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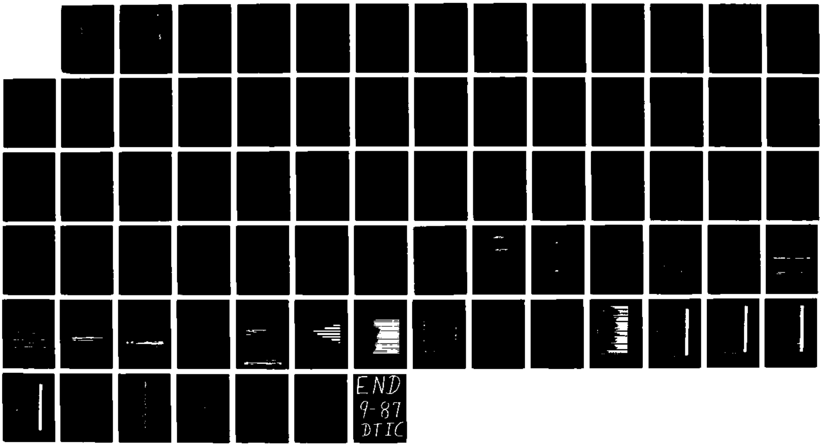

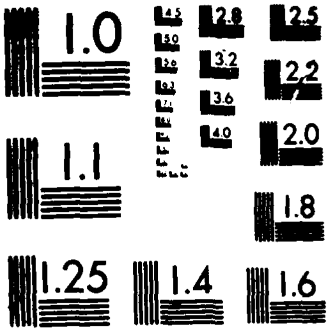

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# ANALYSIS OF THE 20-HZ SIGNALS OF FINBACK WHALES (BALAENOPTERA PHYSALUS)

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## ABSTRACT

The 20-Hz signals of finback whales (_Balaenoptera_ _physalus_) were analyzed from more than 25 years of recordings at a variety of geographic locations on near-surface hydrophones close to whales and on deep hydrophone systems. These signals were composed of 1-sec pulses of sinusoidal waveform with downward sweeping frequency from approximately 23 to 18 Hz at variable levels up to 186 dB (re 1 uPa), usually with slightly lower levels for the pulses at the beginning and end of sequences. These pulses were produced in bouts lasting as long as 32.5 hrs, composed of regularly repeated pulses at intervals of 7 to 26 sec, either at one pulse rate or at two alternating (doublet) pulse intervals. The signal bouts were interrupted by rests of 1-20 min at roughly 15-min intervals and by irregular gaps lasting between 20 and 120 min. The distribution of these signals throughout the year and the signal sequences were analyzed from the continuous drum records of the Bermuda SOFAR Station (Patterson and Hamilton, 1964). These signals occured during winter, sometimes beginning in September and ending in May. The sound sequences were never exactly replicated. The direct association of the signals with the reproductive season for this species points to the 20-Hz signals as possible reproductive displays by finback whales. [illegible]

## INTRODUCTION

Repeated 20-Hz pulse series, later identified with finback whales (Balaenoptera physalus), were prominent in early records of underwater geophysical and military installations (mostly in unpublished or military reports, as in Jensvold and Wright, 1959). These sounds in Bermuda waters were described by Patterson and Hamilton (1964, p. 125) as strong, "pure tone pulsed signals at about 20 cps which repeat at regular intervals several times per minute ... The characteristics of the signals were always the same: a pulse of approximately 20 cps of about 1 sec duration..." The signals sometimes continued for hours, and were reported from both deep and shallow water. Tracks of sources of the sounds were derived from multiple hydrophone records, as on Nantucket Shoals (Walker, 1963, 1964). These sounds had been noted as early as 1950 by J. Johnson and others at the Woods Hole Oceanographic Institution during deep hydrophone ambient noise recordings at various oceanic locations, but the signals had not been found in near-surface recordings from ships (Watkins, 1981). These early assessments emphasized the regularity of the signals, which often seemed too mechanical for biological sources.

Whales were suggested as sources for the sounds from the beginning, but the lack of correlated sightings with recordings made this difficult to demonstrate. By 1962, Schevill, Watkins, and Backus (1964) had accumulated evidence that these stereotyped sequences of 20-Hz pulses were produced by finbacks. Finbacks were found within a few km when the 20-Hz signals were received well above background noise on near-surface hydrophones, and high-level signals (40 dB or more above ambient sound) correlated only with the presence of finbacks within 200 m. With care these whales could be approached by surface vessels at sea without disrupting their behavior, and they could be tracked by their sounds (Watkins and Schevill, 1972; Watkins, 1981, 1985, 1986; Watkins and Wartzok 1985). The 20-Hz signals could be directly associated only with finback whales. To trace the details of their behavior, finbacks were radio tagged and followed both inshore and offshore (Watkins, 1978; Watkins et al, 1981; Watkins et al, 1984). A variety of other low-frequency (17-125 Hz) vocalizations have been attributed to finbacks (Schevill and Watkins, 1962; Thompson, Winn, and Perkins, 1979; Edds, 1980; Cummings, Thompson, and Ha, 1986), and some of sounds were correlated with their behavior (Watkins, 1981). Different low-frequency sound patterns have been noted in scattered geographic locations that also may be associated with this species (cf Kibblewhite, Denham, and Barnes, 1967; Northrup, Cummings, and Thompson, 1968; Northrup, Cummings, and Morrison, 1971; Thompson and Friedl 1982).

Our analysis is focussed on the stereotyped bouts of "20-Hz signals" from finback whales. We have reviewed our observations of finback whales' use of these unique signals, and to put the acoustic data into perspective, the sounds are related to vocalizing whales which were tracked at sea.

## METHODS

### Behavioral Observations --

Observations during the production of 20-Hz sounds by finback whales included records from more than 4000 hours of near-surface single and array hydrophones. These data were from a wide variety of locations in the Pacific and Atlantic Oceans, with particular emphasis on whales off Cape Cod, Massachusetts. By moving our ships in increments of several km to increase the received levels of 20-Hz sounds from near-surface hydrophones and by comparison of sound arrivals on multiple hydrophones, we could consistently locate vocalizing finback whales (Watkins, 1981). Natural marks (chevron and blaze patterns, scars, and fin shapes) could often be used to distinguish individual whales over at least short periods so that they could be followed throughout sequential surfacings, and we often remained with vocalizing finbacks for periods of many hours. Sightings of finback blows from our height of eye onboard ship (usually 5 m or higher) were judged reliable up to 5 km so that the surface movements of scattered groups of whales over several square km could be monitored. The behaviors of finbacks relative to 20-Hz signal production have been summarized (Results) to provide the context for the finback sounds that we have analyzed in detail.

Acoustical Observations --

Recordings of finback 20-Hz signals included magnetic tapes, oscillograph records, and slow-speed drum oscillographs.

(1) Magnetic tape recordings of 20-Hz signals from more than 130 encounters with nearby finbacks were made on a variety of hydrophone and recording arrangements, including FM and Direct systems with overall low-frequency responses to at least 10 Hz and upper bandwidth limits from 10 kHz to more than 100 kHz. Because of the relatively long duration of many 20-Hz signal bouts, our tape recordings usually contained only selected segments of up to 30 min. Recordings by others and from other areas were also reviewed for comparison, including broadband magnetic tapes of some of the signals that also were recorded on the Bermuda drum records (#3 below).

These tapes were analyzed for details of vocalizations and any extraneous effects of reflection, multipath, and competing sounds. Fixed-filter spectrum analyzers (such as Kay Elemetric 7029A) and a variety of digital spectral systems were used for frequency analysis. Time sequences were studied from digitized tape recordings. Frequency sweeps in individual signals were compared by spectrographic and "zero-crossing" analyses.

(2) Oscillograph pen records of 20-Hz sounds were used as monitors during field observations of nearby finbacks, and they provided records up to 4 hrs longer than the magnetic tapes. The bandwidth of oscillographs was often restricted to avoid competing noise. During shipboard studies, oscillographs used

the same hydrophone systems as the tape recordings. In addition, oscillograph records from near-shore, bottom-mounted hydrophones were examined.

Oscillograph traces allowed detailed observation of wave-forms, temporal sequences, and relative sound levels, and provided intermediate record length and measurement precision between the tape recorded signals and the Bermuda drum records.

3) Continuous, slow-speed drum records collected over more than 30 years from the Bermuda Sofar Station (Columbia Geophysical Station, St Davids, 32 22'N, 64 38'W) were analyzed. These records were composed of oscillograph traces with 20 min of signal recorded at each drum revolution. Each record sheet contained 72 hrs of continuous recording from one hydrophone, or 24 hrs for each of 3 hydrophones (Patterson and Hamilton, 1964). These data had a bandwidth of approximately 1 to 40 Hz and included irregular records from 1951 to 1958 and nearly continuous records from 1959 through 1982. Until about 1967, hydrophones for the drum records were located off St Davids Head, Bermuda, in depths of 200 to 1300 m with separations of approximately 2 to 15 km. Other hydrophones (Pers. Comm. F. Watlington) in off Bermuda were used during later records with equivalent separations between units. Most signals were heard on only one hydrophone at a time, but when audible on more than one, the hydrophone with the best signal to noise level was selected. Patterson and Hamilton (1964) estimated listening ranges of this system at about 15 km.

The Bermuda drum records were analyzed in several ways. (A) They were used to document daily and seasonal occurrence of the finback signals. (B) Records for the month of January (mid-season for the 20-Hz finback signals) each year from 1958 to 1982 were studied. (C) Records for different days chosen randomly were examined for signal characteristics. (D) Five full years of recordings were analyzed from July to June 1958-59, 1959-60, 1967-68, and 1978/79, as well as January to June 1967 and July to December 1968. For 1958 only those records with obvious signals had been saved (so low-level signals may have been missed), otherwise these records were complete, and provided details of signal patterns, relative levels, and repetition rates. (E) To allow precise measurement of temporal sequences, selected portions were measured by digitizing tablet (Houston Instruments DT114). The nine digitized bouts (defined below) of the finback 20-Hz signals in Table 1 included 33.93 hrs of 20-Hz signals with 8396 pulses.

Analysis of the Bermuda data required scrutiny of more than 43,800 hrs of oscillograph traces (131,400 separate 20-min record lines) for each hydrophone, often with one or two other hydrophones analyzed as well. In addition, comparisons were made with our other analyses of these data, including more than 18,000 hrs of traces for all months of January. Digitization, storage, analysis, and statistical computation were mostly with laboratory computers: Compaq with expanded memory, Intel 8087 and Breakthru 286, AST multifunction, Mountain 20 MB and Rodime

Winchester 30 MB disks, and Data Translation DT2318 for 27.5-kHz sampling and Metrabyte Dash-16 for 50-kHz sampling. Software included LOTUS 123 and ILS signal processing (Signal Technology, Inc) for data handling and spectral and temporal analyses, with other programs developed by P. Tyack for specific analysis steps.

Each analysis sequence of 20-Hz signals was judged to be from one whale, but the few overlapping series in the Bermuda data may have led to a slight bias in occasional assessment of bout duration. Following standard statistical convention, data measurements have been specified to one decimal place, means to two places, and standard deviation to three places.

## Definition of Terms --

Particular terms (after Watkins, 1981) have been used in the analyses and descriptions to indicate specific sound sequences and concepts:

20-Hz pulses (single pulses) indicate individual sounds and components of longer pulse sequences. These "20-Hz" pulses are composed of downward sweeping frequencies, often 23 to 18 Hz. These can occur as single pulses, in short irregular series, and in bouts with stereotyped pulse intervals.

Pulse intervals include one pulse and the interval before the next pulse. Pulse intervals are measured from a particular point on one pulse to the same point on succeeding pulses so that the interval measurement includes the nominal 1-sec, 20-Hz pulse in addition to the period between pulses.

Short irregular 20-Hz pulse series describe these 20-Hz pulses used in short, irregular series with up to about 15 pulses, apparently as communicative sequences, heard year round.

20-Hz signal bouts refer to the 20-Hz pulses produced with stereotyped pulse intervals, separated by at least 2 hrs from any other bout. Bouts may last up to 32.5 hrs.

Gaps refer to quiet periods lasting between 20 and 120 min within bouts.

Rests refer to quiet periods lasting between 1 and 20 min within bouts.

Vocalizing whales were those producing the 20-Hz signals (not the irregular short 20-Hz pulse series or isolated 20-Hz pulses).

## RESULTS

### Typical 20-Hz Sounds --

The repertoire of sounds from finback whales include single 20-Hz pulses, irregular series of 20-Hz pulses, and stereotyped 20-Hz signal bouts of repetitive sequences of 20-Hz pulses.

Although called "20-Hz" and usually containing energy at that frequency, individual pulses of these finback sounds recorded at close range have had downward sweeping frequency, varying over about 6 Hz. Typically, each pulse started at about 23 Hz and dropped to approximately 18 Hz, over about 1 sec. The range of frequencies varied from about 25 to 17 Hz. The pulse (modulation) frequency usually lowered at progressively slower rates during a sound, dropping most rapidly during the first part. The level in individual pulses increased during the first third of the sound and decreased during the last third so that pulse beginnings and endings often appeared to be lost in ambient noise. When recorded over deep water near a vocalizing finback whale, each pulse included approximately 20 cycles of nearly sine-wave sound, having little or no harmonic content. However, at the longer distances, the effects of reflection and multipath transmission generally have modified the sounds so that they often appeared longer and complicated with harmonics (Watkins 1981).

Single pulses and short irregular series of 20-Hz pulses were produced year-round by finback whales during interactions with other finbacks in many behaviors. These irregular series of pulses often were heard in response to similar lower level sounds from other finbacks estimated to be beyond 5 km. The short irregular series were heard as part of the communicative repertoire of finback whales which also included other "higher frequency sounds", between 40 and 100 Hz (Watkins, 1981).

Typically, bouts of 20-Hz signals were composed of stereotyped repetitions of 20-Hz pulses over prolonged periods at relatively regular intervals, ranging from 6 to 46 sec (typically 7 to 26 sec) or as doublets of two alternating pulse intervals (see Patterson and Hamilton, 1964; Watkins, 1981).

Bouts were interrupted at intervals of approximately 15 min by rests and by irregular gaps.

The 20-Hz signals varied in level from one bout to the next (as with most whale vocalizations, Watkins and Wartzok, 1985). Sequential pulses within bouts of 20-Hz signals were relatively constant in level, except that one to three pulses immediately following or preceeding rests and gaps were normally lower level. The doublet pattern of pulse repetition often had lower level pulses following the short interval. Source levels (referred to 1 uPa at 1 m) for the 20-Hz sounds were between 160 and 186 dB, measured by multiple hydrophones at ranges of 100 to 500 m (similar to levels calculated by others, cf. Patterson and Hamilton, 1964; Cummings, Thompson, and Ha, 1986). Judging by relative sound levels and distances between the location at which the sound was first heard while tracking and that of the sighting of the vocalizing whale, these sounds could be heard reliably over distances of 15 to 25 km, with near-surface sources and receivers.

Behavior of Vocalizing Whales --

Using relative sound levels and direction of sound arrivals, more than 50 vocalizing finbacks have been located and followed for periods of several hours (for example, WHOI cruise #Be-268 on George's Bank, 11 Sept. to 1 Oct. 1961). In each instance, the exponential increase in sound levels with approach to the source left no doubt in the identification of the whale that was vocalizing. Although these data were incomplete and not sufficiently detailed to permit precise tabulation of results, the patterns of behavior associated with the production of 20-Hz signals by these finbacks are summarized.

Finbacks producing 20-Hz signals behaved in stereotyped ways. These "vocalizing whales" were seldom found within 5 km of other finbacks in the area. Vocalizing whales swam slowly, and appeared to stay within about 50 m of the surface. Depth could be extrapolated from sound arrival-times at multiple hydrophones, from the phase reversal of sounds reflected off bottom and surface, and relative water depths. Even when vocalizing whales had temporarily stopped producing the signals, they remained at nearly the same location, blowing with little surface movement, with 3 to 7 blows over approximately 2 min. Then, they submerged slowly, usually without "rounding-out" (raising the arched back and fin above the water, Watkins, 1981).

Generally, only one vocalizing whale was audible at a time from near-surface hydrophones. Occasionally, the start of a signal bout by one whale seemed to stimulate another whale to begin vocalizing within a few min. When other vocalizing whales were audible, they were separated by at least 5 km (judged by relative sound levels and sequential tracks). Vocalizing whales usually were separated from non-vocalizing whales by 200 m or more, juded by sightings. When more than one vocalizing whale was audible, the signals were not synchronized, although they often had similar pulse rates. Surfacings of vocalizing whales also were not synchronized with rests in signal bouts from other whales.

Vocalizing whales in each area tended to have the same pattern of pulse intervals over the same period (for example, 7-sec/11-sec doublets off Cape Cod, and regular 12-sec intervals off Bermuda, see analysis of pulse intervals).

Rests and Gaps in 20-Hz signals --

The 20-Hz signals generally were stopped when a vocalizing whale surfaced to blow, so that the finback 20-Hz signals had periodic interruptions or "rests" of 1 to 20 min duration (average 2 min) at approximately 15 min intervals, range 3 to 21 min (cf. Cummings, Thompson, and Ha, 1986). The signals usually ceased 10 to 15 sec before the whale appeared at the surface, and they restarted about 30 sec after the whale submerged. We often were not sure whether the cessation of signals during a whale's surfacing was the normal result of the change to respiratory activity, or whether signals were stopped because of some disturbance, such as our presence near the vocalizing whale. However, rests and gaps recorded from ships near whales were similar to those from bottom mounted hydrophones. Special procedures were routinely used to minimize effects of our presence on whale activities (Watkins, 1985, 1986).

The 20-Hz signals sometimes continued throughout at least the first portion of a vocalizing whale's blow series, and sometimes signals continued during the entire surfacing period. For example, on 12 September 1961 east of Cape Cod, a vocalizing whale at the surface moved from one end of our hydrophone array to the other, providing proof of the source of the signals (Fig. 13, p. 106, Watkins, 1981). When signals were produced by a whale at the surface, blows occurred between pulses. At other times, signals stopped for a few min and then restarted while the vocalizing whale was still underwater, without any surfacing over the next few minutes. Thus, rests were not always coordinated with surfacings.

In addition to rests during 20-Hz signals, vocalizing whales sometimes stopped their signals for longer periods (gaps) at irregular times during bouts. Gaps lasted between 20 and 120 min, and occasionally coincided with potential disturbances of these whales, as from passing ships. However, signals were also observed to stop (with no disturbance noted) when a vocalizing whale was approached closely (50 m or less) by another finback, and the signals sometimes started up again a few min after the whales separated. It was assumed that a whale diving near the location of a slow moving vocalizing whale would be in such close proximity, but because these associations occurred mostly underwater, the pattern of interaction could not be traced.

