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Subject: Use of Bird Activity Modulation Waveforms in Radar Identification.

Dear Sir!

Please find enclosed above mentioned paper which was given at the 7th Meeting Bird Strike Committee Europe.

Yours sincerely

E.P. Schneider
Chairman BSCE

(A shortened version of this paper was given to the 7th Bird Strike Committee Europe, London, 6 June 1972)

"USE OF BIRD ACTIVITY MODULATION WAVEFORMS IN RADAR IDENTIFICATION"

by E W Houghton and F Blackwell

SUMMARY

Positive "on-line" identification of any target is very difficult using primary radar.

Single birds modulate radar echo signals with periodic waveforms related to their wingbeat frequency and to their wing flapping and wing rest periods. Data from these complex waveforms can be extracted by radar "signature" analysis methods and compared with corresponding data obtained from known species (by tracking them with a radar fitted with a telescope). Identification is obtained by correlating known and unknown data.

Actual "on-line" identification appears feasible if a comprehensive catalogue of waveforms and other flight characteristics of known species is collected and used.

These methods can immediately be put to use in investigating the distribution of species hazardous to aircraft.

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1 INTRODUCTION

Even with a very specialized radar it is not possible to generate a silhouette of a large bird like a swan or a crane. Consequently, identification of birds cannot be made directly by radar as they can when they are viewed optically.

The identification of any point source target by means of radar is a very difficult matter, because the familiar parameters used in visual identification, size, shape, colour and texture are lacking. Radar identification of a target must be sought using unfamiliar parameters such as echo intensity, spatial extent and spatial pattern (in the case of extended targets), velocity and acceleration, and trajectory and long-term trajectory behaviour.

Only one parameter in the case of point source targets, the periodic variation of echo intensity, permits a fairly quick and direct way of relating an identifiable physical property of the target with a parameter obtained by radar.

The periodic variation of echo intensity called the wingbeat-frequency amplitude-modulation of the echo signal is a characteristic of the received radar signal from flying animals such as birds, bats, and insects. It was probably first demonstrated by Captain A Davenport (1), a British territorial army officer using his own AA No 3 Mk 7 tracking radar which he had modified for the purpose. One of the first scientific reports on wingbeat frequency amplitude-modulation was by La Grone et al (2) who were studying weather echoes and "angel" echo phenomena.

It was not immediately clear at the time why although bird movements had been tracked by different workers since the advent of radar the effect had not been revealed before. Subsequent modulation records by Gehring (3) and by Konrad et al (4) who were studying the effect indicated that it might not always be easy to obtain good radar records of periodic wingbeat modulation.

Studies by Houghton (5) and Bruderer (6) showed that wingbeat modulation waveforms from a single bird are affected by:-

1 bird dimension/radar wavelength ratio
2 bird flight behaviour
3 faulty or restricted radar receiver signal processing, spurious signals fed into transmitter or receiver, poor signal to noise and auto-tracking instabilities
and 4 contaminating echo signals from other flying animals, and weather, sea and ground clutter.

Hence, the term bird activity modulation (BAM) waveforms has been coined at RRE to describe all forms of modulation generated by birds, whether they are produced by wingbeating, head turning or rapid aspect changes.

In order to relate the characteristics of a BAM waveform to a particular species it is necessary to use a radar with facilities for tracking the bird at the same time by optical means.

Birds can be specially released, initially tracked visually and then auto-tracked by radar to obtain radar signal, trajectory and velocity data. Alternatively, birds can be acquired on an opportunity basis, either visually or by radar and then tracked. In all cases, visual identification is necessary in order to catalogue the radar data.

An important way of building up a library of bird flight data is by filming them with a high-speed cine-camera and then analyzing the data for wingbeat frequency, wing flapping, wing pauses and glide durations. For most species hazardous to aircraft a cine-camera operating at 125 to 225 frames/sec can provide satisfactory data. Probably the most difficult part of flight photography is to find a good site for filming birds in flight.

2 DIMENSIONAL RELATIONSHIPS

Greenwalt (7) has demonstrated that the mechanism of bird wing activity can be represented by a mechanical oscillator whose resonance frequency corresponds to the physical wingbeat frequency. Investigating the relationship between body weight and wing length for a wide range of species he found that weight is proportional to cube of wing length. Utilizing the mechanical oscillator theory he has postulated that the product of wingbeat frequency and wing length should be constant for dimensionally similar series of animals and that wingbeat frequency will be constant for a particular bird. Furthermore by taking values of wingbeat frequency (f) determined experimentally for a number of species and plotting these values against corresponding values of measured wing length (ℓ) he has found that the law of the resultant curve has the form

$$f\,\ell^{1.15} = 3540 \qquad (1)$$

Recently, the Bird Impact Research and Development Committee (UK) has sponsored a study into the radar properties of birds at Loughborough University with RRE as research authority. This work has resulted in two reports by Griffiths (8)(9) on the wingbeat frequencies of the more common birds of the British Isles and Europe. This data of greater accuracy than used by Greenewalt but of limited range has been used to derive new relationships between wingbeat frequency, winglength and weight. Using a high speed cine-camera, whose film frame rate was calibrated by filming a metronome, Griffiths has determined the wingbeat rates of 80 birds. An independent check on the wingbeat rates of some of the species were made by Houghton, Callister and Craig (RRE film unit and RAE scientific photographic unit) using high speed cine-cameras calibrated with a flashing light driven by a precision oscillator. Excellent agreement, within a few percent, was obtained on the species measured.

From the data obtained in the above measurements, the wingbeat rates on 41 birds have been selected and tabulated in Table 1. Data has been chosen on the assumption that UK species with wingbeat frequencies higher than 18 Hz are relatively unimportant from the bird strike point of view and that in order to obtain sufficient accuracy only values calculated from observation samples of 5 or greater have been used. An exception to this rule has been made in the case of raptors and martins, because these species are inadequately represented in the table.

Winglengths obtained from Coward's "The Birds of the British Isles" and weights obtained from a number of unrecorded sources and "Bird Recognition" by Fisher are shown in the table. Values marked (a) are estimated averages of male and female birds.

Using a programme to compute the least squares fit and correlation coefficient of n pairs of data points for a power curve of the form

$$Y = aX^{b} \;;$$

measured wingbeat frequency and measured wing length pairs of values were used to obtain the expression:-

$$f\,\ell^{0.8272} = 572 \qquad (2)$$

and the correlation coefficient r = -0.9394.

Equation 2 has been used to generate a curve through the measured wingbeat frequency versus measured wing length data pairs as illustrated in fig 1. The numbers on the points on the graph correspond to those given in the table. The equation has been used to calculate values of wingbeat frequency from measured wing length for the table.

Following the same procedure but using measured wingbeat frequency and measured weight pairs the following expression was computed:-

$$f\,w^{0.2544} = 27.88 \qquad (3)$$

and the correlation coefficient r = -0.8387.

Although the data pair for the Mute Swan was used in the computation of equation 3 it has been omitted from the points plotted in fig 2. The equation has been used to compute values of wingbeat frequency from weight as tabulated in Table 1.

Use of the table and fig 1 reveals that the greatest differences between measured and calculated values are for the Lapwing and the Heron who fly slower than their calculated values. Most of the other birds lie within ± 25% of their calculated value. Differences between measured and calculated values on the basis of weight reveal greater discrepancies than those based upon winglength and this is to be expected from the empirical laws given in equations (2) and (3).

Griffith discovered that for the 25 species he was able to obtain large enough samples, the spread in wingbeat frequency ranged from 3% for the Chaffinch to 13% for the Carrion Crow. This constancy of wingbeat frequency has also been demonstrated by Blackwell et al (10) on radar tracked birds.

TABLE 1 MEASURED AND CALCULATED WINGBEAT FREQUENCIES

	SPECIES	CINE-CAMERA MEASURED WING BEAT FREQUENCY (Hz)	WEIGHT CALCULATED WING BEAT FREQUENCY (Hz)	WING LENGTH CALCULATED WING BEAT FREQUENCY (Hz)	WING LENGTH ℓ (mm)	WEIGHT W (gm)
1	CHAFFINCH (F coelebs)	17.84	12.70	14.10	88	22
2	WHITETHROAT (S communis)	17.17	14.00	16.83	71	15
3	REDSTART (P phoenicurus)	16.70	14.12	15.91	76	14.5
4	MEADOW PIPIT (A pratensis)	16.62	13.27	15.10	81	18.5
5	WHEATEAR (O oenanthe)	13.22	12.23	13.28	95	25.5
6	SKYLARK (A avensis)	12.15 °	11.11	11.54	112	37
7	DUNLIN (C alpina)	11.91	10.25	11.21	116	51
8	STARLING (S vulgaris)	11.63 °	9.14	10.40	127	80
9	REDWING (T musicus)	11.46 °	9.84	11.38	114	60
10	SAND MARTIN (R riparia)	10.49	13.56	12.47	102	17
11	BLACKBIRD (T merula)	9.98	8.73	10.40	127	96
12	KNOT (C canutus)	8.86	-	8.38	165	-
13	SNIPE (C gallinago)	8.58	8.27	10.40	127	119
14	SWIFT (A apus)	8.49	11.37	8.06	173	34
15	FIELDFARE (T pilaris)	8.39 °	8.60	9.27	146	102
16	TEAL (A crecca)	8.00	6.33	7.66	184	340 (a)
17	WIGEON (A penelope)	7.53	5.39	5.86	254	640 (a)
18	GADWALL (A strepera)	7.44 *	4.98	5.65	266	870 (a)
19	BAR TAILED GODWIT (L lapponica)	7.23	-	7.06	203	-
20	MALLARD (A platyrhynchos)	6.95 °	4.60	5.43	279	1166
21	PINTAIL (A acuta)	6.93 *	4.95	5.43	279	890 (a)
22	SHOVELER (S clypeata)	6.49	5.45	5.86	254	610 (a)
23	OYSTER CATCHER (H ostralegus)	5.95	5.60	6.00	247	550
24	WOOD PIGEON (C palumbus)	5.63 °	5.71	6.12	241	500
25	KESTREL (F tinnunculus)	5.60 °	7.13	6.13	241	213

TABLE 1 (Continued)

	SPECIES	CINE-CAMERA MEASURED WING BEAT FREQUENCY (Hz)	WEIGHT CALCULATED WING BEAT FREQUENCY (Hz)	WING LENGTH CALCULATED WING BEAT FREQUENCY (Hz)	WING LENGTH ℓ (mm)	WEIGHT W (gm)
26	SPARROW HAWK (A nisus)	5.40	7.99	6.68	217	217
27	SHELDUCK (T tadorna)	5.33	4.54	4.72	330	1250
28	JACKDAW (C monedula)	4.94	7.01	6.25	235	227
29	BARNACLE GOOSE (B leucopsis)	4.58	4.13	3.98	406	1820 (a)
30	WHITEFRONT (A allifrons)	4.53 *	3.81	3.88	418	2500 (a)
31	GREY LAG GOOSE (A anser)	4.33	3.52	3.61	456	3400 (a)
32	LAPWING (V vanellus)	4.30 *	7.07	6.55	222	200
33	BLACK-HEADED GULL (L ridibundus)	4.08	6.53	5.14	298	300
34	BEWICK'S SWAN (C bewickii)	3.95 *	3.04	3.18	533	6100
35	CARRION CROW (C corone)	3.92 [o]	5.71	4.72	330	500
36	ROOK (C frugilegus)	3.86 [o]	5.80	4.79	324	480
37	MUTE SWAN (O olor)	3.46	2.60	2.58	685	11300
38	LESSER BLACK BACKED GULL (L fuscus)	3.42	5.09	3.98	406	800
39	HERRING GULL (L argentatus)	3.10 [o]	4.69	3.69	444	1100
40	GREAT BLACK BACKED GULL (L marinus)	2.91	4.59	3.45	482	1200
41	HERON (A cinerea)	2.64	4.25	3.73	439	1620 (a)

All measured wingbeat frequency values with exception of those marked * are taken from University of Technology, Loughborough Report No 9 by M E Griffiths on work done on Mintech Agreement AT/2170/08/RDI.

