Surf beats: sea waves of 1 to 5 min. period

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(*Communicated by G. E. R. Deacon, F.R.S.—Received* 25 *March* 1950)

Long sea waves with periods of 2 to 3 min. and a few inches in amplitude have been measured. It has been shown that they are due to the varying height of groups of waves breaking on the shore. The amplitude of the long waves is found to be approximately proportional to the amplitude of the ordinary waves and independent of their period. The mechanism by which they are produced is discussed.

Introduction

At the conference of the International Union of Geodesy and Geophysics in Oslo in August 1948, W. H. Munk reported that he had detected fluctuations in sea level of a few inches' amplitude with periods of 2 to 20 min. He attributed the waves of about 2 min. period to variations in the height of the surf and called them 'beats of surf'. He considered that the waves of longer period, about 20 min., might come directly from distant storms, and since waves of this length would travel at several hundred miles an hour, they might be used for the detection and location of storms.

Munk (1948) used a pneumatic apparatus, the maximum sensitivity of which was to waves of 15 min. period with a pass band extending from 2 min. to 2 hr.; it was designed to be insensitive to ordinary sea waves and to the tides, even though their amplitudes are much greater than those of the 2 min. to 2 hr. waves. The apparatus consisted of a series of vessels partly filled with oil and connected by capillary tubes. For the measurements described in this paper it was more convenient to use a wave-pressure recorder of the 'aneroid' type already laid approximately 1000 yards from the beach at Perranporth on the north coast of Cornwall. The voltage from this instrument (about 0·5 mV/ft.) was amplified by a simple photoelectric d.c. amplifier with negative feedback. The output was passed through two resistance-condenser couplings of very long time-constant, designed to remove the tidal components, into a 2 min. period galvanometer slightly less than critically damped and insensitive to ordinary sea-wave frequencies. The circuit arrangement is shown in figure 1, and the relative response of the system to pressure fluctuations of 12 sec. to 20 min. period in figure 2. Owing to a leaky air valve in the undersea unit, the overall response decreased rapidly for periods longer than 5 min. Records of long waves, using the long-period galvanometer, and of ordinary waves, using a galvanometer of $\frac{1}{2}$ sec. period, were made side by side on photographic paper $5\frac{1}{2}$ in. wide moving at $\frac{1}{4}$ in./min. Time marks were recorded every 20 min.

Unfortunately, the 'aneroid' wave recorder—the only one at Perranporth suitable for measuring pressure fluctuations longer than 30 sec. period—was becoming rapidly unserviceable owing to the very slow leakage of air from the rubber bag, and it was possible to obtain satisfactory records only for about 1 hr. on either side of low water. Records were obtained from 6 to 28 December, after which the unit, which had been working for 18 months, failed entirely. The records are, however,

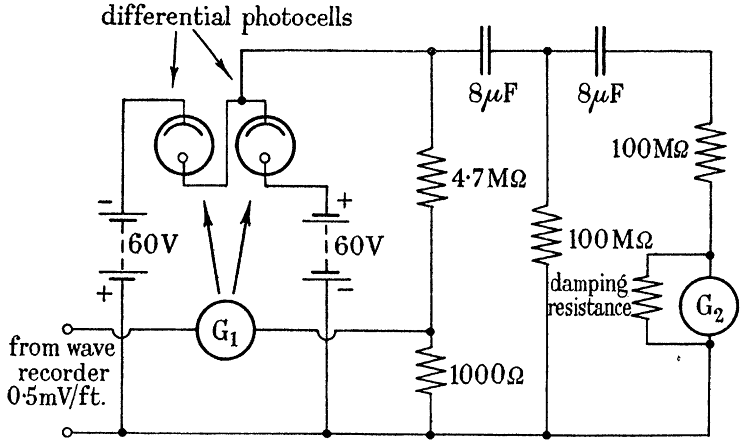

FIGURE 1. Long-wave filter circuit, incorporating simple negative-feedback d.c. amplifier, anti tidal-drift coupling and long-period galvanometer insensitive to ordinary-wave periods. G_1 is a sensitive galvanometer and G_2 a 2 min. period galvanometer.

