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TECHNICAL REPORT No. 90

Temperature Measurements In the Ocean Near Eleuthera

by T. Arase

Sept. 16, 1960

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Technical Report No. 90

TEMPERATURE MEASUREMENTS IN THE OCEAN NEAR ELEUTHERA

by

T. Arase

September 15, 1960

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ABSTRACT

Temperature records have been obtained at depths of 130, 150, 170, 190, and 250 ft from five buoys initially separated from one another by six miles. Each record had a duration of about one day and records for three successive days were taken. These records have been analyzed for autocorrelation and power spectrum. The power spectrum for a typical record is $(180\ f^2)^{-1} \mathrm{deg}^2/\mathrm{cph}$ in the frequency range from 0.5 to 12 cph. No lines were observed in the spectrum, showing that the temperature record cannot be synthesized by a linear combination of a few simple harmonic waves.

INTRODUCTION

This report describes the results of the second of a series of experiments which are being conducted with the twofold aim of obtaining extended temperature measurements in the ocean and of developing reliable equipment for such measurements. Temperature measurements are important in understanding such features of near-surface ocean behavior as internal waves or surface sound channel propagation.

Early experiments have quite often led to the conclusion that the observed temperature fluctuations could be described as a simple harmonic wave or as a combination of a few such waves. Usually these analyses have been performed on data of inadequate duration or with improperly designed instruments.

More recent experiments, of adequate time duration, show markedly different results. The first, Operation STANDSTILL, utilizing BT's taken every half-hour for 25 days from an anchored ship, finds peaks at periods of one and five days in the power spectra.(1) The second, utilizing data taken by thermistors placed on the ocean bottom near Bermuda, for many months, finds a spectrum which decreases monotonically with frequency as f^{-3} as well as evidence for the existence of a peak at the principal lunar tide and a peak at 0.5 cycles per hour.(2)

The experiment described here is for data of one day's duration taken at two-minute intervals and hence yields information on the power spectra of the temperature fluctuations to a higher frequency range than given in the references cited in Footnotes 1 and 2.

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[1] Brown, Corton, and Simpson, <u>Power Spectrum Analysis of Internal Waves from Operation STANDSTILL</u> (U. S. Navy Hydrographic Office, 1955), Technical Report TR-26.

[2] Haurwitz, Stommel, and Munk, On the thermal unrest in the ocean. In <u>Rossby Memorial Volume</u> (Rockefeller Institute Press, New York, 1959).

THE EXPERIMENT

The experiment was conducted from the R/V GERDA during the period August 11 to 14, 1957, approximately 15 miles off the coast of Eleuthera Island, BWI. Figures 1 (a-c) show the tracks of the five buoys which supported the thermometers. Each buoy consisted of a spar buoy from which were suspended four thermometer units and one temperature-pressure unit. Figure 2 illustrates the geometry employed.

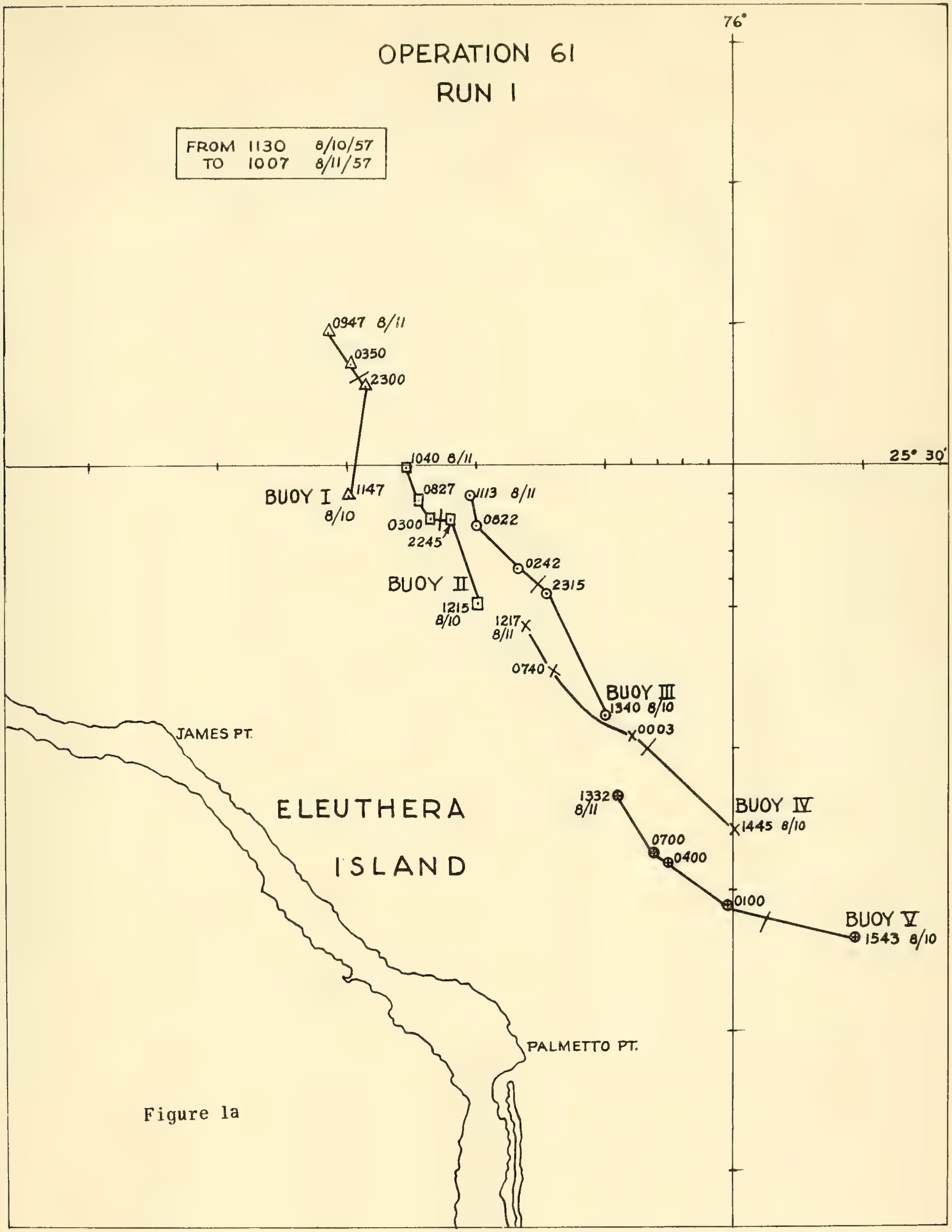
Each thermometer unit consisted of an open-aperture camera which photographed a mercury-in-glass thermometer illuminated at approximately two-minute intervals. The motive power for the film drive as well as the timing of the illumination was supplied by a 24-hour clock. Standard thermometers calibrated to 0.1°C were enclosed in a well to protect them from hydrostatic pressure. Good thermal contact between the thermometer and the well was secured by filling the well with water. The time constant for the complete unit was of the order of 1 to 2 minutes.