* RRE Values

[o] RRE Check points

3 THE ECHO SIGNAL FROM A BIRD

Variations in echo intensity can be related directly to variations in its echoing area. The complete solid echoing area diagram of a bird can be very roughly approximated by a ball of wool, prolate spherical in shape and pierced symmetrically by double pointed knitting needles of different lengths and of different diameters. In general, knitting needles placed about the semi-minor axis (corresponding to the broadside aspect) would be longer and of wider cross-section than those placed about the semi-major axis (corresponding to the head-on and tail-on aspects of the bird). In general, the effect of increasing the body dimension/radar wavelength will be to increase the number of knitting needles and reduce their cross-sections. The effect of wing flapping, changes in body shape and head turning is to change lengths, cross-sections and positions of the needles, but in general the longer and wider cross-section needles remain about the semi-minor axis.

Slow changes of echo signal with aspect occur when the radar looks at spaces between the needles or at needle points. Fast echo signal changes take place when the radar is looking along a needle and away from the point.

The echo signal from a bird consists of at least two components; an averaged or mean signal component and an amplitude modulated component as shown in fig 3. The mean component of the echo signal is broadly speaking proportional to the relatively slow variations in echoing area of the bird taking place in minutes and resulting, for example, from long term variations of the bird's aspect as it flies past the radar. The modulation component follows the rapid variations in echoing area taking place in fractions of a second such as generated by wing flapping or by rapid short term changes in aspect produced for example, by zig-zag flight.

The modulated waveform can be specified by the degree or depth of modulation, by the harmonic frequency content of the waveform and by the presence and duration or absence of wing-beat pauses.

4 BAM WAVEFORM GENERATED BY A SINGLE BIRD

The relationship between bird activity in flight and bird activity modulation can be demonstrated by considering a BAM waveform generated by an unidentified bird during night migration in Autumn. The bird is a typical migrant flying a straight course at a constant height and at constant airspeed. The complete radar signal record, of which only a few cycles are shown, consists of recurring bursts of modulation at a fundamental frequency of 16 Hz, varying in length from 2 to 13 cycles and interrupted by unmodulated pauses of duration equivalent to 3 to 7 cycles. This is a waveform that has not been fully documented but it could have been generated by a finch or a pipit whose flight consists of bursts of wing flapping interrupted by closed wing pauses. Two cycles of the BAM pattern are shown at the bottom of fig 4.

At the top of fig 4, is shown a sketch of the physical position of the bird at moments in flight. Below this diagram is a sinusoidal curve representing the movement of the wings in flight. The curve is produced by considering the relative height of the wings as they move with respect to the body centre line. The curve is an ideal one having a positive peak when the wings are upstretched, a zero when they move through the body centre line and a negative peak at the end of the downstroke.

The bird activity modulation waveform generated by the wingbeating cycle described is shown in the lower graph. All the graphs and diagrams are linked by a common phase or time axis. During the closed wing pause the echo signal takes up an average level, but as the bird flaps its wings the echo signal is modulated in a periodic manner. In the figure the positive cycle of the modulation waveform is generated by the upstroke of wing movement and the negative cycles by the downstroke, but this is not always the case.

Some rough generalizations on BAM waveforms generated by single birds can be made as follows:-

a The body dimension/radar wavelength ratio plays an important part in determining the resultant waveform, especially in the way the waveform is affected by long term and short term aspect changes and wing flapping.

b Physical wingbeat frequency and fundamental frequency of the electrical waveform have the same value and are relatively constant even when the bird zig-zags in flight. However although the amplitude of the BAM waveform fundamental frequency of the BAM waveform is usually larger than that of the harmonics its relation to them may change even with relatively short term aspect changes. At times the amplitude of the fundamental may go to zero but usually some harmonic components remain.

c The magnitude and shape of the BAM waveform may change with changes of the bird's aspect with respect to the radar.

d Clean periodic waveforms are usually generated by single birds flying straight courses at constant height and uniform speed such as occur during migration.

5 SIGNAL ANALYSIS

Generally, the BAM waveform is a complex waveform for a bird whose body dimension/radar wavelength is greater than 0.5 and it is necessary to use spectrum analysis methods to extract the fundamental frequency component which corresponds to the physical wingbeat frequency.

Bird activity modulation waveforms are not perfect mathematical functions, but as all periodic and aperiodic waveforms can be considered as made up of a sum of harmonically related components having various amplitude and phase relationships to one another, they can be separated out into their component frequencies by Fourier analysis methods. BAM amplitude/time waveforms can be fed into a spectrum analyzer and presented as spectra on a power or $(\text{amplitude})^2$/frequency display.

Some examples of amplitude/time waveforms on the LHS and their corresponding power spectra on the RHS are shown in fig 5. These diagrams are not to scale. The first example at the top of the figure is for a continuous sine waveform where amplitude changes are repeated cyclicly every τ seconds. Such a waveform has only a single spectral line positioned at a frequency $1/\tau$ along the frequency axis.

The repetitive sawtooth waveform can be frequency analyzed into a series of odd and even harmonic components spaced at frequencies $1/\tau$ apart. The fundamental frequency component has the greatest intensity and the intensities of the harmonic spectral lines decrease proportionally with increasing harmonic number.

The repetitive square wave has a spectra which consists of the fundamental and only odd number harmonic components. Again the fundamental component has the greatest intensity and the intensity of the harmonics diminishes with increasing harmonic number.

Many BAM waveforms are not continuous or strictly repetitive and they may stop and start in a random manner. A first approximation to such waveforms can be made by considering a single burst of sinusoidal waves. Instead of the single spectral line at frequency $1/\tau$ the spectra is distributed symmetrically about the frequency of the sine wave, $1/\tau$, and spectral envelope has a large centre lobe and smaller side lobes. The spectral envelope follows a sine x/x curve determined by the Fourier Transform of the rectangular pulse envelope. The width of the main lobe of the spectra is proportional to the duration T of the pulse envelope of the sine wave.

A single pulsed square wave has sin x/x envelope spectra occurring at the fundamental frequency $1/\tau$ of the square wave and at every odd harmonic $3/\tau$, $5/\tau$, etc.

When two birds occupy the same radar resolution cell and generate BAM waveforms, which are constant sine waves, the resultant echo signal has the waveform shown at the bottom of fig 16. The resultant wave is at a new frequency $(f_1 + f_2)/2$ whose amplitude is no longer constant, but rises and falls at the beat frequency $(f_1 - f_2)$. If the birds generate a complex wave instead of a sine wave, such that there are a number of frequency components between f_1 and f_2, the sharp null of the simple pattern is extended and the recurrent period of the beat pattern is increased.

6 BAM WAVEFORM AND SPECTRA EXAMPLES

Some of the chief features of BAM waveforms are reviewed in this chapter. Waveforms range from those generated by rapid wing flapping, periodically interrupted by closed-wing pauses, to those produced by slower continuous wing flapping, randomly interrupted by long glide periods.

All waveforms, with one exception, were obtained using the AGC line of a high resolution, monopulse, tracking radar operating in C-band. The AGC line was fed to an Ampex multi-channel magnetic tape recorder together with speech and time code. The BAM waveforms were recorded on a fast UV photographic paper recorder and the spectra were obtained later using the Ubiquitous Averager and Spectrum Analyzer.

Details of BAM waveforms and spectra for the illustrated examples are summarized in Table 2. Reading across the table, type indicates whether the wing flapping is repetitive beat and pause (B/P), continuous (C) or continuous interrupted by "random" glides (C/G). The fundamental frequency (F) modulation can be fairly constant or fluctuates or it can be given a numerical value. Beat indicates the wingflapping duration in terms of the number of wingbeat frequency cycles, while pause indicates the duration of the pause period in seconds. The standard deviation (SD) is given where appropriate. In the column, spectrum remarks, the fundamental and the most prominent harmonics are given, while in the column on species the known or most likely species obtained from consideration of Griffiths report is given. In some cases there are insufficient visual flight characteristics available on species to enable a good match to be made between visual and radar data.

The first three examples shown in fig 6, 7 and 8 are waveforms from birds that rythmically flap their wings rapidly and then periodically pause with closed wings. They were all produced by night migrants in Autumn and the depth of modulation is fairly constant in all cases.

In the case of bird-R4 and bird-R27 the flapping period is fairly long, 12 to 18 beats, but in the case of bird-R17 only 2 flaps occur between pauses. In all cases the pause periods are short, ranging from approximately 0.1 to 0.3 seconds. Although these waveforms can be clearly specified only bird-R17 can be matched using Griffiths catalogue. The choice of species in the other two cases rests on closed wing pause species having the right order of wingbeat frequency.

The spectrum of bird-R4 is composed of odd and even harmonics with fundamental, and harmonics progressively decreasing in intensity. Bird-R27 has a less complex waveform, in places it is sinusoidal, and consequently its spectrum consists of a single lobe, but bird-R17 has a complex waveform, which results in a broad lobed spectrum of odd and even harmonics.

The next two examples, Fig 9 and Fig 10 illustrate that birds having similar values of fundamental frequency component can have wingflapping and pause periods of different duration. The waveform from the night migrant, bird-R72, possibly a missel thrush has a fundamental frequency of 8 Hz, but the flapping duration is less than 1 second and the pauses less than 0.2 seconds. In complete contrast the swift waveform shown in fig 10, obtained on an August evening, has a fundamental frequency of 7.8 Hz, a flapping period which ranges from 3 seconds on average up to 12 seconds and a pause of 3 seconds average. Note that the second harmonic is larger than the fundamental frequency, and the fourth harmonic is reduced in intensity in the spectrum of bird-R72.

The next four examples are from birds that flap their wings continuously, often for minutes without rest. The waveform shown in fig 11, from the night migrant, bird-R6, (if the fine structure is ignored) varies from sawtooth to triangular in form. The spectrum is as one would expect from such waveforms. The bird is likely to be a duck species from its signature and speed.

The waveform shown in fig 12, of a night migrant, bird-18 has a fairly constant depth of modulation and is generated by a continually flapping bird. The waveform is approximately sawtooth in shape and the spectrum is consequently rich in odd and even harmonics. The bird was flying at a speed of 32 mph approx.

The waveforms and spectra shown in fig 13 and 14 were from mallard released by the Wildfowl Trust near to the tracking radar. The mallards flew, at speeds around 40 mph, evasive flights. Their waveforms have not the clear periodic nature of previous waveforms and the depth of modulation fluctuates wildly. Nevertheless although the lobe structures are broadened and more filled in than previous examples, values of fundamental and harmonic frequencies are easy to read. The fundamental frequencies of both birds are similar at 6.7 Hz, which is a slightly lower value than 6.9 Hz obtained by Griffiths and Houghton from cine data on the mallard.

The amplitude/time waveform shown in fig 15 is from a herring gull. The 1 second timing markers are shown above the waveform. The depth of modulation fluctuates throughout the record. Considering the waveform from left to right, there is a 10 second flapping period followed by a glide period. The glide is interrupted by a single beat at 4 seconds and then further single beats. At about 17 seconds the glide is interrupted by a large change of signals caused by head or body turning. A period of wing flapping follows and then a glide period which is again interrupted by a large dip in signal level. The wingbeat frequency is approximately 3.2 Hz.

The last examples, fig 17, are waveforms generated by two carrion crows in the same resolution cell. The top and bottom waveforms show the beat phenomena mentioned at the end of Chapter 5. The crows were cine-recorded at the same time the radar echo waveform recording was being made. The cine-data has shown that the crows were flapping their wings at 3.7 and 4 Hz. The beat frequency is therefore about 0.3 Hz. The waveform has not been fully analyzed, because it was made prior to the use of tape recording and spectrum analysis.

7 FLOCKS AND GROUPS

It has been emphasized that clear BAM patterns can be obtained by tracking single birds; a situation which results in the radar resolution cell being occupied by a single bird and no other target. Usable BAM waveforms can also be obtained from the resultant echo signal produced by two birds occupying the same resolution cell, although there is some loss of information in this case when the birds are of the "beat and pause" species.

However, it is fairly well known that even a small number of birds (as low as 5) generating similar echoing areas and occupying the same radar resolution cell will produce a noise-like signal, from which it is practically impossible to obtain a usable wingbeat modulation frequency spectrum.