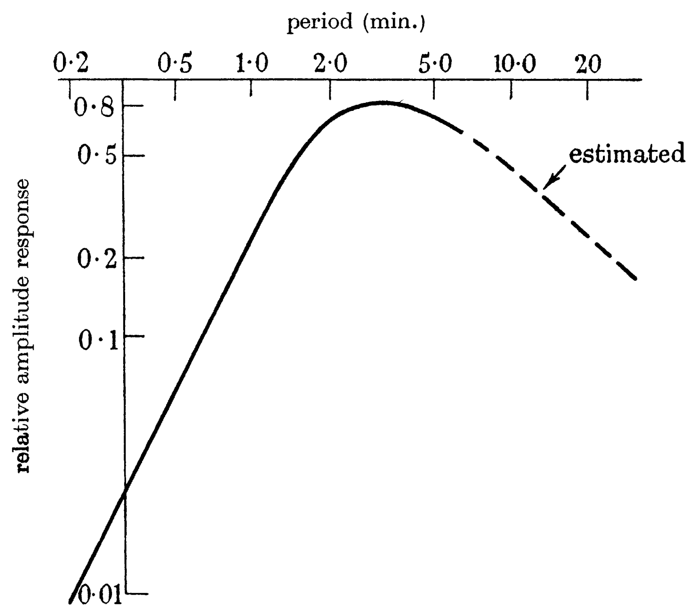

FIGURE 2. Frequency response of the recorder system, taking into account the leaky air valve in the undersea unit.

adequate for investigation of waves of about 3 min. period. No waves of longer period were detected, but the decreased sensitivity of the apparatus for waves longer than 5 to 10 min. period leaves room for doubt as to whether they were present.

Relationship between long and ordinary waves

On 23 December 1948 a calm period was interrupted by the arrival of swell from a storm which developed off Newfoundland (2000 miles from Perranporth) on 21 December. The peak heights of the long and ordinary waves are plotted against time in figure 3. The peak-wave height is the difference in height between the crest and trough of the highest wave on the length of record examined. It is an easy measurement to make and experience has shown that it is approximately proportional to the average wave height. There is an approximately linear relationship between the amplitudes of the long waves and ordinary waves. This is further illustrated in figure 4 by plotting the two measurements against one another.

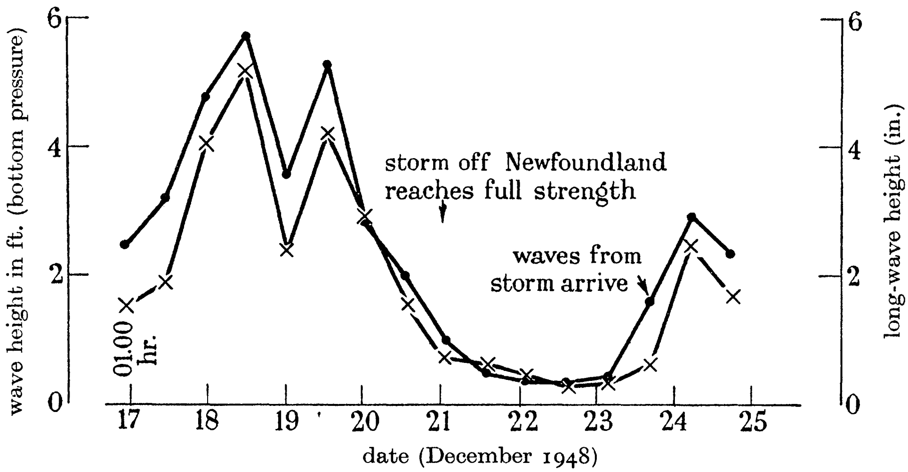

Figure 3. Variation of the ordinary-wave height and long-wave height with time: ●, ordinary waves; ×, long waves.

