AUTOMATIC RECORDING AND PROCESSING OF MARINE GEOPHYSICAL DATA

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1. — INTRODUCTION

The great increase in observational data recorded at sea during the last decade produced a requirement for automatic digital recording systems which allow treatment of the data by digital computers. There are, broadly, three procedures which may be followed.

A ship-borne data logger can be installed and the data tapes analysed at the end of the cruise on a land-based computer. Alternatively, an on-board computer may be used to process the data tapes at sea. Finally, the raw data can be converted to a form suitable for direct acceptance by the ship-borne computer. In deciding which approach to adopt — whether to progress from one to another, correcting and modifying at each stage, or whether to plan for a single system — consideration must be given to such factors as the complexity of the data, sampling rate, the requirement for on-the-spot analysis in order to modify experiments or trials, the average period spent at sea, the amount of resources available both in manpower and equipment, and the size of the research vessel.

A common procedure is to adopt the first course initially. For many experiments analogue recorders provide sufficient information during a cruise to enable decisions to be taken at sea as required. There are also advantages in testing and modifying analysis techniques, and in dealing with unforeseen eventualities on land rather than under the more restricted conditions at sea.

Data recording at SACLANTCEN has followed the first approach during the last few years. Processing and analysis of the tapes were made on the Centre's Elliott 503 Computer. At present, approximately 12 sensors are routinely recorded on punched paper tape. These include ship's speed, course, wind speed and direction, air temperature, sea-surface temperature, insolation, etc. This paper describes the equipment designed and built at the Centre for the automatic recording of navigational and geophysical data. Processing and editing techniques are described briefly. The Centre programme has reached the point where geophysical data (magnetic field, gravity and depth) can be plotted directly on navigational charts from punched tape recordings made at sea. The next part of the programme will be the installation of a small, on-board computer to allow 'real-time' processing.

2. — GENERAL SYSTEM DESCRIPTION

The instruments for which digital recorders were designed and built by SACLANTCEN are a Loran-C receiver, an echo-sounder and a universal digital clock to provide an accurate time reference for all recordings. A punched-tape read-out for the proton magnetometer was provided by the manufacturers and a gravitymeter read-out has since been developed.

These systems were designed more or less independently, and apart from a standardisation in component parts, their only common feature is the time input from the digital clock. Since each instrument is provided with its own analogue recorder any malfunctioning of a digital recorder will not affect the performance of the instrument for the other digital recorders : data reduction will merely be more tedious and time-consuming.

Editing and smoothing of the recorded data is made on an Elliott 503 computer. Each tape contains recordings of only one parameter which, initially, allows easier handling of computer programmes for processing. The universal time reference, recorded at least once every hour on each tape, is then used to relate corrected values of depth, magnetic field and gravity to smoothed Loran-C positions. A simple plot routine is used to plot the desired parameter against ship's position on an off-line Benson-France Electroplotter, Model J, which has a plotting area of 136×95 cm^2.

3. — THE UNIVERSAL DIGITAL CLOCK

3.1. Function

The clock was designed to carry out a wide variety of functions which include :

(*a*) the provision of date/time information in binary-coded decimal to the paper tape punches;

(*b*) generation of accurate standard frequencies for other instruments;

(*c*) remote control of instruments placed in various localities on the ship;

(*d*) time marks at any desired time interval from 1 second to 10 hours on analogue recorders.

3.2. Basic Components

The basic components consist of a master crystal clock with digital display of days, hours, minutes and seconds, a mechanical timer consisting of two rotating drums each with ten rows of sixty holes around the periphery into which rubber studs can be pressed, five repeater clocks distributed throughout the ship and a power supply with batteries and battery charger to guard against power failure.

The simplified block diagram of the clock is shown in fig. 1. A photograph of the master unit is shown in fig. 2.

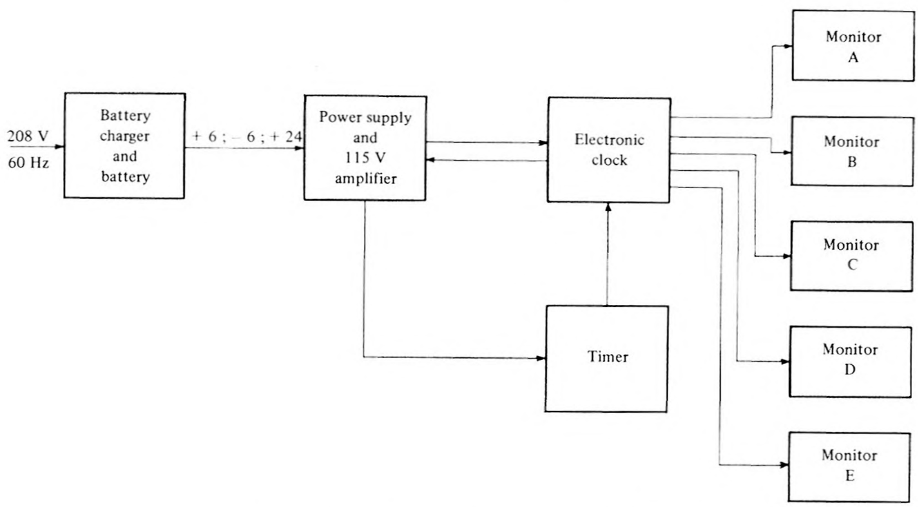


FIG. 1. — Simplified block diagram of digital clock.

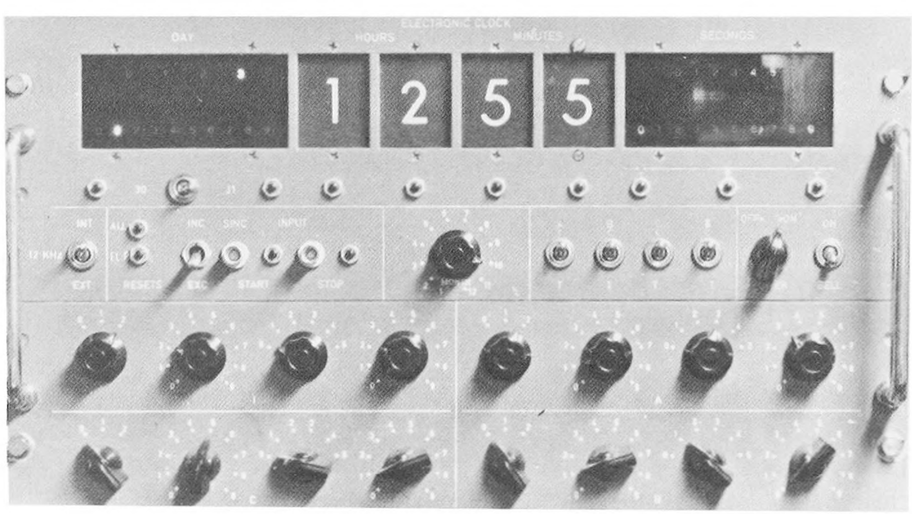


FIG. 2. — The master unit of the digital clock.

The output of a 12 kHz oscillator is divided down in steps to provide output frequencies of 1 000, 400, 60, 50, 10, 1 and 0.1 Hz and 1 pulse/min, 1 pulse/hour and 1 pulse/day. The division from 1 pulse/min to 1 pulse/day is achieved by rotary switches. There is provision for an external oscillator to substitute the internal crystal if greater accuracy is required.

The day of the month automatically changes when the hour changes from 2359 to 0000. A switch on the clock selects between months of 30 and 31 days so that at midnight the next date will change to 1. No provision is made for February and the change from 28 or 29 to 1 must be made manually.

