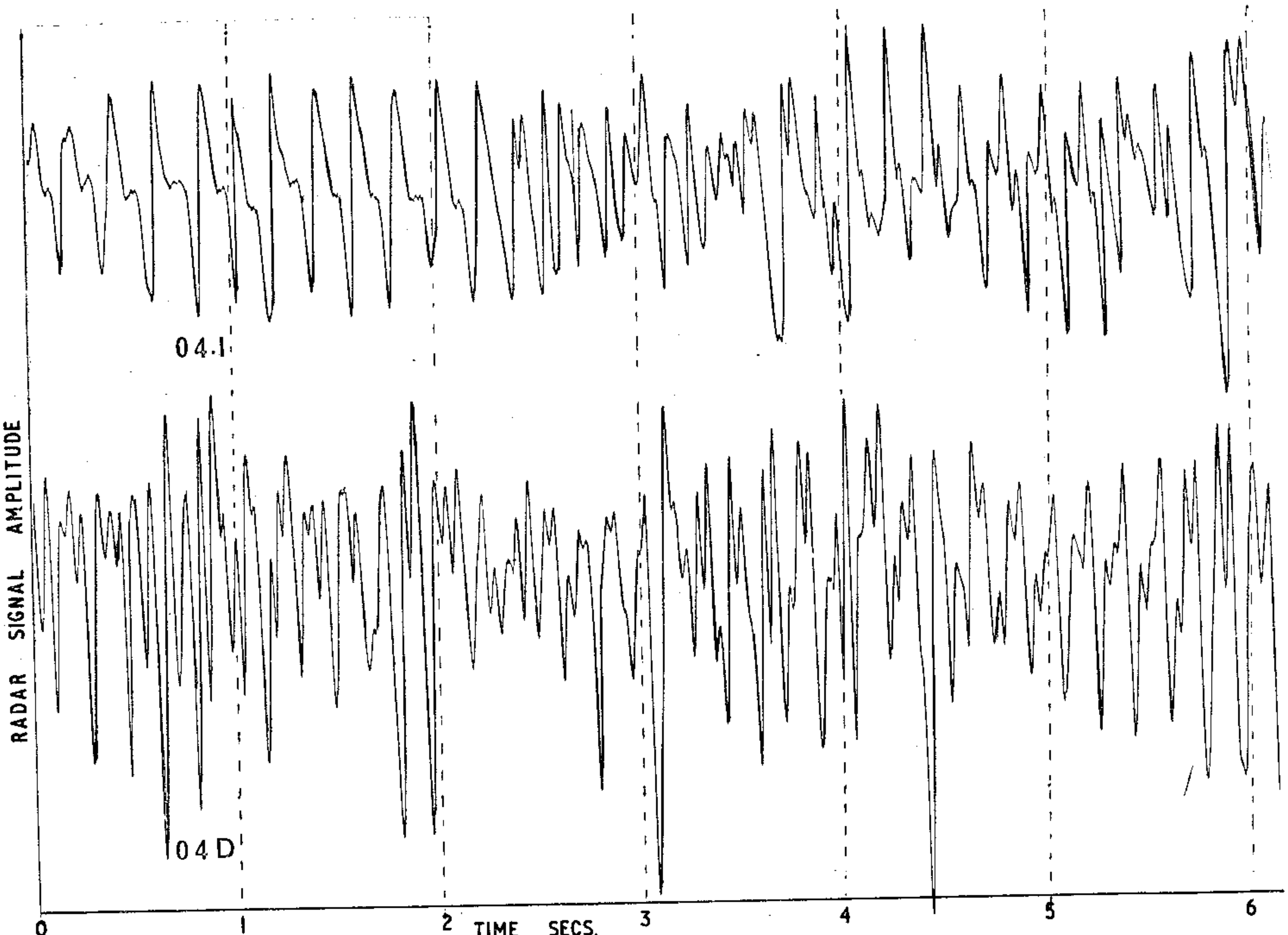
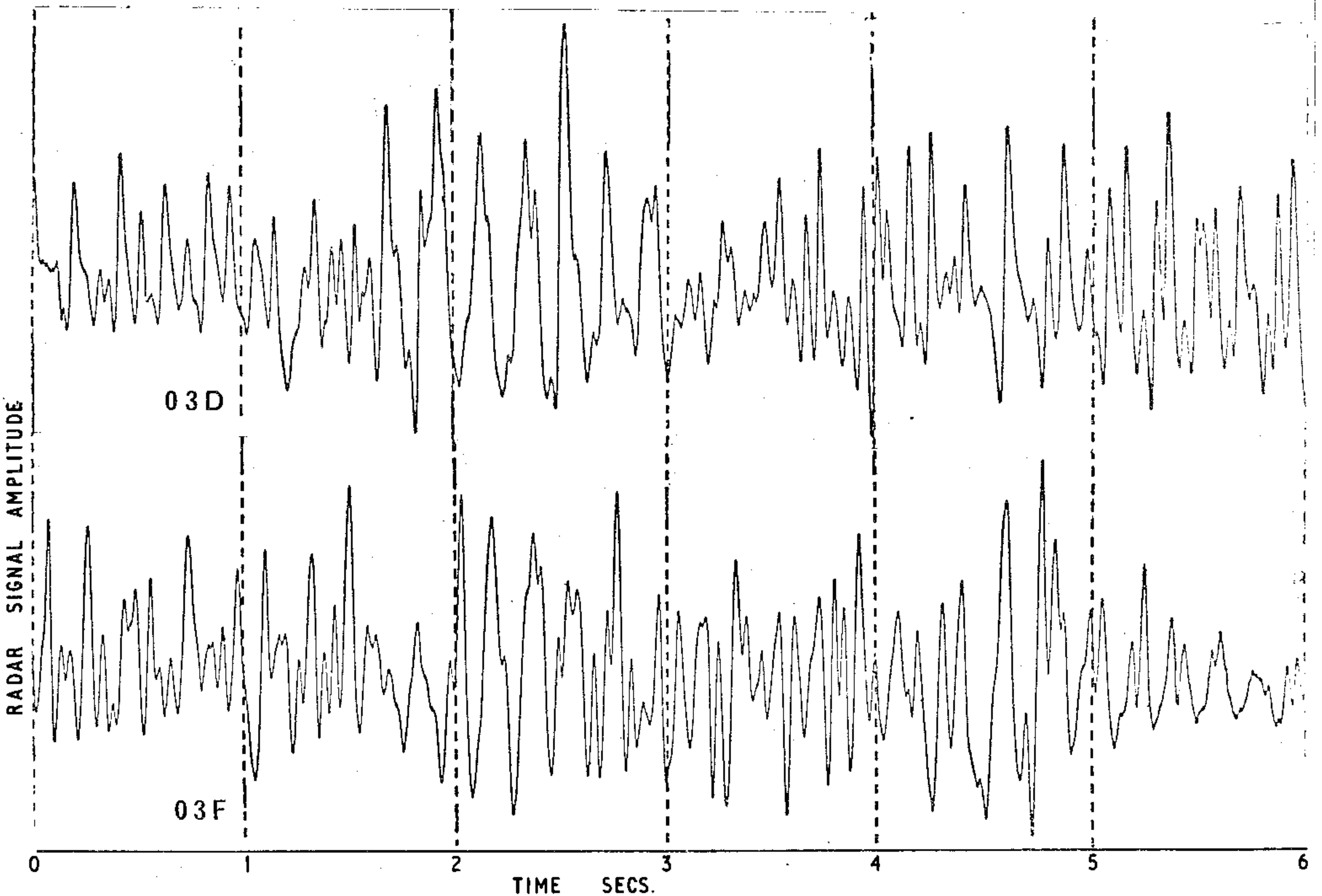


Fig 1 a and b. Aspects of release box.
c. Diagram of tower.