A detailed examination of the records (those in figure 7 for example) suggests that high groups of ordinary waves are followed by long waves after a time delay of 4 to 5 min. This is approximately the time taken for the groups of waves to reach the beach and for the long waves to travel back to the pressure recorder, which indicates that the long waves are produced by groups of high waves breaking on the beach. If this is so, the long-wave records should be similar to the envelope of the ordinary waves recorded 4 to 5 min. before.

To make a more thorough investigation, a correlation meter was constructed. It allows a comparison to be made between the long-wave record and the envelope of the ordinary waves, with the long-wave record delayed or advanced by varying amounts with respect to the ordinary-wave record. The meter produces a graph of the coefficient of correlation against the time displacement as one record is moved relative to the other. The apparatus and method are described in detail in appendix 1. Eight pairs of long-wave and short-wave-envelope records were compared, and the results are shown in figure 5. In the first five records at least, there is a marked correlation pattern when the comparison is made with the long-wave record lagging 4 to 5 min. behind the ordinary-wave envelope. The mean of the first five graphs, shown in figure 6, strengthens this conclusion. A positive correlation means that an increase in wave height corresponds to an increase in water level. The shape of the correlation pattern gives an indication of the wave-form of the long wave produced by a single group of waves (or a single wave), and shows that such a group would propagate a disturbance which consists in sequence of a rise, fall and rise in water level. In pursuing the subject it must be remembered that the shape of the long waves may have been smoothed to some extent by the long-wave filter.

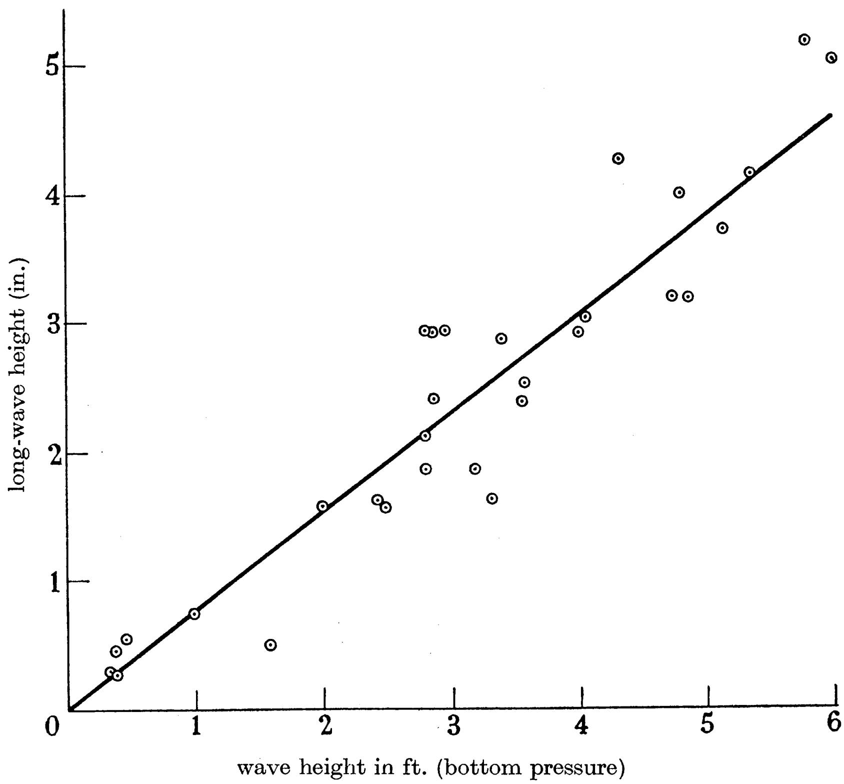

FIGURE 4. Relation between long-wave height and ordinary-wave height

In using the aneroid recorder with only a small volume of air in the rubber bag there is some danger that apparent 'long waves' might be due to an unsymmetrical response of the unit to positive and negative pressures when a group of high waves passes over it. The fact that there is only a small amount of correlation when the two records are compared with no time separation proves that this fear is unfounded.