On many occasions when a number of birds have occupied the same resolution cell it has been possible to obtain a wingbeat modulation frequency spectrum from the resultant echo signal by long term averaging or by selectively discarding the "noisiest" parts of the echo record and then by long term averaging. It would appear in these cases that the resultant echo signal is dominated by the echoing areas of one or two of the birds, while the remaining birds have presented much smaller echoing areas. A spectrum of such a record has been described (11) and it reveals a broadening of wingbeat modulation frequency lobes and a higher level of noise than obtained from a single migrating bird.

Experimental work on night migration in Britain and Gibraltar has shown (using a radar with a resolution cell of 100 metre sides) that although a large number of birds occupy the resolution cell alone it is possible to obtain a fairly large number of multiple bird echoes also. Many of these targets cannot be analyzed within the first minute of record but yield results after prolonged tracking time. Some of these multiple targets are the result of pseudo-grouping (12) but in other cases there are indications of true grouping.

8 USAGE

The first purpose for obtaining BAM waveforms is to enable a target to be specified quickly and unambiguously as a flying animal. Once the waveform is recorded its spectrum can be analyzed and its fundamental frequency obtained. At this stage, depending upon the final use intended for the waveform, a preliminary filtering exercise is made using computer logic. Bounds are written into the programme, governed by knowledge of species on the basis of regional location, abundance, and seasonable distribution. Tactical bounds can also be set such as a high frequency limit to the fundamental frequency component of the BAM waveform.

If as a result of this selection the waveform still remains to be processed further selection can be carried out as follows. Assume that Table 1 covers the list of possible species and that the value for each species is monotonic.

Create a histogram based on a window width of say 1.8 Hz, so that the frequencies in Table 1 are covered from 0-18 Hz by 10 windows. The histogram would show that no birds will be in region 0-1.8 Hz and only a few percent lie in the region 12.6 to 16.2 Hz. Most species lie between 3.6-9 Hz. Therefore it is in this area that further identifying features have to be obtained in order to discriminate between species. One important parameter, speed, which has probably been used in the preliminary filtering stage can now be brought in to sort out faster flying species like duck from some of the slower flying birds like crows.

Alternatively, all targets with waveforms whose fundamental frequencies are below 8 Hz deserve attention from the bird hazard point of view, because as can be seen in fig 2 they could be produced by birds weighing 500 gms or more. Birds generating continuous waveforms with fundamental frequencies lying between 6-7 Hz and flying at speeds greater than 30 knots are likely to be duck. While birds generating fundamental frequencies of 3 to 5 Hz may be very heavy swans or geese, or much lighter or equally dangerous gulls.

The use of BAM waveforms is likely to be confined to research work and investigation of distributions of particular species hazardous to aircraft at the present, until a comprehensive catalogue of BAM waveforms of known species has been collected. Such a catalogue would be incomplete without details of airspeed and other characteristics of flight.

TABLE 2 SUMMARY OF BAM WAVEFORMS AND SPECTRA DATA

	DESIGNATION	BAM WAVEFORM							SPECTRUM REMARKS	SPECIES	AIR SPEED
		TYPE	F (Hz)	M INDEX	BEAT	SD	PAUSE	SD			
Fig 6	Bird-R4/2	B/P	17	Constant	18	3	.11	.03	1,2,3	Whitethroat	
Fig 7	Bird-R27/2	B/P	15.8	Fairly constant	12	3	.24	.08	1	Pipit	41 ft/sec (28 mph)
Fig 8	Bird-R17/2	B/P	11.3	Fairly constant	2	1	.27	.12	1,2,3	Lark	
Fig 9	Bird-R72/1	B/P	8	Constant	5	2	.18	.04	1,2,3,4,5	Thrush	
Fig 10		B/P	7.8	Fairly constant	23 (1-94)	20	3.1	.8	-	Swift	47 ft/sec (32 mph)
Fig 11	Bird-6	C	6.6	Constant	-		-		1,2,3,4,5	Duck	(36 mph)
Fig 12	Bird-18	C	6.7	Fairly constant	-		-		1,2,3,4,5	Duck	47 ft/sec (32 mph)
Fig 13	Mallard-P *	C	6.7	Fluctuates						Duck	60 ft/sec (41 mph)
Fig 14	Mallard-S *	C	6.7	Fluctuates						Duck	64 ft/sec (44 mph)
Fig 15	*	C/G	3.2	Fluctuates	-		-		-	Gull	34 ft/sec (23 mph)
Fig 17	*	C	3.7 & 4.0 beat	Fluctuates	-		-		-	2-Crows	(28 mph)

* optically and radar tracked

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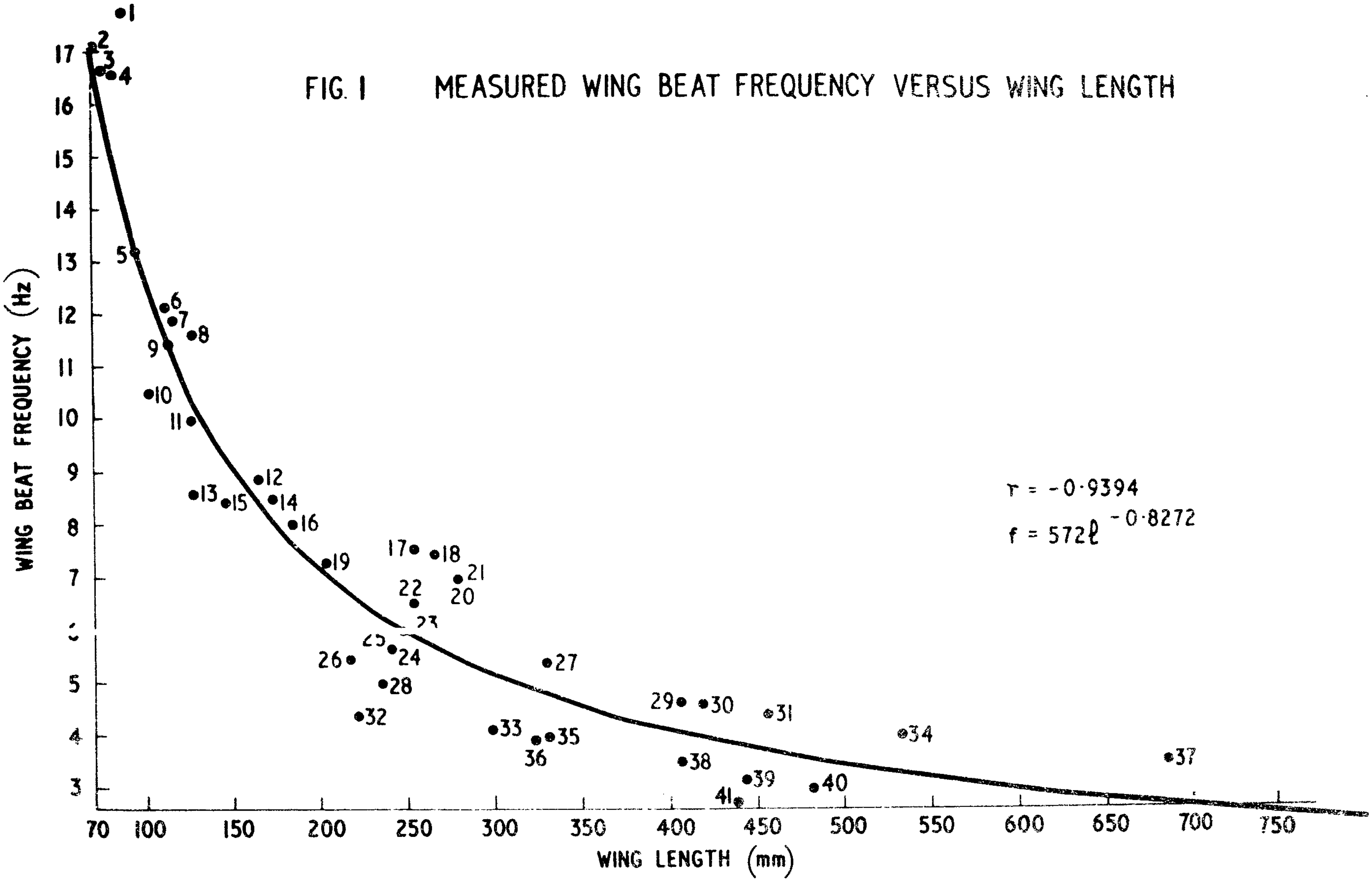
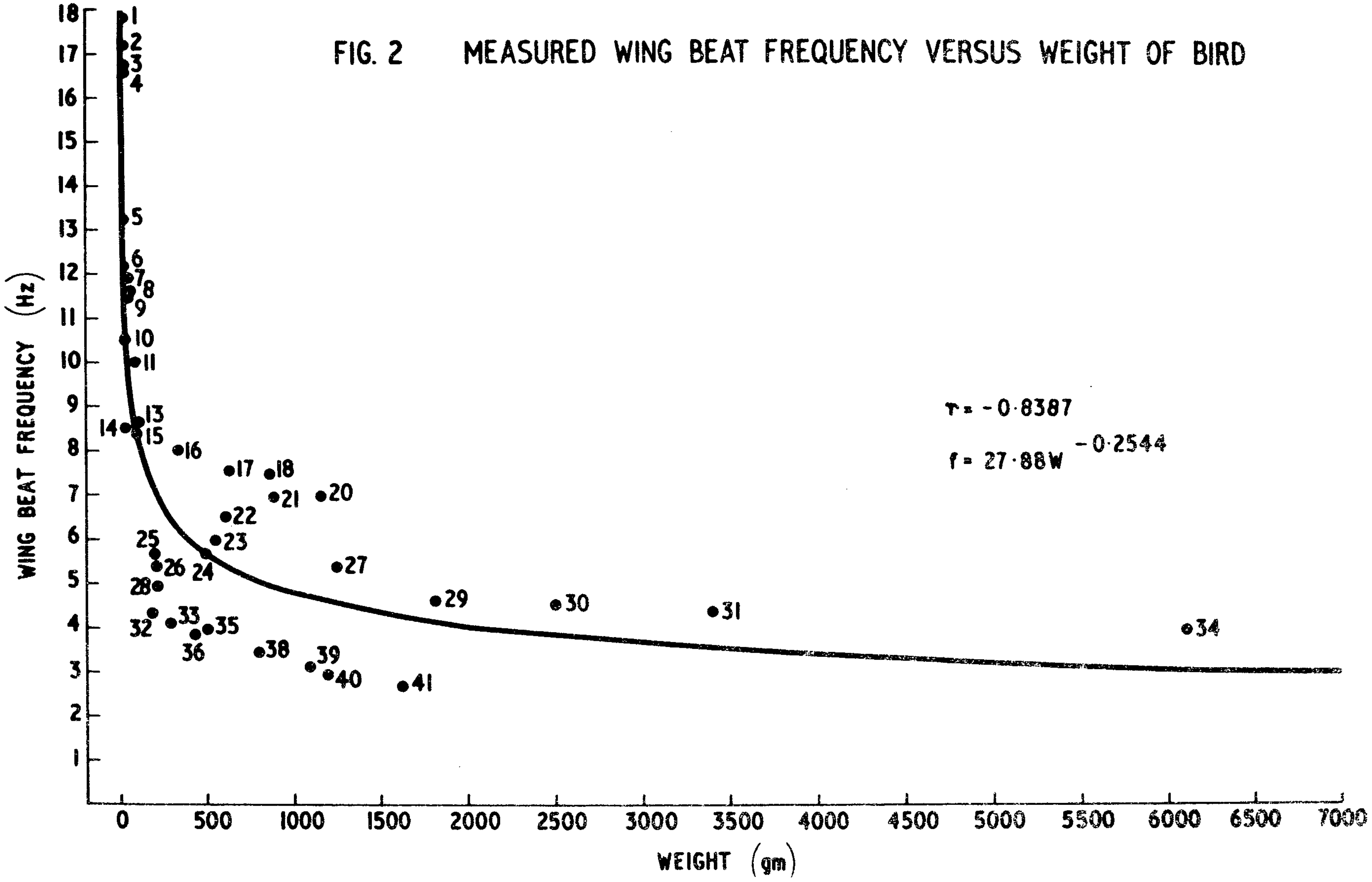
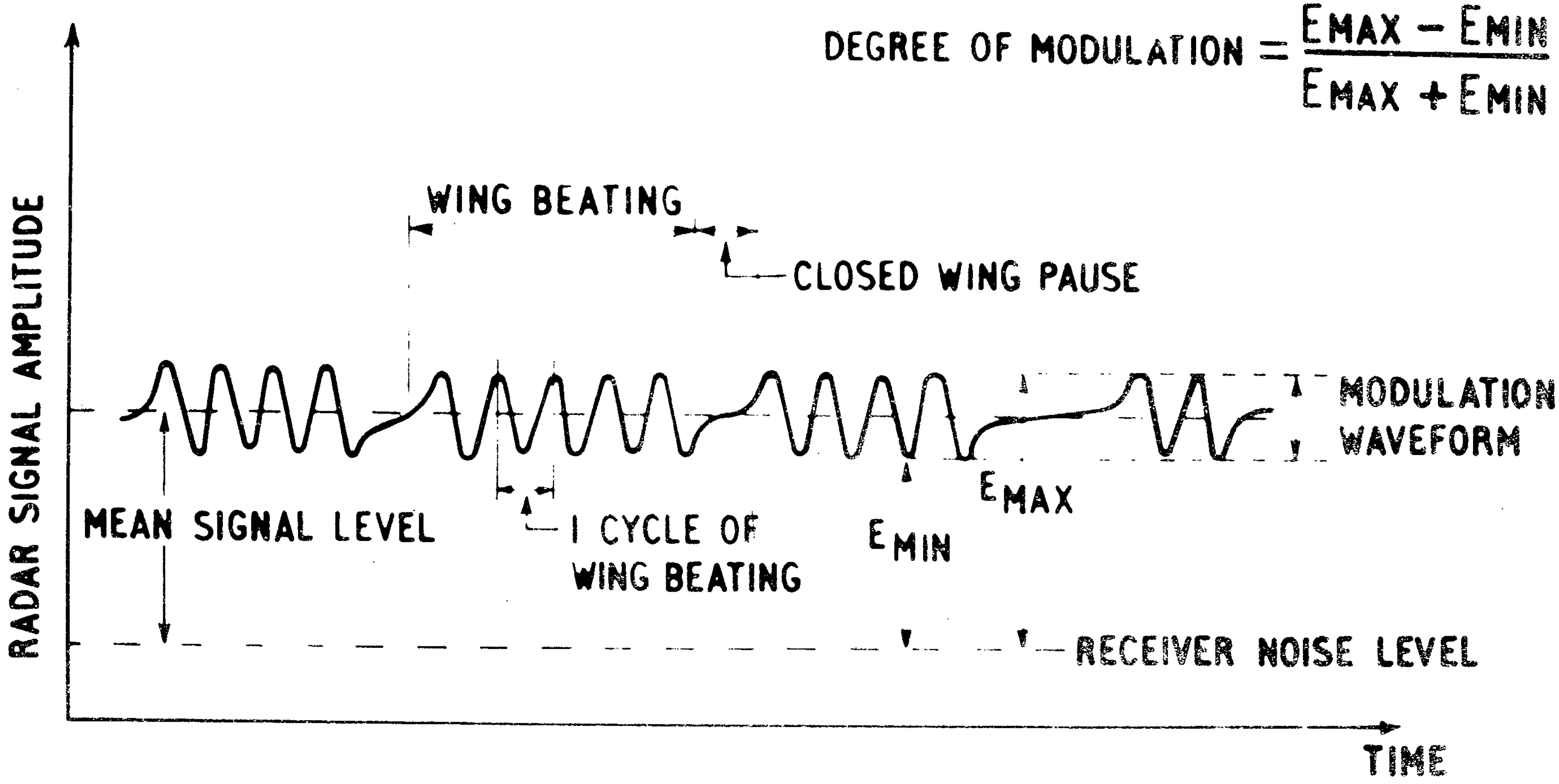