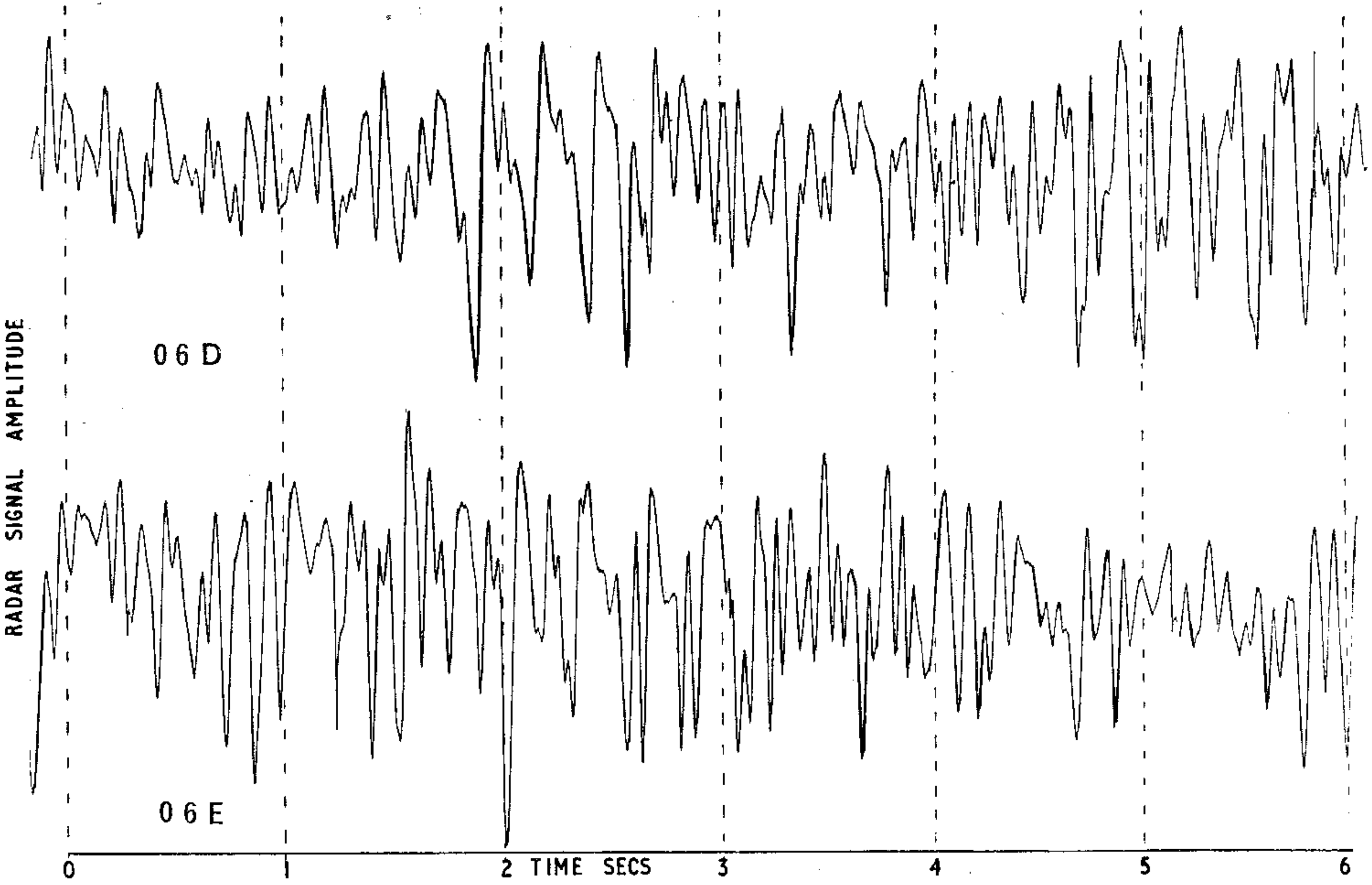


04.1
04 D
RADAR SIGNAL AMPLITUDE
0
1
2
3
4
5
6
TIME SECS.