A comparison of the ratio of long- to ordinary-wave heights with the period of the ordinary waves showed that the ratio was independent of the period of the waves.

CONCLUSION

If the evidence of figures 4 and 6, that the long waves are produced by the breaking of groups of high waves on the beach, is accepted, it becomes necessary to explain why the correlation between the envelope of the wave record and the long-

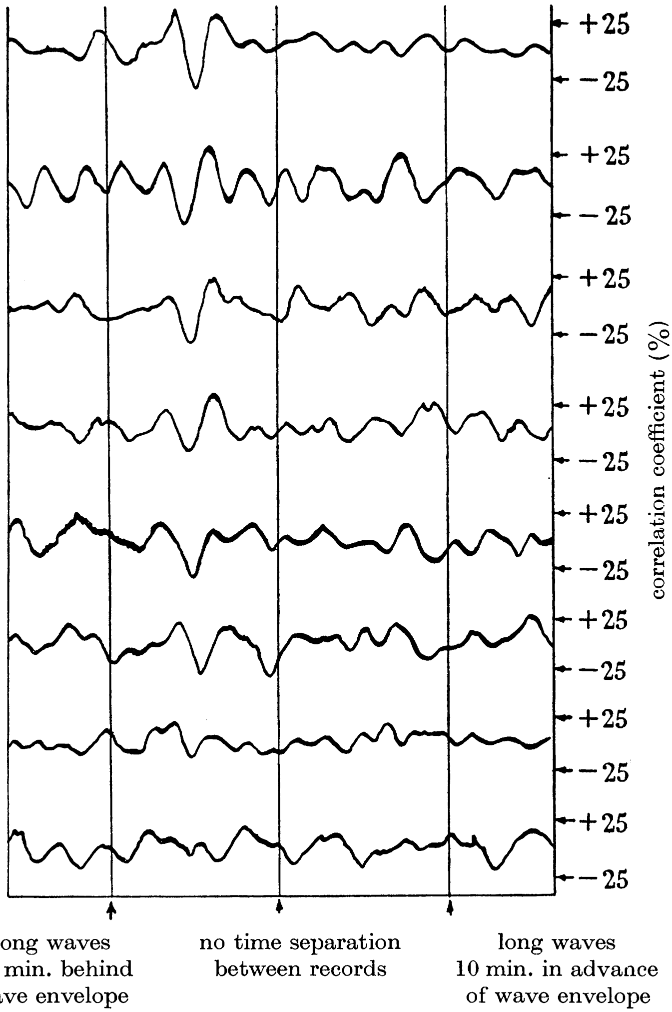

FIGURE 5. Change in correlation between the long waves and the ordinary-wave envelope with time separation of the records.