FIG. I MEASURED WING BEAT FREQUENCY VERSUS WING LENGTH

FIG. 2 MEASURED WING BEAT FREQUENCY VERSUS WEIGHT OF BIRD





$$\text{DEGREE OF MODULATION} = \frac{E_{MAX} - E_{MIN}}{E_{MAX} + E_{MIN}}$$

FIG. 3

RECEIVED AMPLITUDE MODULATED SIGNAL FROM A BIRD

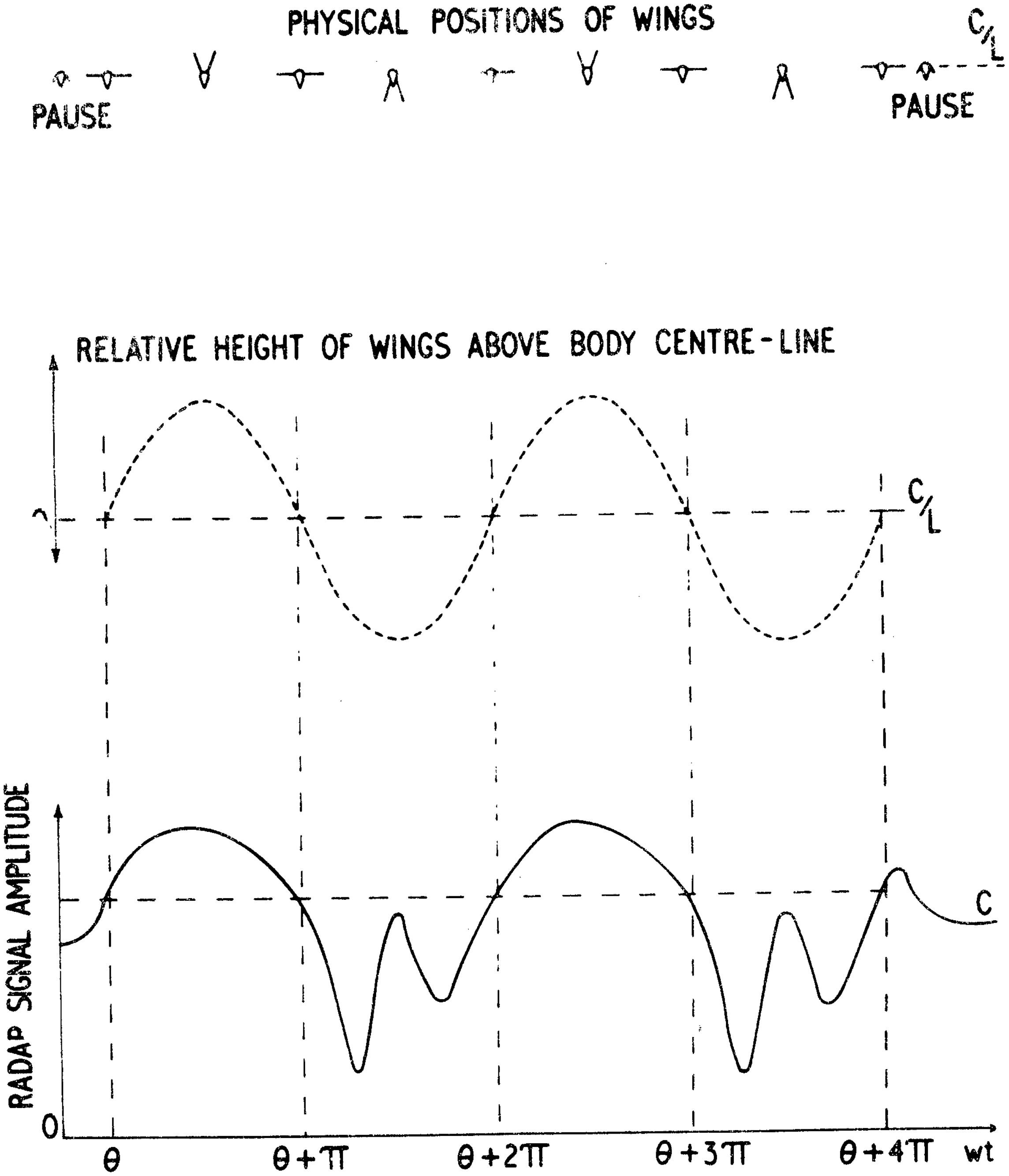

PHYSICAL POSITIONS OF WINGS
C/L
PAUSE
PAUSE
RELATIVE HEIGHT OF WINGS ABOVE BODY CENTRE-LINE
C/L
RADAR SIGNAL AMPLITUDE
C
0
θ
θ+π
θ+2π
θ+3π
θ+4π
wt

FIG. 4

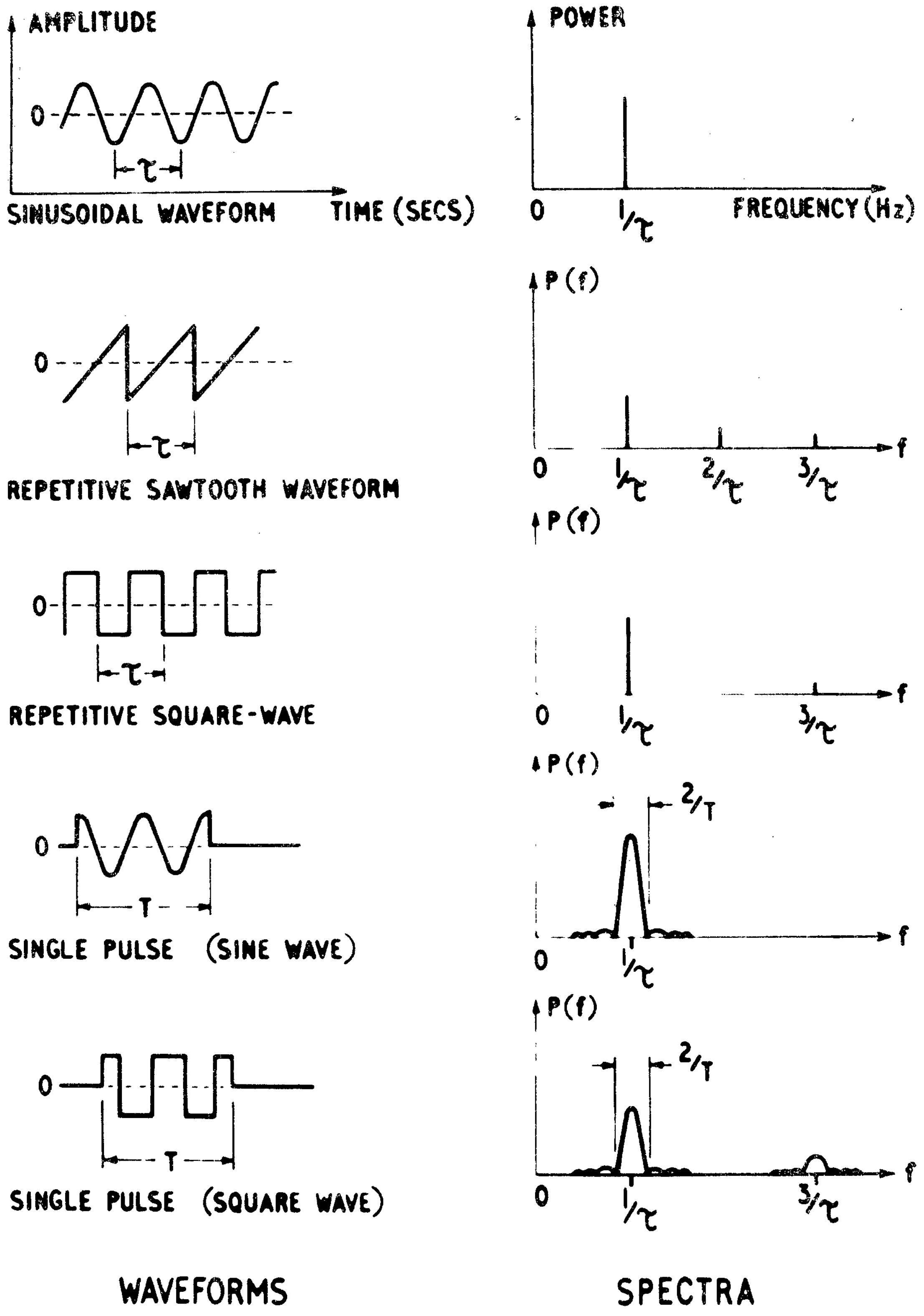

AMPLITUDE
0
τ
SINUSOIDAL WAVEFORM
TIME (SECS)
POWER
0
1/τ
FREQUENCY (Hz)
P(f)
0
τ
REPETITIVE SAWTOOTH WAVEFORM
0
1/τ
2/τ
3/τ
f
P(f)
0
τ
REPETITIVE SQUARE-WAVE
0
1/τ
3/τ
f
P(f)
0
T
SINGLE PULSE (SINE WAVE)
2/T
0
1/τ
f
P(f)
0
T
SINGLE PULSE (SQUARE WAVE)
2/T
0
1/τ
3/τ
f
WAVEFORMS
SPECTRA