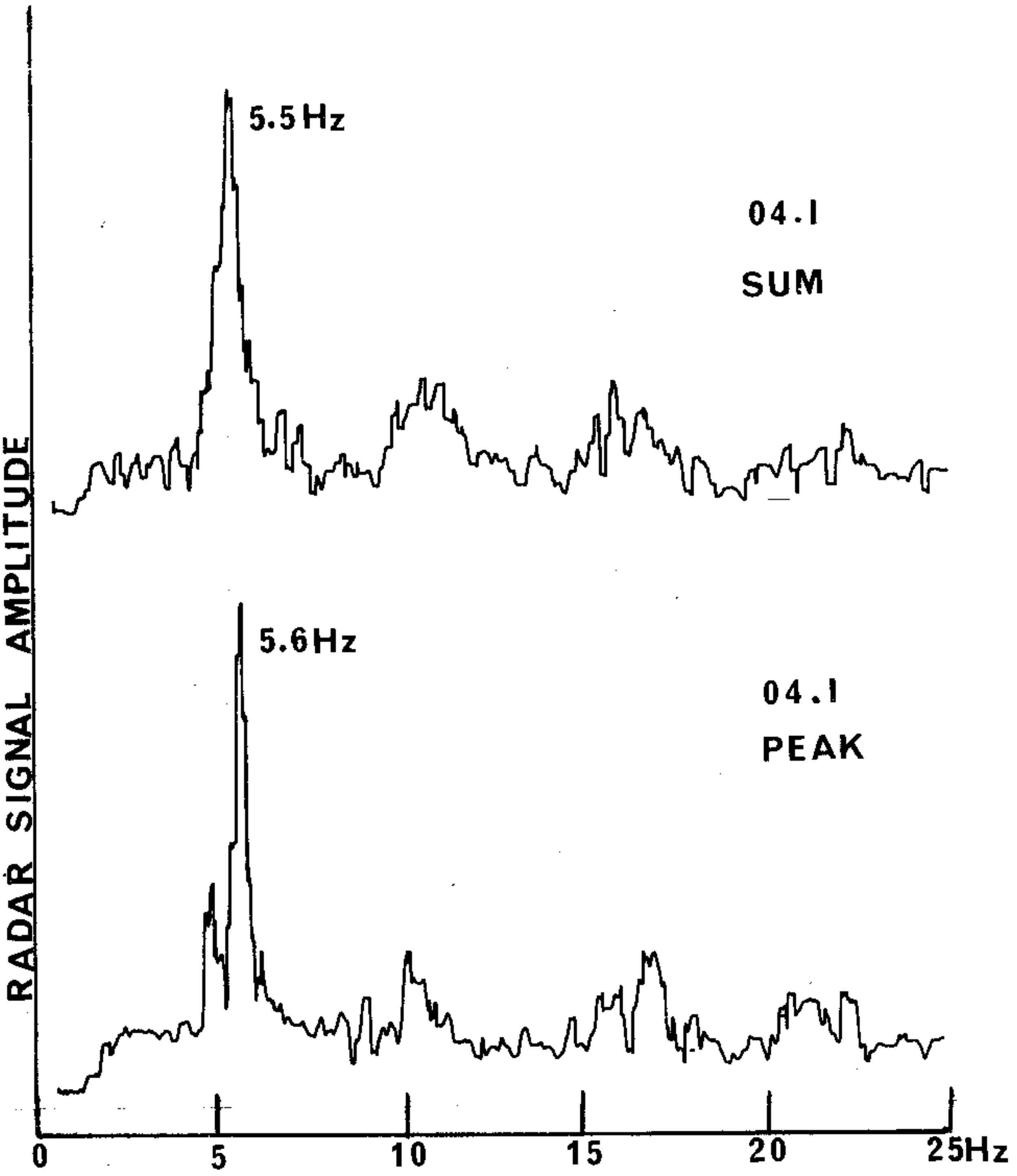
BAM WAVEFORMS OF OYSTERCATCHERS

FIG. 2b

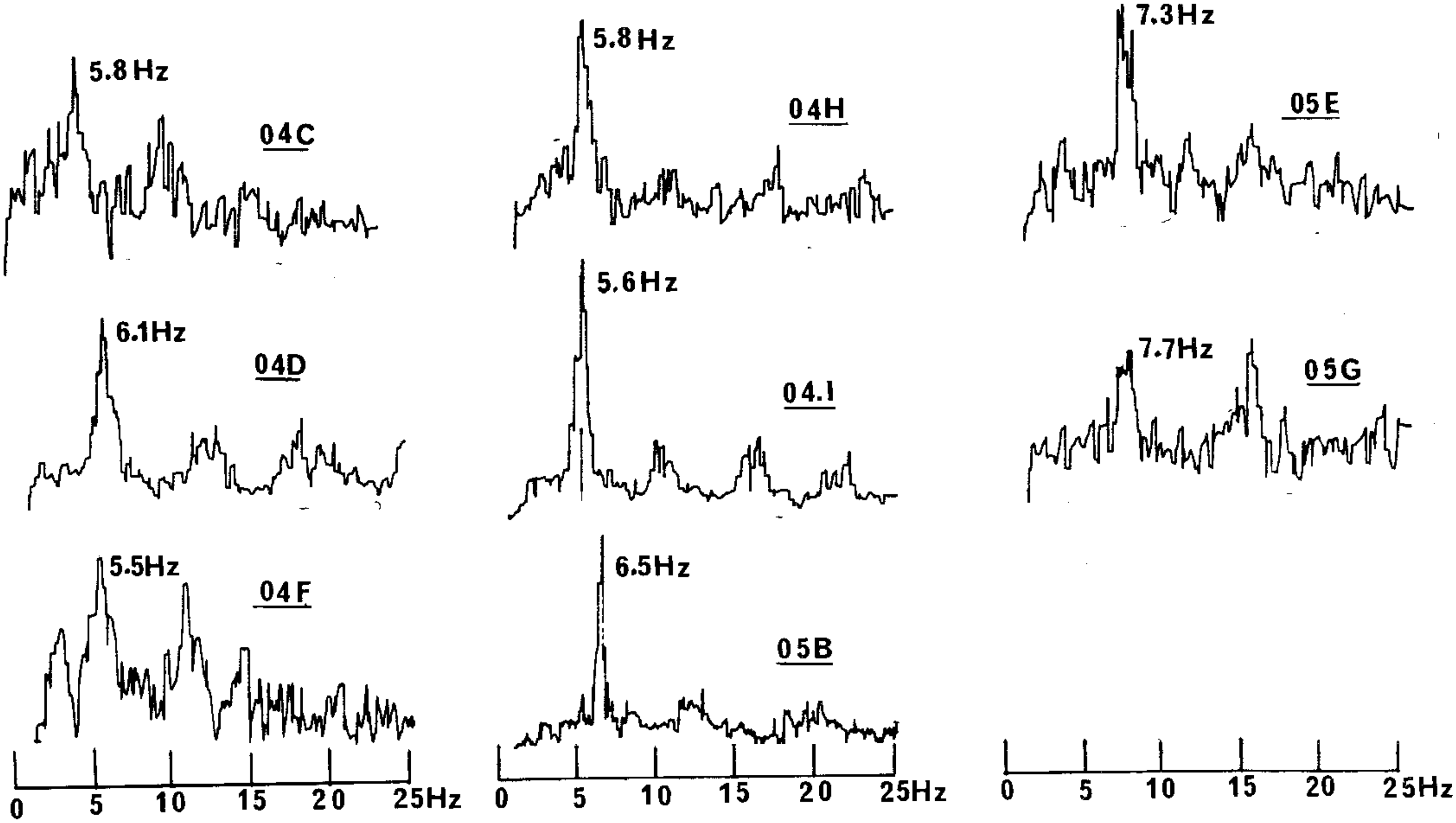


BAM WAVEFORMS OF CURLEWS

FIG. 2c.