We could sometimes stimulate the production of sequences of 20-Hz signals by producing our own 1-sec low-frequency noise bursts at similar intervals to the 20-Hz signals (such as by starting and stopping our generator engine which had strong

20-Hz components) near a finback that had previously been producing the 20-Hz signals. Such whales often responded immediately after our noise bursts with a series of 20-Hz pulses.

It was also obvious that vocalizing whales immediately stopped producing 20-Hz signals (at least for a period) whenever they were disturbed, such as by the start-up of propeller cavitation sounds nearby. Generally, the whales stopped their signals at the occurrence of most loud, underwater sounds from near-by sources (see Watkins, 1986).

## Seasonal Distribution of 20-Hz Signals --

We have recorded 20-Hz signals from shipboard systems and identified the sounds with finback whales in a wide range of locations, including shoal water (Cape Cod, Nova Scotia, Long Island), in deep water off oceanic islands (Azores, Bermuda, Iceland), and in mid-ocean areas (700 km NE Bermuda, mid-Atlantic ridge, Gulf Stream off N. Y. bight). Our records (geophysical and other listening systems) and others reports (cf. Cummings, Thompson, and Ha, 1968) also indicate that similar 20-Hz sounds have been recorded from most ice-free oceans in winter. Although most of these have been without sightings, they show similar seasonal, winter occurrence for the finback 20-Hz signals. Only sporadic 20-Hz pulses (mostly irregular series not organized into stereotyped signal bouts) have been recorded in summer, although finbacks were commonly seen during this period in these areas.

## SIGNAL ANALYSES

### 20-Hz Signals --

Individual pulses of 20-Hz signals recorded from nearby finback whales are illustrated in Figs. 1 and 2. To show the consistent character of these signals, samples were chosen from recordings in the same area, 50 km NE of Cape Cod, Massachusetts, 42 14'N, 69 07'W, but 17 years later (27 Sept. 1961 for Fig.1 and 11 Oct. 1978 for Fig. 2).

The pulses in bouts of 20-Hz signals were in stereotyped series with relatively stable patterns of pulse repetition. The doublet pattern common in New England waters is shown in Fig. 3, with alternating long and short pulse intervals. This was recorded off Cape Porpoise, Maine (43 15'N, 70 15'W) on 10 December 1957. Long intervals of this doublet pattern ranged from 11 to 12.2 sec (av 11.46, sd 0.319, N=25), and short intervals ranged from 7.6 to 8.2 sec (av 7.85, sd 0.197, N=25).

The 20-Hz signals in Fig. 4 were recorded 25 km N of Cape Cod (42 30'N, 70 15'W) on 11 October 1978, approximately 100 km from those of Fig. 3, 22 years later. The plots of Figs. 3 and 4 show the characteristic variability as well as the continuing tendency toward alternating long and short doublet patterns of pulse repetition. Pulse intervals in the signal bout shown in Fig. 4 ranged between 9.2 and 7.6 sec (av 8.46 sec, sd 0.732, N=93), excluding the rests.

### Oscillographs from Bermuda --

Selected portions of the continuous drum oscillograph records from Bermuda were analyzed to show the details of typical long-term patterns of occurrence of 20-Hz signals. A sample of these drum records out of the middle of one record sheet is shown in Fig. 5, with only a portion of the record reproduced here so that the individual pulses could be large enough to be easily distinguished. Individual signal pulses in this sequence were produced at a nominal 12-sec rate. The bout lasted at least 3 hrs (over nine of the original 20-min lines) and included rests of 1.5 to 4.5 min as well as a gap of more than 20 min (pulses missing for more than one complete 20-min line). Note also the lower relative levels of the first and last few pulses at the beginning and end of rests separating sequences of 20-Hz signals.

### Seasonality of 20-Hz Finback Signals --

To analyze these long-term Bermuda drum records for seasonality, the complete record of bouts of 20-Hz finback signals for each day of the year were plotted relative to time of day for 12 month periods. A continuous 2-year period, July 1958 to June 1960 is plotted in Figs. 6 and 7. The complete record of bouts are plotted in Fig. 8 for one year, approximately one decade later (July 1967 to June 1968), and the plot in Fig. 9 is two decades later (July 1978 to June 1979). These detailed analyses demonstrate the occurrence patterns that have been consistent in spite of sampling from only a small area of a species that is highly mobile and widely dispersed during the breeding season.

Only signals that we recognized as from finback whales were included in Figs 6, 7, 8, and 9. Other sounds with similar though different structure, and repetition patterns which we labeled "questionable" finback-like sounds also were measured for comparison. Such sounds had been noted in the shipboard records, and we were interested to find that they could be distinguished also in the Bermuda data. The features of these sounds that distinguished them from characteristic finback signals included different (longer or shorter) pulse durations, non-varying pulse repetition rates, constant pulse levels, long bouts with little sound variation, and complete lack of periodic rests and gaps in longer series. The questionable signals for the 1978-1979 year are plotted in Fig. 10 for comparison with the occurrence of the characteristic finback signals of that same year, Fig. 9. These questionable, finback-like sounds are more common in the data from approximately 1977 on, and they were found distributed throughout the year, unlike the seasonal finback sounds.

A third category of 20-Hz sounds with similar form on the Bermuda drum records included those that we labeled "non-finback" because of regularity of pulse duration and intervals, lack of rests over long periods and lack of the characteristic variations in level and timing of finback signals. The non-finback sounds for the same 1978-1979 year are plotted in Fig. 11. Compare Figs. 9 and 11. The non-finback sounds were clustered at specific times of the year, including the summer months when finback 20-Hz signals were characteristically absent.

Comparison of the occurrence of the finback signals in different years (Figs. 6, 7, 8, and 9) demonstrated their consistency of occurrence as well as their variability. The average percent-of-time that the signals were heard throughout the year is plotted in Fig. 12. This is from the combined data of four full years (from Figs. 6-9 and two more connecting half-years, Jan. to June 1967 and July to Dec. 1968).

### Diurnal Differences in Occurrence --

The diel variation in occurrence of finback 20-Hz signal bouts in the five-year sample indicated only small differences between daylight and darkness. This was plotted on Fig. 13 as the number of hours of 20-Hz signals relative to time of day (local standard time). A few more 20-Hz signals were produced between 1900 and 0300 hrs, and they gradually dropped to their lowest rate between 1600 and 1700 hrs. Although this correlated with our radio tracking observations of this species which indicated times of more social activity and resting near the surface during the dark (Watkins, 1981; Watkins, et al, 1981), the start and end times of signal bouts indicated variability without consistent diurnal patterns.

## Bout Duration --

The duration of bouts of 20-Hz signals varied from less than one to 32.5 hrs. Analysis of the five-year sample demonstrated a negative exponential distribution of bout lengths. A "log survivor" plot (see Fagen and Young, 1978, for application of this to respiration intervals in Balaenopter musculus) of bout length in Fig. 14 indicates the number of bouts (ordinate) relative to their duration (abcissa). The ordinate is plotted logarithmically, so the near linearity of this plot indicates an exponential decay in bout durations. This means that the probability of a finback stopping a bout was relatively independent of how long it vocalized.

The distribution of bout durations over the five-year Bermuda data showed a month by month variation (Fig. 15). Bout durations were longer in October, gradually shortening throughout the season until March, and shortening further through June. No bouts were recorded in July and August. A Kruskal-Wallis analysis (Siegel, 1956) of this variation in the non-doublet pulse intervals indicated a significant variation over the year (N=581, K=34.6, p=0.00007), but a similar analysis of variation in bout duration by year for three full seasons separated by approximately a decade each, 1959-1960, 1967-1968, 1978-1979, indicated no significant variation (N=277, K=2.7, p=0.26).

Rests and Gaps --

Within bouts of 20-Hz finback signals, the distinctions between the pulse intervals of 7 to 26 sec, rests between 1 and 20 min, and gaps between 20 and 120 min were based on our previous experience with vocalizing whales at sea. The digitized bouts from the Bermuda data in Table 1 indicated similar divisions and allowed more precise examination of the pulse intervals in these 20-Hz signals. These were mostly mid-season bouts from 1960, 1968, and 1979, with the earliest in the year on 30 October and the latest on 18 April. Bout #8 (30 October 1968) had a rough doublet pattern of pulse repetition while the others each contained one nominal pulse interval.

The digitized bouts from the five-year data are plotted in Fig. 16 as a log survivor plot (Fagen and Young, 1978) of the finback pulse-interval durations, with the rank order of intervals between pulses plotted relative to the duration of pulse intervals. Horizontal sections of this curve (the section below 10 sec and from 25 to 60 sec) indicate that there were few pulse intervals with these durations. The vertical part of the curve between 10 and 25 sec includes over 8300 pulse intervals, showing that these intervals predominated in this sample. The vertical steps (at 10 to 20 sec and at 1 to 3 min) indicate the range in duration of pulse intervals and rests, respectively.

The lack of pulse intervals around 60 sec indicates the validity of our previous assessment of the lower limit of 1 min for rests, although 45 sec would have included the long pulse intervals of 46.2 sec (bout #4) and 54.6 sec (Bout #6) which occurred at the expected times for rests. Three intervals over 300 sec were not included in the plot.

The 20-Hz signals were characteristically interrupted by rests (with only occasional exceptions). This is shown by the signal bouts in Table 1, which gives dates of the digitized bouts, the mean duration of the rests during those bouts, the number of rests in each bout, and the duration of the signal period between rests. Bout #3 is listed twice, including and then excluding a long 766.2-sec rest. The next longest rest was 436.8 sec in Bout #8, 30 November 1978. For all of the 8396 digitized pulses there were only three intervals between 40 and 50 sec and only one between 50 and 60 sec. Bout #4 and #6 are listed twice, first without and then with intervals that are too short for our definition of rest, a 46.2-sec and a 54.6-sec interval, respectively. The mean duration for all 110 rests from the nine bouts was 115.35 sec (sd 48.369), excluding the 766.2-sec interval in Bout #3. For all bouts, the mean signal duration between 96 rests was 15.62 min (sd 6.954). Rests over 60 sec from the nine digitized bouts of 20-Hz finback signals are plotted in Fig. 17 to show the variability of rest duration within bouts characteristic of these finback signals.

Successive intervals between all 20-Hz pulses in representative digitized bouts are plotted in Fig. 18 (Bout #1), Fig. 19 (Bout #4), Fig. 20 (Bout #5), and Fig. 21 (Bout #9). The duration of intervals between pulses (ordinate) are plotted against successive pulses (abscissa) with a constant increment for each pulse. The bouts of 20-Hz signals in these figures demonstrate both the relative regularity of the occurrence of rests in all the bouts spread over these years, as well as the characteristic variability of rest durations. There were few differences between the general patterns of 20-Hz signals from 1960 (Fig. 18), 1968 (Figs. 19 and 20), and 1979 (Fig. 21).

There was no obvious pattern indicating the presence of rests during a bout or the duration of rests to any other parameters of finback 20-Hz signals. Because rest duration might be related to surface time which often appears correlated with length of dives, we used a product-moment correlation coefficient for small and medium sample sizes (Sokal and Rohlf, 1981) to test for association of rest duration with the duration of the signal periods between rests. The relation between rest duration and signal duration between rests was not significant, for example, #4 with 24 rests ($r23 = 0.0989$, $df = 21$, $p > 0.05$).

### Pulse Intervals --

The digitized data from the Bermuda data showed that the distribution of pulse intervals in bouts of 20-Hz signals was as varied as those from other areas, such as in Figs. 3 and 4 from waters off Cape Cod. Most of the Pulse intervals from Bermuda varied between 9 and 15 sec, as in Fig. 22. The average pulse interval for each of the digitized 20-Hz signal bouts are listed in Table 2, ranging from 10.08 sec to 13.51 sec. Each bout is presumed to be from one whale. The overall average pulse interval from 7829 pulses was 12.48 sec (sd 2.309), excluding the less common doublet pattern for this area, Bout #8 (30 Oct. 1968).

Portions of these data from Bermuda sometimes appeared to have more variability in pulse intervals toward the end of a bout than in the beginning. Therefore, pulse intervals were divided in half for each of the digitized bouts and compared (Table 2), but no no significant differences were found, except for Bout #8 with doublets. There also appeared to be no pattern of increasing or decreasing pulse intervals in first or second half of the bouts, although in four, variances were determined to be unequal (F-test greater than 0.001, Sokal and Rohlf, 1981) with the higher variance in the second half of the bout.

During 20-Hz signals, some of the pulse intervals appeared to be relatively stable, especially when plotted with a reduced scale, as in the middle part of Fig. 20. However, the characteristic variability is seen when these same pulse intervals are plotted at expanded scales, as in Fig. 23. The doublet pattern of pulse intervals in the 20-Hz signals from the Bermuda area is illustrated in Fig. 24 from Bout #8, showing the alternating sequence and the characteristic short-term variations in pattern of pulse repetition.

Although average pulse patterns from different areas, such as Bermuda, Nova Scotia, and Cape Cod have appeared somewhat different, there have not been enough long-term data to assess this. In the Bermuda data, overall patterns of seasonality and bout duration have appeared to be relatively stable over two decades, and the general pulse intervals also have remained similar (Fig. 25A, B, and C.), although they are significantly different when considered year by year. These histograms of frequency of bouts relative to pulse intervals are from full years of the five-year data, using intervals from the digitized bouts (Table 1) when available, and nominal pulse intervals for the rest of the bouts. Nominal pulse intervals were assigned by measuring three to ten apparently representative pulse intervals for each bout with a Gerber scale, and the median of these was selected as the nominal pulse interval. A Kruskal Wallis analysis of nominal pulse intervals for three seasons, each separated by approximately a decade, demonstrates the extent of the variation ($N=259$, $K=40.2$, $P=1.9\times10^{-9}$).

Monthly differences in nominal pulse intervals are shown in Fig. 26 for the five-year Bermuda data, except for 1958 which may not have included some lower level bouts. Here analysis indicates a significant lengthening of average pulse intervals over the peak season. A Kruskal Wallis analysis of pulse intervals by month also shows a significant variation ($N=610$,

$K=63.3$, $P=3.1\times10^{-10}$). Compare these data on pulse interval lengthening during the peak season with the analysis of Fig. 15 which shows shortening of bout length from month to month over the season. This variability in short-term and seasonal measures of pulse intervals, rests, and bouts is characteristic of the finback signals, while the longer-term measures indicate general stability.

## SUMMARY

Analysis of signal bouts from finback whales have confirmed that individual 20-Hz pulses of these signals had (1) downward sweeping frequency modulation, often 23-18 Hz, (2) durations of approximately 1 sec, (3) sinusoidal wave form, and (4) variable but relatively high source levels, 186 dB max (re 1 uPa). The pulses were produced in stereotyped series having (5) relatively regular sequences of repetition at intervals ranging from 6 to 45 sec, typically 7 to 26 sec, (6) long signal bouts up to 32.5 hrs, (7) periodic rests averaging 115-sec duration at roughly 15-min intervals, (8) longer irregular gaps between 20 and 120 min, and (9) usually lower level pulses at beginning and end of sequences, such as between rests. Bouts of 20-Hz signals also had (10) strong seasonal occurrence over the winter, during the breeding season, (11) progressively shorter bout durations and longer pulse intervals over the season, and (12) the signals were characteristically variable; the 20-Hz finback signals were never exactly replicated.

## DISCUSSION

Our analyses of finback whale 20-Hz signal bouts have been based on massive amount of data, which gives confidence in the assessments of the features of these signals. This is unlike the usual studies of cetacean acoustic behavior which generally have permitted only studies of short segments of particular repertoires, so that even the variability in the sounds cannot be described.

The seasonal occurrence of 20-Hz signals fits with the estimates from whaling data on finback whales of a gestation period of approximately one year with a reproductive season over the winter (Ohsumi, Nishiwaki, and Hibiya, 1958; Laws, 1961; Haug 1981; Lockyer 1984). The occurrence of the 20-Hz signals throughout the year matches the seasonal reproductive curves calculated for this species (note the concurrence of our Fig. 12 with the equivalent reproductive curve for the southern hemisphere, p. 404 in Laws, 1961).

The direct association of the 20-Hz signals with the reproductive season is also consisitent with our identifications of vocalizing whales apparently only with males. This has included two direct observations (Watkins): on 12 April 1970 and 11 October 1978 east of Cape Cod, whales that had previously been identified as vocalizing were observed to participate in rolling and close contact with other large finbacks (interpreted as probable courtship activities) -- in both instances, male genitalia were visible on the whales that had been producing 20-Hz signals. In addition, vocalizing whales have consistently been slightly smaller than the largest whales in an area (Watkins, 1981). Adult finback females are consistently about 1 m longer (and look larger) than males of about the same age (True, 1904: Ohsumi, Nishiwaki, and Hibiya, 1958; Lockyer 1984). The vocalizing whale has never been one identified as female.

The finback 20-Hz signals, therefore, appear similar in function to the "song" described for some other marine mammals (noted also by Cummings, Thompson, and Ha, 1986). Songs have been described for bearded seals (*Erignathus barbatus*, Ray, Watkins, and Burns, 1969), humpback whales (*Megaptera novaeangliae*, Payne and McVay, 1971; Winn, *et al*, 1981; Payne and Guinee, 1983; Payne, Tyack, and Payne, 1983; Payne and Payne, 1985), and for bowhead whales (Cummings *et al*, 1983). These stereotyped and repetitive marine mammal songs appear to be acoustic displays during the reproductive season, apparently by males in most of these species (*E. barbatus*, Ray, Watkins, and Burns, 1969; *M. novaeangliae*, Winn, *et al*, 1981, and Glockner, 1983).

The relatively large amount of evidence reviewed here from the tracking data confirms that the stereotyped bouts of 20-Hz signals are only identified with finback whales. The distinctions observed in the repetitive patterns of these signals in separate geographic areas argues for some distinctions between finback populations in these different locations. Significant variations in details of the signals recorded in the same small local area probably reflect either or two possibilities: that different groups of whales were sampled each of which had different signals, or that the same whales changed their signals over time.

Periodic rests during 20-Hz finback signals were consistently demonstrated by the data: (1) Most signal bouts had rests whether they were recorded from near-surface or from deep hydrophones. (2) Rests on near-surface records usually coincided with observed respiration surfacings. (3) On deep hydrophone records, there were no obvious differences in the way rests were received between day and night, when propagation characteristics could have been markedly different for distant signals. (4) High-level signals on deep hydrophones probably from nearby whales above the receiver showed the same probability of periodic rests as the lower level distant signals (arriving by more horizontal paths which would be more likely to be affected by propagation differences).