FIG. 5

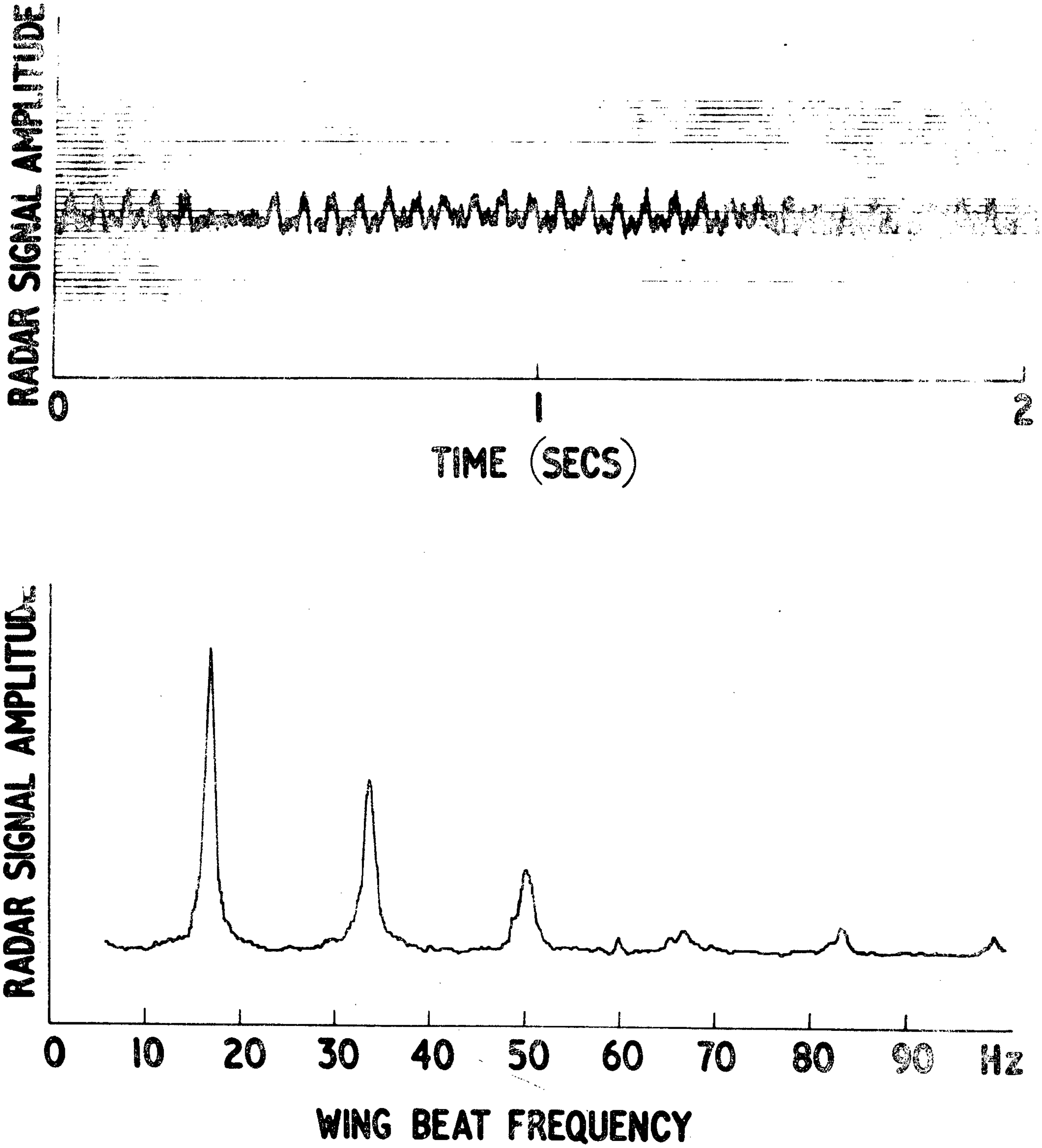


FIG. 6
BAM WAVEFORM AND SPECTRUM OF
BIRD - R4

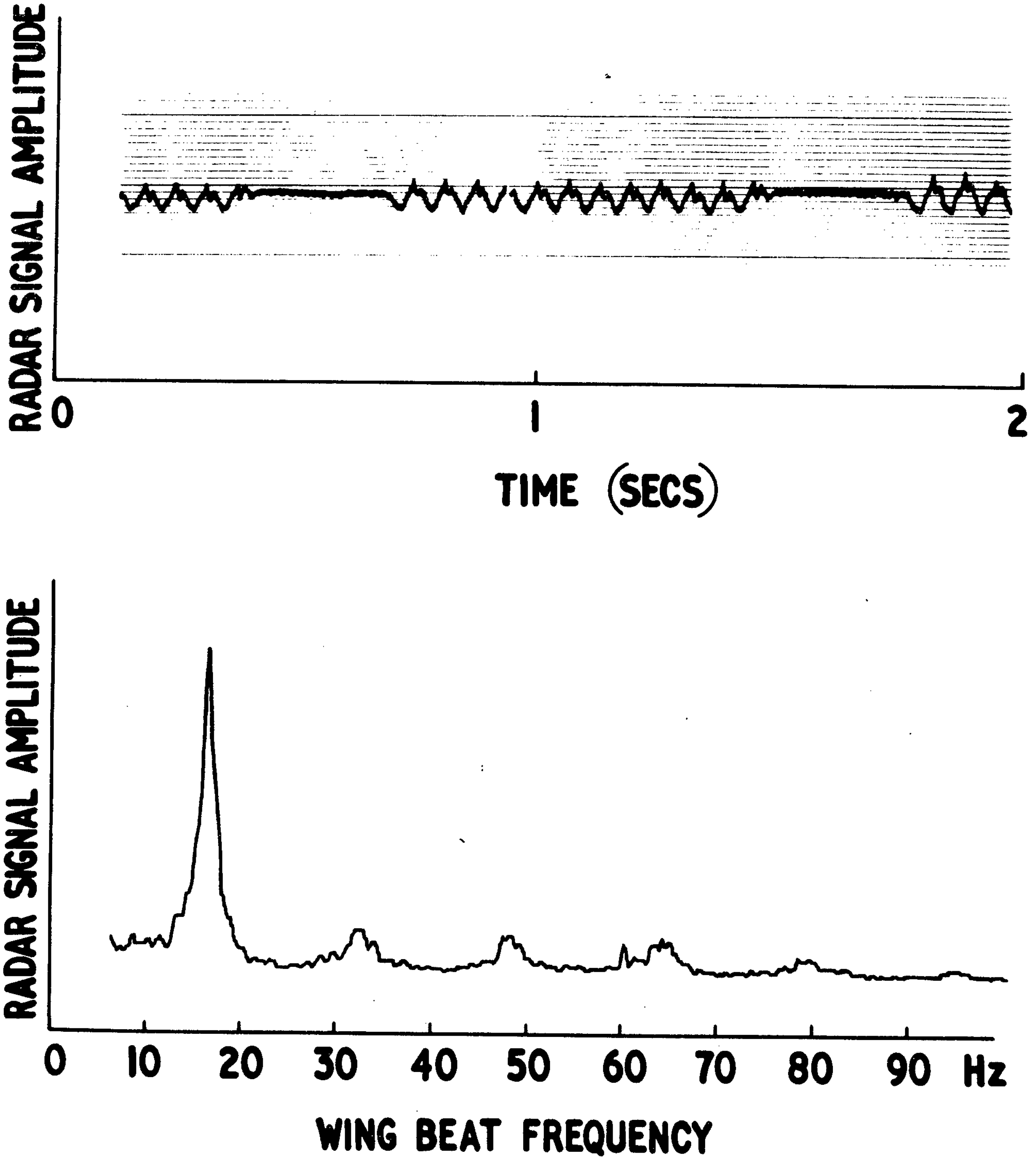


FIG. 7
BAM WAVEFORM AND SPECTRUM OF
BIRD-R27

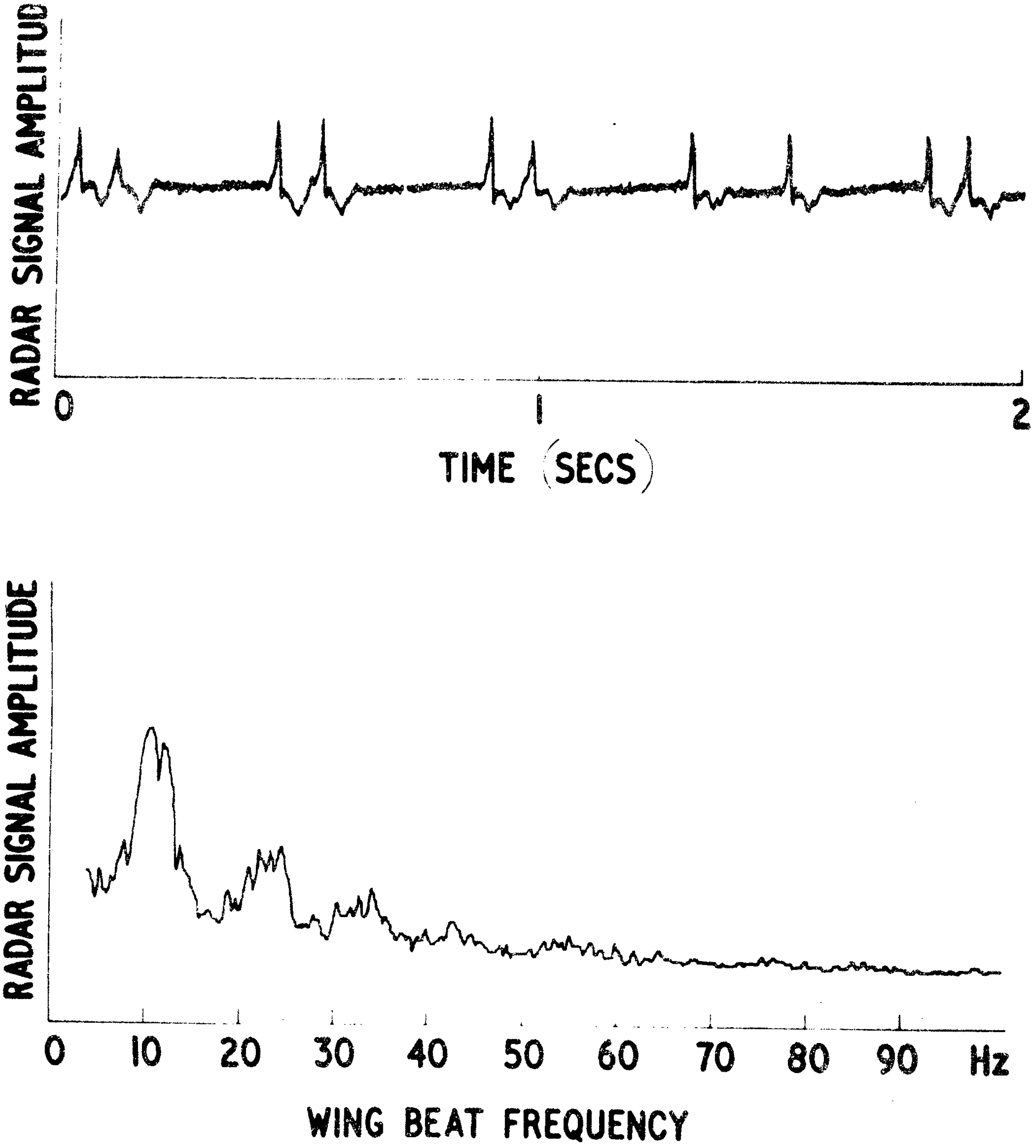


FIG. 8
BAM WAVEFORM AND SPECTRUM OF
BIRD - R17

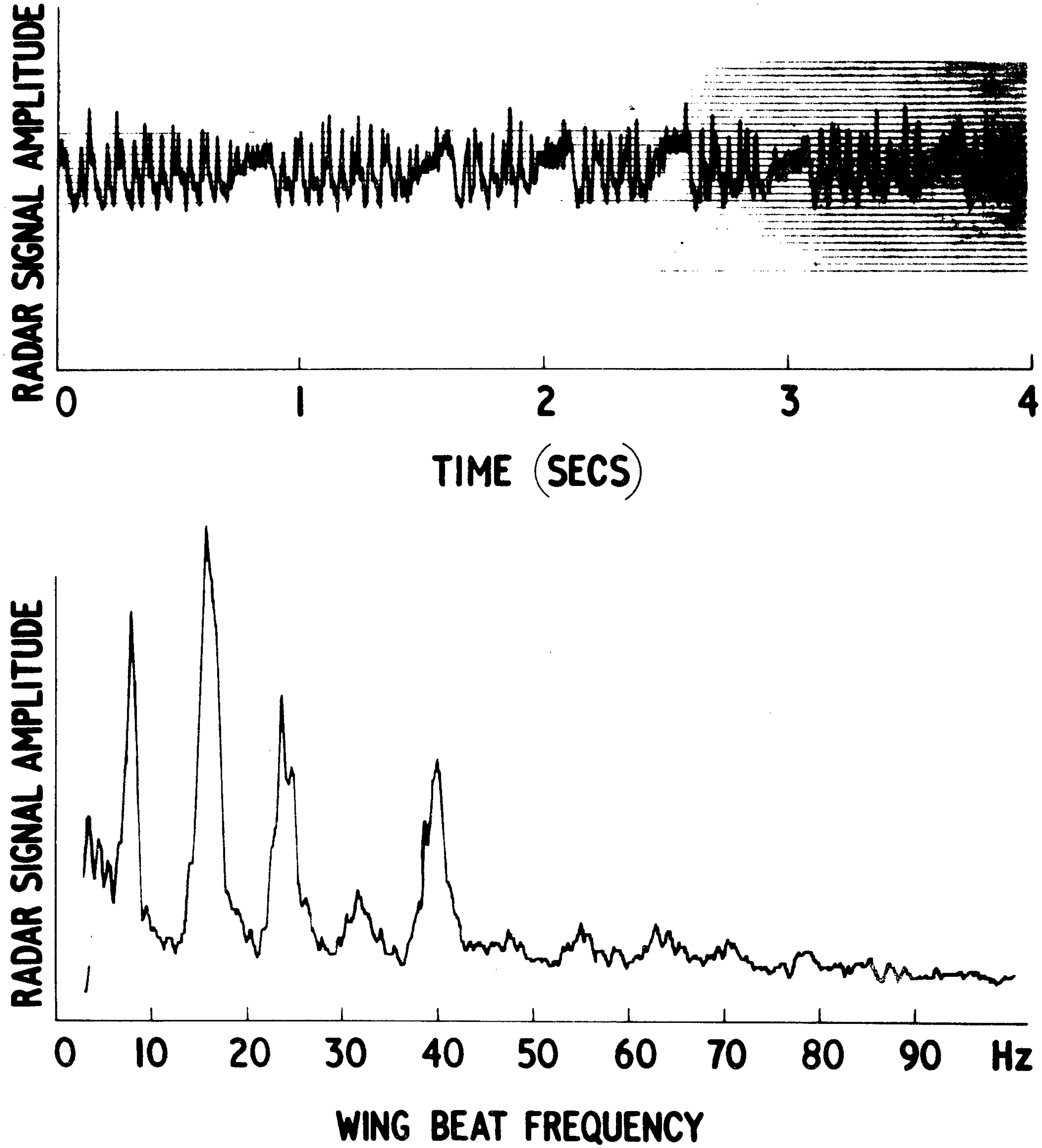