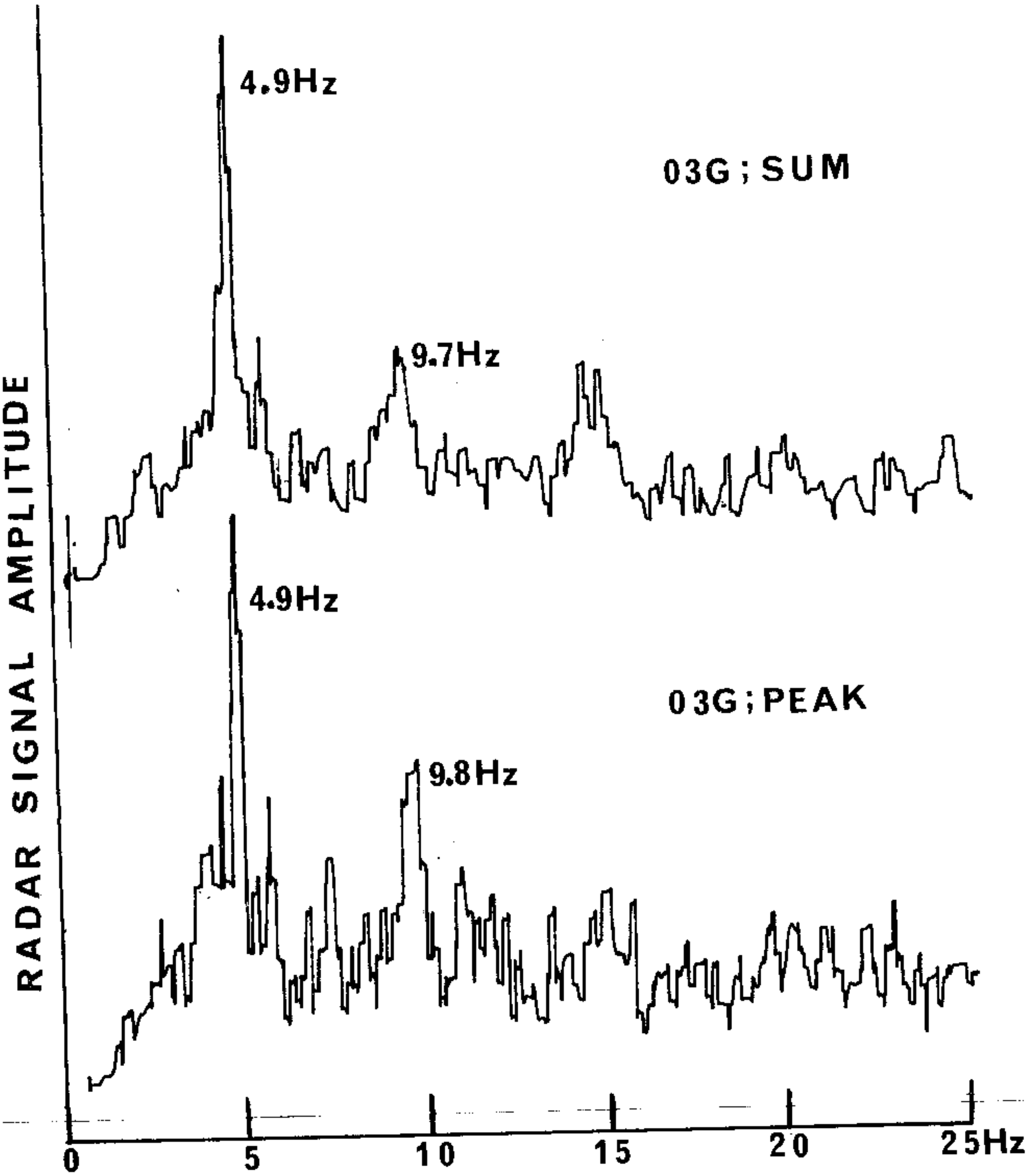


WING BEAT FREQUENCY
SPECTRA OF RELEASED DUNLIN
40 SECS AVERAGE
FIG.3a



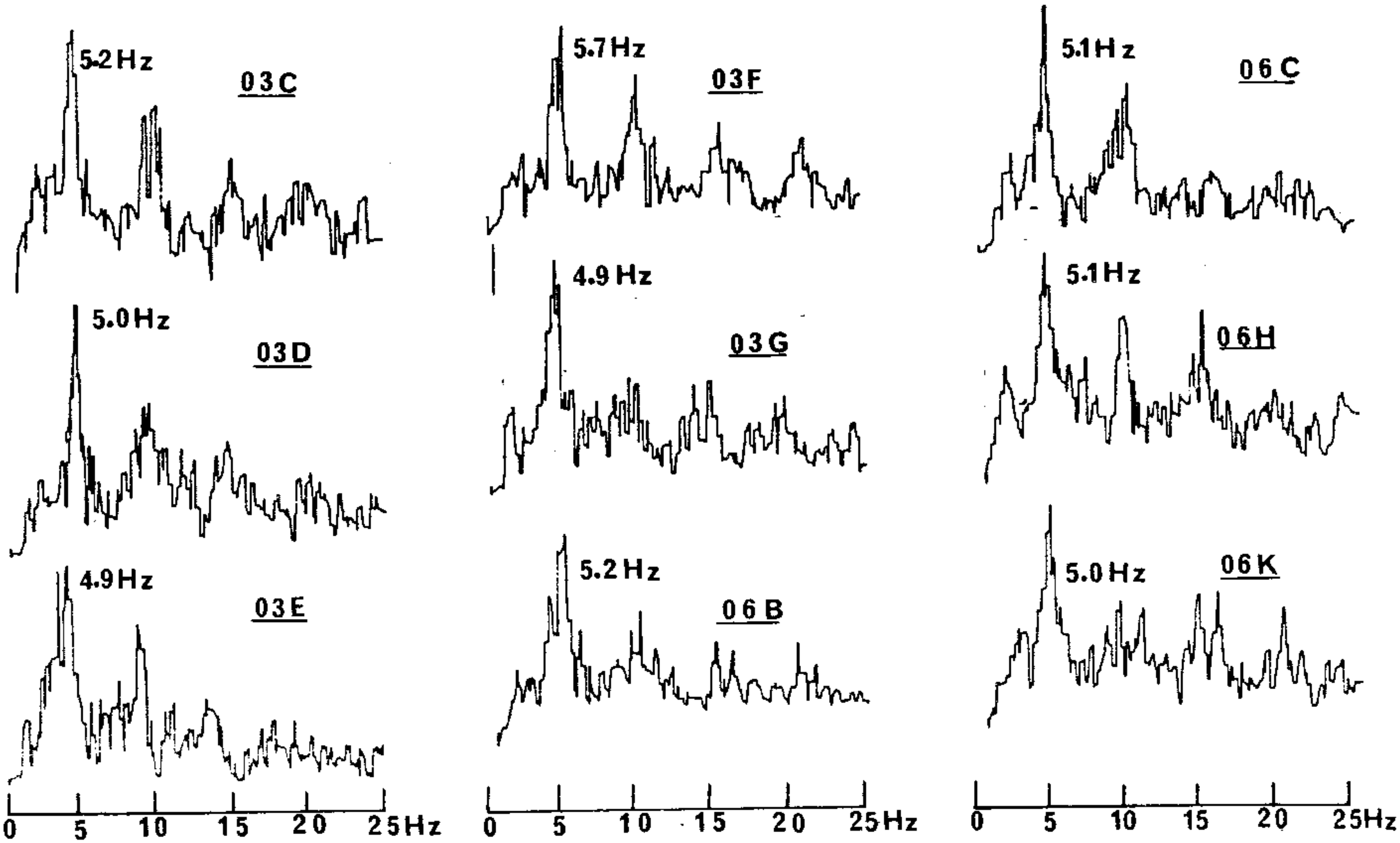
WING BEAT FREQUENCY
SPECTRA OF RELEASED DUNLINS (40 SECS AVERAGE)