The clock is started and stopped by the buttons shown in the left-hand side of fig. 2. Alternatively, provision is made for using an external signal so that, for instance, the clock can be synchronised with radio signals.

Five outputs, each of 31 conductors, are provided for carrying date/time information in binary-coded decimal to tape punches.

Four programmers labelled I, A, B, C are shown in the bottom half of fig. 2. They are connected through signal generators to the master itself and to the three repeaters A, B, and C. At the time pre-set on the programmers a signal of approximately 1 second duration and 6 V amplitude is sent to the selected repeater. If desired the commands to the signal generators can be transferred from the clock programmers to the mechanical timer.

The timer was constructed as a mechanical adjunct to the clock. It has two drums, one of which rotates at either 1 rpm or 0.1 rpm and the other at 1 rph or 0.1 rph. Studs pressed into the peripheral holes activate a microswitch. Since connections are made between some of the channels of the timer and the repeater units, time marks can be generated for any analogue recorder and instruments can be remotely controlled.

To ensure uninterrupted operation in the event of power failure battery banks have been included in the power supply. These are kept charged when main power is available and are therefore fully charged to take over when the main supply is cut off.

The batteries are ferro-nickel cells with a capacity of 80 ampere-hours. If the clock plus lamps, timer and repeater units are all kept on, the total current required is 2A and the system can therefore continue for 40 hours. If only uninterrupted operation of the clock is required (without lamps), then the batteries will have a life of 10 days.

4. — THE LORAN-C DIGITAL RECORDING SYSTEM

4.1. Background

Loran-C is a long-range navigational aid intended primarily for ocean navigation. It uses pairs of pulse-transmitting ground stations and acquires an extended range by transmitting in the low-frequency, 90-110 kHz, band. The master station in a Loran-C network transmits groups of pulses received by the ship's receiver and the slaves. After a controlled time delay the slaves transmit similar groups of pulses. The constant time difference between reception of the master and slave pulses establishes a Loran line of position which is a hyperbola.

The position of the stations in the Eastern Atlantic and the Mediterranean and the areas covered by ground waves under normal conditions are shown on chart No. 15 308-1 published by the U.S. Naval Oceanographic Office.

Prior to the construction of the digital recording system the method of using Loran-C at the Centre was as follows.

A hyperbolic grid was drawn by hand on the nautical chart of the area to be surveyed. The time-delay values of the curves were taken from Tables prepared by the U.S. Naval Oceanographic Office. During a survey the Loran-C reading was recorded in a log book every 15 minutes and for any special event. The reading was then plotted by interpolating between adjacent curves of the grid.

The errors inherent in the procedure include :

(i) Draughting errors in the original grid.

(ii) Operator's error in recording the readings.

(iii) Recording the reading before or after the stipulated time (an error of 15 seconds, for example, at a ship's speed of 10 knots, corresponds to a positional error of 250 ft).

(iv) Errors in plotting the point.

(v) Error between the clock of the measuring instrument (magnetometer, echo-sounder, etc.) and the navigational clock.

A further error that was found to arise during operation in the Mediterranean was an ambiguity between the envelope reading (the first four digits of the six-digit reading) and the cycle reading (the last two digits). The effect is shown in fig. 3. In the first example the envelope reading is 1694 and the cycle reading is zero. The graduated scale on the least significant digit of the envelope reading is zero and, since this agrees with the cycle reading, there is no ambiguity. It can happen however that the reading of the envelope in the last digit falls between 3 and 4, as in the second example shown. It is not clear whether the correct reading should be 169300 or 169400. In such a case an " ambiguity " switch on the receiver can help to resolve the ambiguity. But it is not uncommon for the envelope to be more than one revolution out of phase with the cycle, as in the third example. In such a case the reading would be taken by any human operator as 169300, which would introduce an error of 10 μs. To prevent this danger it was found necessary for manual recording to record not only the Loran readings but also the successive differences.

A system of recording Loran-C readings automatically which would be free from " human " errors and which would give an unambiguous reading appeared to be a first essential in designing a fully-automated data-logging system. No digital recording system existed on the market when the Centre approached the problem in 1964.

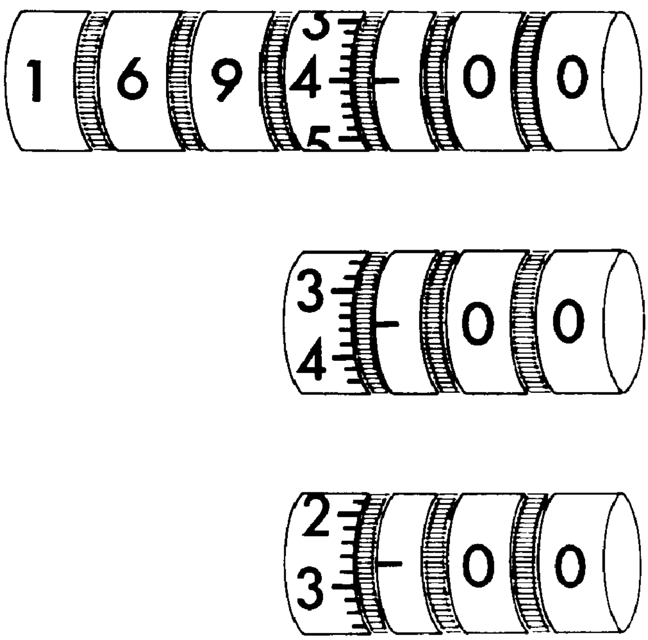


FIG. 3. — Ambiguity between the envelope and cycle readings of Loran-C reading.

4.2. The Digital Recording System

The basic purpose of the recording system was to transform the rotations of a shaft into a digital output that could be punched on to paper tape using standard techniques. When " time " is also recorded on the tape then the ship's tracks can be reconstructed through a computer with plotting capability.

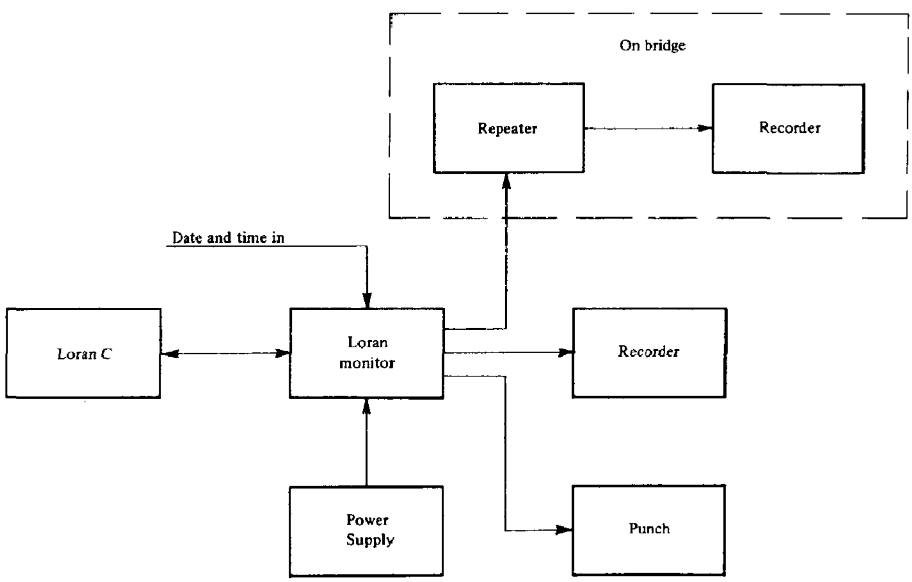


FIG. 4. — Simplified block diagram of the Loran-C Digital Recording System.