On the first morning, the five buoys were launched six miles apart and allowed to drift. The next morning, the thermometer units were retrieved and replaced with another set of thermometer units and similarly on the third day. Hence the final result is a set of one-day thermometer records from five buoys at four depths. Due to various difficulties with the apparatus, usable data was obtained from only 36 of the 60 units launched. Of these, 29 records were processed for autocorrelation and power spectrum analysis.

RESULTS

A. Temperature Records

The temperature records are typically fairly irregular functions of time with some short sections being oscillatory, with a vague hint of a daily or semidaily period, and with root-mean-square fluctuations in the order of 0.3°C. No obvious correlations of the temperature fluctuations exist with



OPERATION 61
RUN I
FROM 1130 8/10/57
TO 1007 8/11/57
76°
25° 30'
0947 8/11
0350
2300
1040 8/11
BUOY I
1147
8/10
0827
1113 8/11
0300
0822
2245
0242
2315
BUOY II
1215
8/10
1217
8/11
0740
BUOY III
1340 8/10
0003
JAMES PT.
1332
8/11
BUOY IV
1445 8/10
ELEUTHERA
ISLAND
0700
0400
0100
BUOY V
1543 8/10
PALMETTO PT.

Figure 1a

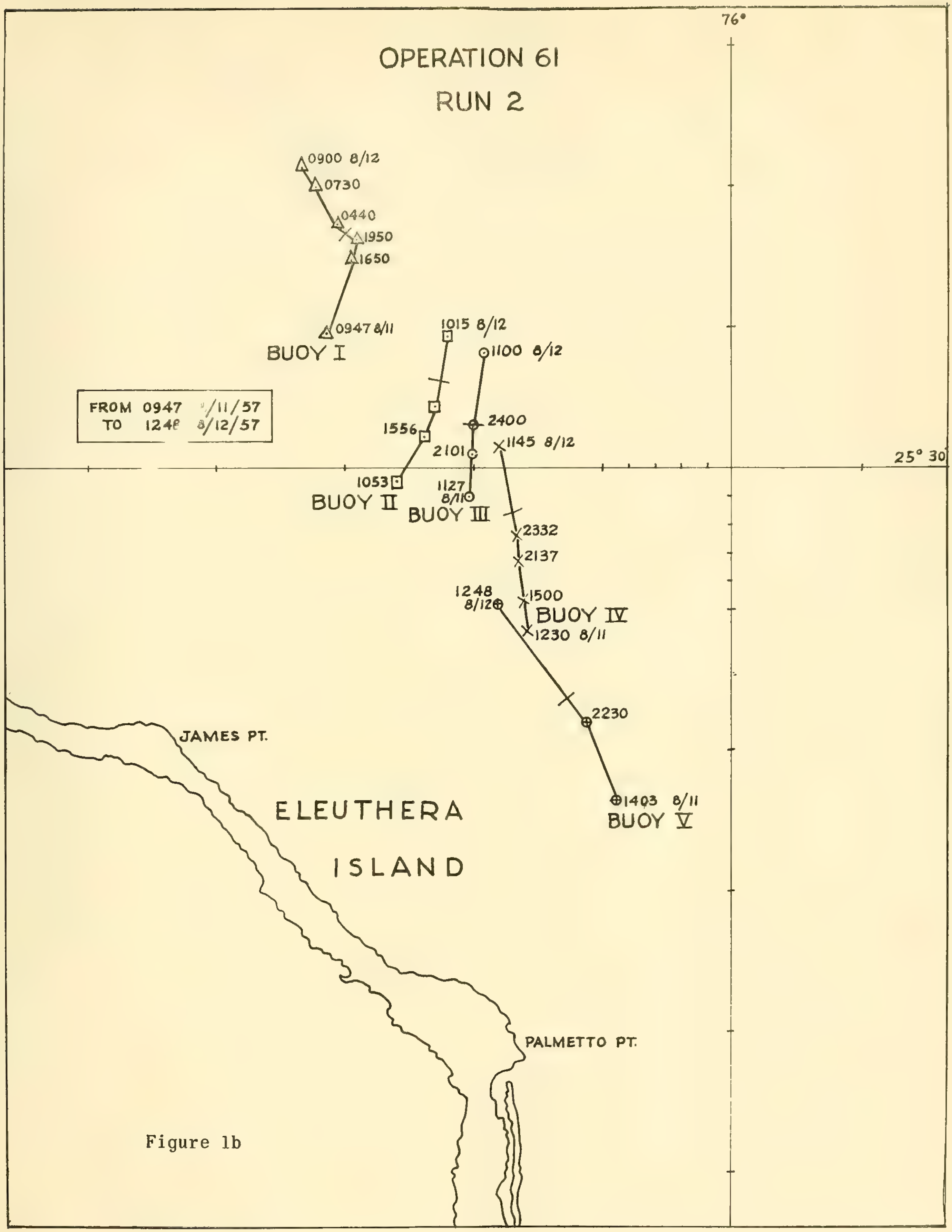
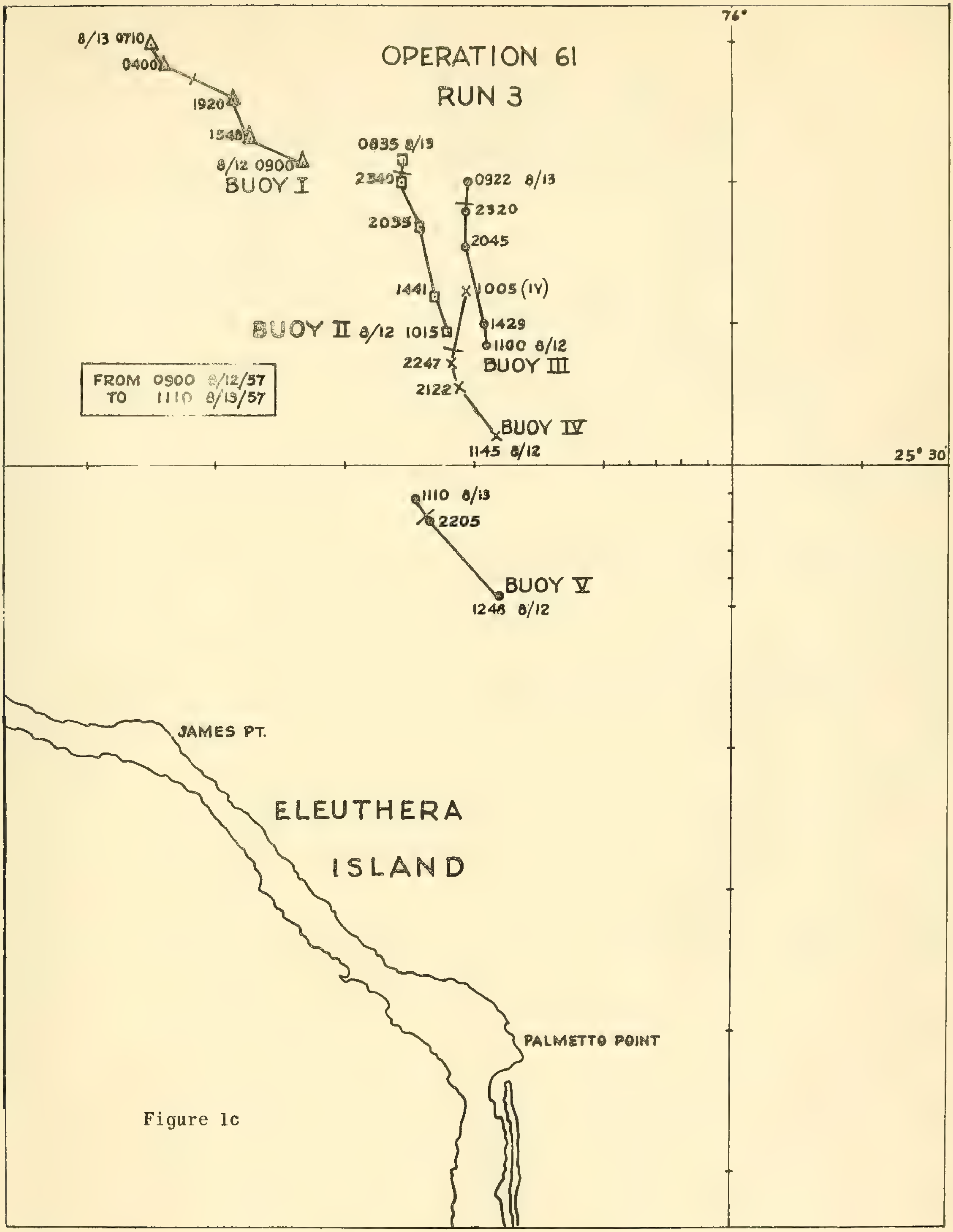

76°
OPERATION 61
RUN 2
0900 8/12
0730
0440
1950
1650
0947 8/11
BUOY I
1015 8/12
1100 8/12
FROM 0947 8/11/57
TO 1248 8/12/57
1556
2400
2101
1145 8/12
25° 30'
1053
BUOY II
1127
8/11
BUOY III
2332
2137
1248
8/12
1500
BUOY IV
1230 8/11
2230
JAMES PT.
1403 8/11
BUOY V
ELEUTHERA
ISLAND
PALMETTO PT.