FIG. 3b



WING BEAT FREQUENCY
SPECTRA OF RELEASED OYSTERCATCHER
40 SECS AVERAGE

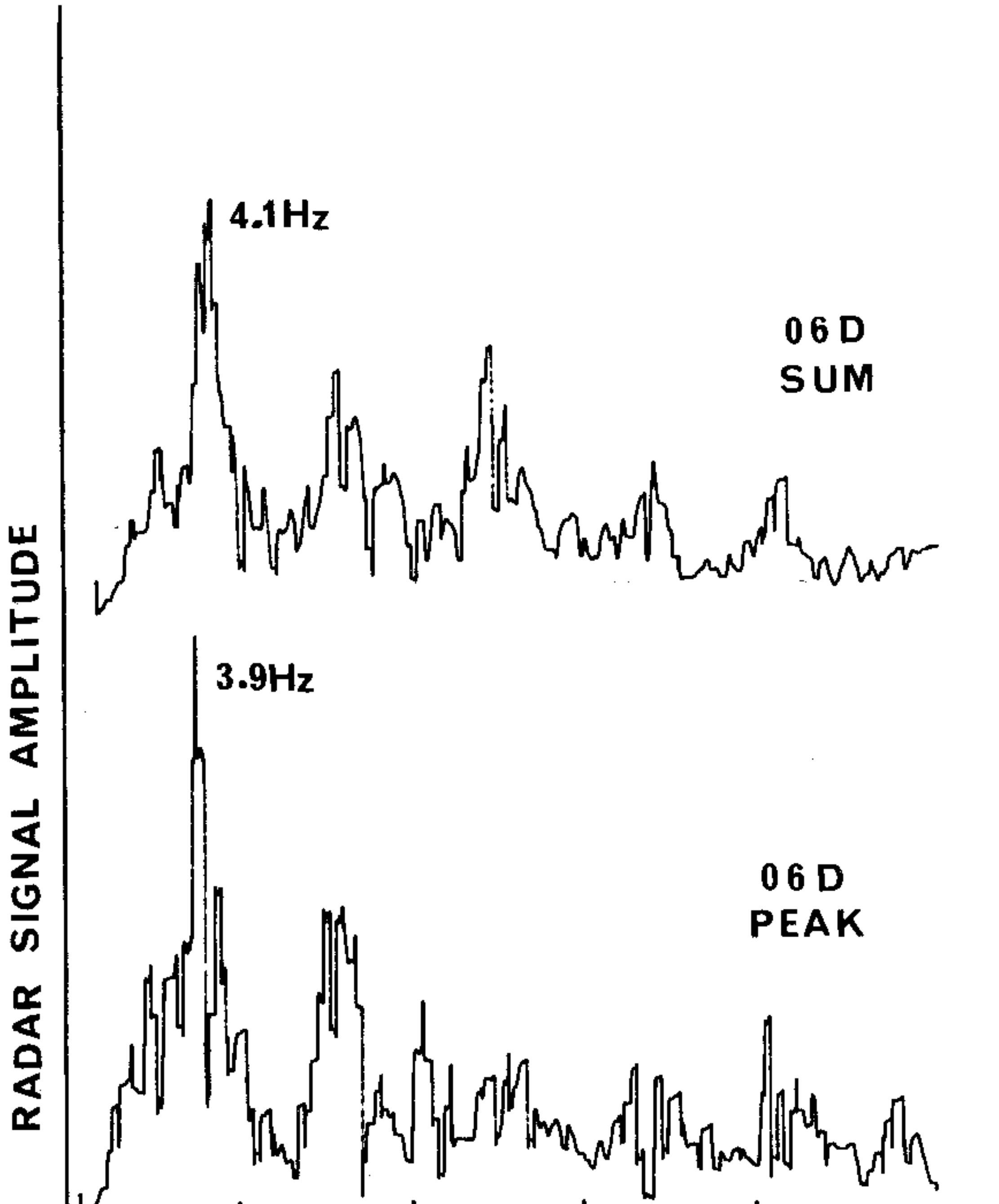
FIG. 4a



WING BEAT FREQUENCY

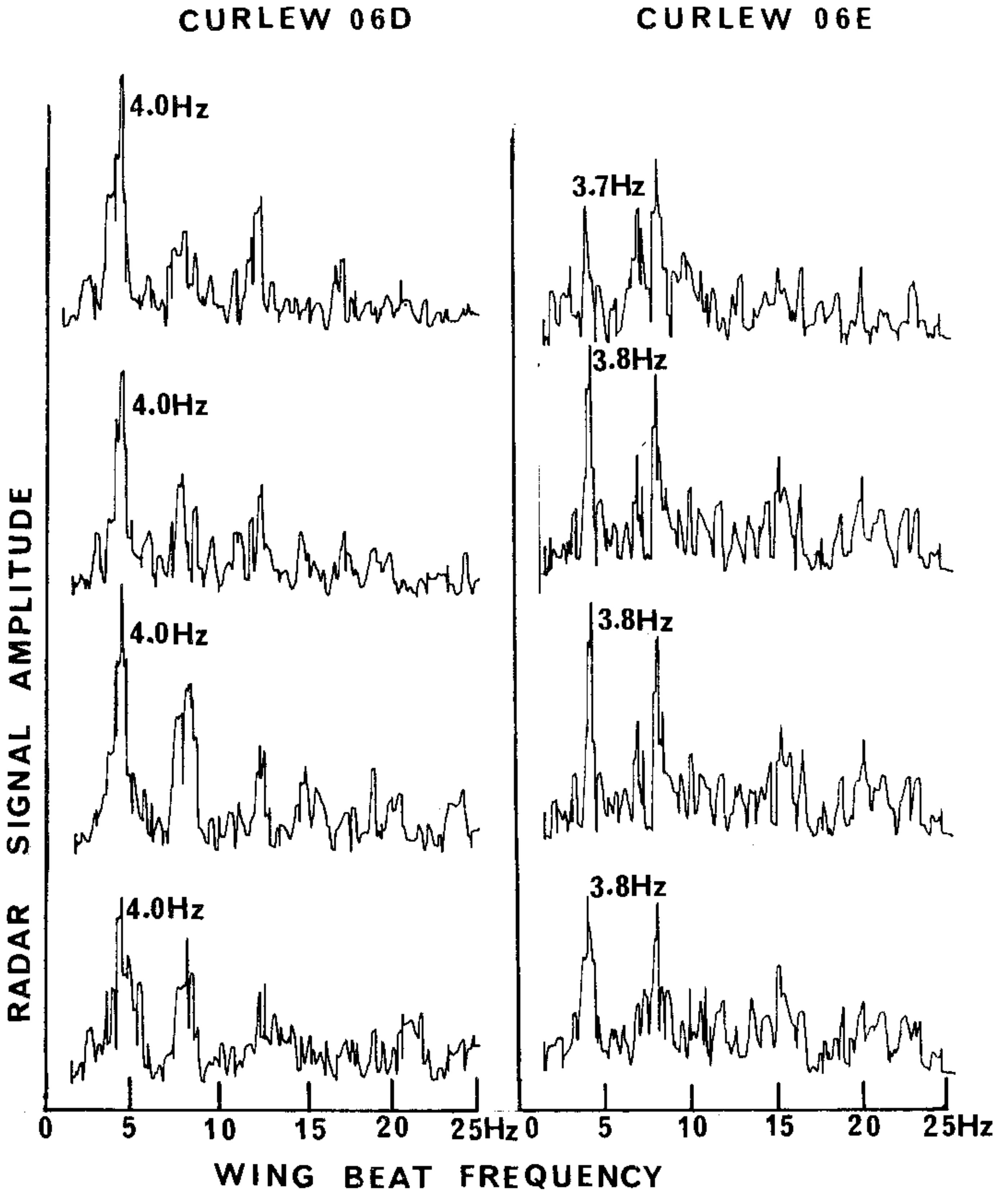
SPECTRA OF RELEASED OYSTERCATCHERS (40SECS AVERAGE)