A simplified block diagram of the system is shown in fig. 4. The design is basically simple, consisting of a set of photodiodes to count the rotations of the drive shaft, a set of reversible decade counters for reproducing the receiver readings from pre-set values, a pen recorder that gives continuous registration of X and Y readings, and a tape-punch for recording the last three digits of X and Y.

Light aluminium discs were attached concentrically to the drive shaft of the least significant digit in the cycle of both X and Y. Figure 5 shows one such disc. To enable easier access, and to accommodate the necessary additional equipment, a special case was built to house the two slave delay servo units of the Loran receiver.

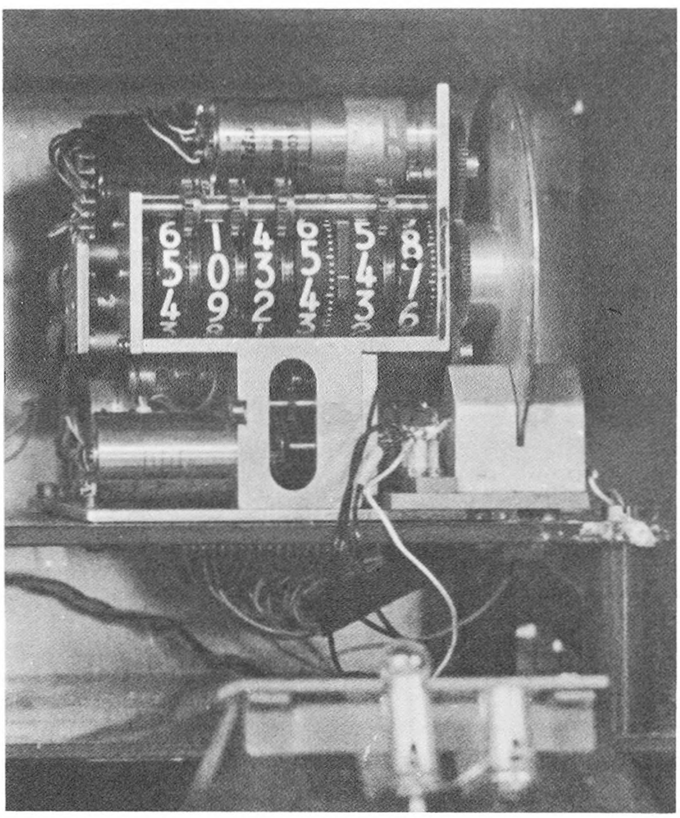


Fig. 5. — Photodiode system and aluminium disc fitted to the slave delay modules.

The discs have ten equally spaced holes around their periphery, and their revolutions are monitored by light sources and photodiodes mounted on either side. Three photodiodes are necessary to determine the sense of rotation and to recognize " dither " when it occurs.

The signals from the photodiodes pass to the Loran Monitor Unit (fig. 6) which houses an analogue-to-pulse convertor, a sense detector and a set of reversible decade counters.

The last three digits of the six-digit Loran readings are pre-set manually on the counters and displayed on Nixie Tubes. For every 1/10 rev of the dics, " 1 " is added to, or subtracted from, the pre-set monitor reading.

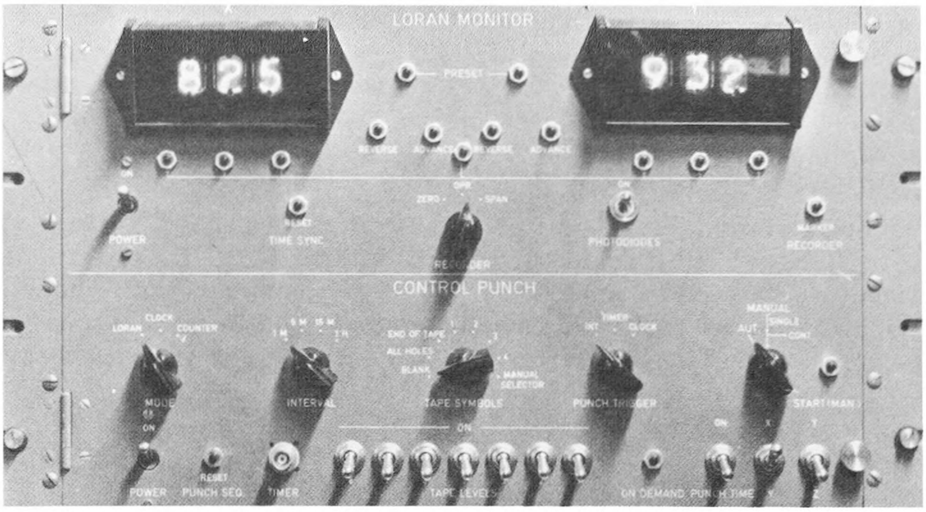


FIG. 6. — The Loran Monitor Unit.

A Texas Instruments " Servoriter " pen recorder records the last two digits of the X and Y readings through a digital analogue convertor.

The dual traces are recorded on 10 inch wide chart paper (see fig. 7) each trace employing the full width of the chart so that 0.1 μs can be resolved with no difficulty.

The X and Y values appearing on the Nixie Tubes are punched on to paper tape at selected time intervals of 1, 5, 15 or 60 minutes. When the time interval is changed, date and time (normally punched automatically every hour) will be punched, together with a symbol corresponding to the new interval selected.

There is provision for punching a reading " on demand " in order to mark a special event. Pressing the " on demand " button will cause the reading at that instant to be punched, preceded by an " on demand " symbol and the date and time to the nearest second.

Manual operation of the tape-punch is controlled from the panel in the bottom half of the monitor unit.

The Loran receiver, monitor unit, punch and pen recorder are installed in the ship's laboratory. In addition, a monitor repeater and pen recorder have been installed on the ship's bridge. The bridge repeater, mounted in front of the helmsman, allows the ship to follow Loran lanes rather than conventional compass courses.

4.3. **Improved Accuracy with Automatic Recording**

The human errors in the manual recording of Loran-C readings discussed in Sect. 4.1, are virtually eliminated by an automatic recording system. The digital clock ensures synchronous recordings of all parameters and the Loran readings can be converted to latitude and longitude on a computer. The ambiguity discussed in Sec. 4.1. can give trouble during