Because the 20-Hz signals were observed to stop when vocalizing whales were approached by other finbacks, any cessation of the signals including gaps and maybe some rests may have been due to such temporary associations with other whales, similar to the reactions of singing humpbacks to approaching conspecifics (Tyack, 1981).

Because of the possibility that other similar signals might be confused in the Bermuda data with the oscilloscope traces of finback 20-Hz sounds, we carefully categorized likely signal sequences into (1) finback signals -- those that consistently followed the acoustic patterns we recognized from our work at sea with nearby finback whales, (2) questionable finback-like sounds -- those that had many features like the finback signals but because of irregularities (noted in the text), they were considered separately, and (3) those sounds that clearly were not from finbacks, yet were received with the same general pattern of pulse repetition, frequency range, and intensity. It is interesting that these categories also proved to be distributed differently throughout the year: (1) the finback signals occurred only seasonally, (2) the questionable finback-like signals were scattered all throughout the year without apparent seasonal bias, and (3) the non-finback signals were clustered in particular periods including those without the true finback signals. We have no sources identified for the questionable finback-like signals, but they were sufficiently different from finback 20-Hz signals to warrant treating them separately. This is not to rule out finbacks as a possible source for at least some of these anomalous signals. The non-finback signals occurred in different forms throughout most of the 30 years of data, and we assume that they were from various mechanical noise sources, such as geophysical and seismic sound sources.

The observations that finbacks responded to 20-Hz sounds from other distant whales, that they sometimes were stimulated to produce signals by those of other vocalizing whales, and that they could be stimulated into resumption of signals by our production of noise pulses perhaps indicate that playback of 20-Hz signals might be a useful technique for study of these acoustic behaviors in finbacks.

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# FIGURE CAPTIONS

Figure 1 -- Oscillograph traces (25 div.-per-sec) show one pulse of a series of 20-Hz signals from a finback whale recorded on two hydrophones 250 m apart. The whale was observed to be within 400 m of the closest hydrophone and nearly in line with the array (signal separation approximately 160 ms between traces, 4 div.). The signal was more than 50 dB above background noise. No filters were used during recording or analysis. This the characteristic waveform and envelope of the 20-Hz signal.

Figure 2 -- Spectrographic analysis shows two successive pulses of a bout of 20-Hz signals from a nearby finback whale recorded 17 years after those of Fig 1, in nearly the same location. The filter bandwidth (resolution) of the analysis was 5.6 Hz, otherwise no filters were used. The characteristic changing slope of the downward frequency sweep within pulses is indicated best by the leading edge of the traces (signal level indicated by trace length and darkness of trace).

Figure 3 -- A plot of the pulse intervals for 52 pulses of a bout of 20-Hz signals recorded 10 Dec. 1957 off Cape Porpoise, Maine, shows a doublet pattern of pulse repetition. Except for the 9.8-sec interval, the pulse intervals alternated between those averaging 11.46 sec (sd 0.319) and 7.95 sec (sd 0.197).

Figure 4 -- Pulse intervals are plotted for 98 pulses of a bout of 20-Hz signals recorded 11 Oct. 1978 in Cape Cod Bay, Massachusetts. There were four rests of 488, 200, 70, and 75 sec, respectively, and one longer 13.6-sec interval in the final portion. Excluding the rests, the average pulse interval was 8.46 sec (sd 0.732, N = 93).

Figure 5 -- A sample from the middle of a drum oscillograph record from Bermuda, 12 Dec 1979, shows a typical bout of finback 20-Hz signals. This sample includes 44 incomplete lines (10 min of each of the original 20-min lines, 1-min markers) taken from the center of a drum recording. The sample shows a bout which lasted at least 3 hrs, with 1-sec pulses, (nominal 12-sec intervals), rests, and gaps (used also in Watkins, 1981).

Figure 6 --

All bouts of finback 20-Hz signals from the Bermuda drum records are plotted relative to time of day for the year, July 1958 to June 1959. Note the concentration of signals during the winter season.

Figure 7 --

Finback 20-Hz signal bouts from the Bermuda records are plotted for July 1959 to June 1960, to show the continued seasonality of the signals and show the high variability in occurrence of the signals from season to season, Fig. 6.

Figure 8 --

Finback 20-Hz signal bouts from the Bermuda records are plotted for July 1967 to June 1968 to provide a comparison of signal occurrence approximately a decade after Figs. 6 and 7.

Figure 9 --

Finback 20-Hz signal bouts from the Bermuda records are plotted for July 1978 to June 1979. In spite of considerable variation over two decades, the signals consistently occurred during the winter season, with the greatest concentration usually between December and February.

Figure 10 --

"Questionable" 20-Hz finback signals from the Bermuda records are plotted for the same 1978-1979 year, as in Fig. 9. These "questionable" finback sounds were scattered throughout the year, instead of being confined to the winter season.

Figure 11 --

"Non-finback" 20-Hz signals from the Bermuda records are plotted for the same 1978-1979 year, as in Figs. 9 and 10. The "non-finback" signals were clustered during some periods that were very different from the occurrrence of the finback signals.

Figure 12 --

The seasonal occurrence of bouts of finback 20-Hz signals are plotted as a histogram of percentage of bout duration for each month of the year. Five full years of data were pooled for this plot, including those used for Figs. 6, 7, 8, and 9, and two other consecutive half-years (Jan. to June 1967 and July to Dec. 1968).

Figure 13 --

The diel variation in occurrence of 20-Hz signals from the five-year pooled data (as in Fig. 12) are plotted relative to local standard time.

Figure 14 --

A "log survivor" plot (Fagen and Young, 1978) of all 20-Hz signal bouts in the five-year data is plotted logarithmically against bout duration. The linear relationship indicates a nearly random distribution of bout duration to about 24 hrs, so that the probability of a bout stopping was constant.

Figure 15 --

Average bout durations are plotted by month from the Bermuda five-year data (except for 1958 which may have been incomplete). Horizontal bars mark the average value for the month, and vertical bars mark the standard error of the sample from that month.

Figure 16 --

Intervals between the pulses of the 9 bouts from the digitized Bermuda data (see table 1) are shown as a log survivor plot (Fagen and Young, 1978) of rank order of pulse interval (log scale) relative to the duration of pulse intervals. The log survivor plot shows there were few intervals between 26 and 60 sec, confirming distinctions between pulse intervals (typically less than 26 sec in these data) and rests (over 60 sec).

Figure 17 --

The 107 "rests" in the 9 digitized bouts of from the digitized Bermuda data are plotted in order of occurrence to show their relative durations and the characteristic high variability. Each of the vertical bars represents one rest, the rests of each bout are grouped together, and the numbered bouts (see Table 1) are separated by larger spaces. Rests are portrayed successively without the duration of signals between rests.

Figure 18 --

The pulse intervals for the pulses of bout #1 (Table 1, 13 Jan. 1960) are plotted relative to the duration of those intervals. The 623 pulse intervals are plotted consecutively along the abscissa without accounting for the exact time continuum of the intervals -- for example, rests (longer than

60 sec) occupy the same space on the abscissa as other pulse intervals. Note the relatively regular occurrence of rests and of the general regularity of pulse intervals.

Figure 19 --

The pulse intervals for the 1160 pulses of bout #4 (14 Jan. 1968) are plotted relative to their duration to show the consistency of the 20-Hz signals -- compare with Fig. 17 eight years earlier. The 46.2-sec interval is short for a rest as we defined it, but note that it fits the pattern of occurrence for rests in this bout. Successive pulse intervals are plotted without attention to their exact time continuum.

Figure 20 --

The pulse intervals for the 2450 pulses in bout #5 (14 Jan. 1968) are plotted relative to their duration. The scale is different from that of the previous figures because of the greater number of pulse intervals, again plotted sequentially without attention to their exact time continuum. Note the usual regularity of the occurrence of rests, and pulse intervals, although the durations of rests varied. One gap occurred just before the end of this bout.

Figure 21 --

The duration of 510 pulse intervals are plotted from bout #9, 18 April 1979 to demonstrate that the signal patterns changed little over the two decades, Figs. 18-20 for the years 1960 and 1968. The two longer rests (300.6 and 436.8 sec) are the same as in the last portion of Fig. 16. Pulse intervals are plotted sequentially without attention to their actual time continuum.

Figure 22 --

The distribution of 7829 pulse intervals in the 20-Hz finback signals from the nine digitized bouts (Table 1) of the Bermuda data are plotted relative to the number of intervals. The pulse intervals cluster around 12 sec although there were scattered intervals between that and the 60-sec lower limit defined for rests.

Figure 23 --

Successive pulse intervals are plotted for a sequence of 100 pulses from the middle of the 2450 pulses in Bout #5 (14 Jan. 1968) in Fig. 20. This is the most regular portion of that sequence of pulse intervals, but even so, the variability inherent in these finback whale signals can be seen with the enlarged scale.

Figure 24 --

Successive pulse intervals for the first 100 pulses of Bout #8 are plotted to show the alternating "doublet" pattern occasionally found in the Bermuda data. A rest of 148.2 sec is included. Compare with the characteristically shorter and generally more regular doublet patterns recorded off New England (Figs. 3 and 4).

Figure 25 --

Yearly differences in the nominal pulse intervals for each bout were plotted from the five-year Bermuda data as frequency histograms for the years (July-June) 1959-1960, 1967-68, and 1978-79. Doublet patterns of pulse intervals were not included. Frequency of bouts are plotted relative to pulse intervals to show the general similarity from decade to decade and the significant differences from year to year.

Figure 26 --

Monthly averages in nominal pulse intervals during signal bouts are plotted from the five-year Bermuda data, except for 1958. Pulse intervals are tallied for the month in which the bout started. Horizontal bars mark the average for the month, and vertical bars mark the standard error of the monthly sample.

Table 1. Rest durations and signal durations between rests for digitized bouts of 20-Hz signals.

| DATE | BOUT # | MEAN REST DURATION (Sec) x | sd | n | MEAN SIGNAL DURATION BETWEEN RESTS (Min) x | sd | n |
|---|---|---|---|---|---|---|---|
| 13 Jan. 1960 | 1 | 163.02 | 13.812 | 7 | 16.36 | 1.029 | 6 |
| 20 Feb. 1960 | 2 | 104.10 | 24.915 | 14 | 14.36 | 7.486 | 13 |
| 21 Feb. 1960 | 3 | 150.06 | 153.785 | 19 | 10.09 | 5.333 | 16 |
| 21 Feb. 1960[1] | 3 | 115.83 | 38.334 | 18 | 10.59 | 5.125 | 15 |
| 14 Jan. 1968 | 4 | 91.62 | 17.860 | 10 | 21.83 | 9.850 | 9 |
| 14 Jan. 1968[2] | 4 | 87.49 | 21.786 | 11 | 19.57 | 3.882 | 10 |
| 14 Jan. 1968 | 5 | 102.68 | 26.297 | 24 | 19.69 | 3.947 | 23 |
| 15 Jan. 1968[3] | 6 | 106.25 | 24.245 | 11 | 18.95 | 5.156 | 10 |
| 15 Jan. 1968[4] | 6 | 101.95 | 27.509 | 12 | 17.15 | 2.220 | 11 |
| 30 Oct. 1968 | 7 | 130.90 | 29.176 | 6 | 13.62 | 5.926 | 5 |
| 30 Nov. 1978 | 8 | 90.30 | 31.692 | 8 | 7.74 | 4.617 | 7 |
| 18 Apr. 1979 | 9 | 185.85 | 120.236 | 8 | 13.16 | 1.680 | 7 |

[1] Means calculated deleting a 766.2 sec rest.

[2] Means calculated counting a 46.2 sec interval as a rest.

[3] This bout is a continuation of Bout #2, 14 Jan., but they were recorded on two separate drum recordings. They were treated as separate bouts because several minutes were lost between records and a rest may have occurred.

[4] Means calculated counting a 54.6 sec interval as a rest.

Table 2. Mean pulse interval (<60 sec) for digitized bouts

|  |  | Overall Bout Mean Pulse Interval |  |  | First Half Bout Mean Pulse Interval |  |  | Second Half Bout Mean Pulse Interval |  |  | F-test for Equality of Variances |  |  | T-test 1st half x vs 2nd half x |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DATE | BOUT # | x | sd | n | x | sd | n | x | sd | n | Fs | p | df | Ts or T'[1] | p | df |
| 13 Jan. 1960 | 1 | 12.75 | 2.698 | 616 | 12.64 | 2.453 | 308 | 12.86 | 2.922 | 308 | 1.42 | <0.05 | 614 | 1.012 | >0.2 | 614 |
| 20 Feb. 1960 | 2 | 12.55 | 1.943 | 935 | 12.59 | 1.457 | 468 | 12.52 | 2.332 | 467 | 2.56 | <0.001 | 933 | 0.550 | >0.5 | 933 |
| 21 Feb. 1960 | 3 | 12.24 | 1.734 | 924 | 12.28 | 1.312 | 462 | 12.21 | 2.072 | 462 | 2.49 | <0.001 | 922 | 0.614 | >0.5 | 922 |
| 14 Jan. 1968 | 4 | 11.90 | 1.813 | 1149 | 11.84 | 2.001 | 575 | 11.97 | 1.601 | 574 | 1.56 | <0.05 | 1147 | 1.216 | >0.2 | 1147 |
| 14 Jan. 1968[2] | 4 | 11.87 | 1.504 | 1148 | 11.78 | 1.396 | 574 | 11.97 | 1.601 | 574 | 1.32 | <0.05 | 1146 | 2.143 | <0.05 | 1146 |
| 14 Jan. 1968 | 5 | 12.34 | 2.392 | 2424 | 12.36 | 2.420 | 1212 | 12.32 | 2.365 | 1212 | 1.05 | >0.5 | 2422 | 0.412 | >0.5 | 2422 |
| 15 Jan. 1968[3] | 6 | 12.39 | 2.784 | 966 | 12.32 | 2.835 | 483 | 12.46 | 2.733 | 483 | 1.08 | >0.5 | 964 | 0.781 | >0.4 | 964 |
| 15 Jan. 1968[4] | 6 | 12.35 | 2.431 | 965 | 12.23 | 2.078 | 483 | 12.46 | 2.432 | 482 | 1.37 | <0.05 | 963 | '1.579 | >0.1 | 963 |
| 30 Oct. 1968 | 7 | 10.08 | 2.478 | 456 | 10.14 | 2.491 | 228 | 10.02 | 2.469 | 228 | 1.02 | >0.5 | 454 | 0.517 | >0.5 | 454 |
| 30 Nov. 1978 | 8 | 12.16 | 3.319 | 313 | 11.57 | 1.273 | 157 | 12.75 | 4.453 | 156 | 12.24 | <<0.001 | 311 | 3.183 | <0.01 | 311 |
| 18 Apr. 1979 | 9 | 13.51 | 1.606 | 502 | 13.43 | 1.342 | 251 | 13.59 | 1.831 | 251 | 1.86 | <0.001 | 500 | 1.117 | >0.2 | 500 |

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[1] If the F-test showed a highly significant difference between variances (<0.001), we used the T' statistic (Sokal and Rohlf 1981).

[2] Means calculated counting the 46.2 sec pulse interval as a rest and deleting it.

[3] See footnote 3, Table 1.

[4] Means calculated counting the 54.6 sec pulse interval as a rest and deleting it.