Figure 1b



OPERATION 61
RUN 3
8/13 0710
0400
1920
1540
8/12 0900
BUOY I
0835 8/13
2340
2035
1441
BUOY II 8/12 1015
0922 8/13
2320
2045
1005 (IV)
1429
1100 8/12
BUOY III
2247
2122
BUOY IV
1145 8/12
FROM 0900 8/12/57
TO 1110 8/13/57
76°
25° 30'
1110 8/13
2205
BUOY V
1248 8/12
JAMES PT.
ELEUTHERA
ISLAND
PALMETTO POINT

Figure 1c

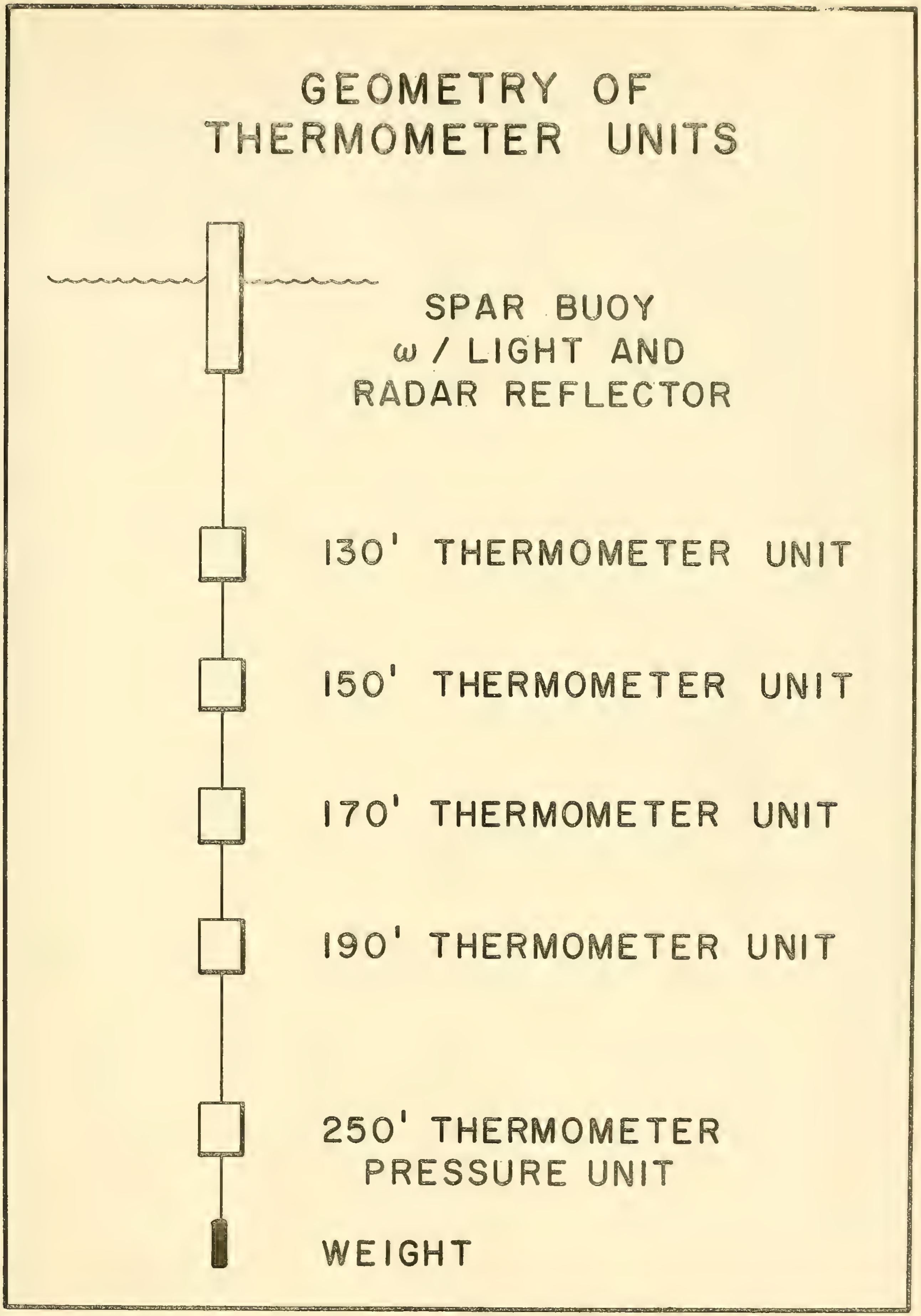

GEOMETRY OF
THERMOMETER UNITS
SPAR BUOY
ω / LIGHT AND
RADAR REFLECTOR
130' THERMOMETER UNIT
150' THERMOMETER UNIT
170' THERMOMETER UNIT
190' THERMOMETER UNIT
250' THERMOMETER
PRESSURE UNIT
WEIGHT

Figure 2

regard to either local tides or times though one might expect to find them present However the presence of these effects may be determined only by records of much greater time duration. We shall separate the discussions of the temperature records by classifying them as to day, buoy, and depth at which taken. Table I gives the figures illustrating the three temperature record categories

TABLE I

	DAY	BUOY	DEPTH
Fig. 3	same	same	different
Fig. 4	same	different	same
Fig. 5	different	same	same

Records taken on the same day at various depths at the same buoy (see Fig. 3) generally have the same characteristics, that is, if the temperature increases at one depth, it increases at all depths. The magnitude of the temperature change is different for the different depths, being greatest for the unit at the depth where BT's indicated a large change in temperature with depth.

Records taken on the same day at different buoys, and at the same depth are illustrated in Fig. 4. We note that there are no obvious correlations between these records. From Fig 1(a), we see that the tracks of the buoys range from northerly to northwesterly with slightly differing speeds. Table II gives the spacing of the buoys at various times after launching.

TABLE II

Spacing of buoys in miles at various times during the first day's run

BUOY	TIME At launching	2000	2400	0400
1	6	5-3/4	5-1/2	6
2	12	11	10-1/4	8-3/4
4	6	7	7-1/4	7-1/2
5				

The mean temperature observed at each unit during four-hour periods is given in Table III.