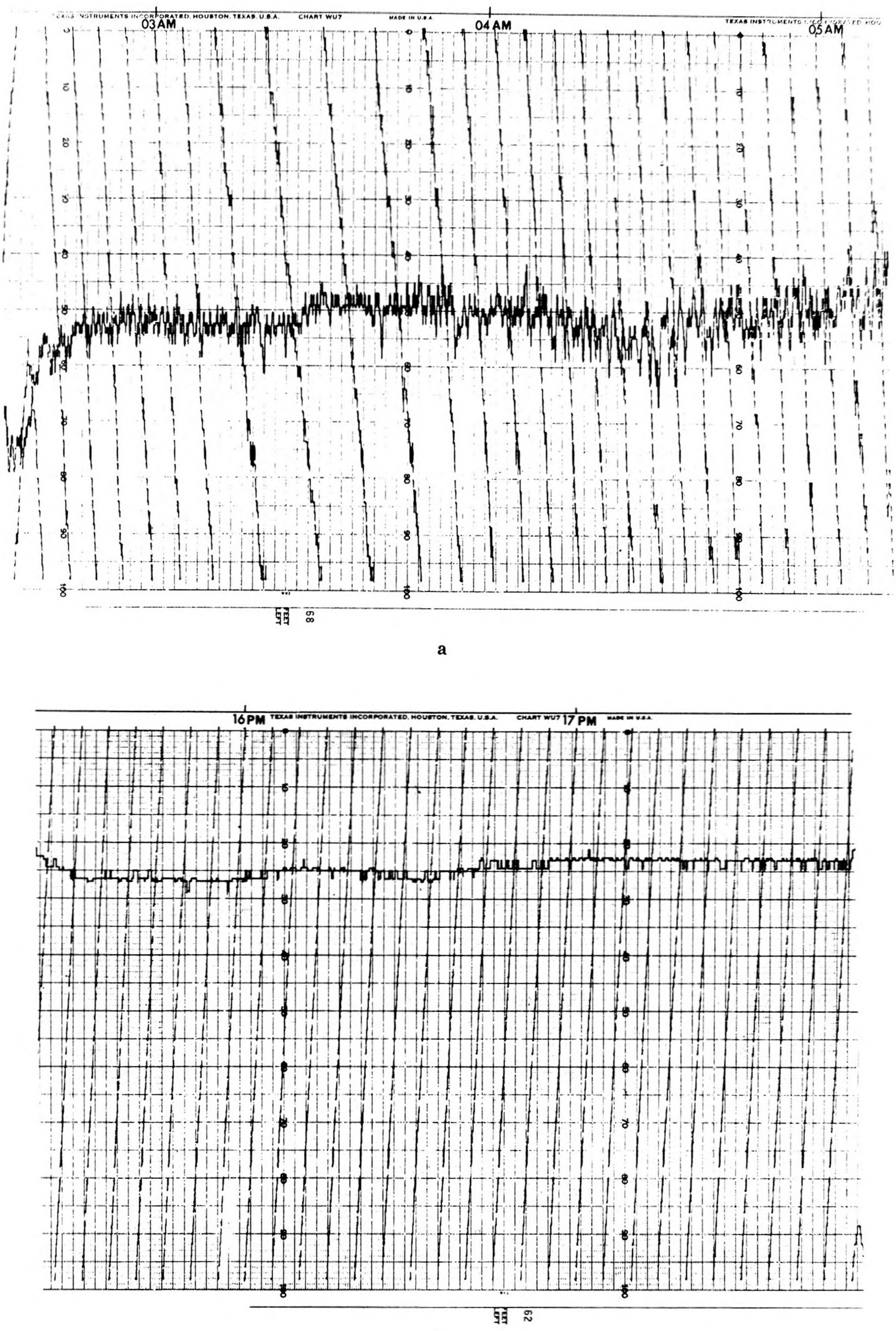


FIG. 7. — Traces of Loran-C (a) during the night; (b) during the day. The width of the chart paper represents 10 μsecs.

manual recording and a scrupulous check must be kept on successive differences. There is no such problem with automatic recording, for, provided the correct reading is set on the monitor unit at the start of an operation, the monitor will always give an unambiguous reading since its function depends only on counting shaft rotations and not on the relative phases of the envelope and cycle servos.

Environmental factors affecting radio wave propagation such as interference, increased atmospheric noise during night operation, refractivity of the earth's atmosphere etc., will always inhibit the overall accuracy of Loran-C (see fig. 7). However, by using an automatic recording system and sampling at frequent intervals it becomes possible to use smoothing techniques on the computer.

A brief description of the treatment of recorded data is given in Section 6.

5. — DIGITAL DEPTH RECORDER

5.1. Basic Specifications

In principle, a digital depth recorder (hereafter referred to as DDR) is quite simple, as indicated in the block diagram of fig. 8. The transmission of the echo-sounding pulse starts an electronic counter that is stopped when the bottom echo returns. The output of the counter is connected to a punch, thus permitting the reading to be perforated on paper tape.

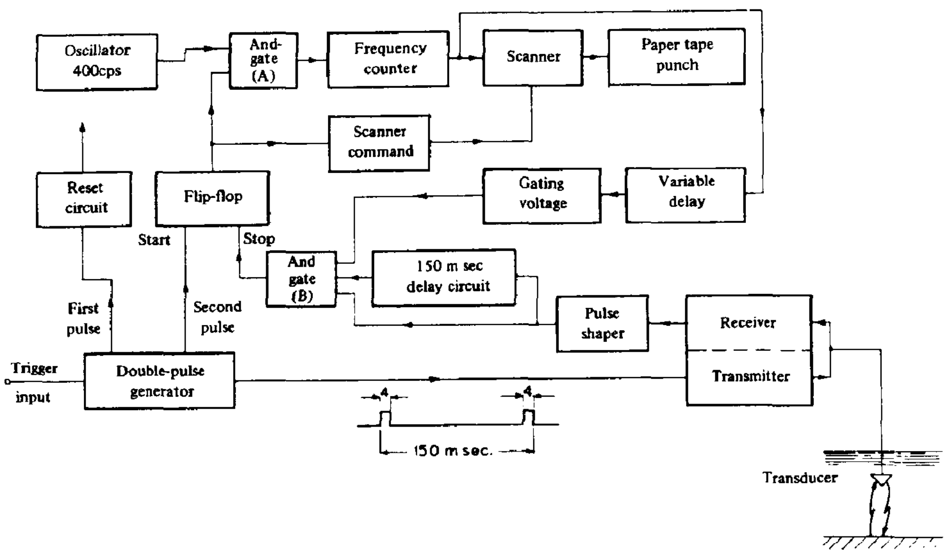


FIG. 8. — Simplified block diagram of digital depth recorder.

The problem is to discriminate the bottom echo from background noise (caused by the ship, waves, etc.), echoes from fish and other scatterers, and from pulses emitted by other sounding systems simultaneously in use aboard the research vessel. To carry out this discrimination it was considered necessary to take the following measures.

(*a*) To use an amplifier with time-variable gain in the receiving channel. The gain should increase with time after each transmission of the echo sounder, thus suppressing the echoes from shallow fish and scattering layers. This measure also makes the DDR more automatic, as gain adjustment of the echo sounder is not necessary.

(*b*) To use a coded transmission instead of the conventional single sound pulse. The receiving system is constructed so that it will only admit the coded echoes, thus almost eliminating the possibility that background noise or pulses from other sounding systems operate the DDR.

(*c*) To be able to control the stop of the electronic counter during severe background noise conditions (as for example during a storm). Under such conditions it should only be possible to stop the counter during a short time interval occurring around the expected time of arrival of the bottom echo.

(*d*) To further reduce interference with other sonar equipment aboard the ship by using a separate working frequency for the DDR echo sounder.

In order to find the desired relationship between gain and time for the variable gain amplifier, the sound propagation losses have been calculated. The approximate total propagation losses at 15 kHz and relative to a depth of 100 fm are given in Table I. It was considered practical to specify that no gain adjustment of the echo sounder should be necessary for depths between 100 to 2 000 fm, and therefore that the gain of the amplifier ought to increase with time in approximately the same way as the losses.

TABLE I

Total relative propagation loss at 15 kHz vs depth and time

Depth in fm	100	500	1000	1500	2000
Relative prop. loss in dB	0	19	31	41	49
Corresponding time in seconds	0.25	1.25	2.5	3.75	5.0

Preliminary sea trials were carried out in order to determine a suitable code for the coded transmission. The following four codes were tried.

(1) One 50 ms long pulse (the pulse length of the Echo Sounder is normally 5 ms or less).

(2) Two pulses, each 50 ms long, transmitted with an interval of 100 ms in between.