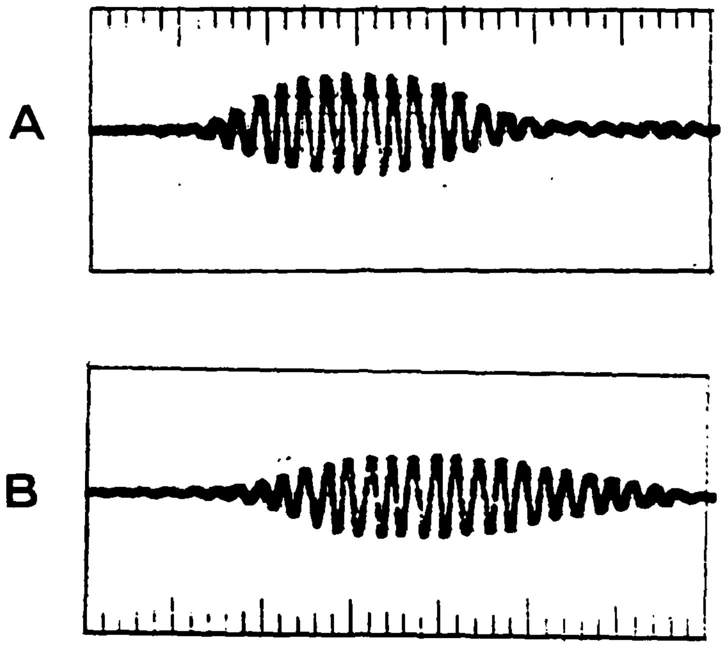


Fig 1

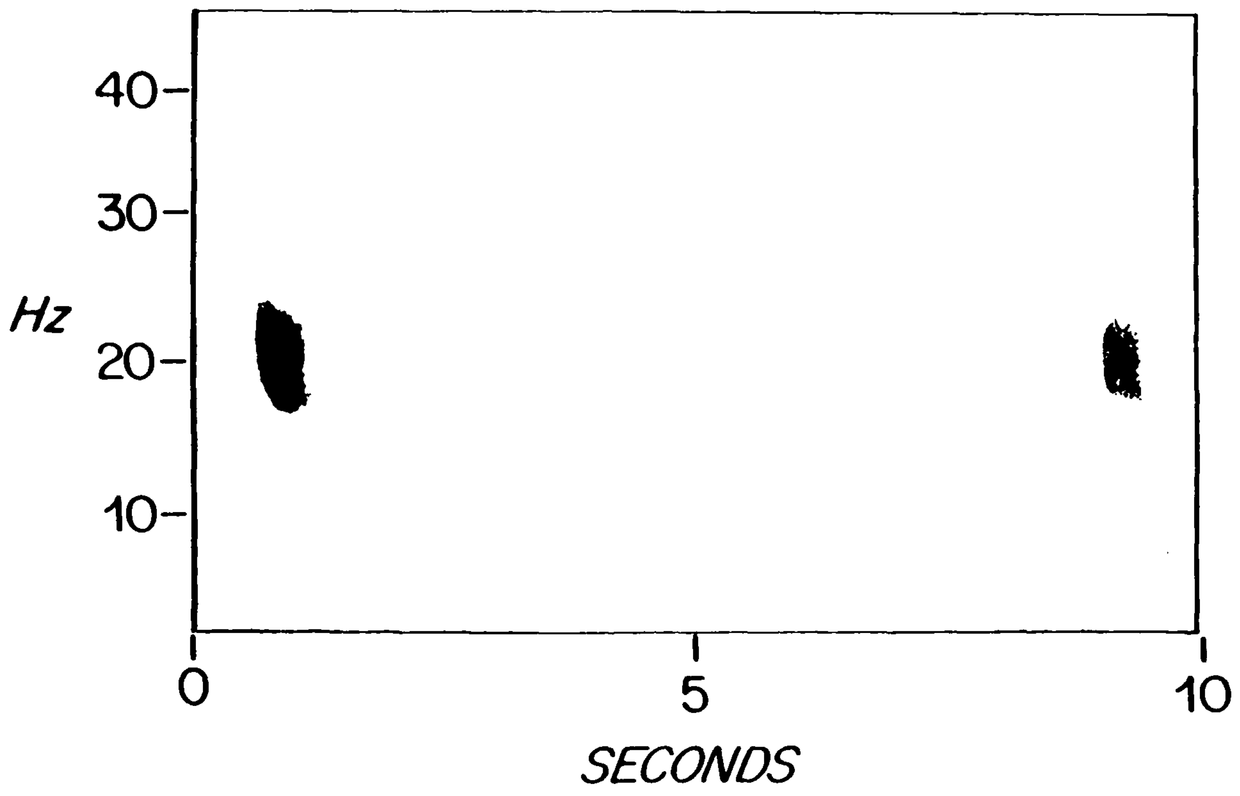


Fig 2

10 Dec 1957 - Sanborn - Fletcher's Neck
PULSES 1 TO 52

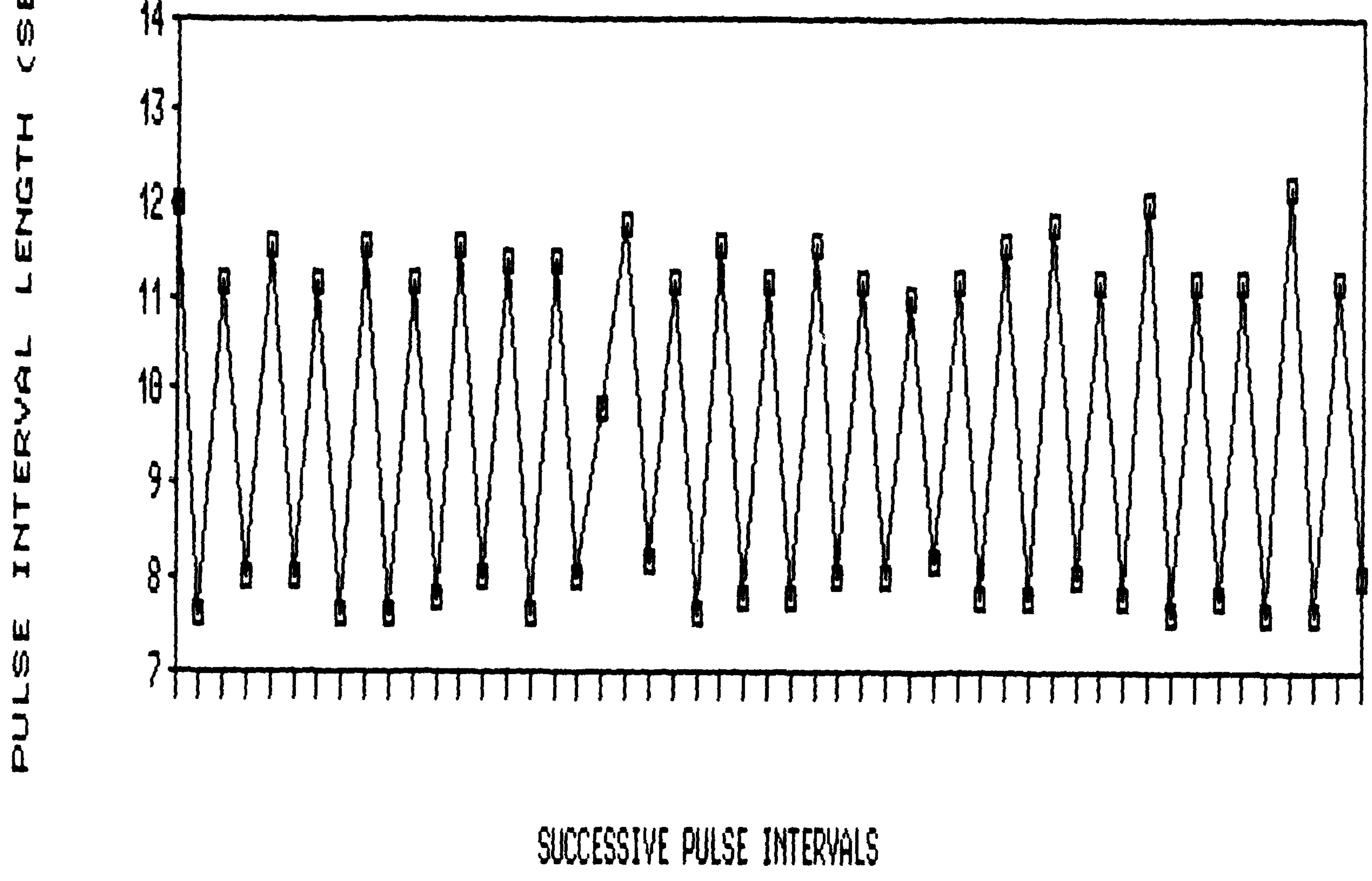


Fig 3

11 Oct 1978 - Sanborn - Cape Cod Bay
PULSES 1 TO 98

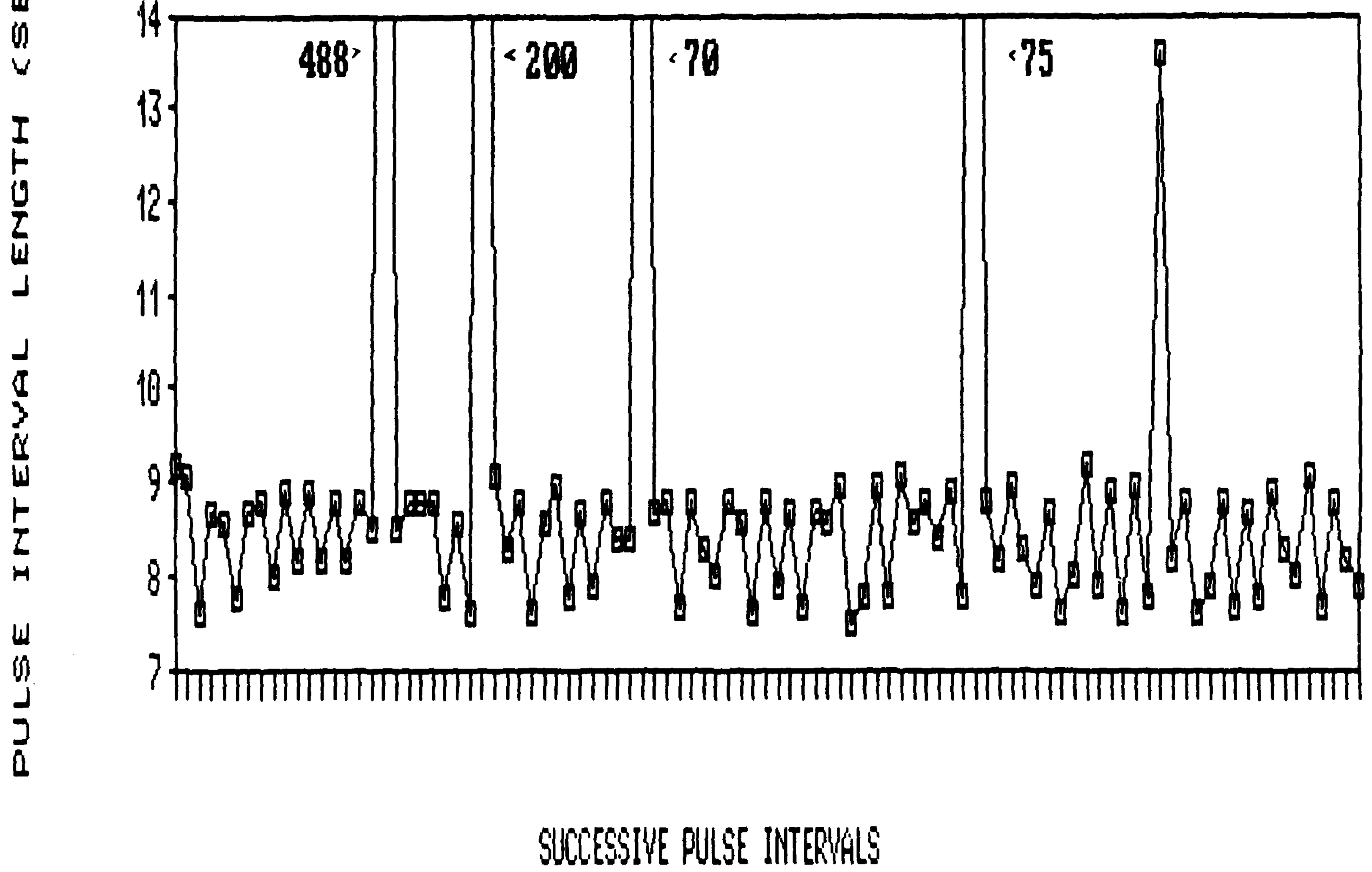
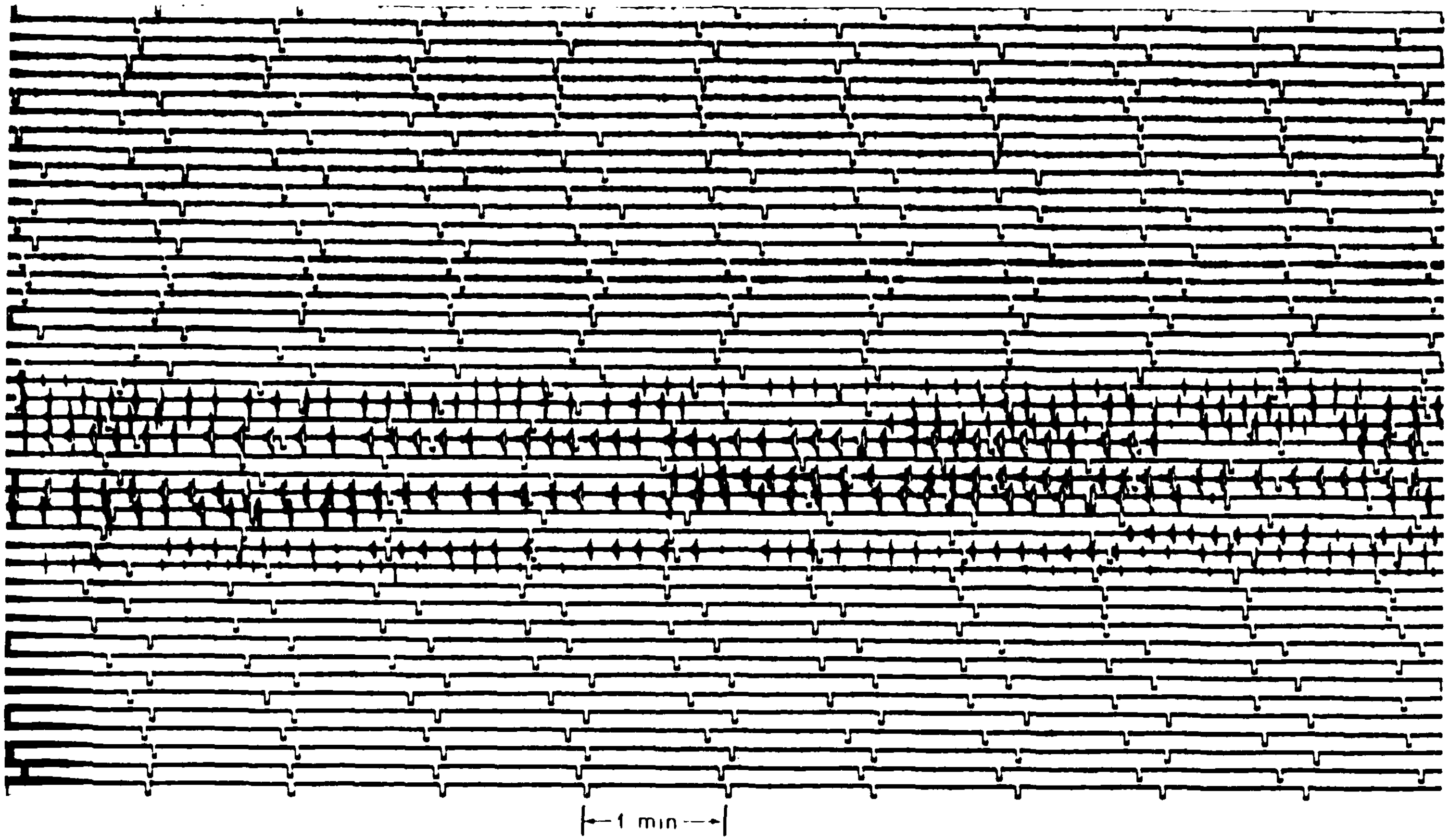


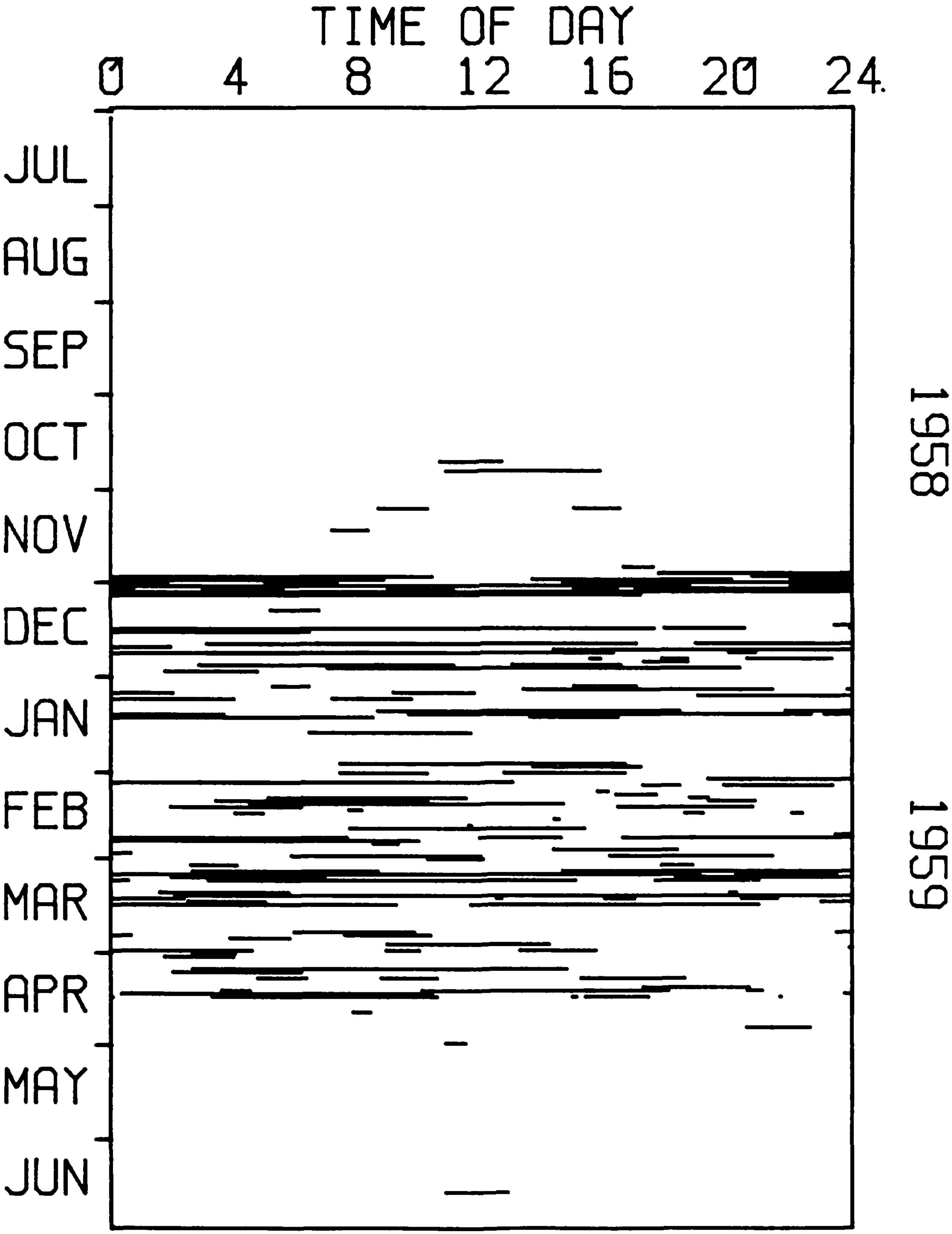
Fig 4



20-Hz PULSE PATTERNS FROM FINBACK WHALES
(*Balaenoptera physalus*)

Fig 5

Fig. 6



TIME OF DAY
0
4
8
12
16
20
24
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1958
1959