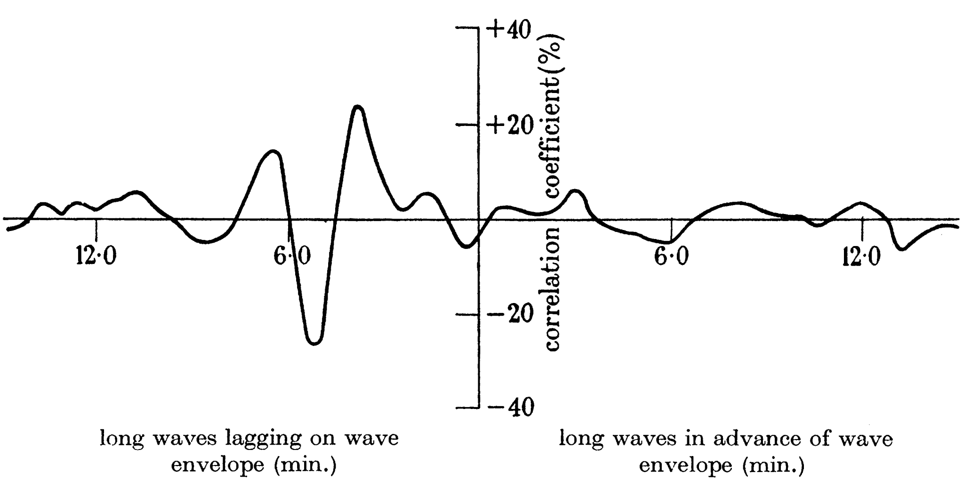

FIGURE 6. Mean of the five best correlograms (the first five in figure 5).

wave record delayed 4 to 5 min. is much better in some records than in others. The best correlation was obtained when the waves were produced by a distant storm. Under such conditions the wave groups were long and regular and would be expected to reach the beach without much change of shape; also, the length and distribution of the groups is such that the long waves from one group would not tend to be cancelled by those from adjacent groups. The worst correlation was

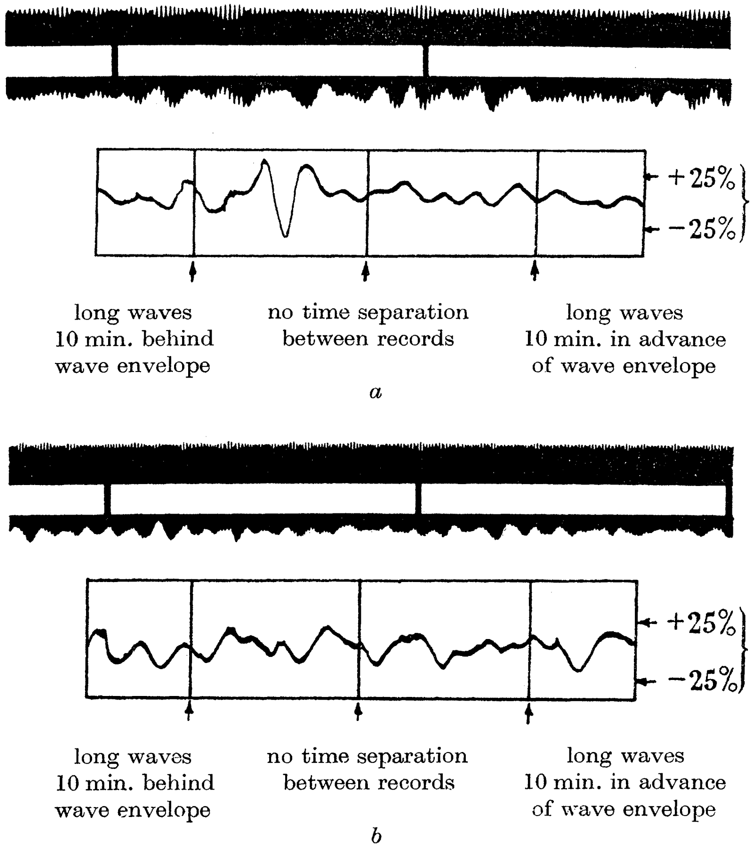

FIGURE 7. Wave record, long-wave record and correlation diagram for the best and worst correlation patterns: *a*, 05·00 hr. 24 December 1948; *b*, 22.00 hr. 16 December 1948.

obtained when the waves were generated over a large area near the coast and the groups were short and irregular. Such groups might change shape considerably before reaching the beach, and long waves from adjacent groups would tend to mask each other (see figure 7).

It seems reasonable at first to attribute the formation of the 'long waves' to the varying transport of the water in groups of high and low waves approaching the coast: the extra water released when a high group reaches the beach starts a surge, or a long wave, travelling out to sea. Such a simple explanation disagrees with the observations in two major respects: according to theory, the mass transport with a wave (in a given depth) is proportional to the square of the height, whereas the observations show that the long-wave height is approximately linearly proportional to the ordinary-wave height. The simple explanation also requires that the long wave should be an elevation, whereas figure 6 shows that the outstanding feature of the observed wave is a depression in water level.