(3) Two 4-ms pulses transmitted with an interval of 146 ms.

(4) Three 4-ms pulses transmitted with intervals of 146 ms.

All four codes appeared to give reasonably good protection against noise and pulses from other Echo Sounders, but the depth-measuring accuracies were found to be widely different. When using code (1) the discrimination process was an integration of the received signals, the integration time being about 30 ms. In order to avoid accumulation of noise signals in the integration capacitor, the latter was automatically short-circuited if the signal level dropped below a certain, prefixed value. Thus, if the level of an echo pulse dropped below this value during the first 25 ms of its appearance, the integration process would start all over again. Due to this, inaccuracies of up to 10 fm were experienced.

The same was true of code (2). Here the discrimination process was a combination of integration and pulse delay.

Codes (3) and (4) proved to give accuracies of the order of 1 fm. The discrimination process was in both cases a combination of integration and pulse delay, but no automatic discharging of the integration capacitor was used. The integration time was 1 ms.

As a result of the trials it was decided to use code (3), because this was the simplest code giving both good accuracy and good protection against unwanted signals.

Several ways of controlling the stop of the electronic counter during severe background noise conditions were considered. One was to equip the DDR with a memory (of the last reading) and let this memory open a signal gate shortly before the return of the next bottom echo. This system would work well if the precaution were taken of widening the memory unit automatically when the bottom echo is lost. Such a feature will be introduced into the system to reduce the number of erroneous readings presently recorded (about 15 %).

At present a generator creates a gating pulse of adjustable width at a manually selectable time after the sound-pulse transmission. During periods of low noise the gating pulse can be set wide, thus permitting the DDR to operate automatically over a wide range of depth, but under high noise conditions a narrow gating pulse, needing readjustment from time to time, is used.

A working frequency of 15 kHz was chosen for the DDR echo sounder because no other sonar equipment aboard the ship used this frequency and because, not being too far from the 12 kHz of the standard echo-sounder, attenuation losses would not be greatly increased.

5.2. General Description

A simplified block diagram demonstrating the working principle of the DDR is shown in fig. 8. When triggered, the double-pulse generator generates two 4-ms wide, 150-ms spaced pulses. The first pulse is fed to the reset circuit, thus resetting all bi-stable elements of the DDR; the second pulse reverses the start-stop flip-flop that in turn starts the counter counting the 400 pps from the oscillator.

Both pulses are fed to the transmitter of the echo sounder, thus causing two sound pulses to be transmitted into the water. A little later the two corresponding echoes are received and, after being filtered, are amplified and shaped, and fed simultaneously to the 150-ms delay circuit and the and-gate (B). The first echo pulse, being unable to pass through this gate, travels through the delay circuit and arrives at the input of the gate at the same time as the second echo pulse appears at the output of the receiver. Provided that the variable-delay gating voltage for protection during severe noise conditions is present, the second echo pulse will pass the and-gate (B) and reverse the start-stop flip-flop thus closing the and-gate (A). Consequently, the counter stops after having counted the number of pulses occurring during the time period from the transmission of the second sound pulse to the reception of the corresponding bottom echo. A counting frequency of 400 pps, delivered by the digital clock, has been chosen in order to have the uncorrected depth-reading directly in fathoms. As the flip-flop is reversed to its " stop " position, the scanner command circuit is triggered and makes the scanner successively connect the four decade counters (of the frequency counter) to the punch. The scanner command also gives the punching orders to the punch. As soon as the data are punched on the paper tape the DDR is ready for a new cycle. The repetition rates selected for the DDR are 10 sec, 30 sec, 1 min, and 5 min.

The time to the nearest second, delivered by the digital clock, is punched every hour. As for the Loran unit, the time is punched automatically if the DDR repetition rate is changed.

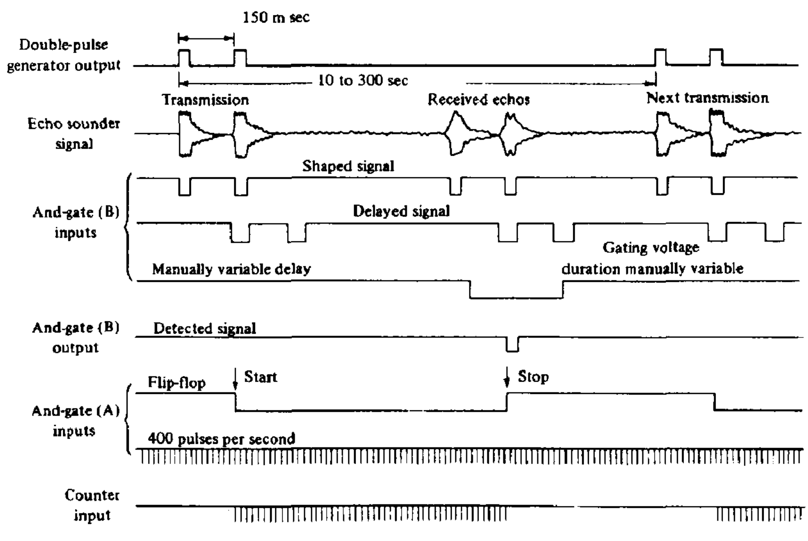


FIG. 9. — Digital depth recorder — some waveforms.

Some waveforms from the DDR are given in fig. 9. From the top, the waveforms shown are :

The output of the double pulse generator;
The output of the echo sounder receiver;
The inputs of and-gate (B) : the shaped signal,
the delayed signal,
the variable gating voltage;

The detected signal on the output of and-gate (B);
The inputs of and-gate (A) : the flip-flop output,
the 400 cps from the oscillator;
The input of the frequency counter.

The repetition rate selector, apart from triggering the double-pulse generator, also synchronises the exponential waveform generator, which again varies the gain of the time-variable gain amplifier.

Sometimes the amplitude of the received echo pulses is not large enough to trigger the pulse shaper. In this case the frequency counter will go on until the count is 3 000. At this count the and-gate (C) will open and the pulse thus generated will pass through the or-gate and reverse the start-stop flip-flop. Consequently, the reading of the counter will be 3 000 fathoms and the computer will be instructed to regard this as " No echo received ".

Four Nixie tubes with decoders are connected to the counter and visually display the depth in fathoms.

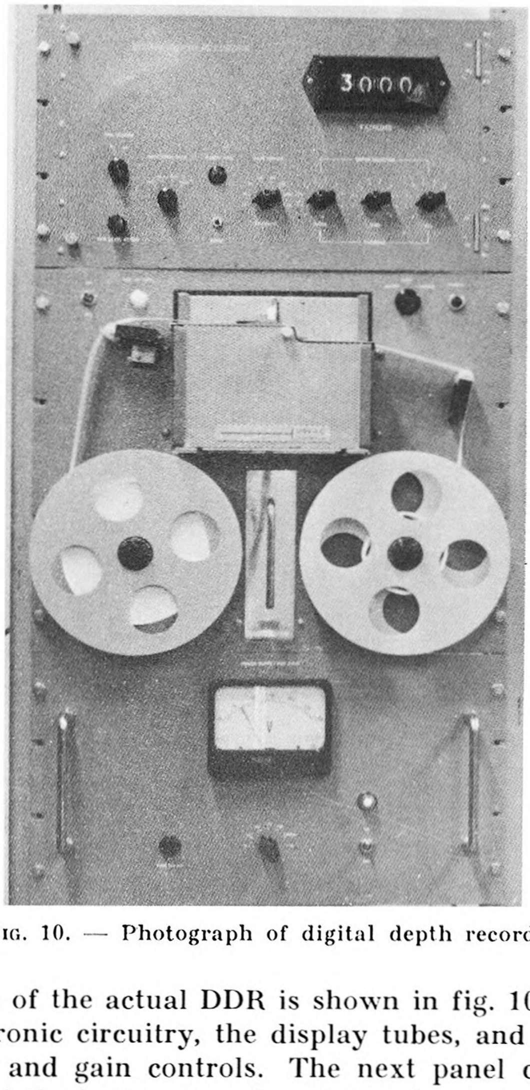


FIG. 10. — Photograph of digital depth recorder.