Fig - 7

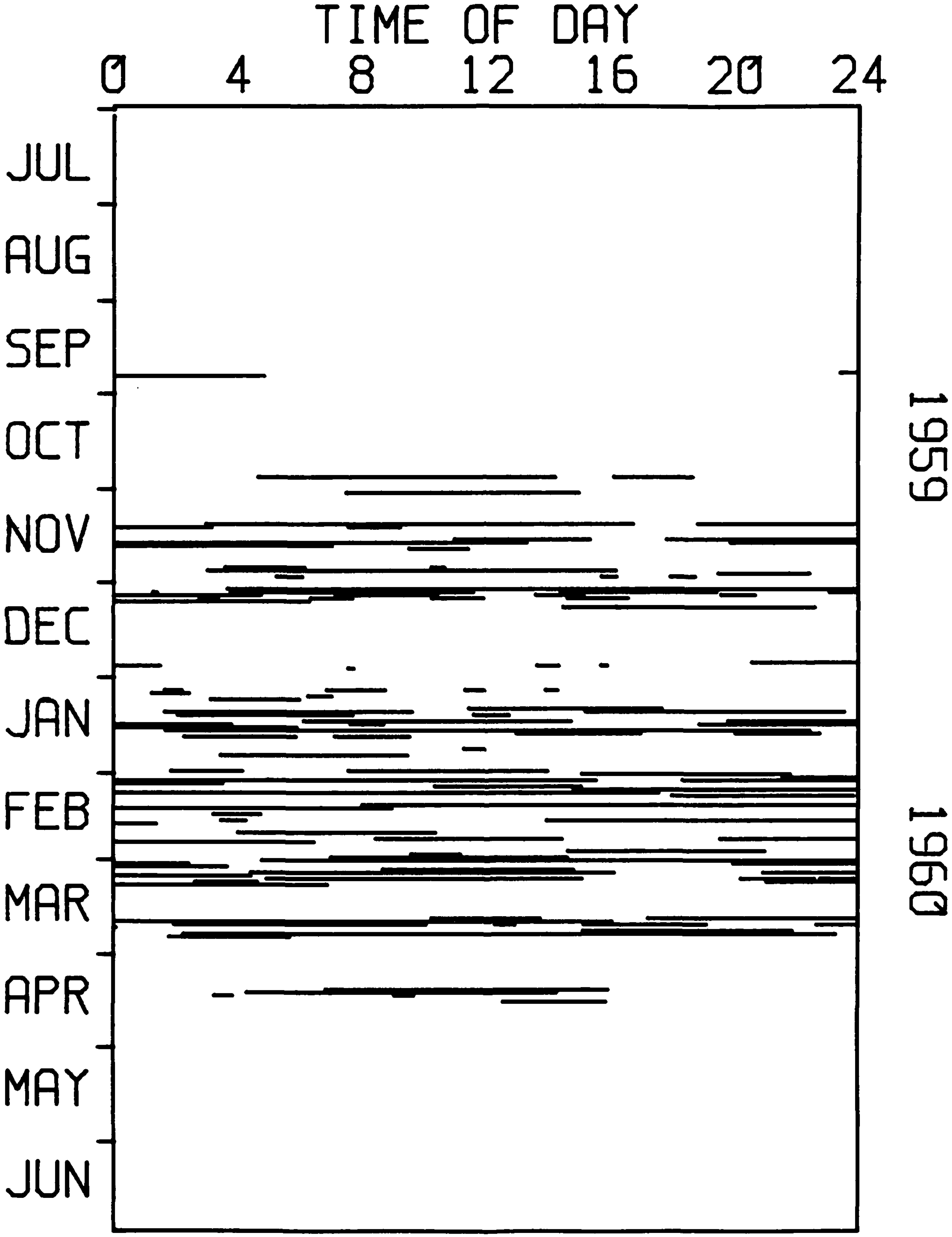

TIME OF DAY
0
4
8
12
16
20
24
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1959
1960

Fig 8

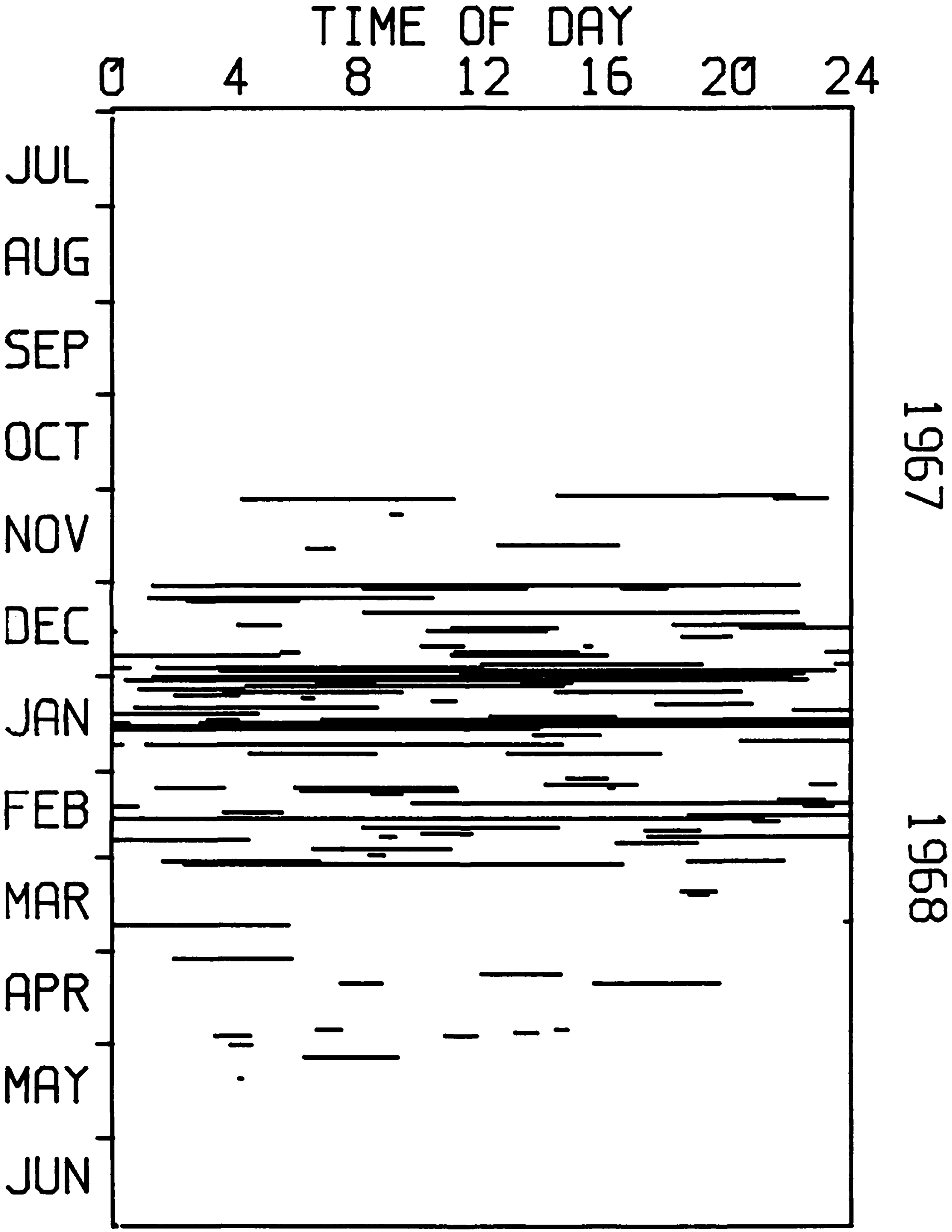

TIME OF DAY
0
4
8
12
16
20
24
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1967
1968

Fig 9

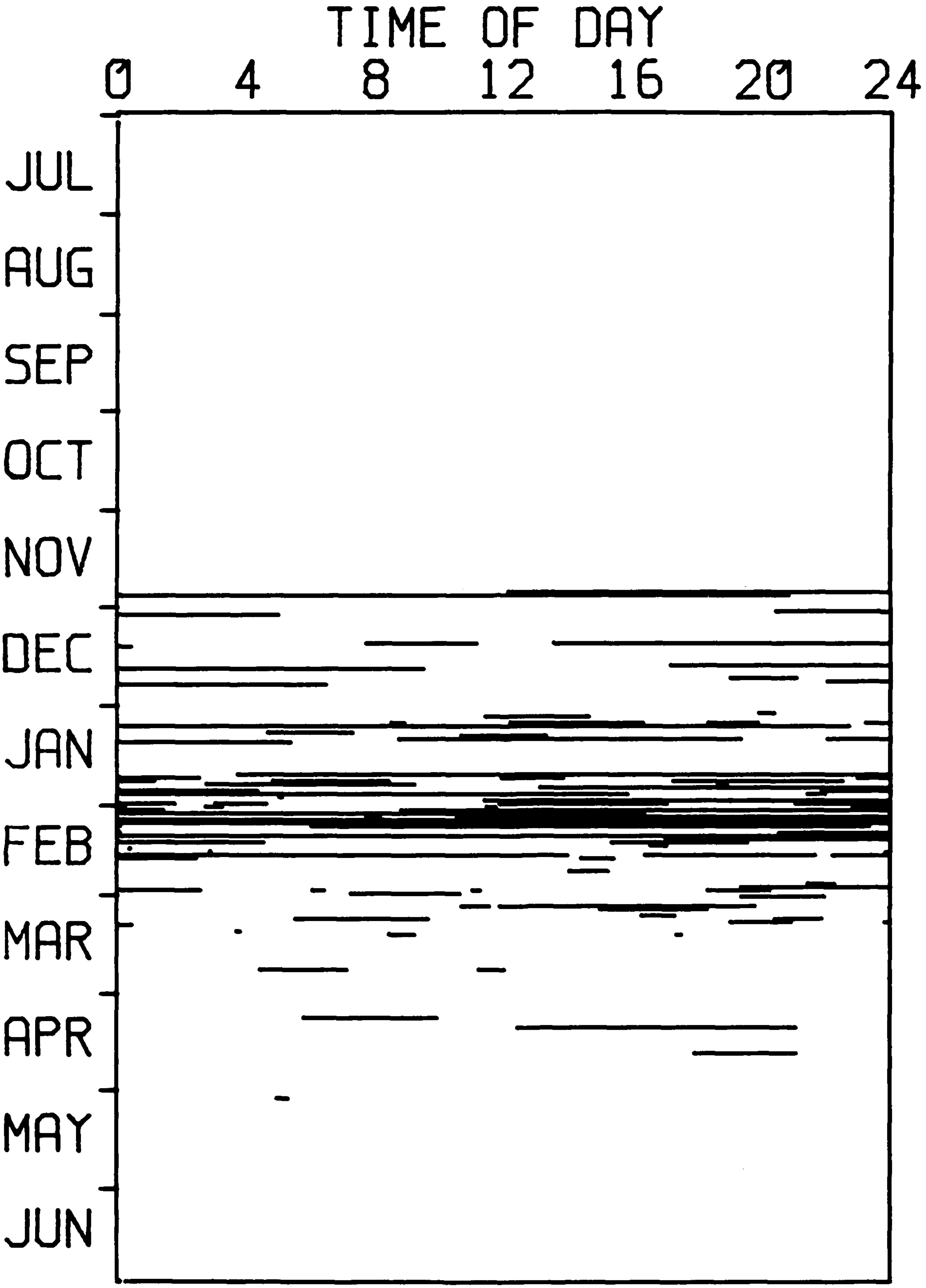

TIME OF DAY
0
4
8
12
16
20
24
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1978
1979

Fig 10

QUESTIONABLE FINBACK
TIME OF DAY

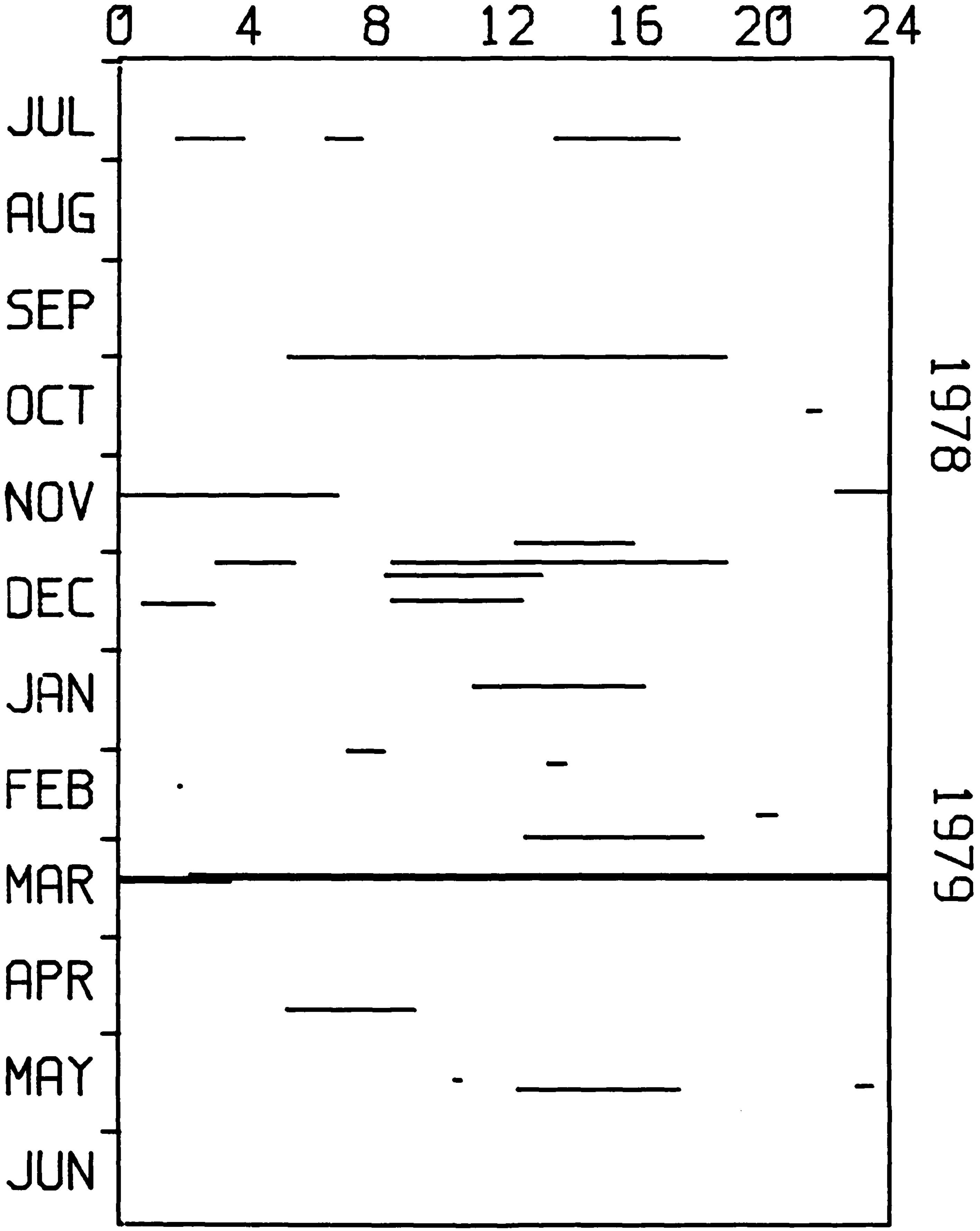
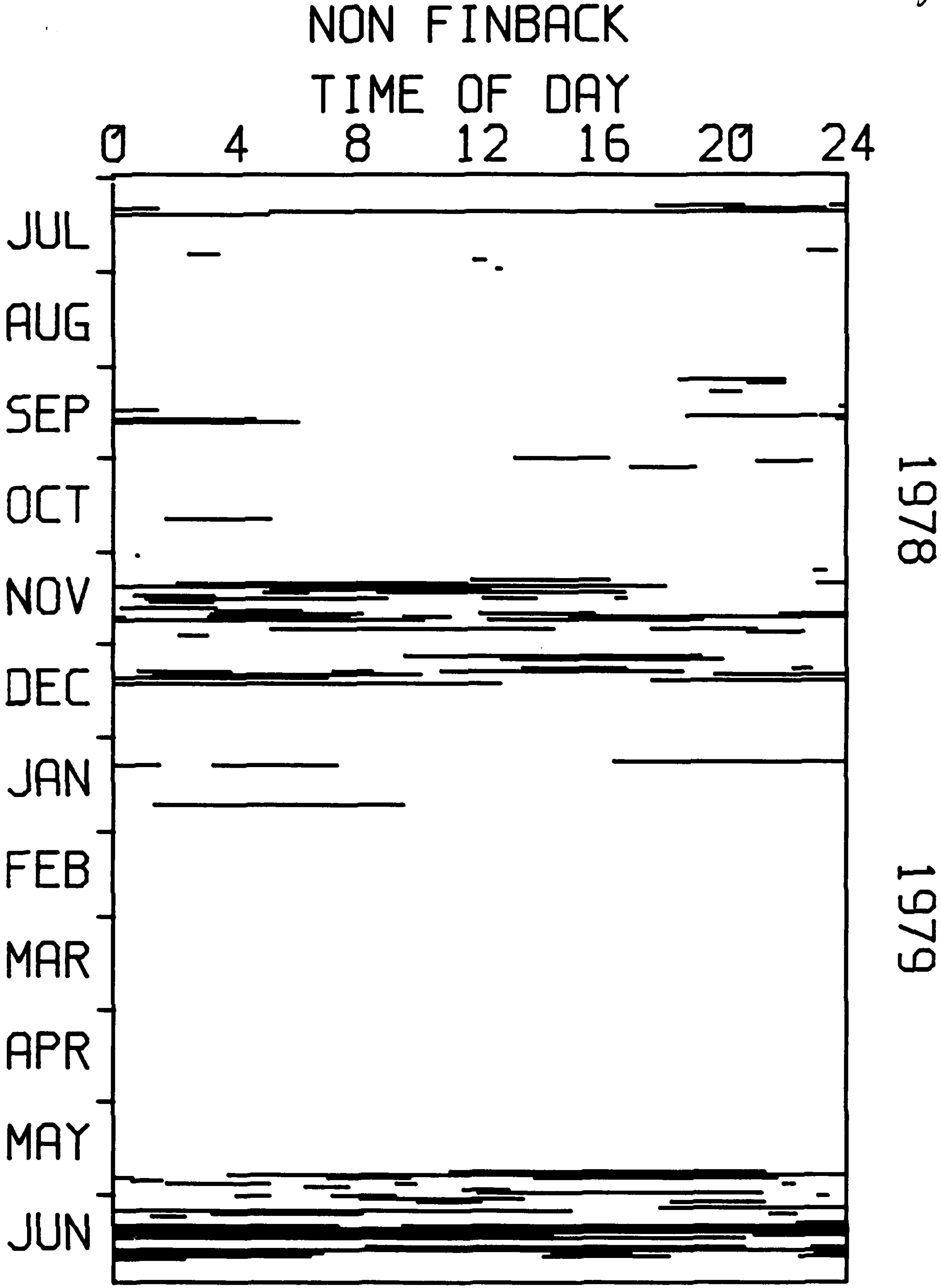


Fig 11


NON FINBACK
TIME OF DAY
0
4
8
12
16
20
24
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1978
1979