It is probably more correct to attribute the long wave to a sharp increase in shoreward transport of water in or near the breaking zone. In order to increase the forward mass transport, water is accelerated towards the beach, and there must be a corresponding acceleration out to sea because the momentum of the water moving in the two directions must be equal. To put it simply, the waves must have something to push against to accelerate water shorewards, and as a wave group reaches the breaker zone one long-wave elevation should be sent shorewards and another seawards, leaving a depression in between. The shorewards elevation would be reflected from the beach, and the observed sequence of elevation, depression and elevation would be established.

The increase in mass transport in the breaker zone may explain why the long-wave height is approximately linearly proportional to the height of the ordinary waves instead of to the square of their height, as might be expected from the theoretical result that the mass transport in a given depth of water is proportional to the square of the wave height. Low waves should undergo a proportionately greater increase in height and increase in mass transport than high waves because they travel farther up the beach before breaking; such an increase would make the transport in the low waves greater than the value expected from the square-law, and more in agreement with a linear relationship.

Considerable theoretical work has been done on the mass transport in waves, but there is still doubt as to what happens under actual conditions.

It is interesting to note that frequency analysis of a long-wave record shows that the energy of these 'beat-of-surf' waves lies almost entirely in the period range of 1 to 5 min.—a result that would be expected from the shape of the correlogram in figure 6. To detect still longer waves, such as may travel direct from a storm, it seems advisable to use an apparatus sensitive only to periods greater than 10 min.

Appendix 1. The correlation meter

A sketch of the apparatus is reproduced in figure 8. The two records to be correlated are prepared in the form of black and white profiles (see figure 7), and they are stretched round the outside of a celluloid sheet fixed in an arc of a circle centred on a gramophone turn-table. The gramophone turn-table carries two cylindrical lenses, and screens which cut off all light that does not pass through the lenses. The lamp filament is focused to a vertical line of light across the two records, and the rotation of the turn-table causes this to sweep from right to left along the records; two lenses are used to reduce the time during which no signal is picked up. The instantaneous value of the scattered light is proportional to the sum of the two ordinates of the records measured from their means plus an amount due to the mean width of white paper exposed; this unwanted mean value is removed in the subsequent electronic circuit and may therefore be ignored. The scattered light is picked up on a photoelectric cell, the output of which is amplified and fed into a square-law meter using a thermistor bridge circuit which has a slow response and which gives an output proportional to the mean square of the signal. A mechanical device moves one record slowly along its time axis.