A photograph of the actual DDR is shown in fig. 10. The upper panel contains the electronic circuitry, the display tubes, and the repetition rate delay, gate width and gain controls. The next panel contains the punch with its driver and the bottom panel contains the power supplies.

Printed circuits have been used throughout, and the logic components are Philips circuit blocks.

6. — TREATMENT OF THE DATA

All of the recorded data contain errors which arise from various causes. In the case of the depth recording there can be missing or false echoes. For the magnetometer bursts of noise can cause an erroneous frequency measurement and, for Loran-C, atmospheric noise or skywave reception can cause erroneous recordings. By recording in a systematic form the data are amenable to editing and filtering processes on the computer.

The increase in the atmospheric noise level at night causes the Loran readings to "dither" so that observations made at infrequent time intervals will be slightly in error. This effect is clearly seen in fig. 7 where the top trace represents continuous recordings of both X and Y made at night in the Tyrrhenian Sea and the bottom trace represents recordings made during the day in the same area.

From an examination of the Loran recorded traces and of the ship's tracks recorded on a gyro-recorder, it was concluded that, for a ship attempting to follow a straight course, oscillations of a period of about 10 minutes or greater were more likely to be due to real motion of the ship and that apparent oscillations of periods much less than 10 minutes were likely to be introduced by noise. Although the choice of 10 minutes may be rather arbitrary it is probable that the dividing line lies somewhere between 7 and 15 minutes.

To smooth the data a moving average was made over 10 successive observations taken at 1-minute intervals. The equation of the best straight line through the points was calculated by the method of least squares. The calculated gradient of the line was used to determine the smoothed interval between the two mid-points of the line. The first point was then dropped, the eleventh point introduced and the process repeated for points 2 to 11. The process continued in this way for all observations — each smoothed value being derived from a new calculated gradient and the previous smoothed value.

The positions plotted on the Electroplotter and shown in fig. 15 were smoothed by this method. Comparison between a plot of observed readings during the night and smoothed positions is shown in fig. 11. Figure 12 shows more clearly the results of the smooth process for 15 hours recording. The top two traces represent the plotted differences, in tenths of microseconds, between the recorded X and Y values and the smoothed values. The third trace represents these differences converted into metres. There is a notable decrease in the corrections from night to day. The bottom trace shows successive first differences in distance between the smoothed geographical positions. A remarkably high relative accuracy is achieved — successive positions vary by no more than 10 metres.

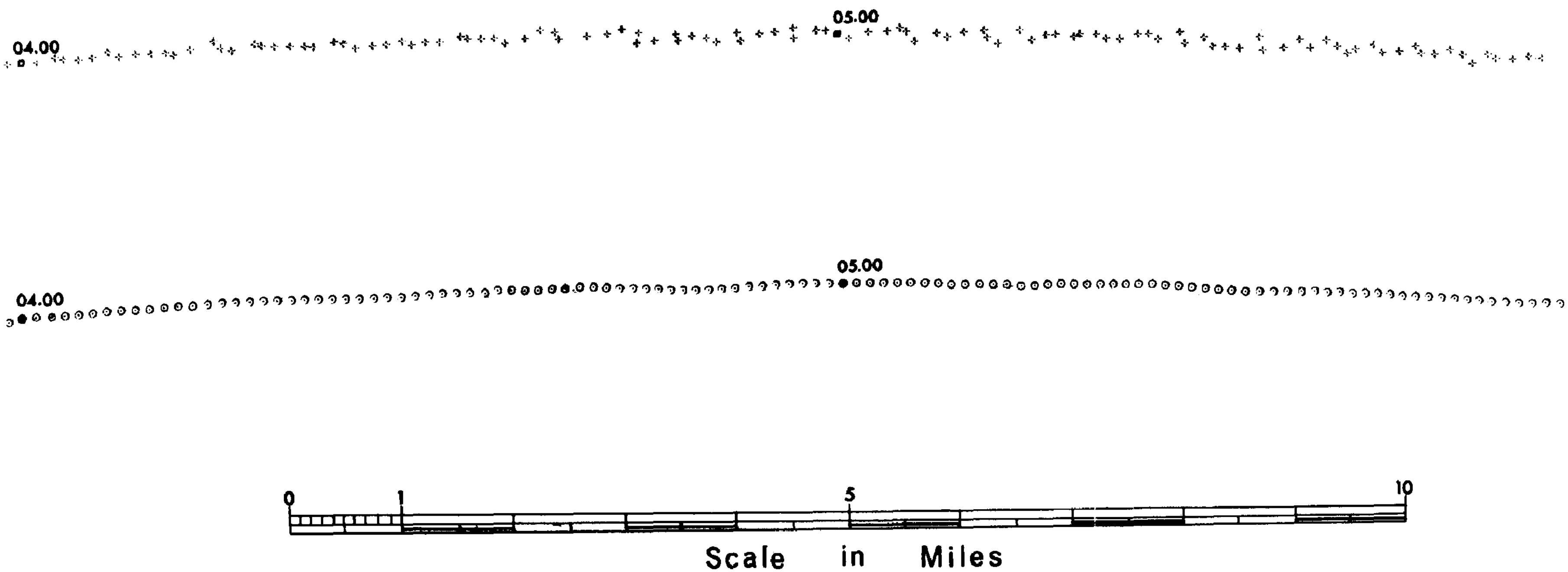


Fig. 11. — Comparison of smoothed and unsmoothed plotted Loran positions along one profile.