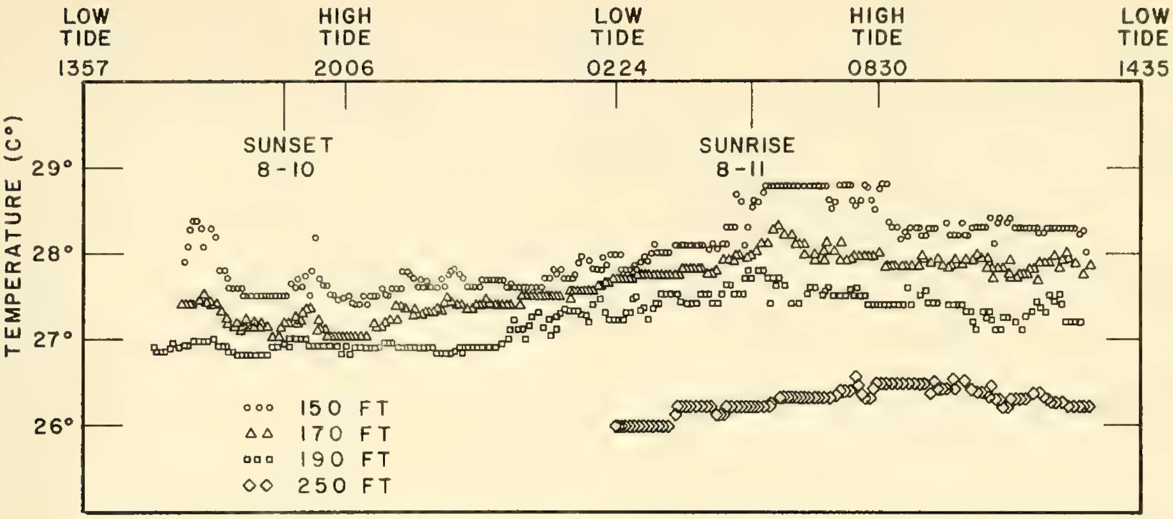


Figure 3. Temperature records for the first day, Buoy 5, at various depths.

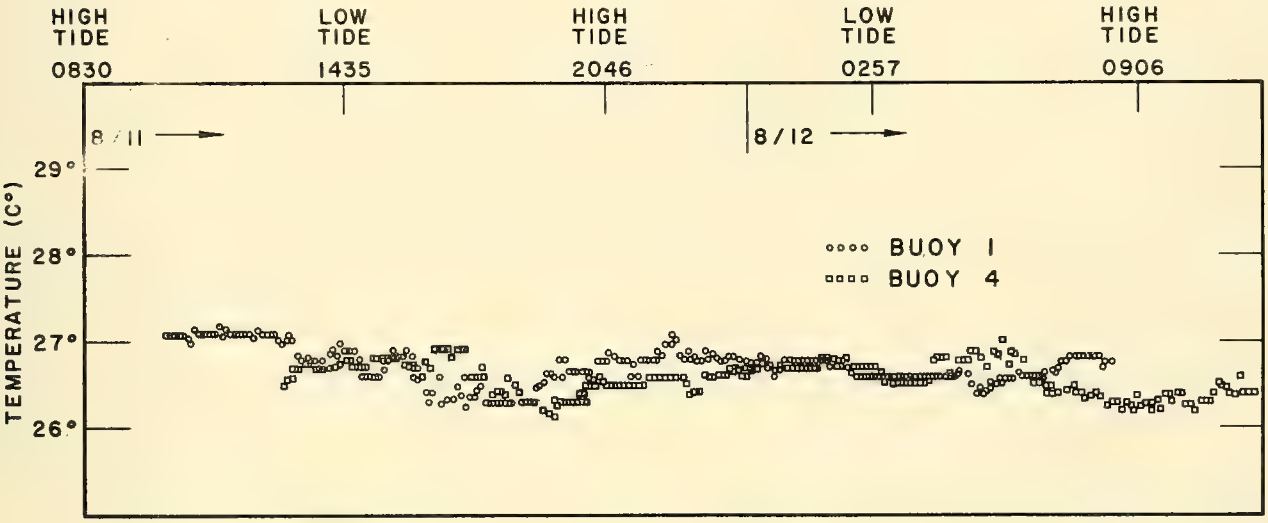


Figure 4. Temperature records for the second day, Buoys 1 and 4, at 170 ft.

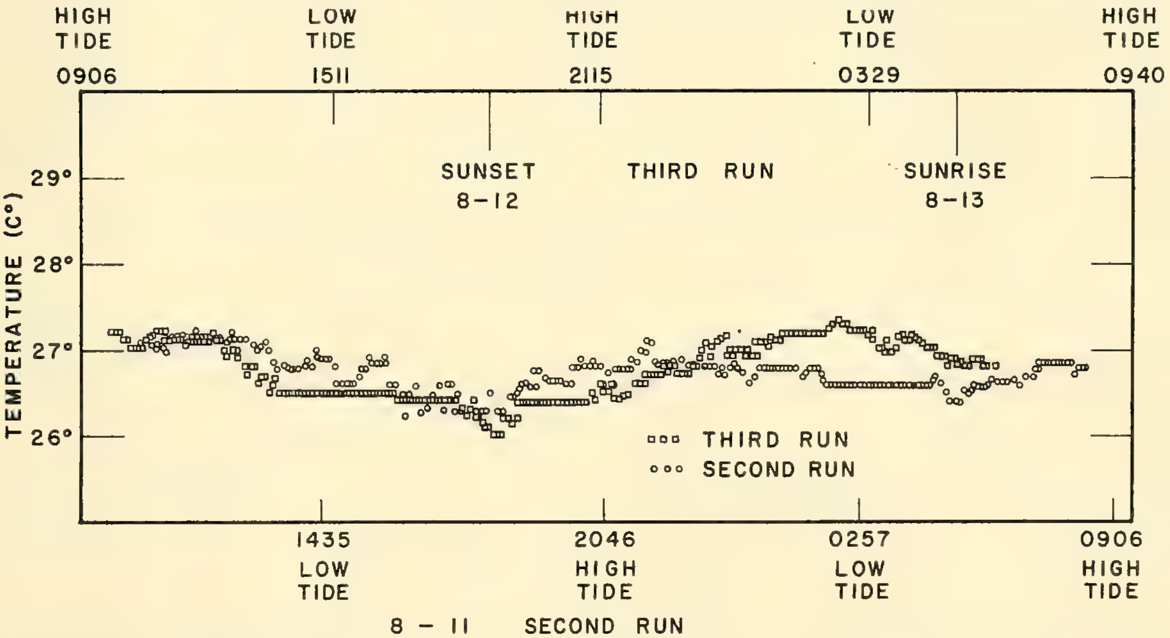


Figure 5. Temperature records for second and third runs, Buoy 1, at 170 ft.