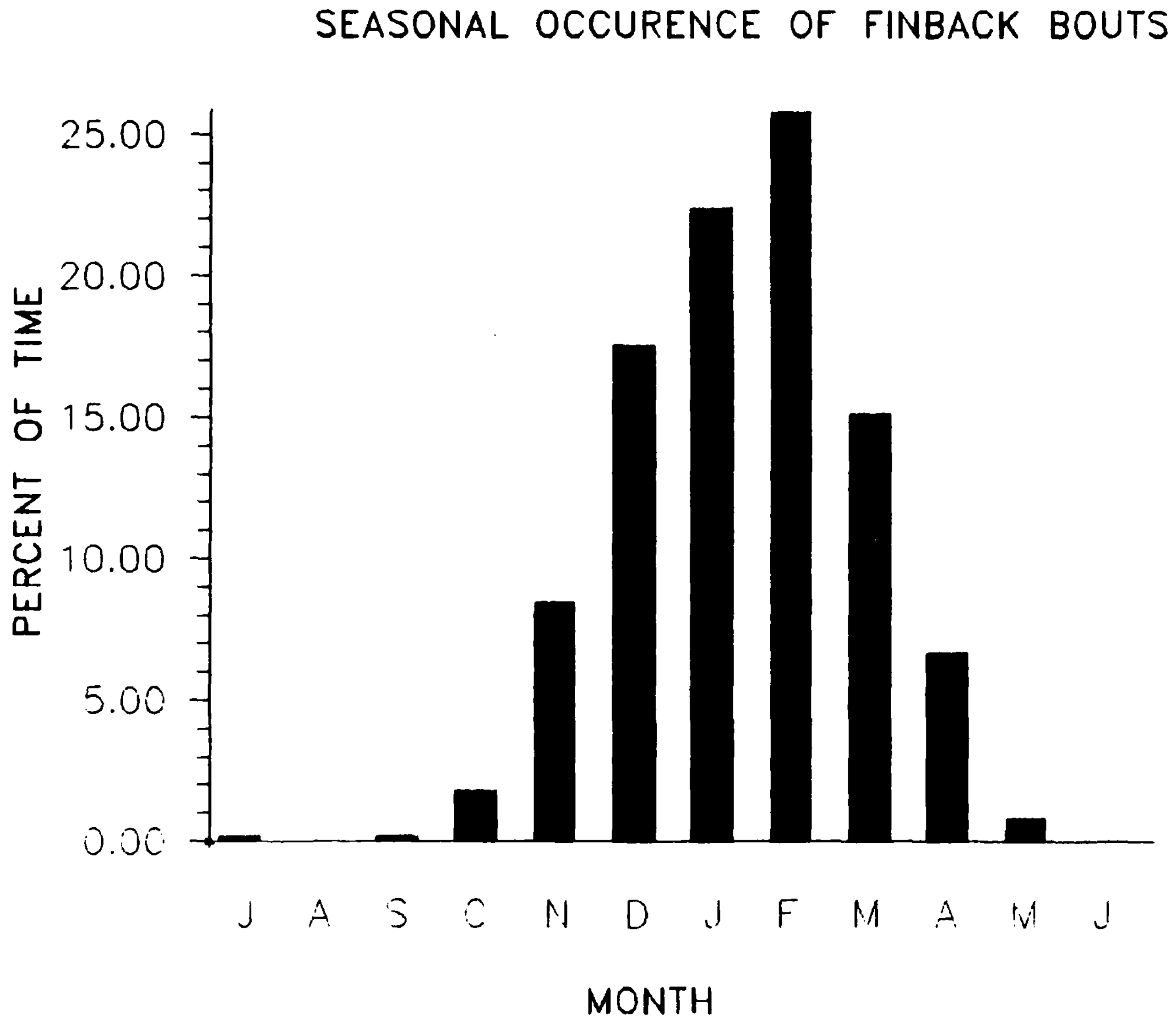

SEASONAL OCCURENCE OF FINBACK BOUTS
PERCENT OF TIME
25.00
20.00
15.00
10.00
5.00
0.00
J
A
S
O
N
D
J
F
M
A
M
J
MONTH

Fig 12

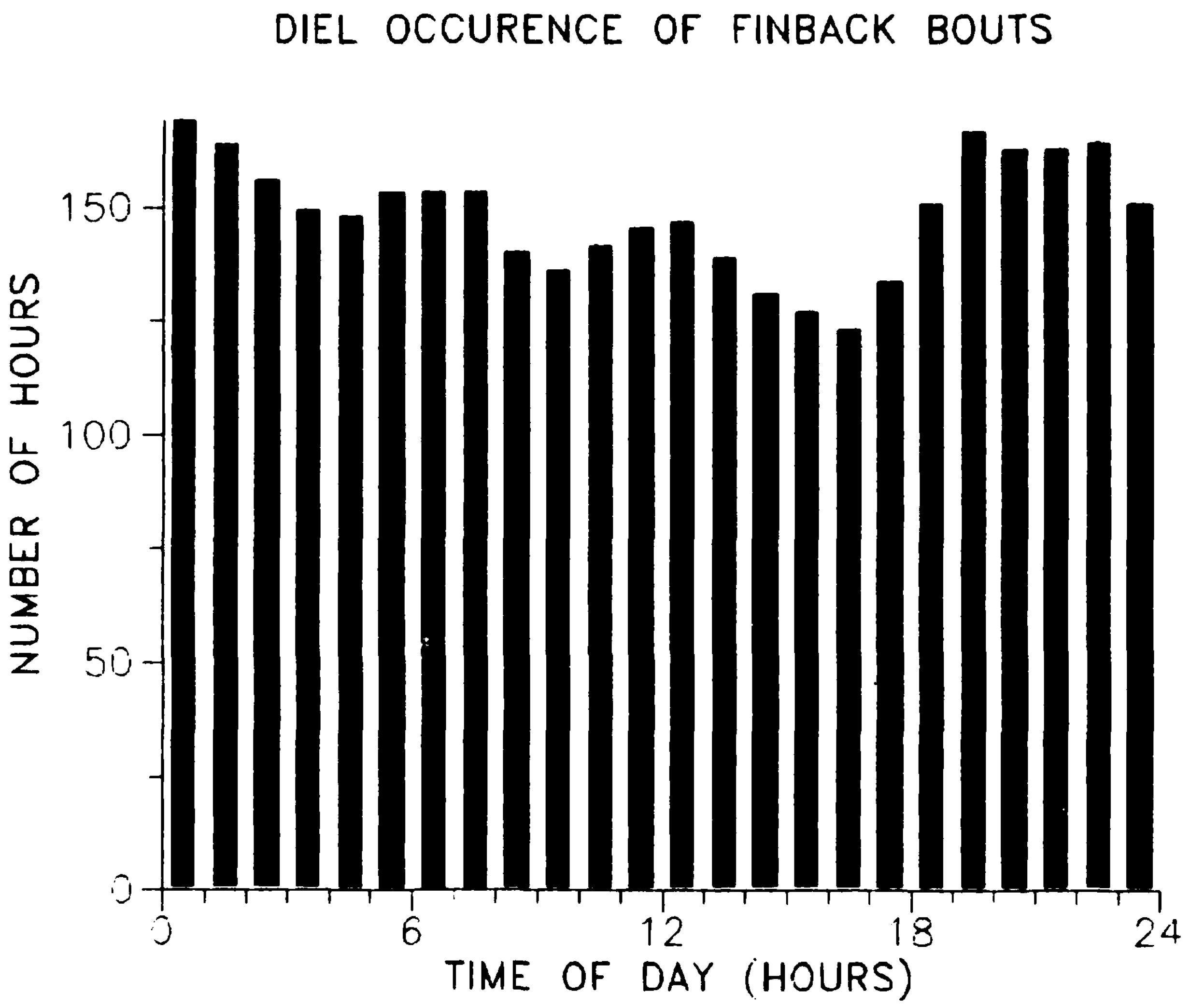

DIEL OCCURENCE OF FINBACK BOUTS
NUMBER OF HOURS
0
50
100
150
0
6
12
18
24
TIME OF DAY (HOURS)

Fig 13

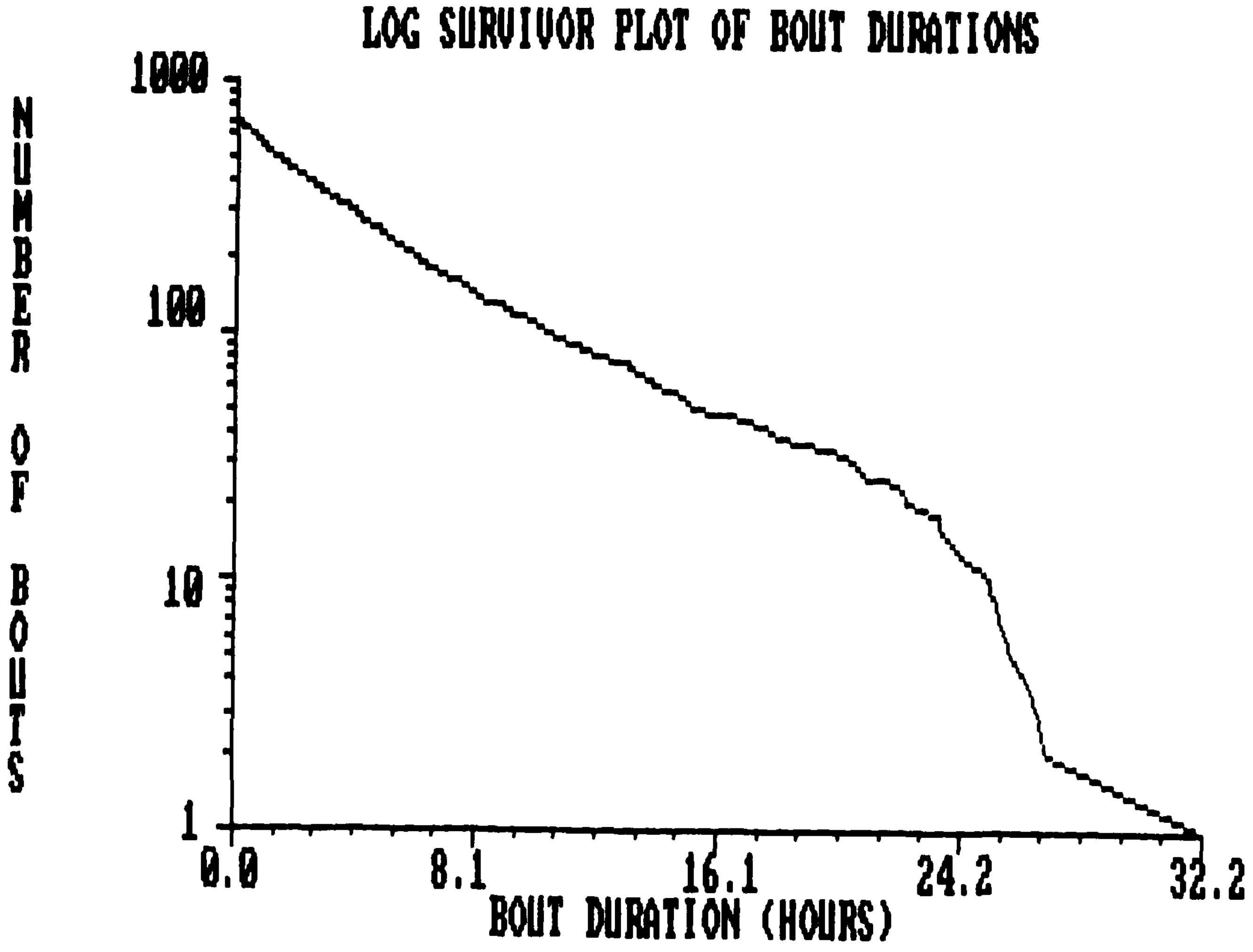

LOG SURVIVOR PLOT OF BOUT DURATIONS

Fig 14

PLOT OF MEAN DURATION OF FINBACK SIGNAL
BOUTS POOLED BY MONTH

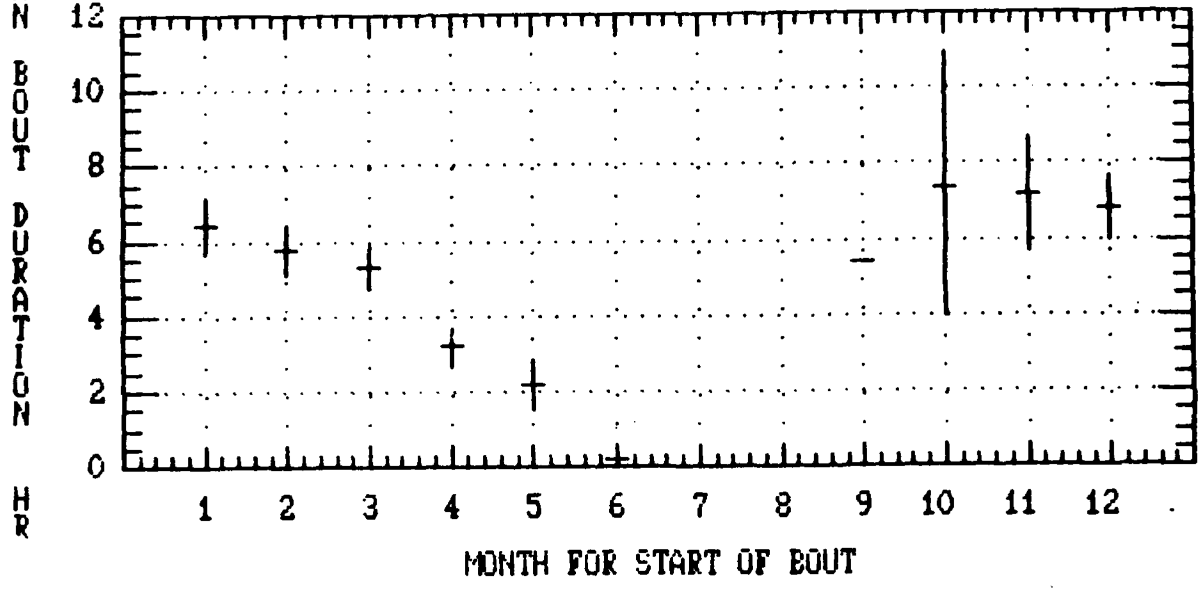
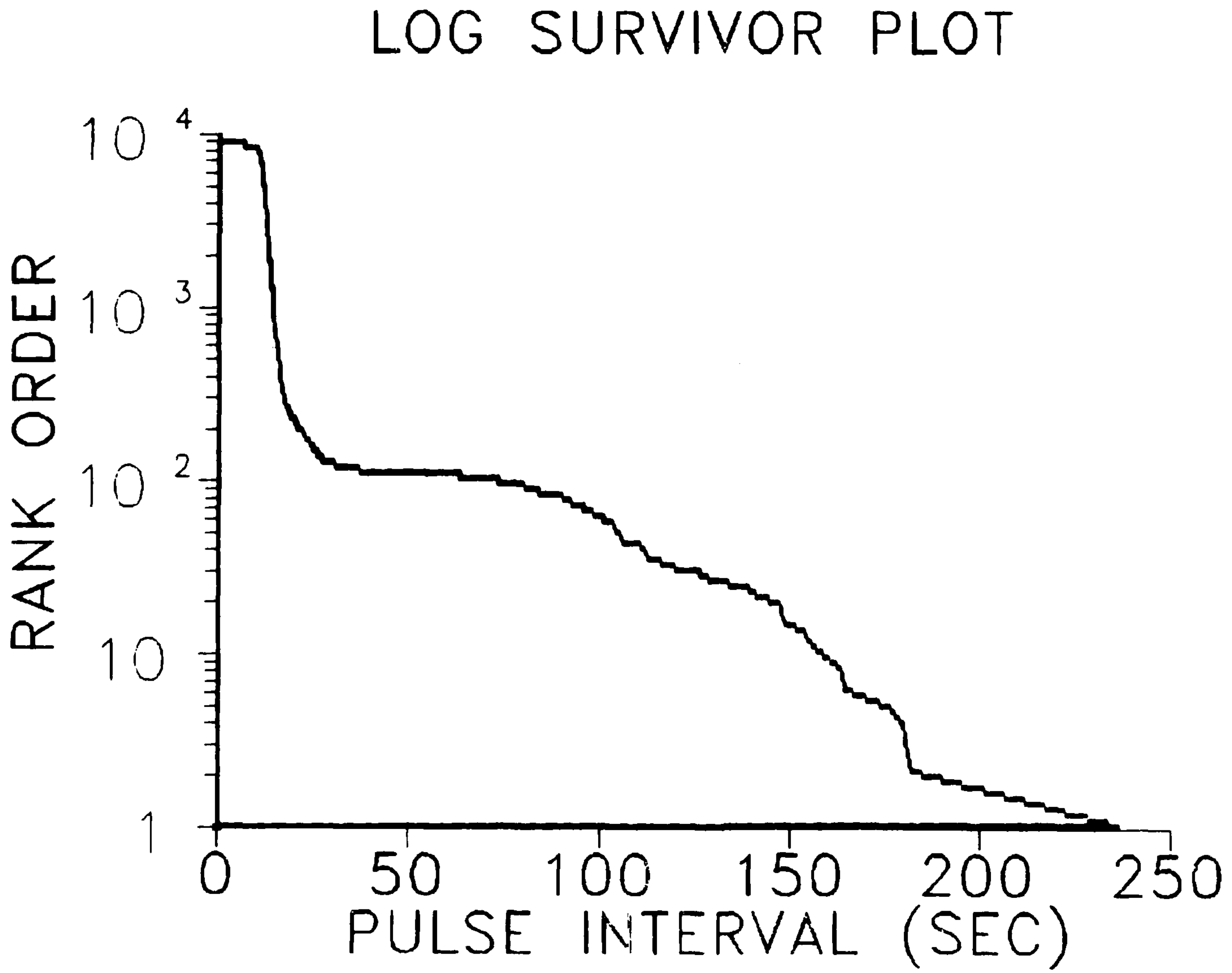


Fig. 15

Fig 15


LOG SURVIVOR PLOT
RANK ORDER
$10^4$
$10^3$
$10^2$
10
1
0
50
100
150
200
250
PULSE INTERVAL (SEC)