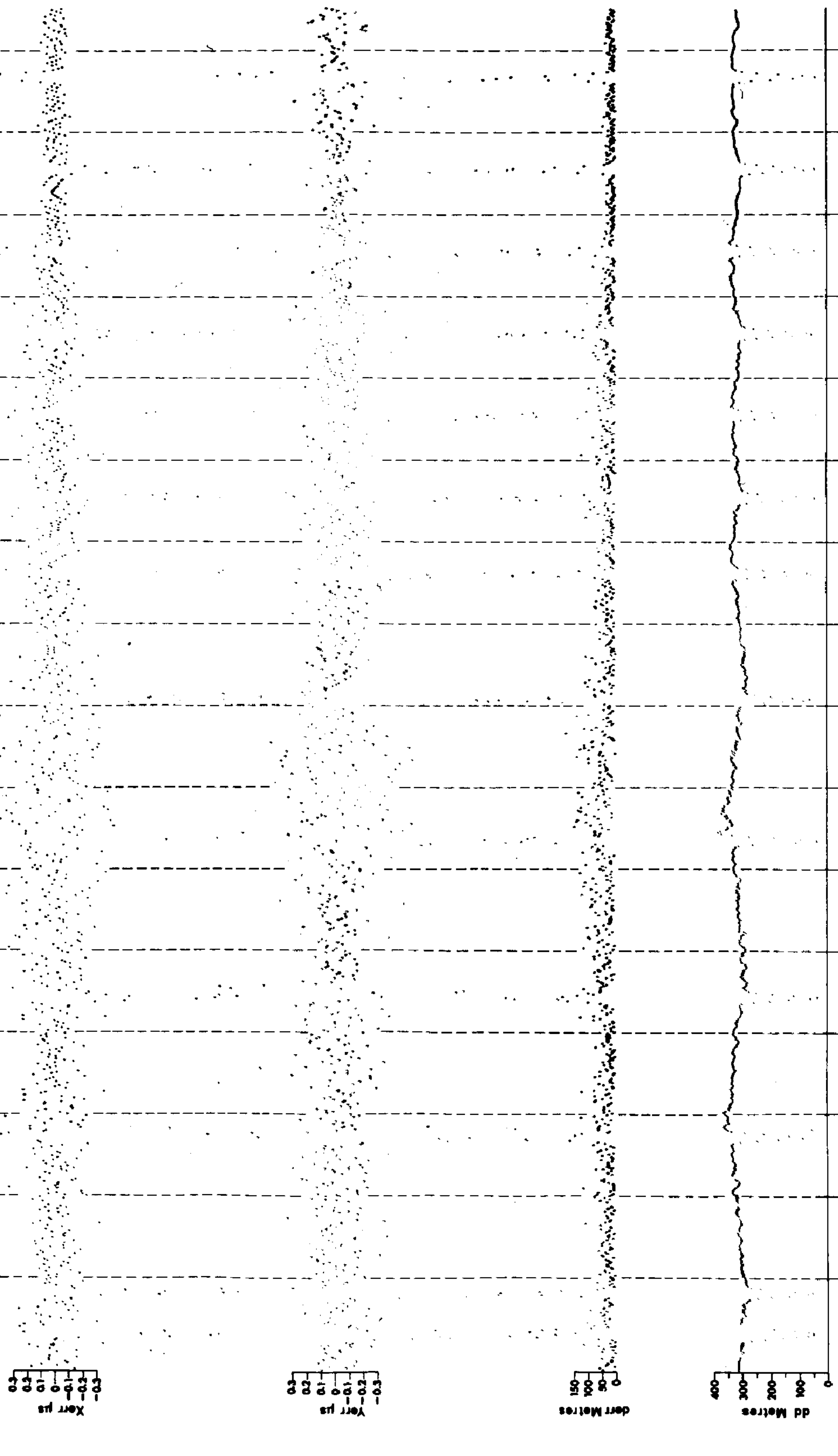


FIG. 12. — Effect of smoothing Loran observations. The top two traces show differences, in tenths of microseconds, between observed and smoothed X and Y values. The third trace shows differences, in metres, between observed and smoothed positions. The bottom trace shows differences between successive smoothed positions.

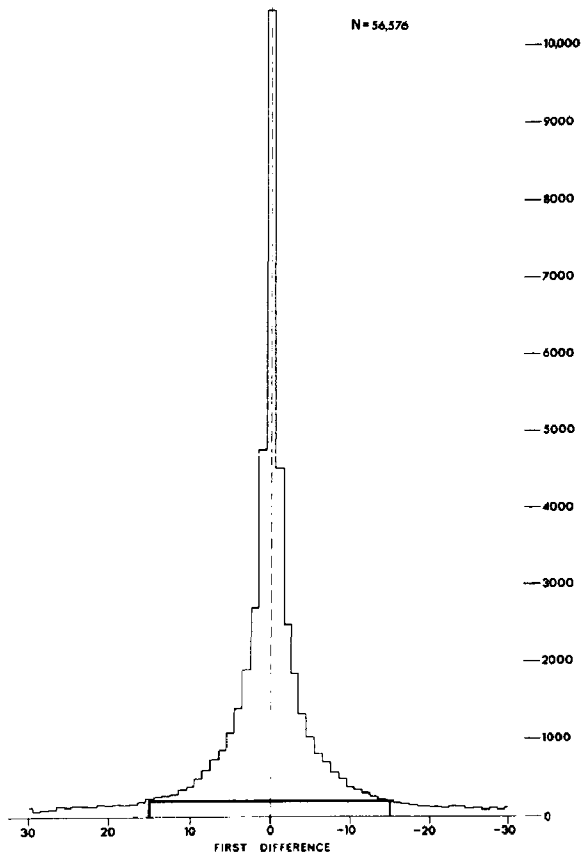
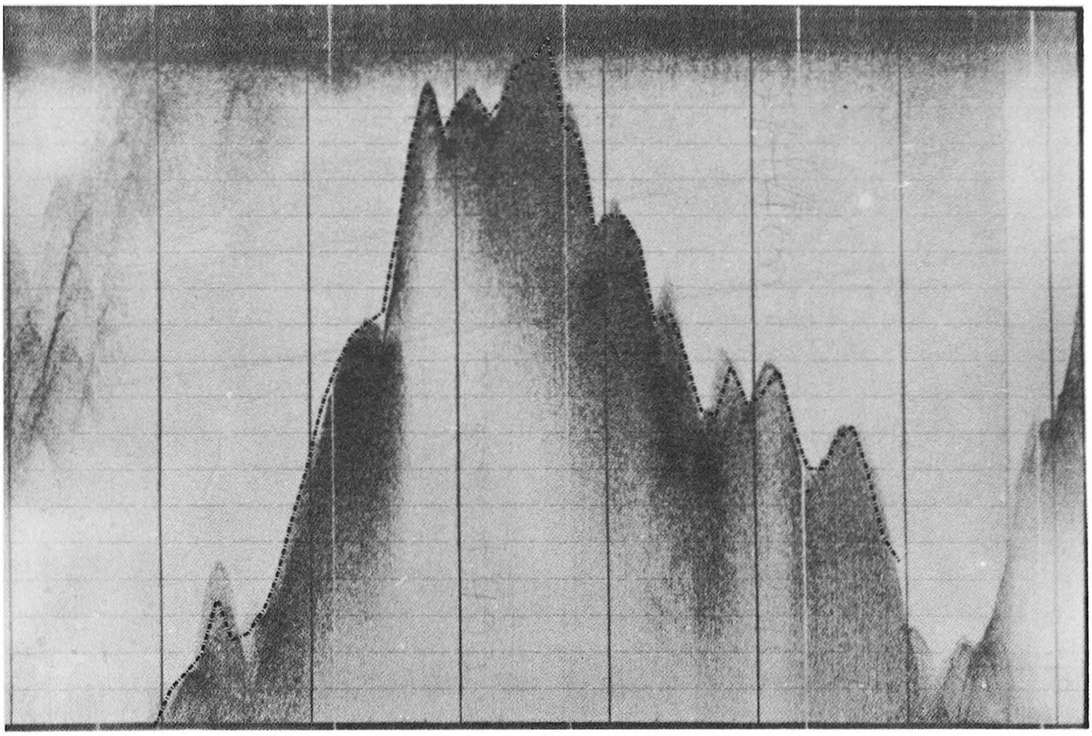


FIG. 13. — Histogram of first differences between successive digital depth recordings made every 10 secs over a period of 7 days. From this plot it was decided to set a limit of ± 15 fathoms on aceeptable first differences for editing the tapes.