TABLE III

Four-hour average temperatures in °C observed at 150-ft depth at various times during the first day's run

	TIME		
BUOY	2000	2400	0400
1	27.7	27.7	27.75
2	28.25	28.0	28.2
4	27.75	27.75	27.95
5	27.6	27.65	28.25

Comparing the entries in this table, we see that the greatest average temperature difference for a given separation is that between Buoys 1 and 2 at 2000 hr, of magnitude 0.1°C per mile. This difference is small in comparison to the difference in average temperature at different depths at the same buoy on this day, which averaged 0.1°C for 5 ft. Thus, there is a factor of about 1000 in the ratio of horizontal to vertical average temperature differences. Part of this ratio can be accounted for if the depths of these units differed by several feet. This may have been due to differential stretchage, tangling, or slippage of the suspension points on the Manila rope to which all the units were connected. However, every effort had been made prior to the launching to make the buoys identical in construction.

Records obtained on successive days at the same buoy and depth are illustrated in Fig. 5. Note that they appear to share the same general character. These records will be further analyzed and illustrated in the next section.

B. Correlation and Spectrum Analysis

Autocorrelation and power spectrum computations were carried out on all records according to the methods of Tukey,[3] who gives formulae for the digital computation of these quantities for data obtained at equal time intervals. The formulae are summarized below.

Let the N+1 numbers

$$X_0, \; X_1, \; X_2, \; . \; . \; . \; X_N$$

be the time series taken at time intervals Δt, with zero mean. The quantity corresponding to the autocorrelation function is the mean lagged product

$$C_r = \frac{1}{N-r} \sum_{q=o}^{N-r} X_q X_{q+r} \qquad r=0,\ 1,\ 2,\ .\ .\ .\ m \quad .$$

The raw spectral density estimate is formed by

$$V_r = \Delta t \left[C_o + 2 \sum_{q=1}^{m-1} C_q \cos \frac{qr\pi}{m} + C_m \cos r\pi \right] ,$$

which is the estimate of the two-sided spectral density at the frequency

$$f_r = (r/2m\Delta t) \qquad\qquad r = 0,\ 1,\ 2,\ .\ .\ .\ m \quad .$$

This process of obtaining spectral density estimates is analogous to obtaining the power spectrum of electrical signals by determining the strength of the signal transmitted by various bandpass filters. Just as these filters respond to components of the signal whose frequencies lie outside the main passband and at a side lobe, so the raw spectral density estimate gives an erroneous reading for signals at the side lobes of the effective passband for this computation. Several procedures are available for reducing this error by reducing the amplitude of the side lobe response. We have used the procedure known as hanning, which reduces the maximum side lobe response to

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[3] R. B. Blackman and J. W. Tukey, The Measurement of Power Spectra (Dover Publications, New York, 1958).

2 percent of the main passband. The result of applying the hanning procedure yields the refined spectral density estimates. Further details are given in the reference cited in Footnote 4.

In this method of calculating the power spectrum, error may be introduced by aliasing, which is serious because its presence cannot be detected in the final result. Aliasing (also known as spectrum folding) arises from the fact that the data is taken at discrete time intervals Δt. The highest frequency at which spectral density estimates can be made is the Nyquist frequency $f_N = (2\Delta t)^{-1}$. If appreciable power is present at frequencies greater than f_N, they will appear at the frequencies

$$f;\ 2f_N \pm f,\ 4f_N \pm f,\ \ldots\ .$$

For example, Fig. 6 shows how the aliased spectrum of the form f^{-2} will appear. Hence, in the design of the experiment, one must insure that the upper frequency cutoff of the measuring instruments is less than f_N. Alternately, the data may be lowpass filtered by digital computation before the spectrum analysis is performed. An example of aliasing is shown in the experimental data taken by BT's in Fig. 9, discussed later.

Some typical results of the autocorrelation computation are given in Fig. 7. For zero delay, the value of the autocorrelation is the variance of the record. For the three records shown, this varies by a factor of four, which is typical of the range of values obtained for all the units. The autocorrelation decreases with delay time at differing rates, reaching zero most quickly for the second day while remaining large for the third day. It is tempting to interpret the autocorrelation in terms of the results for known functions. For example, if the time series were composed of a set of random numbers, then the autocorrelation should be a delta function. Again, if the time series were a cosine function, then the auto-

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[4] T. Arase, A Guide to the Usage of Power Spectrum Calculations According to the Methods of Tukey (Columbia University, Hudson Laboratories, 1960), Technical Memorandum-to-File No. 47.