Fig,
Fig 16

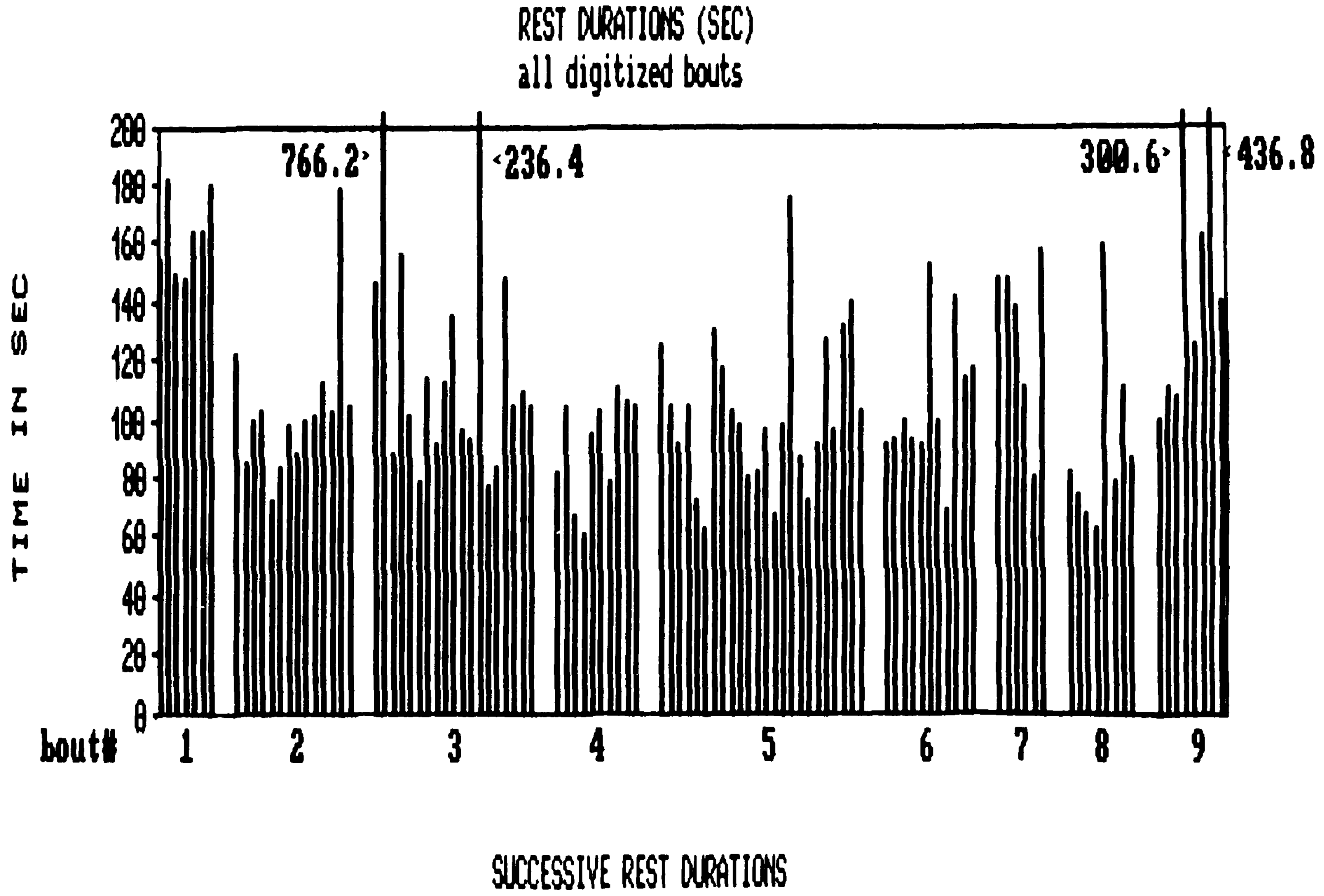
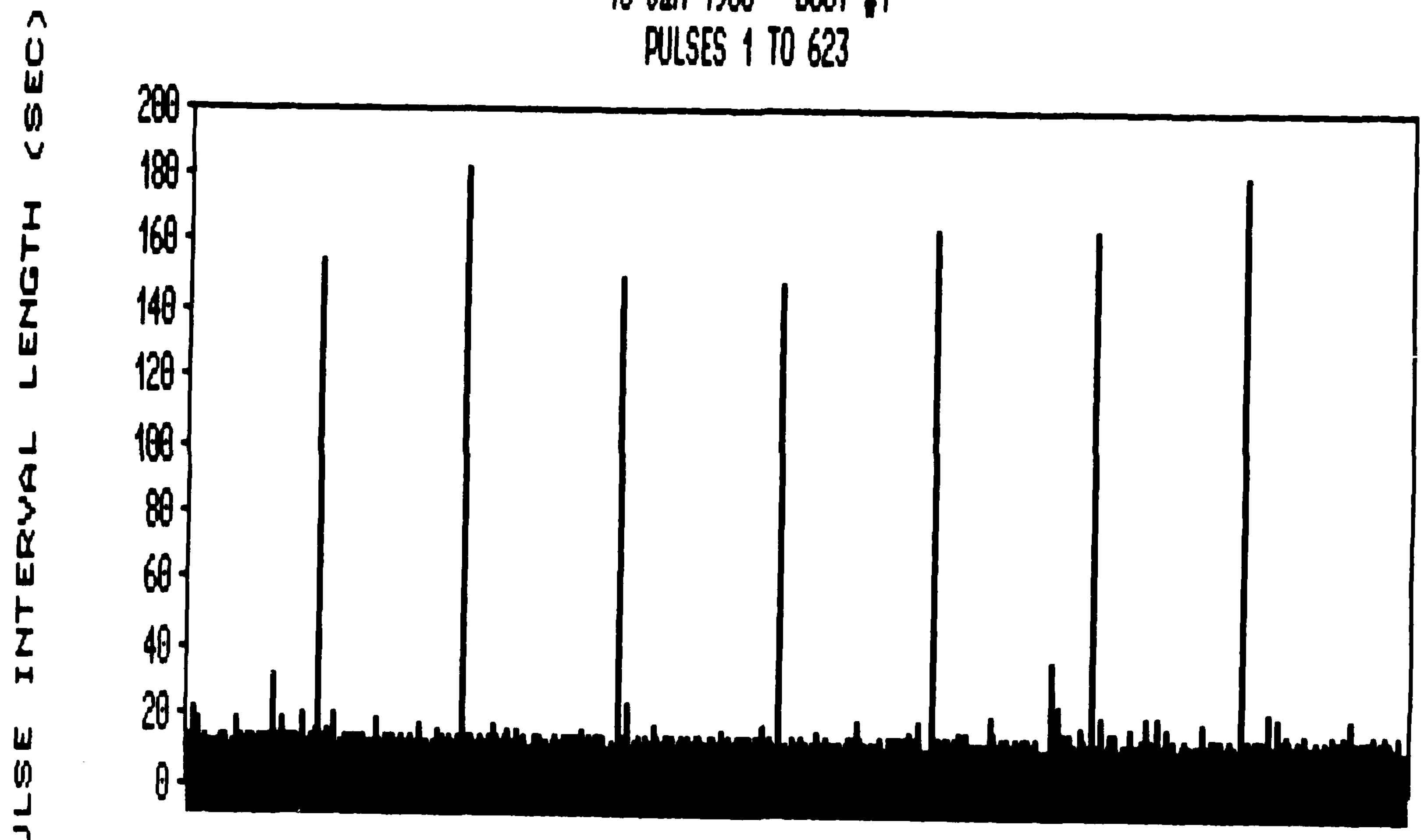

REST DURATIONS (SEC)
all digitized bouts
TIME IN SEC
200
180
160
140
120
100
80
60
40
20
0
bout#
1
2
3
4
5
6
7
8
9
766.2›
‹236.4
300.6›
‹436.8
SUCCESSIVE REST DURATIONS

Fig 17

13 Jan 1960 - BOUT #1
PULSES 1 TO 623



SUCCESSIVE PULSE INTERVALS

Fig 18

14 Jan 1968 - BOUT #4
PULSES 1 TO 1168

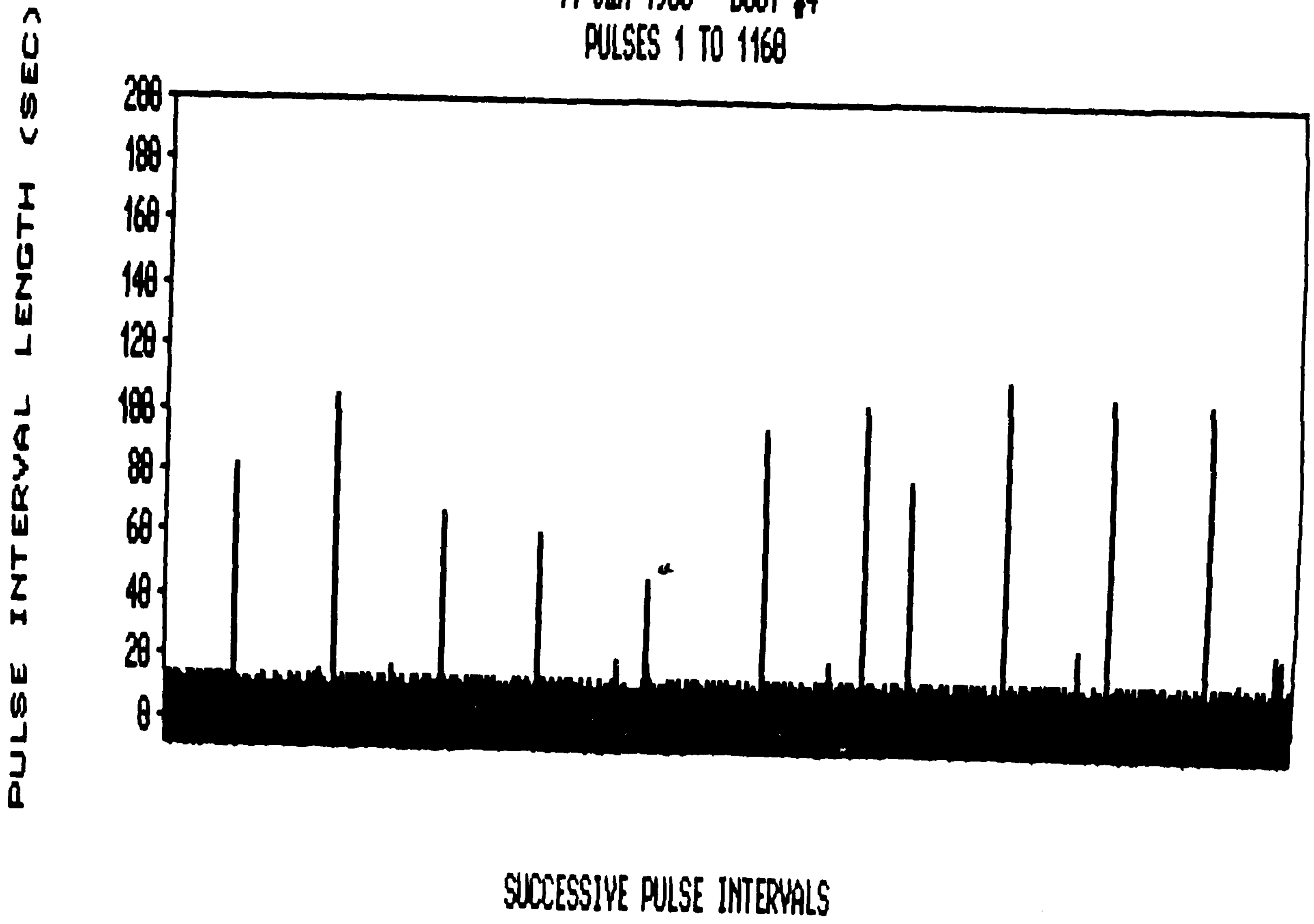


Fig 19

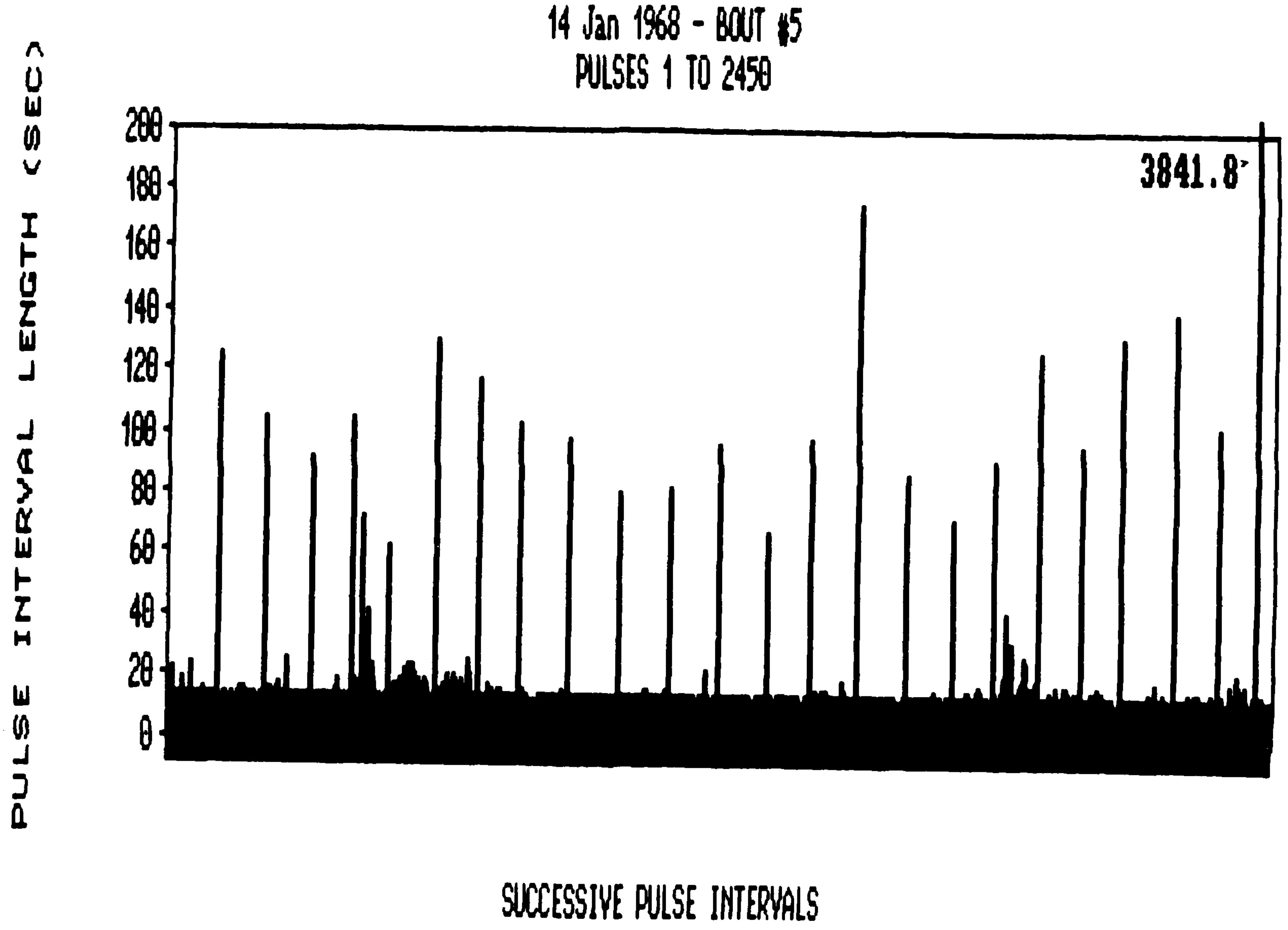

14 Jan 1968 - BOUT #5
PULSES 1 TO 2450
PULSE INTERVAL LENGTH (SEC)
200
180
160
140
120
100
80
60
40
20
0
3841.8
SUCCESSIVE PULSE INTERVALS

Fig 20

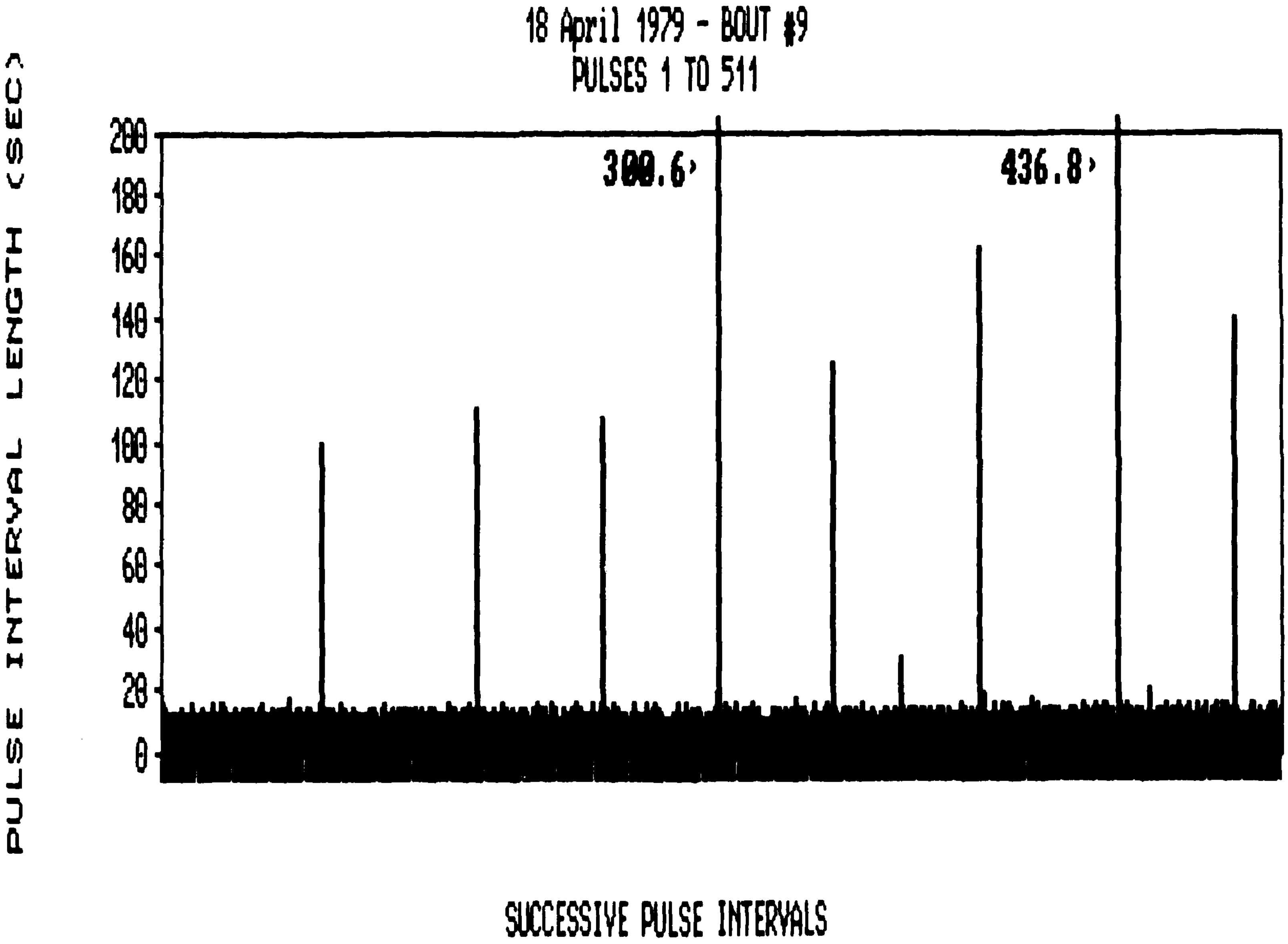

18 April 1979 - BOUT #9
PULSES 1 TO 511
PULSE INTERVAL LENGTH (SEC)
200
180
160
140
120
100
80
60
40
20
0
300.6›
436.8›
SUCCESSIVE PULSE INTERVALS