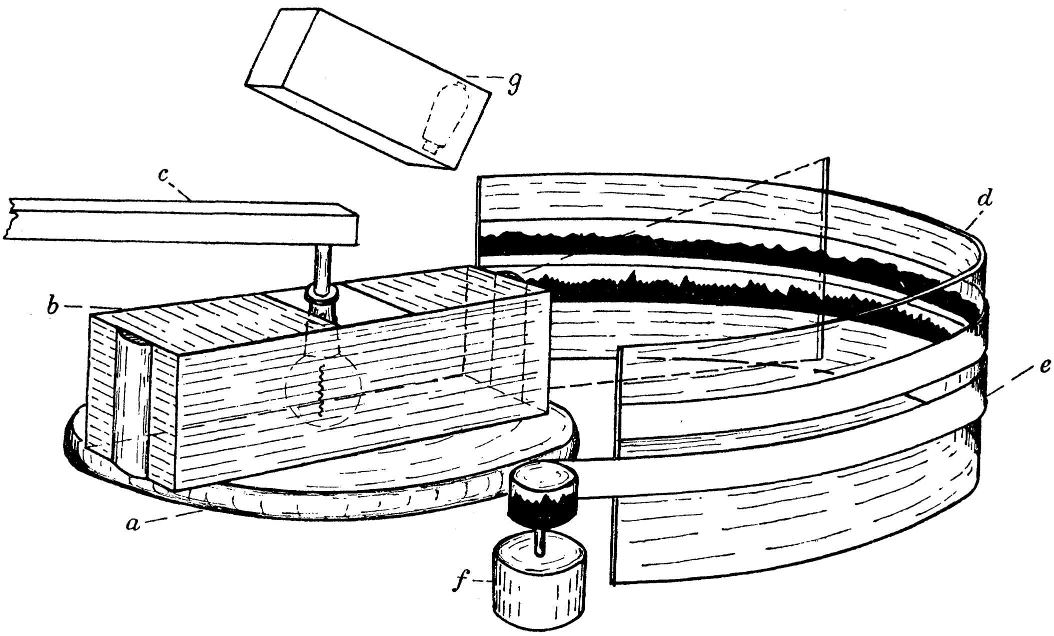

FIGURE 8. The correlation meter. *a*, gramophone turn-table carrying *b*, screened box with cylindrical lenses; *c*, stationary support for lamp; *d*, celluloid sheet; *e*, variable area records; *f*, device for slowly moving one record; *g*, light-sensitive cell.

It can be shown that the correlation coefficient r is given by

$$r = \frac{E_s - (E_A + E_B)}{2\surd(E_A E_B)},$$

where E_A is the mean square output from the meter with one record alone, E_B with the other record alone, and E_S with both records taken together.

If we assume that the mean square of the examined portion of the moving record remains constant, variations in the output of the square-law meter are proportional to variations in the correlation coefficient as the time separation of the record changes. The zero may be found, and the scale calibrated, by measuring the output when each of the records is on the meter alone.

To obtain records suitable for use on this machine without destroying the originals, the wave envelope on the original was blacked in with soft lead pencil, and the whole record printed by placing it face downwards on to photographic paper. It was covered with a sheet of Perspex held down by weights, and a bright light was then shone through for a suitable time. The print was processed, and a grid consisting of a series of lines at 1 in. intervals and perpendicular to the time axis was drawn on the back. The long-wave record and the wave envelope were then cut off as long narrow strips, using a sharp knife and a steel straight edge, and in this form were ready for use.

In conclusion the author wishes to thank Mr N. F. Barber for his stimulating interest and helpful advice during the progress of this work, and the Admiralty for permission to publish the work.

Reference

Munk, W. H. 1948 *Rev. Sci. Instrum.* **19**, 654.

Programme organization and initial orders for the EDSAC

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(*Communicated by D. R. Hartree, F.R.S.—Received* 4 *April* 1950)

Orders for the machine are presented to it in coded form on punched tape, and are translated by the machine itself into the form in which they are held in the store, in accordance with a standard set of 'initial orders'. In the course of this input of orders it is possible to use the machine to make systematic modifications to the orders as punched on the tape; the modifications required, if any, are indicated by a code letter included in each order as punched on the tape. This system allows the use of a more flexible system of representing orders than the binary form used inside the machine.

It also enables sub-routines to be drawn up in a form independent of the particular values of parameters in them, the values of these parameters in any particular application of the sub-routine being inserted by the machine in the course of the initial input of orders, or in the course of operation of the machine. This simplifies the formation of a library of sub-routines and its use in the construction of long programmes.

A complete example is worked.

1. Introduction

This paper is concerned with some aspects of the organization of work for one kind of automatic calculating machine, of which the EDSAC, installed at the Mathematical Laboratory of the University of Cambridge, is an example. A general description of this machine has been given by Wilkes & Renwick (1949, 1950).

The essential parts of any automatic digital calculating machine are a store for holding numbers, an arithmetical unit, and a control unit. The store holds numbers in storage locations which are numbered so that we can refer to a storage location by means of an integer, known as the 'address' of that location, or of its content.

The essential features of the EDSAC for the purpose of this paper are three. First, it uses a single-address form for orders, that is, each order refers to a single storage location; the order code is given in appendix I. Secondly, the orders are