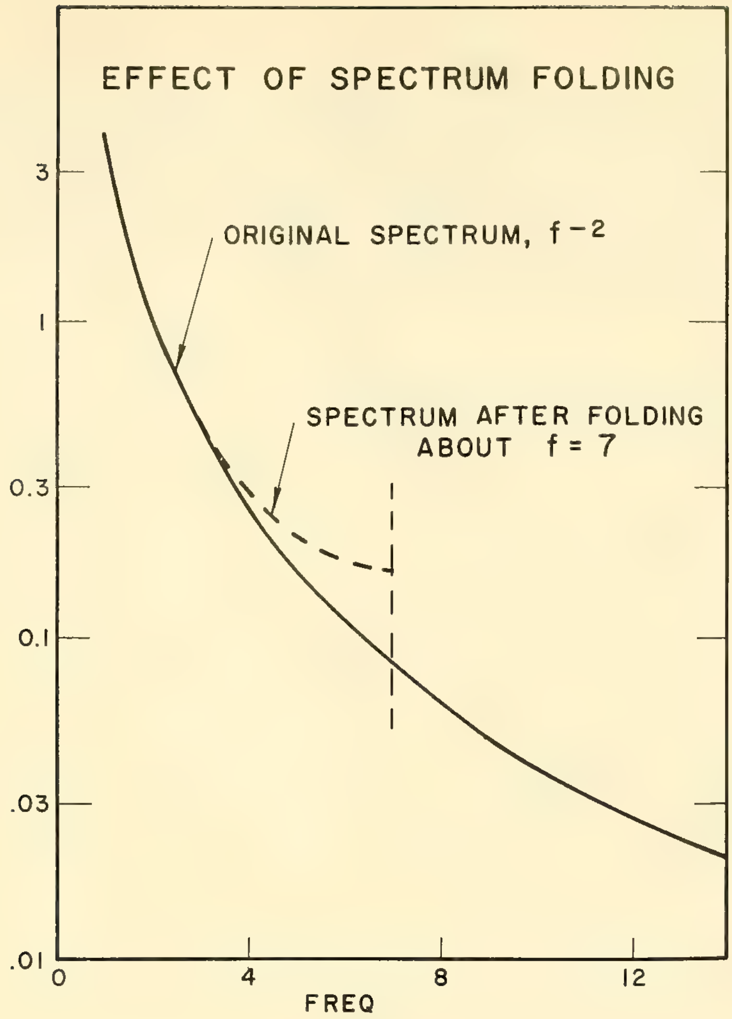

Figure 6

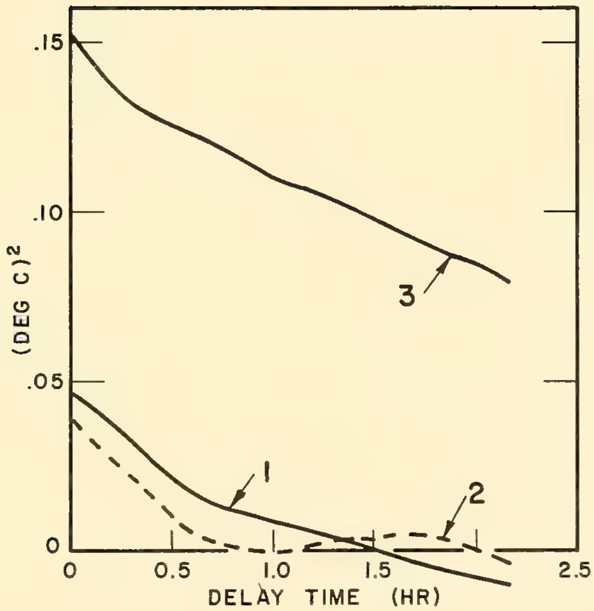

Figure 7. The temperature records of mean lagged products for three successive days, Buoy 2, at a depth of 150 ft.

correlation should also be a cosine function. Hence, one might conjecture that the oscillatory portion represented by the autocorrelation for the second day is indeed due to a periodic component in the time series. Similarly, the time in which the autocorrelation decreases to some small number is a measure of the correlation time for the phenomena beyond which the time series is uncorrelated. However, a study of the time series does not appear to support these conjectures. In no case can one point out the differences in the time series which would account for the differences in their autocorrelations. It is not a function which one can compute mentally. Suffice it to say that it is useful as an intermediate step in the computation of the power spectrum, except for certain exceptional cases.

The power spectra corresponding to the autocorrelations previously discussed are given in Fig. 8. The very interesting result is obtained that the power spectra all have the same form within the error associated with the results. There are slight differences but these reflect large differences in the autocorrelation. For example, at 0 frequency the autocorrelation which decreased slowest has the highest value, exceeding by an order of magnitude the results of the other two. Again, the autocorrelation with one oscillatory cycle shows peaks in its spectrum. These peaks, however, are within the errors to be associated with the computation (shown as the error bar) and hence must be ignored. The overwhelming similarity is in the form of the power spectra, for, excluding the data obtained at frequencies less than 1 cycle per hour as reflecting errors due to the finite sample time, and excluding the data at the highest frequency as perhaps being influenced by the response time of the thermometers, the power spectra follow the f^{-2} law as indicated. This is true for data obtained at various depths at the same buoy and at the same time; it applies also to data obtained at the same depth at different buoys; and the data shown is data obtained at the same depth, at the same buoy, and on successive days.

Power spectra representing the extremes of those calculated were plotted with those of the bottomed thermistors at Bermuda[2] (see Fig. 9). The difference in slope between the thermistor data and the thermometer data