Fig 21

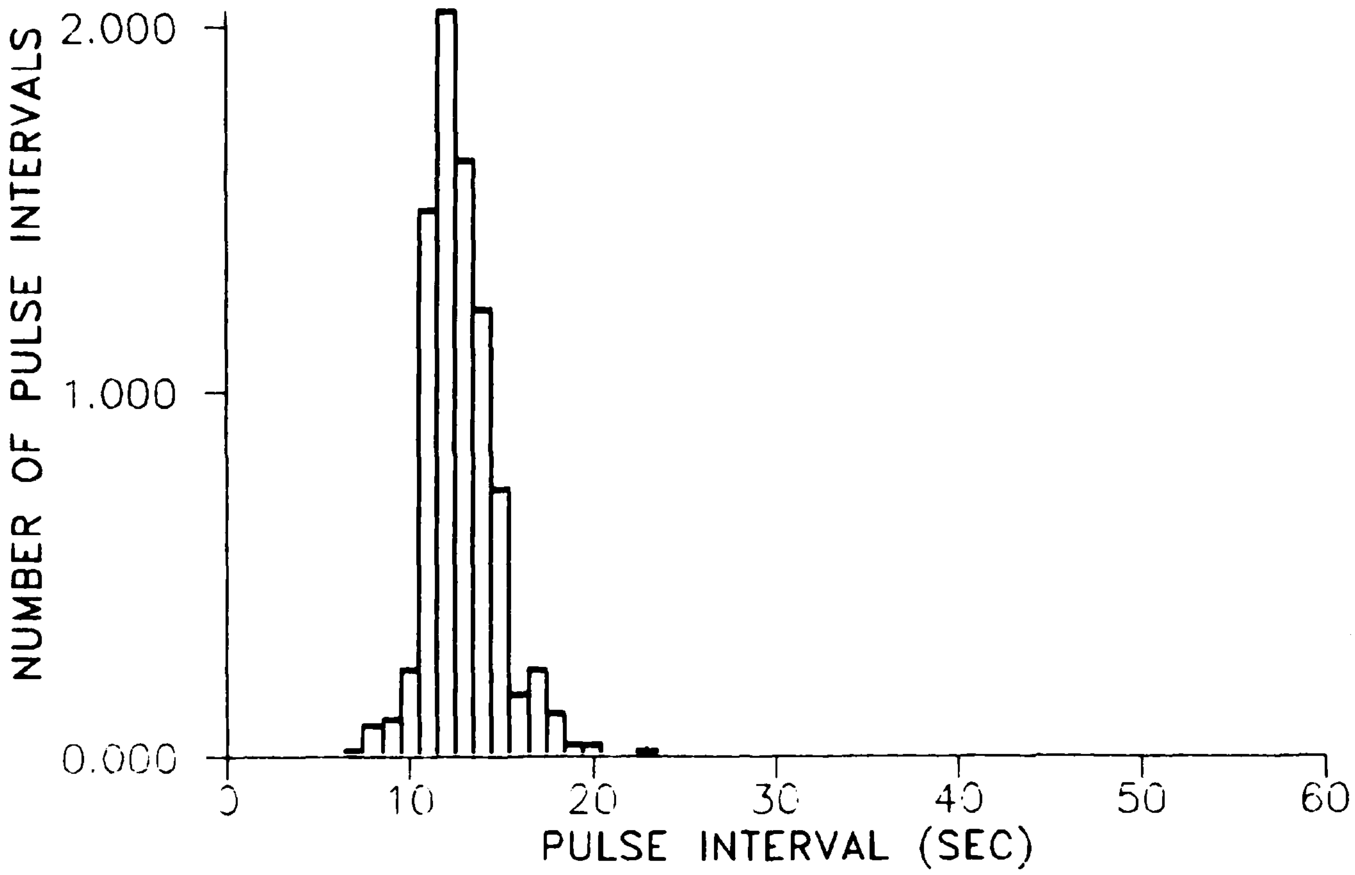

NUMBER OF PULSE INTERVALS
2.000
1.000
0.000
0
10
20
30
40
50
60
PULSE INTERVAL (SEC)

Fig 22

14 Jan 1968 - BOUT #5
PULSES 891 TO 990

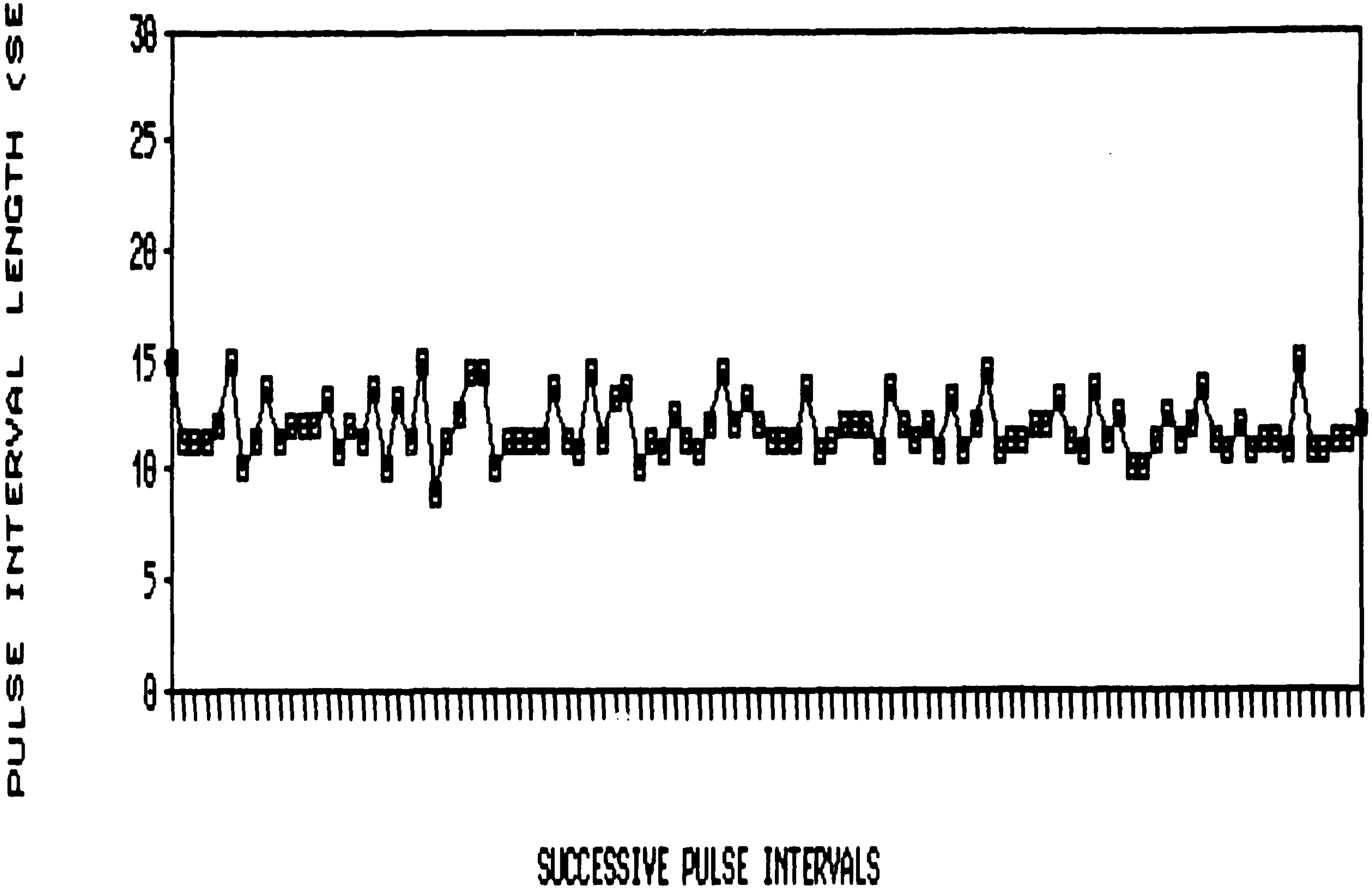


Fig 23

30 Oct 1968 - DOUBLET - BOUT #7
PULSES 1 TO 100

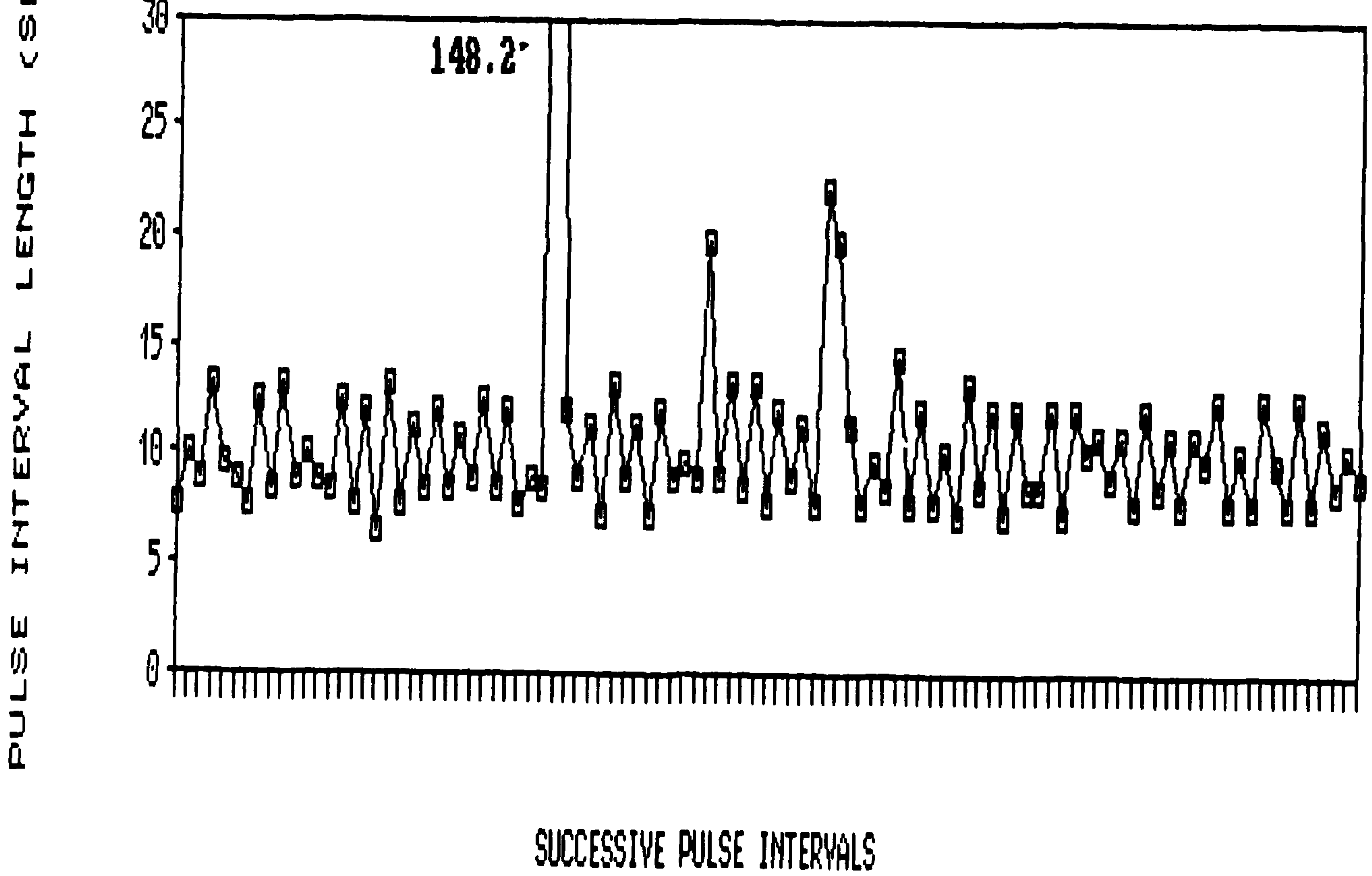
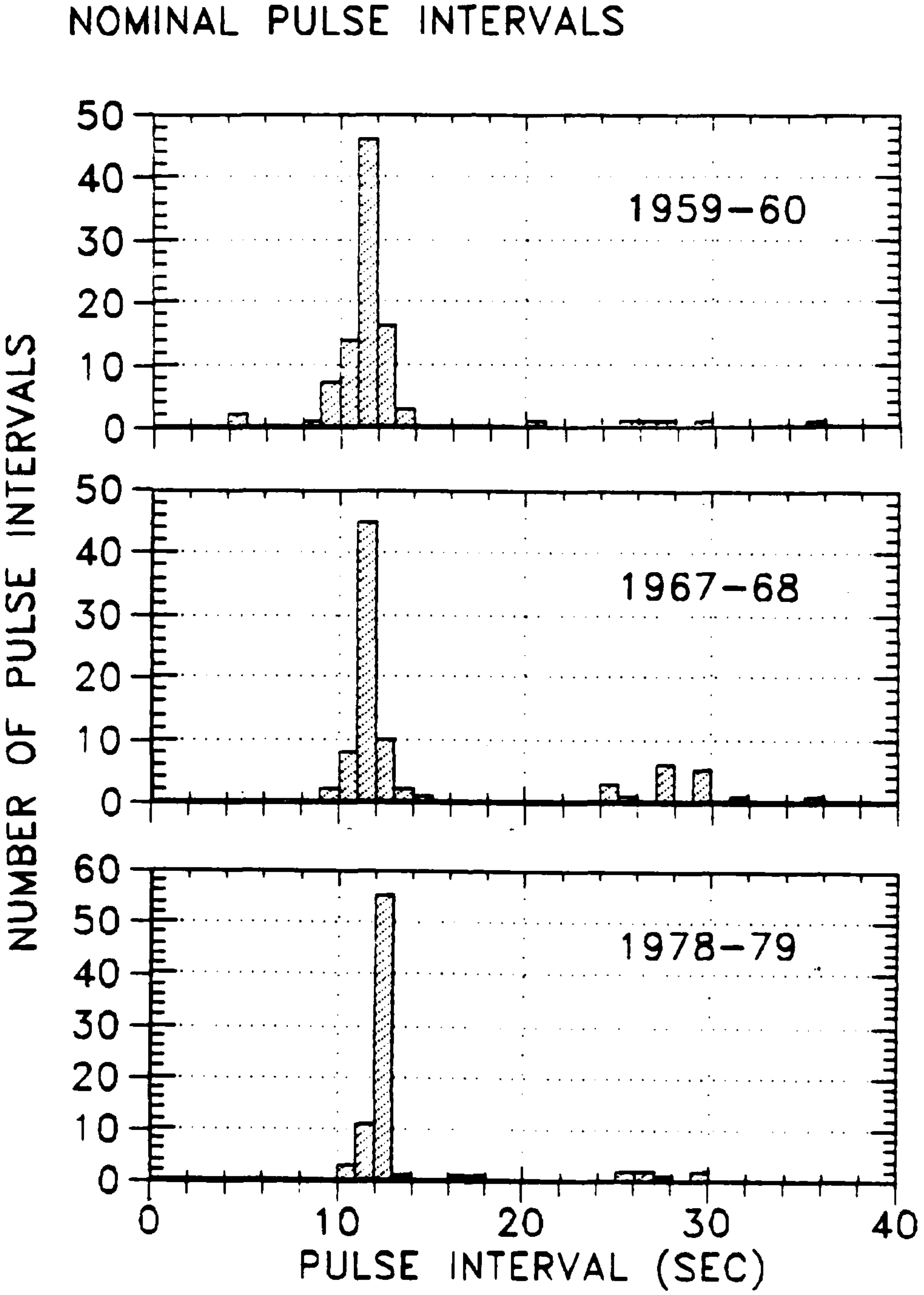


Fig 24

Fig 25



NOMINAL PULSE INTERVALS
NUMBER OF PULSE INTERVALS
50
40
30
20
10
0
1959-60
50
40
30
20
10
0
1967-68
60
50
40
30
20
10
0
1978-79
0
10
20
30
40
PULSE INTERVAL (SEC)

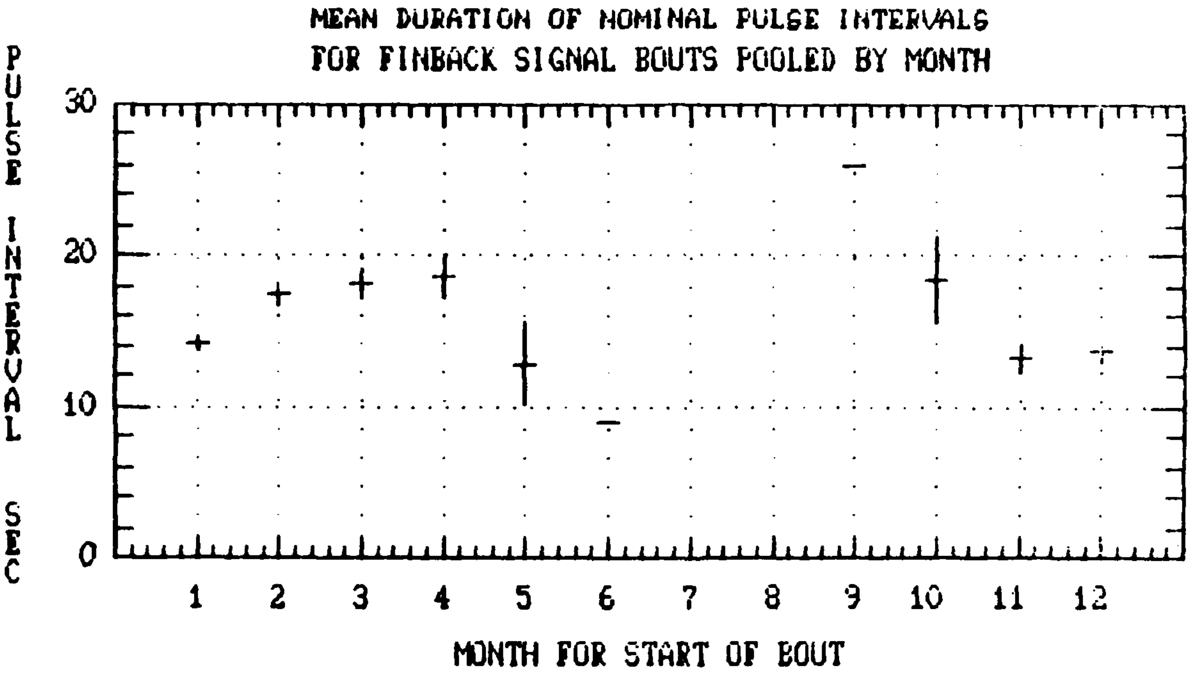

MEAN DURATION OF NOMINAL PULSE INTERVALS
FOR FINBACK SIGNAL BOUTS POOLED BY MONTH

FIG. 26

END

9-87

DTIC