FIG. 4b



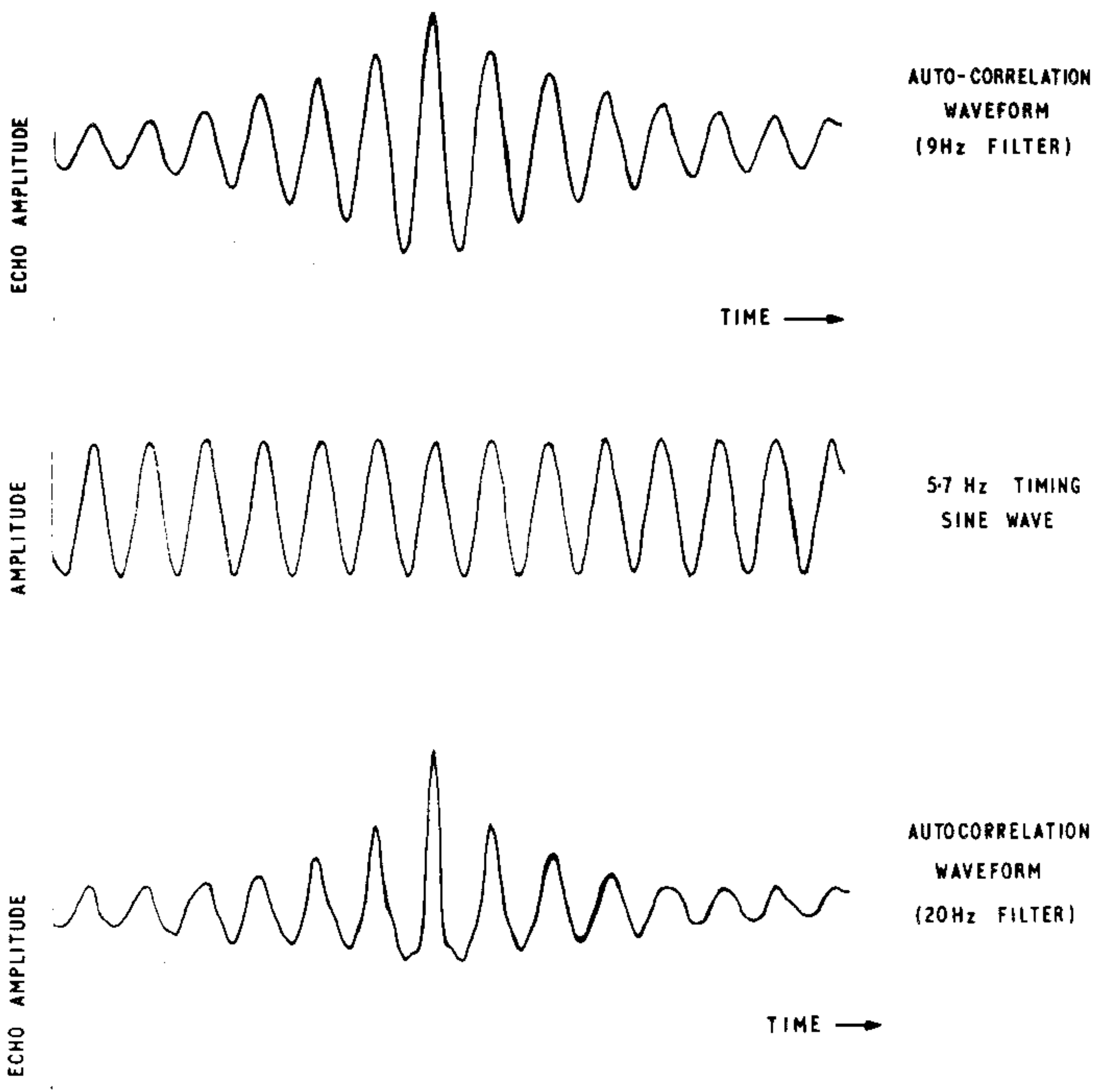
WING BEAT FREQUENCY
SPECTRA OF RELEASED CURLEW
40 SECS AVERAGE

FIG. 5a



SPECTRA OF RELEASED CURLEW (10 SECS AVERAGE) TAKEN FROM TWO SEPARATE RUNS 06D & 06E

FIG. 5b


ECHO AMPLITUDE
TIME
AUTO-CORRELATION WAVEFORM (9Hz FILTER)
AMPLITUDE
5·7 Hz TIMING SINE WAVE
ECHO AMPLITUDE
TIME
AUTOCORRELATION WAVEFORM (20Hz FILTER)

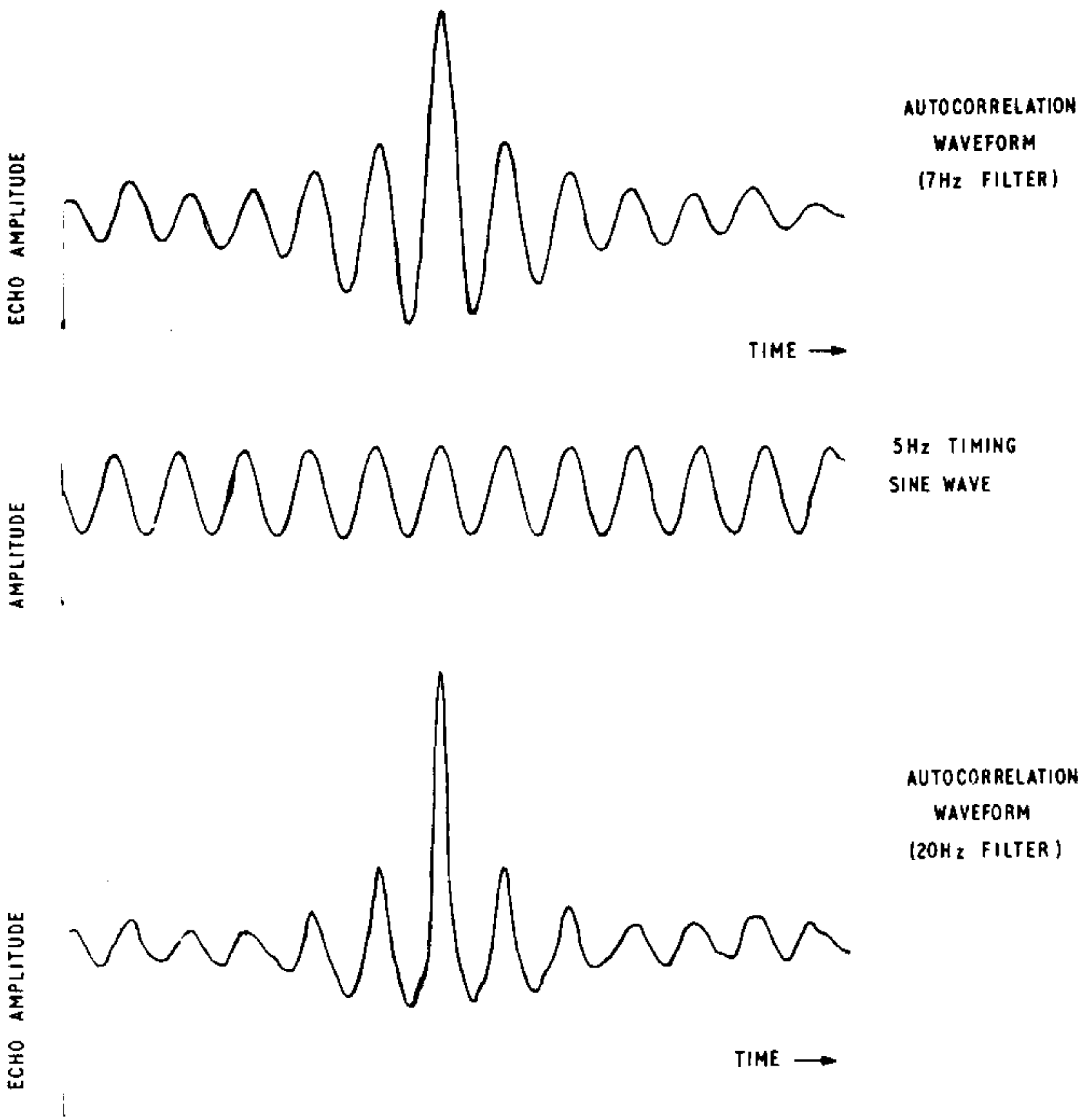


FIG. 7. AUTOCORRELATION WAVEFORMS OF OYSTERCATCHER-O3G.