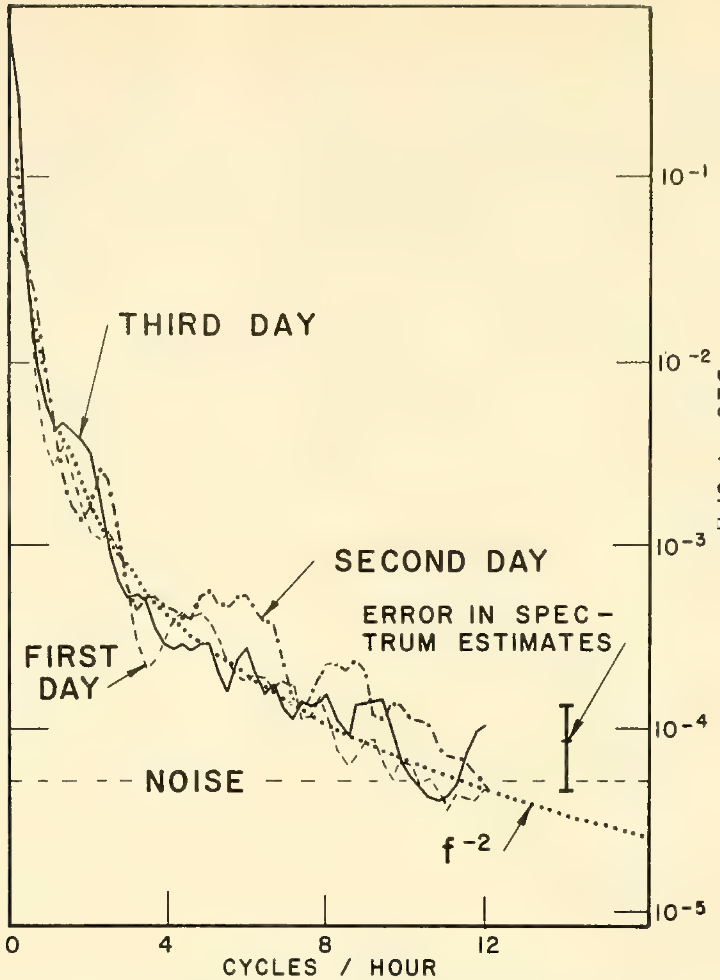

Figure 8. Spectral density estimates for the temperature records of three successive days, Buoy 2, at 150 ft.

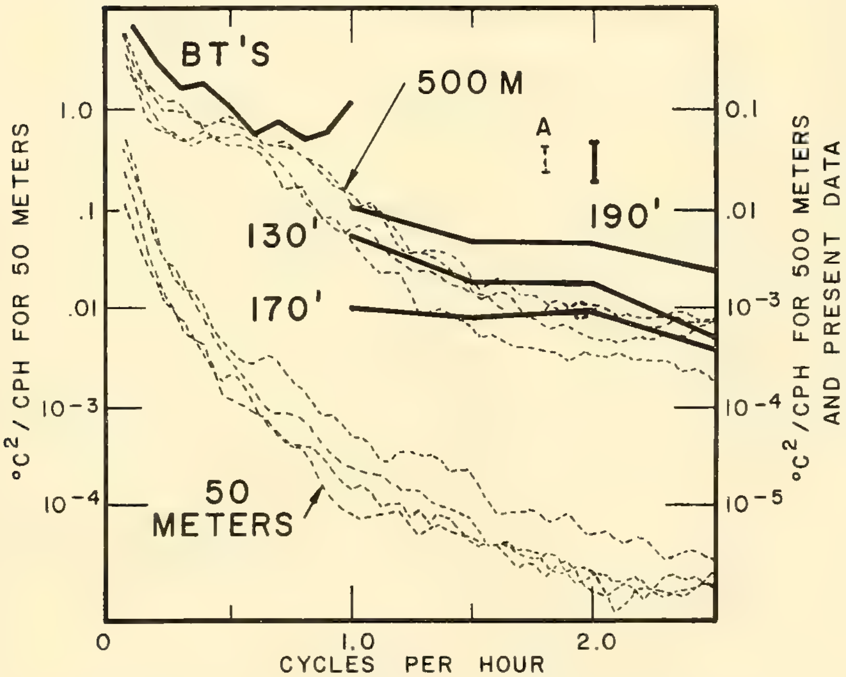

Figure 9. Comparison of power spectra of temperature fluctuations obtained by thermistors at Bermuda[2] (dotted lines) and by thermometer units at Eleuthera (solid lines). The corresponding estimates of error are given by the error bars.

is evident even for this frequency range. What is more important is that the orders of magnitude of the power spectra from these two experiments are similar. The data of 50 m is puzzling because it is so much lower in level than that of 500 m. This difference was explicitly pointed out in Reference 2.

The power spectra of the temperature at 150-ft depth as obtained by BT's taken during the course of the three days, every half-hour, is also plotted in this figure. Here again the order of magnitude and the rate of falloff are similar to the data of 500 m. The rise at 1 cycle per hour is due to aliasing, which shows that the BT responds to temperature changes at a greater rate than it ought to for observations taken at this slow rate.

A second important result shown in Fig. 8 is the absence of lines of any sort in the power spectra. Essentially this means that this data is not susceptible to interpretation as being composed of a simple harmonic temperature wave or even as a combination of a few simple harmonic waves. This is quite different from the results obtained by early experimenters who reported the frequency and wavelength of the simple harmonic waves with which they reconstructed the experimental temperature record. Perhaps the temperature records are analogous to sea surface records, which are describable only by their power spectra and by statistical measures.

CONCLUSIONS

For the data obtained in this set of one-day observations, spread over 24 miles horizontally and 120 ft vertically, the power spectra of the temperature fluctuations have been found to obey the f^{-2} law in the frequency range from 0.5 to 12 cycles per hour. No lines have been observed in the spectra. These results differ from those of early experimenters. However, they cannot be considered to be at variance with the data reported in the references cited in Footnotes 1 and 2 because the frequency range covered differs so widely.

Additional experiments are planned to extend the recording time so that such a comparison can be made. An experiment has been completed in the Bermuda area, but the longest record obtained of the temperature was less than two days. A power spectra analysis of this data is in progress.

ACKNOWLEDGMENTS

Captain Kou Walter and the crew of the R/V GERDA were of great help in the conduct of this experiment. Tom Farrell designed the thermometer units. Tom Kelly was responsible for the maintenance, launching, and recovery of the thermometer units.

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