FIG. 9
BAM WAVEFORM AND SPECTRUM OF
BIRD - R72

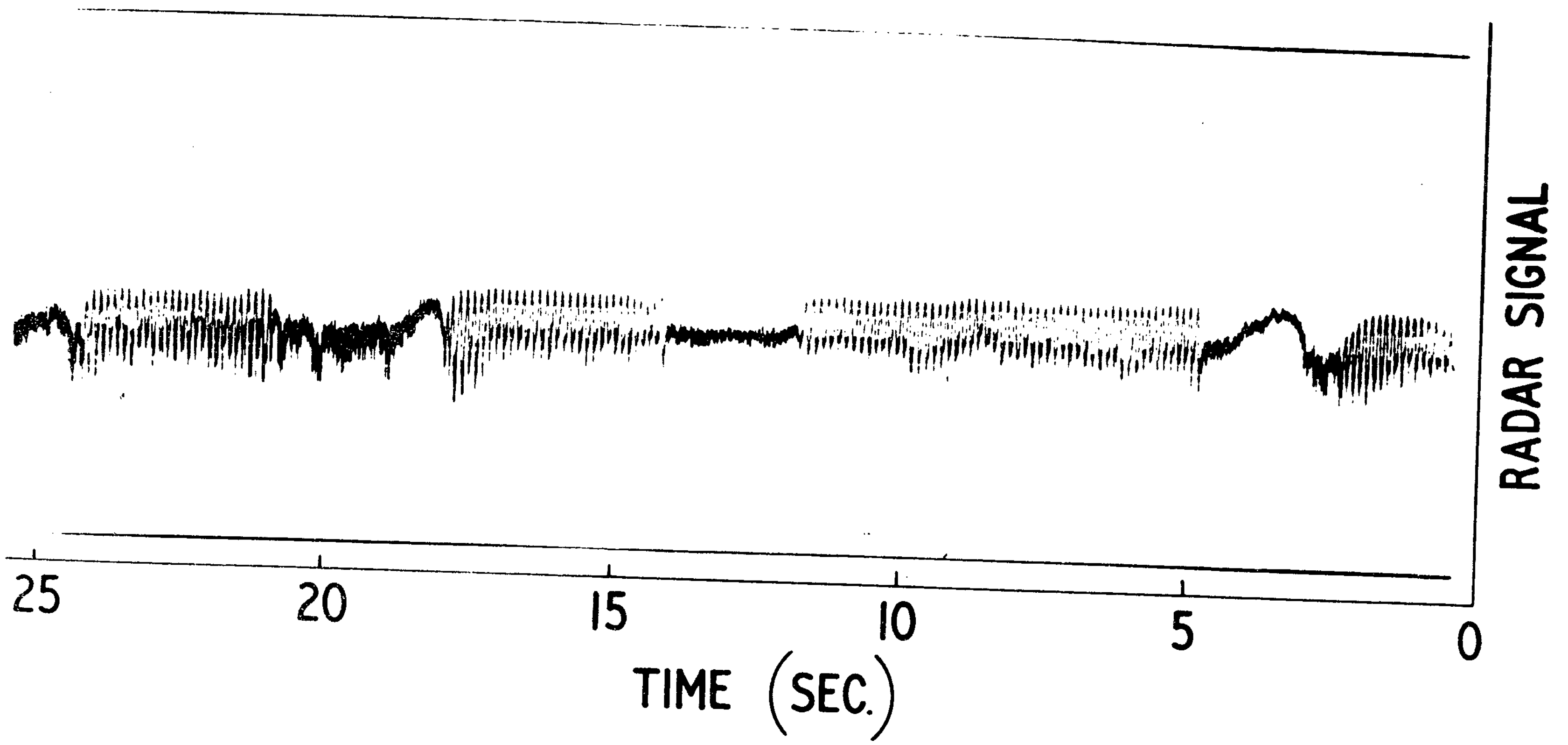


FIG. 10

BIRD ACTIVITY MODULATION WAVEFORM FROM A SWIFT

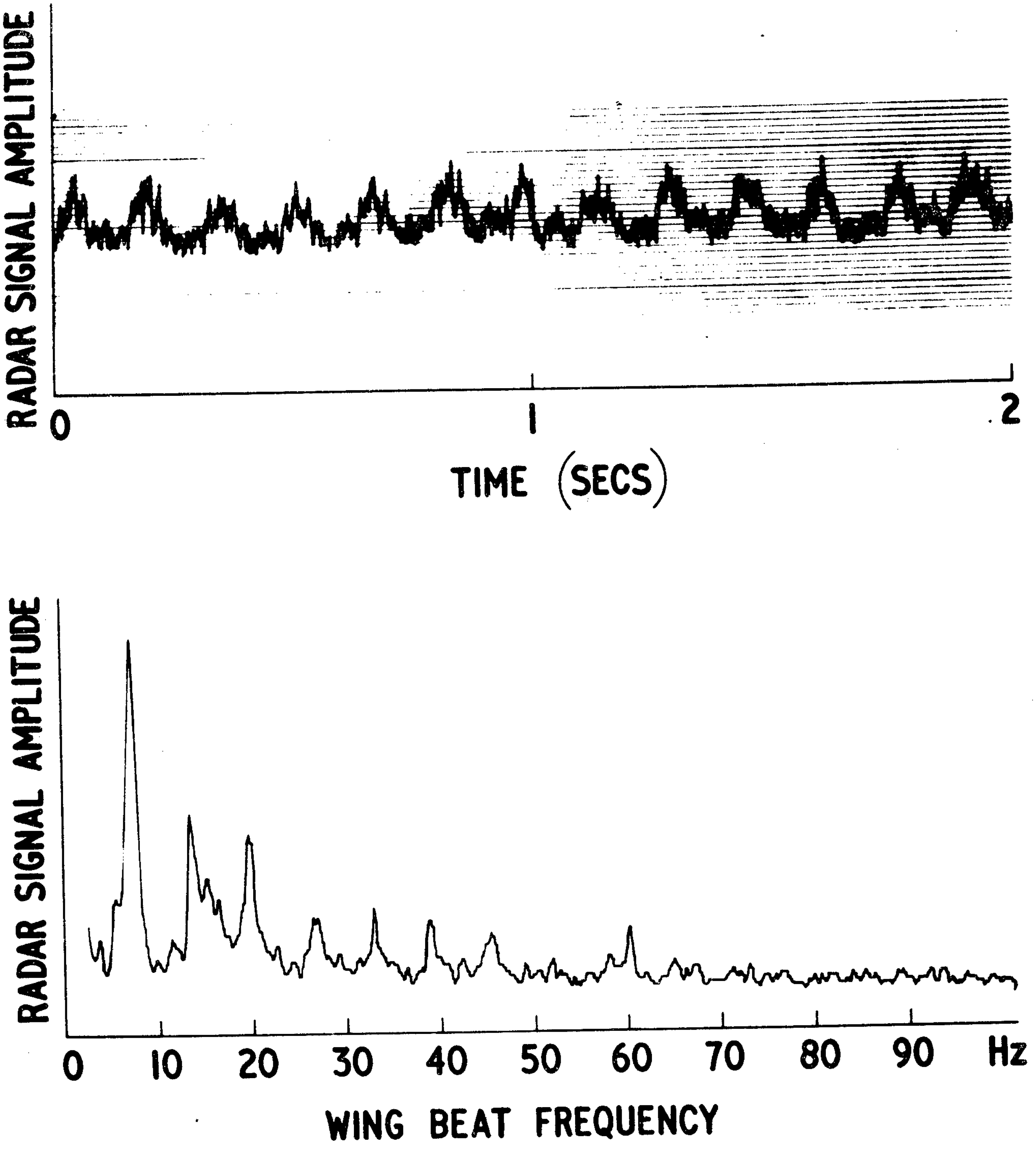


FIG. 11
BAM WAVEFORM AND SPECTRUM OF
BIRD - R6

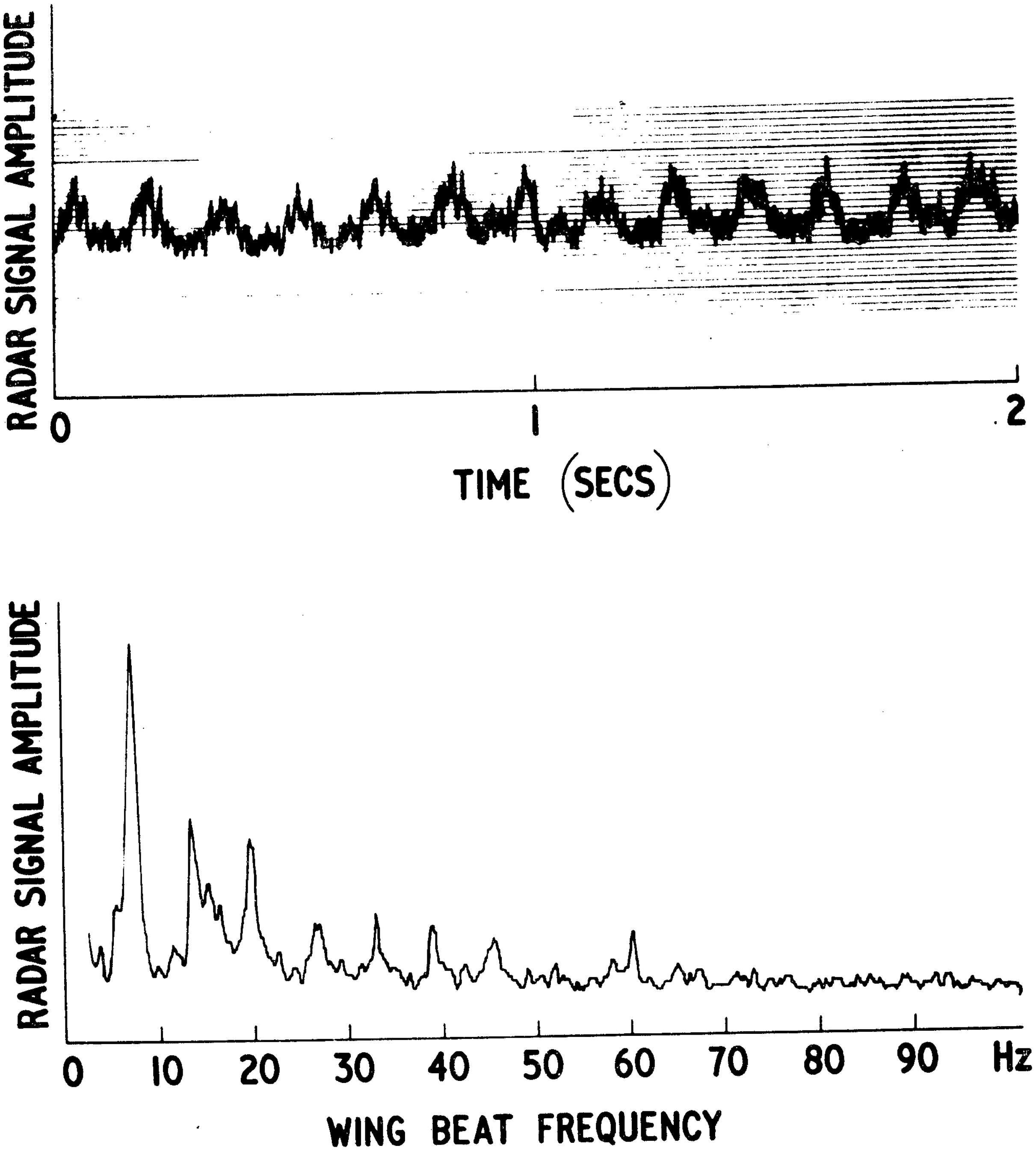


FIG. 11
BAM WAVEFORM AND SPECTRUM OF