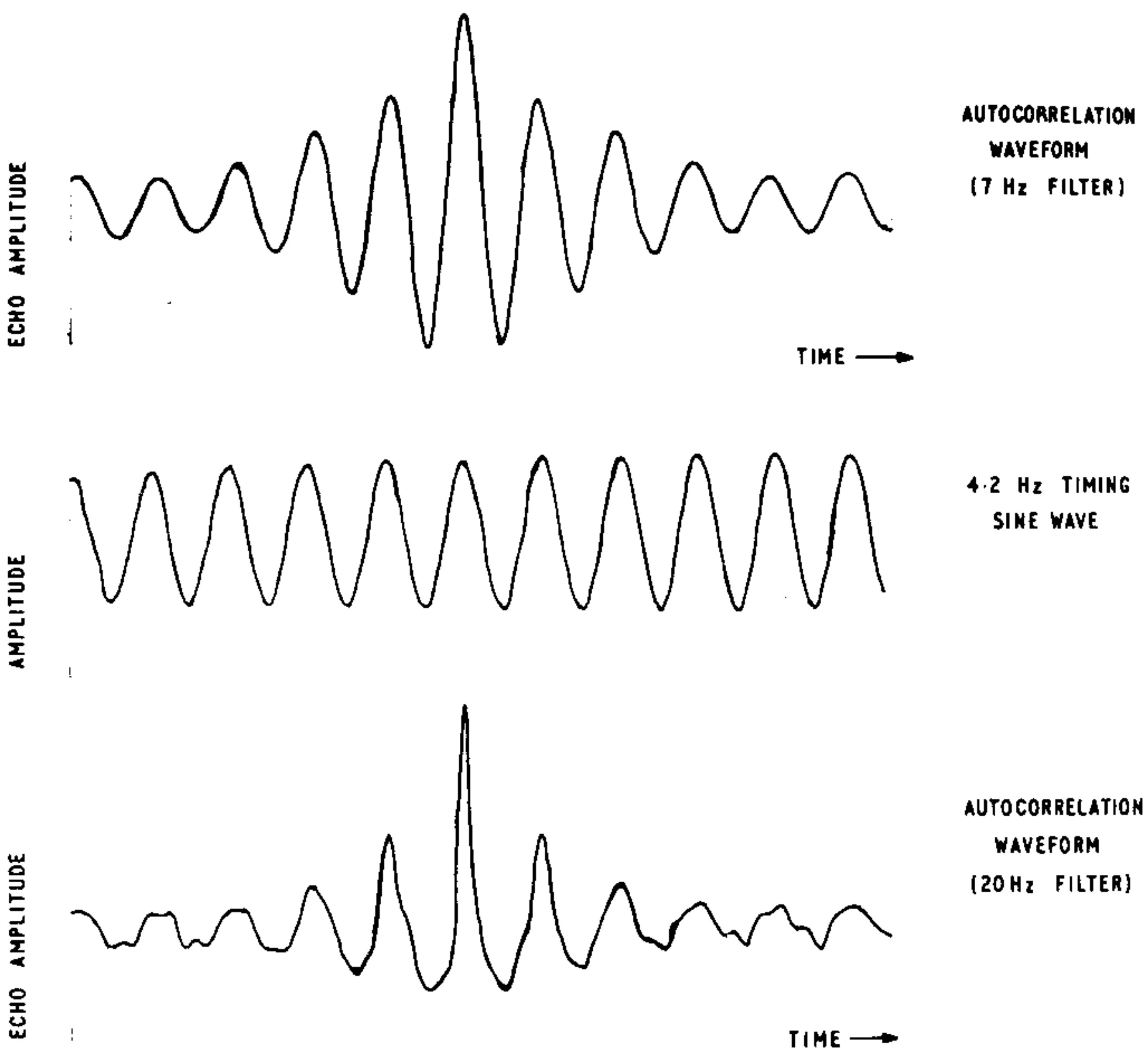


FIG. 8. AUTOCORRELATION WAVEFORMS OF CURLEW – O6D.

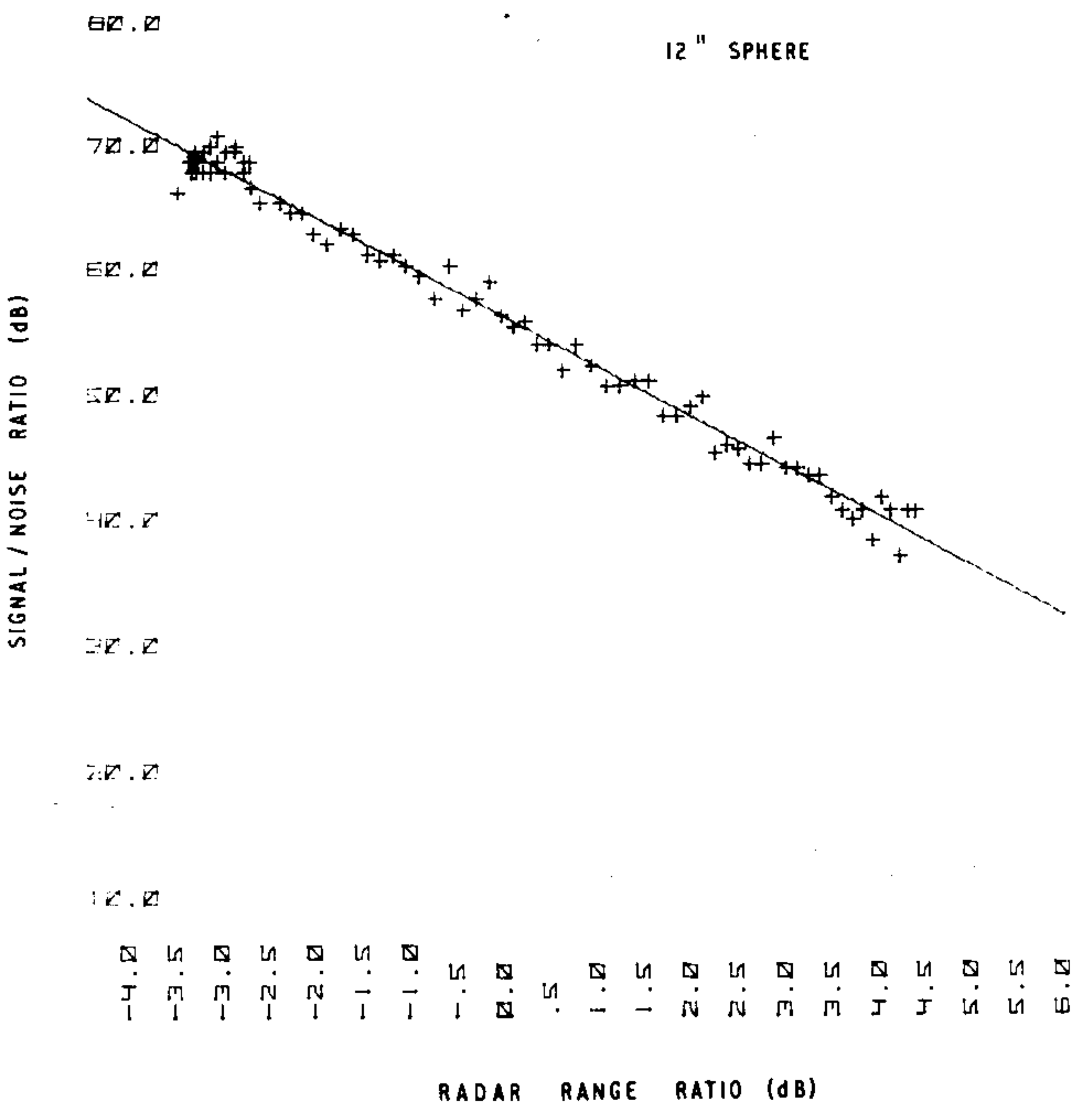


FIG. 9. SPHERE ECHO SIGNAL / NOISE RATIO VERSUS RANGE RATIO.