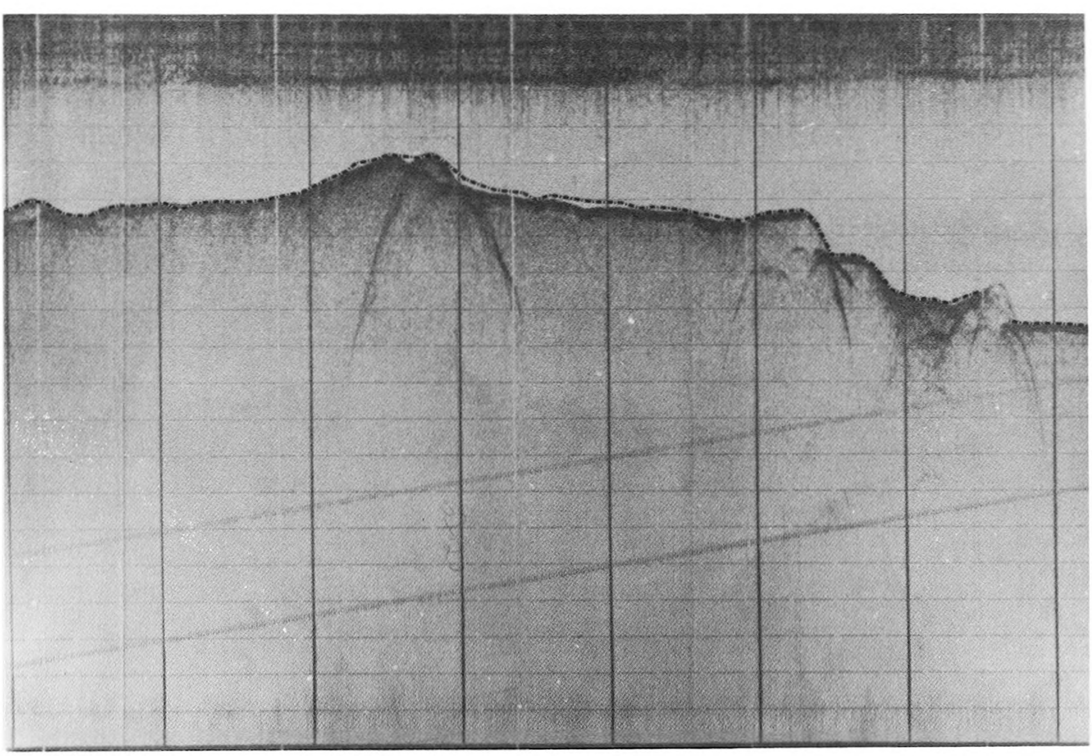
A histogram of differences in successive depths recorded every 10 seconds during a 7-day survey is shown in fig. 13. The histogram was made on the raw data before editing. From this analysis it was decided to accept readings with first differences in the range ± 15 fathoms. This value is in good agreement with the calculated acceptable difference for a ship's speed of 10 knots and an echo-sounder transducer beam half-width of 30°. Subsequently depth recordings were edited based on acceptable first and second differences. It was found that editing deleted approximately 15 % of the readings.

Magnetic field measurements were edited in a similar way to the depth recordings though in this case the percentage of erroneous recordings was less than 1 %.

When the edited tapes of Loran, depth and magnetic field have been prepared it is a straightforward routine to relate position to the other parameters by relating the recorded times and to plot positions with corresponding depth or magnetic field value on an electroplotter. An example of 24-hour recording is shown in fig. 15.



a



b

FIG. 14. — Comparison of depth traces plotted from the paper tape recordings and the echo-sounding records for the same period (*a*) over rough topography in the range 400-800 fm.; (*b*) over smoother topography in the range 1680-1780 fm.

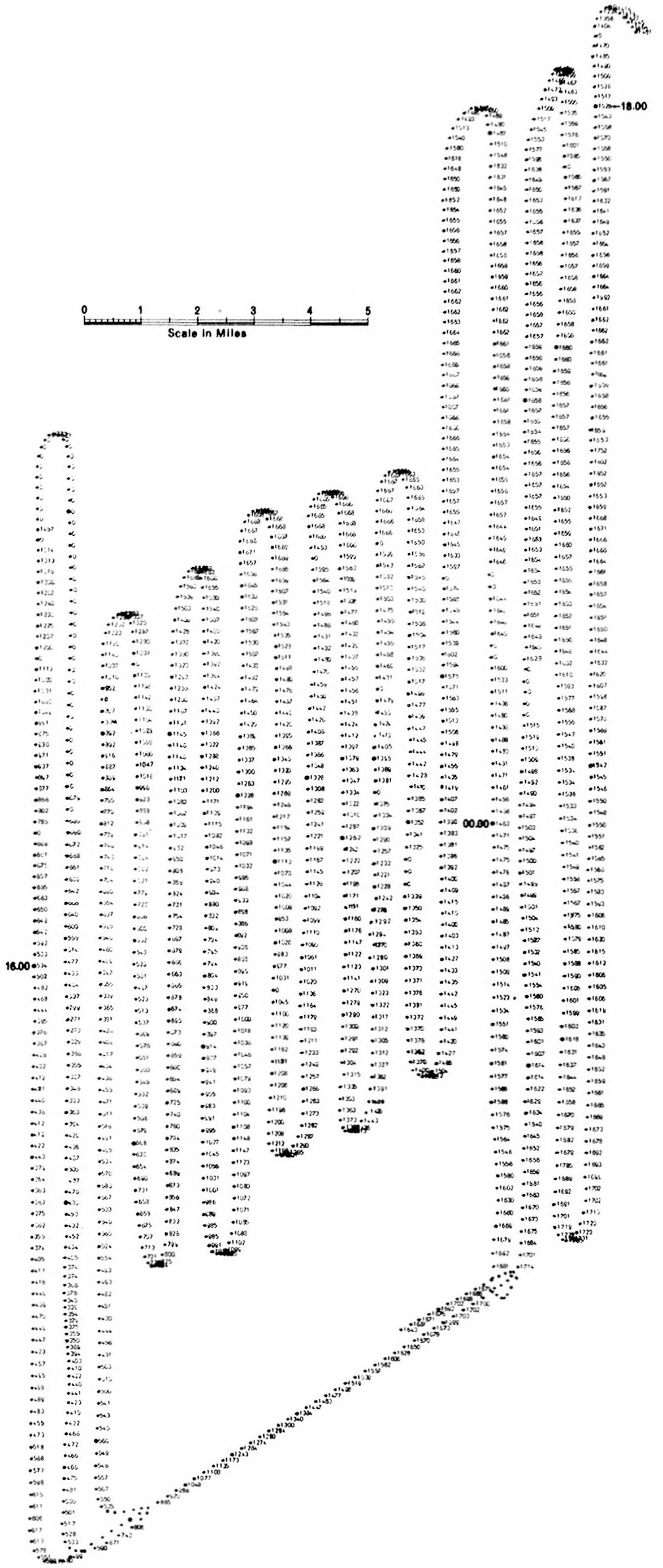


FIG. 15. — Plot of depths recorded every minute against Loran smoothed positions for a 24-hour period. The chart was prepared directly on an off-line electroplotter from tapes of Loran and depth readings.

7. — CONCLUSIONS

The automatic digital techniques for recording Loran-C, water depth, magnetic field and gravity, used successfully on R/V *Maria Paolina G.* since October 1966, permit quicker and more accurate data-processing than the manual methods previously used. By sampling more frequently than is normally possible when reading analogue records, the quality of the data is significantly increased.

The approach at SACLANT ASW Research Centre has been different in concept to that adopted by Woods Hole Oceanographic Institution and IBM and reported by BOWIN *et al.* (1967). No computer has yet been installed on *Maria Paolina G.* although this is planned.

At SACLANTCEN, first priority was given to the design of low-cost, digital recorders which would allow data-processing to be made on a land-based computer. However, it is felt that the necessary software that has been developed to handle the data, provides an essential step prior to the installation of a ship-board computer.

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