BIRD - R6

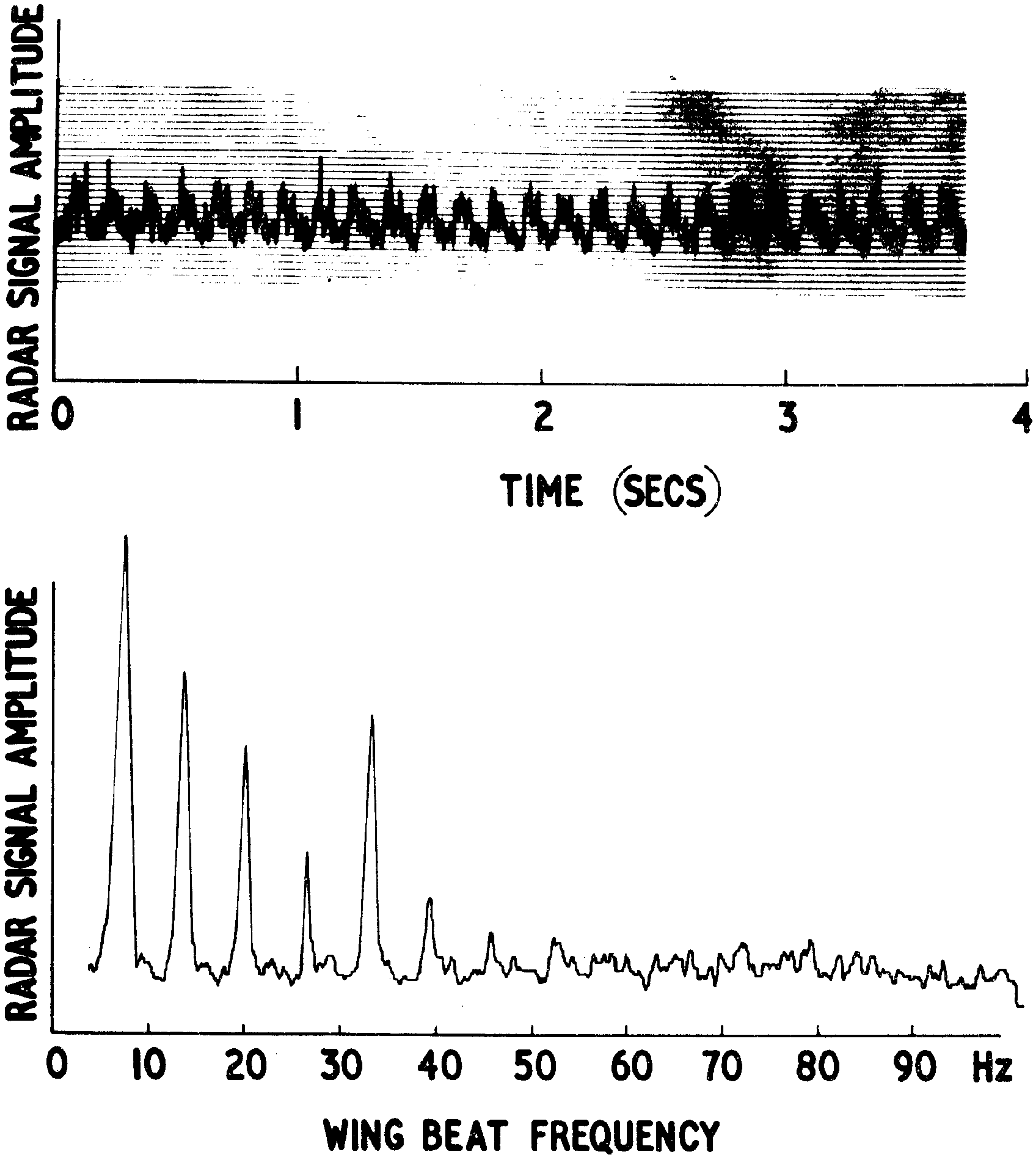


FIG. 12
BAM WAVEFORM AND SPECTRUM OF
MIGRATING WILD DUCK

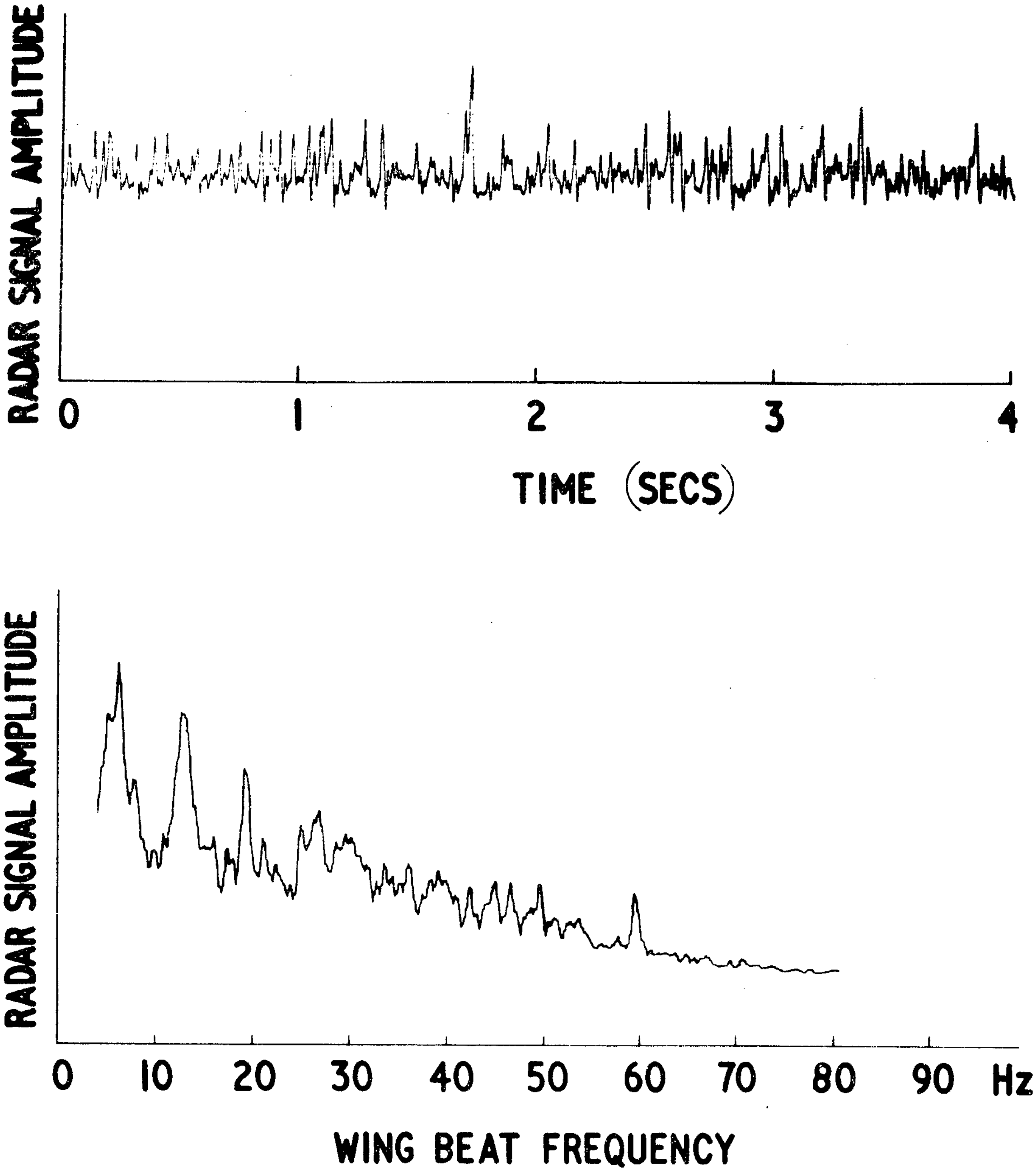


FIG. 13
BAM WAVEFORM AND SPECTRUM OF
MALLARD-P

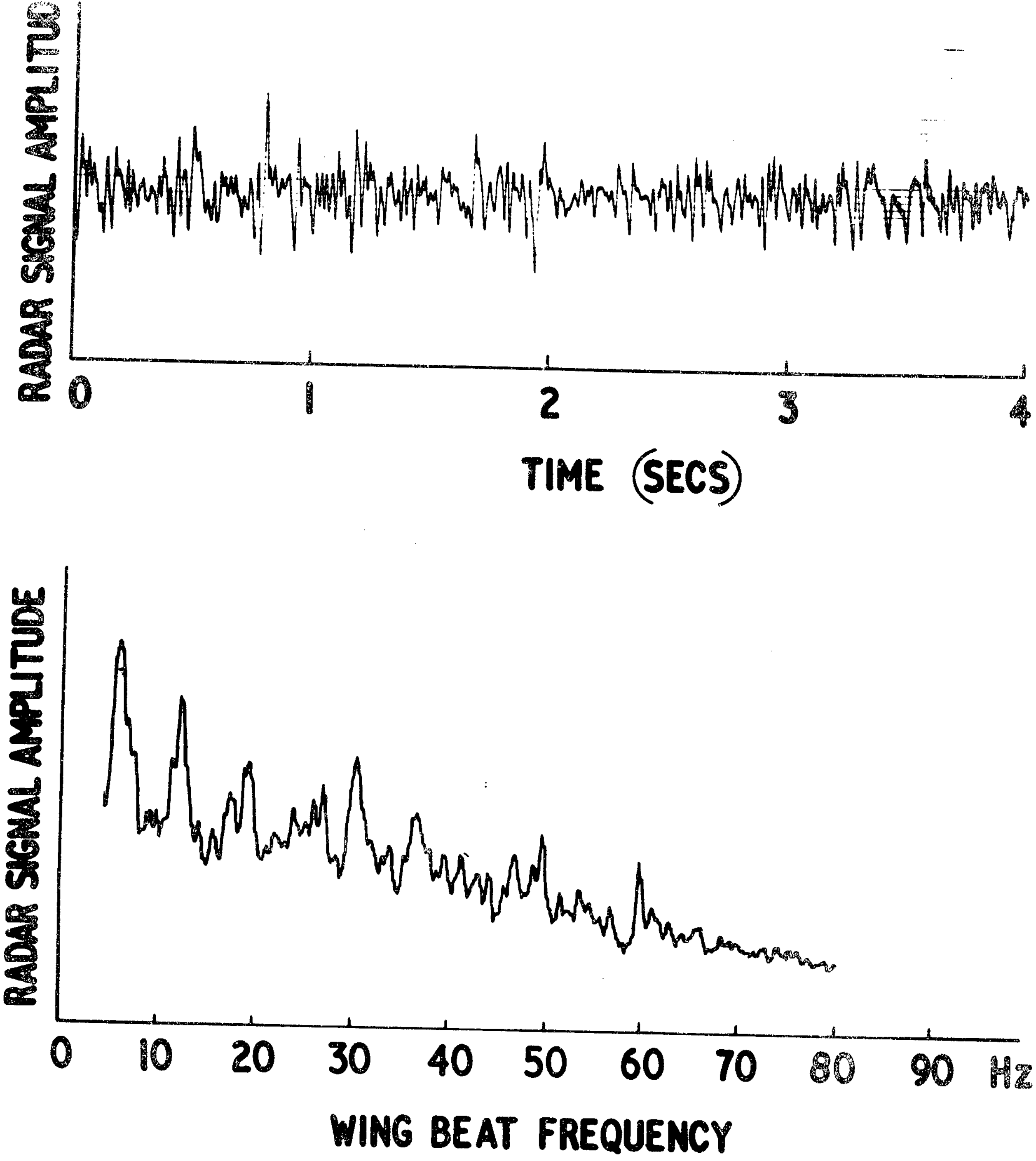


FIG. 14
BAM WAVEFORM AND SPECTRUM OF
MALLARD-S