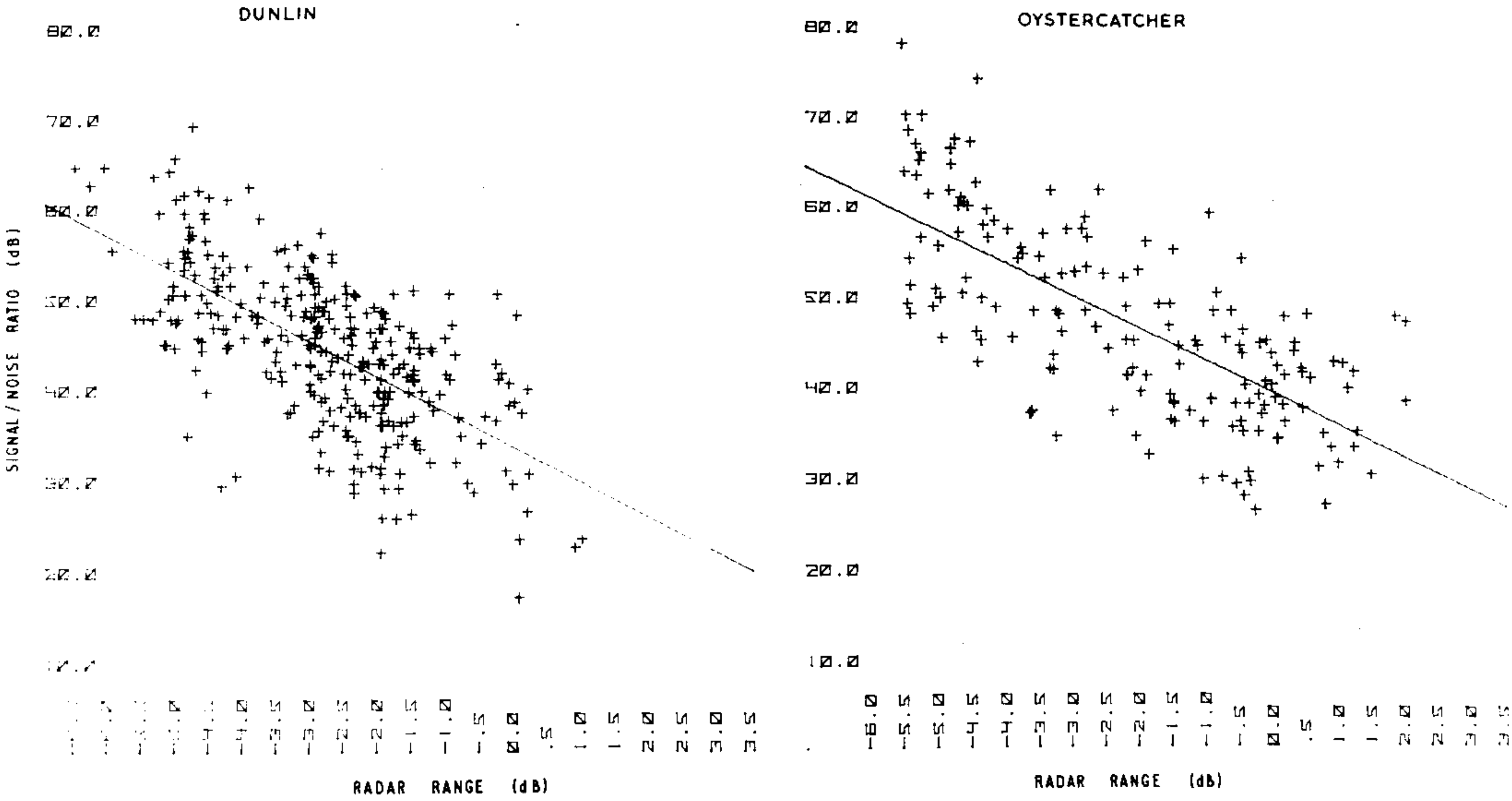


FIG.10. BIRD ECHO SIGNAL/NOISE RATIO VERSUS RANGE RATIO.

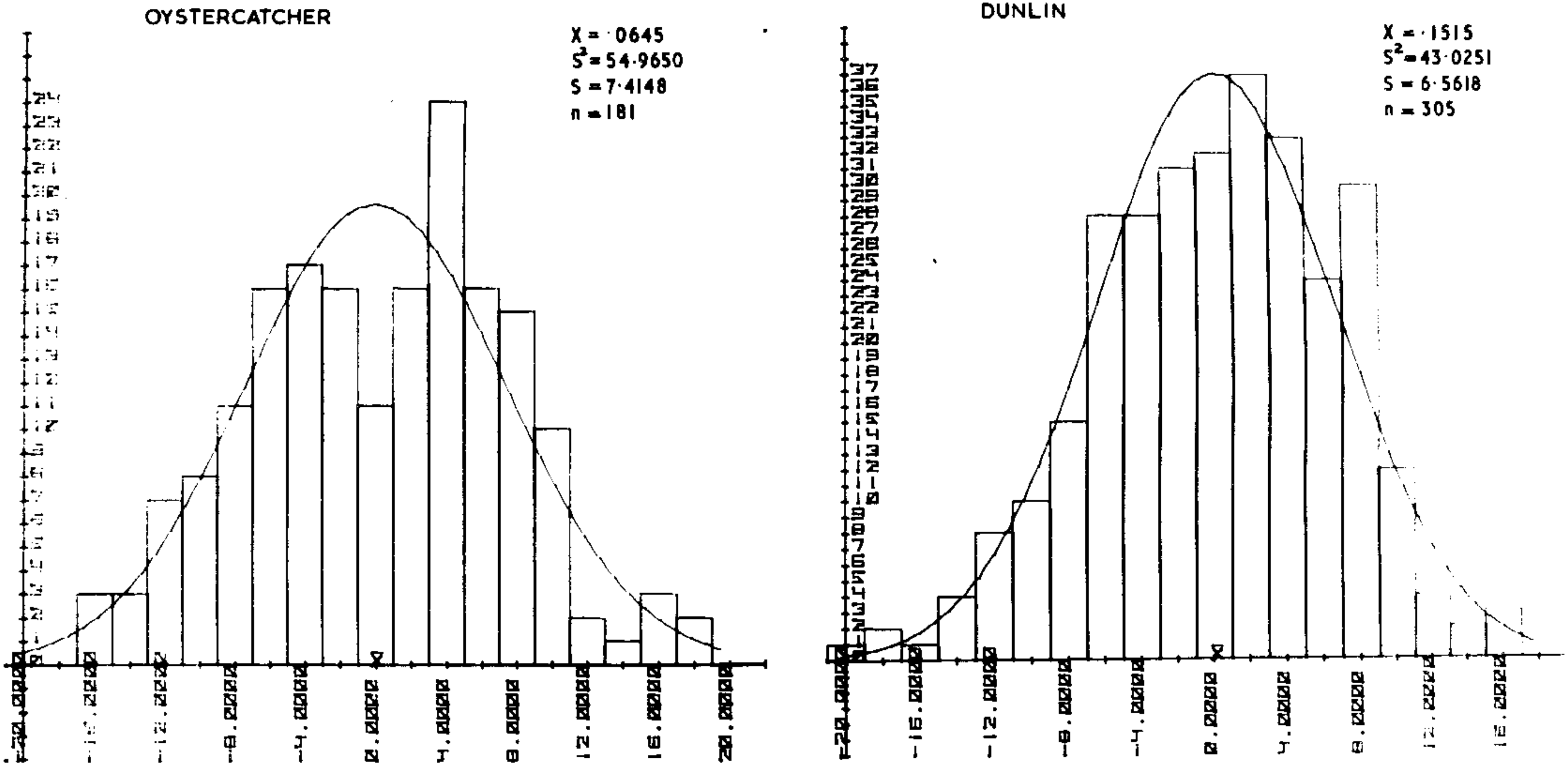


FIG.11.

HISTOGRAMS OF ECHO (S/N) RATIO
FLUCTUATIONS ABOUT THE MEAN VALUE.