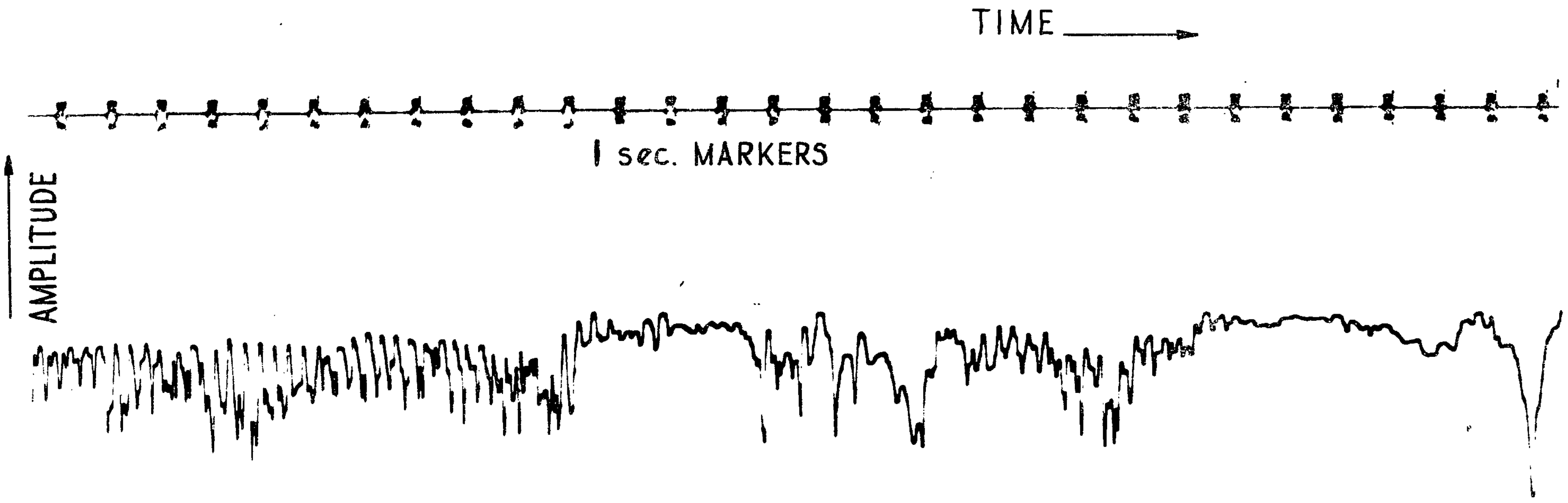


FIG. 15 BAM WAVEFORM OF A GULL

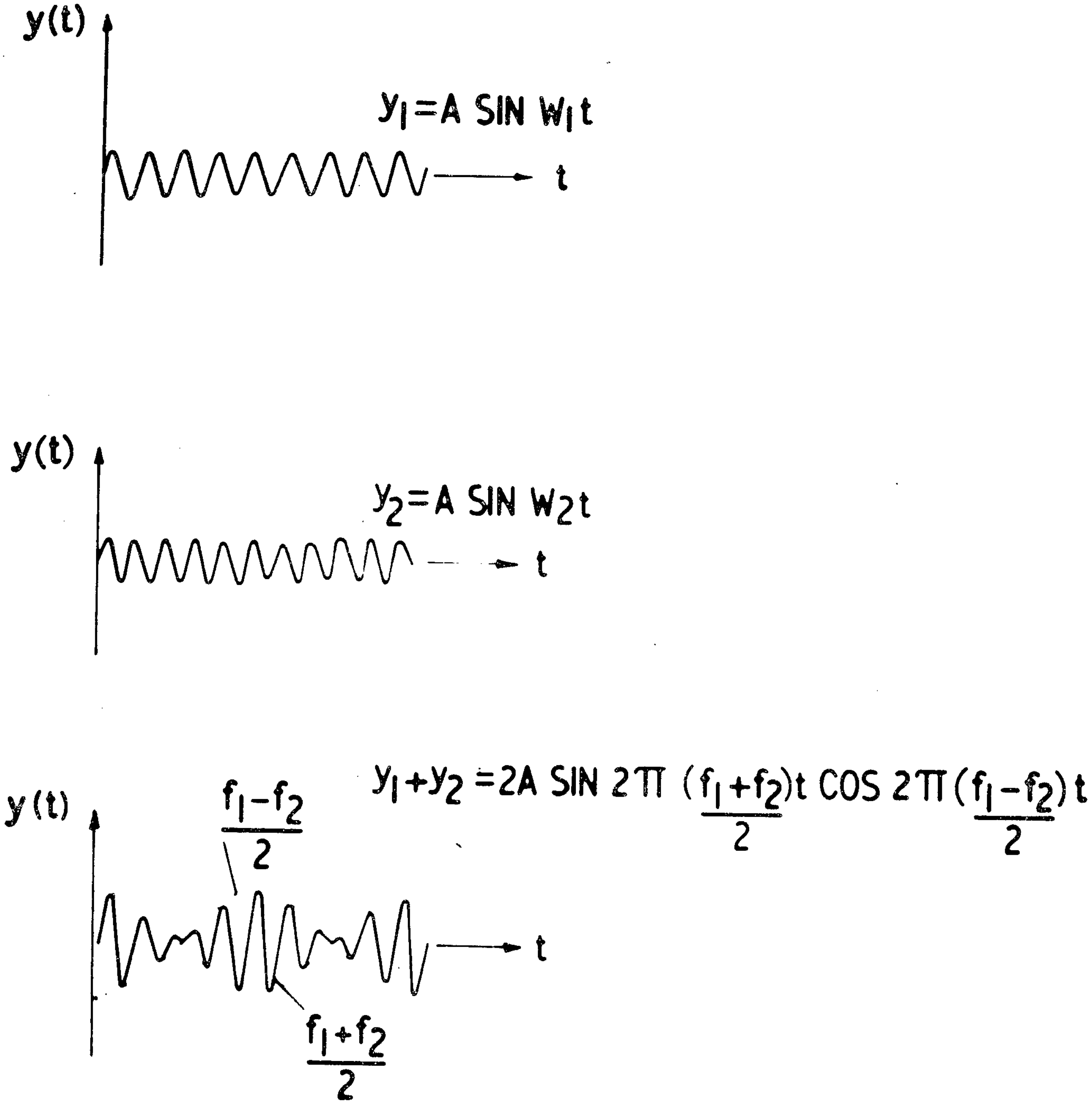
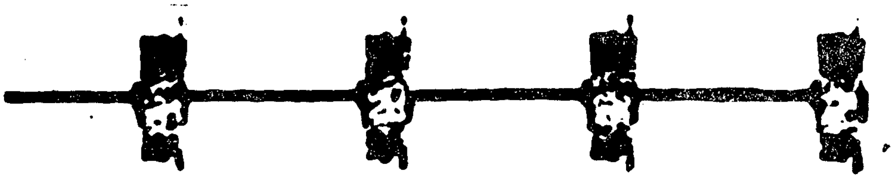


FIG. 16

BEAT PHENOMENA



I SECOND MARKERS

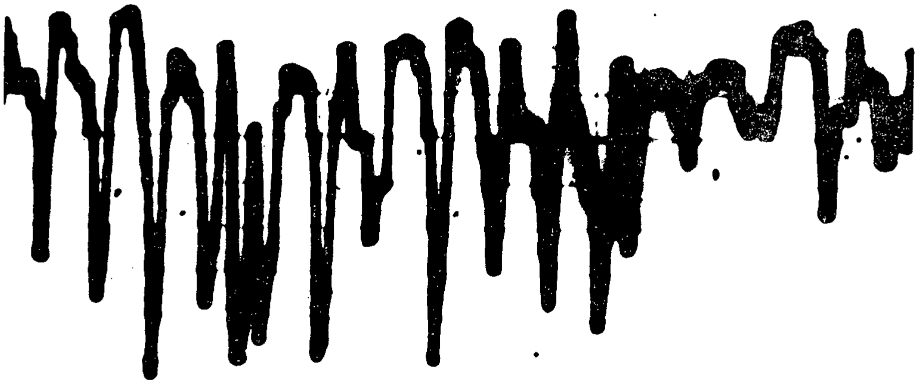


FIG.12a. RADAR RECORD OF TWO CARRION CROWS

FIG.12b. RADAR RECORD OF TWO CARRION CROWS