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A SHIPBOARD OCEANOGRAPHIC DATA PROCESSING AND CONTROL SYSTEM

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TECHNICAL REPORT

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Approved for Distribution ______________________
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ABSTRACT

In June of 1962 a digital computer (IBM 1710) was placed aboard the Research Vessel CHAIN of the Woods Hole Oceanographic Institution for real-time reduction of measurements of the earth's gravity and magnetic fields. This system has made it possible to automatically sample, compute, and record data concerning the ship's heading and speed, latitude and longitude, water depth, gravity in terms of total acceleration, free-air and Bouguer anomalies, and the magnetic field of the earth. The system was expanded in November 1963 to provide on-line plotting of bathymetric, gravity anomaly, and magnetic field profiles; computer control of gravity meter spring tension; processing of surface temperature measurements and ocean sound velocity measurements; display of ship's position and numerical data at remote stations aboard the ship and malfunction detection and alarm message generation. Experiments are being made using three remote input/output typewriters to improve collection, dissemination, and availability of scientific and navigational information logged during the course of a cruise. Three magnetic-disk storage units are used for data and program storage and provide the ability to merge real-time, on-line computations with background off-line computations (time-sharing).

The advantages of a shipboard computing system are: the automatic acquisition, computation, and recording of data; the availability of reduced data in real-time for use aboard the ship, thus providing increased opportunities for the development of scientific hypotheses at sea; provisions for automatic control of, and performance of checks on, scientific instruments, thereby saving scientists' time for creative work; and providing general purpose computation facilities aboard the ship.

INTRODUCTION

Oceanography is a branch of science that is rapidly expanding in national and international significance. The number of oceanographic institutions is increasing as well as their capacity for doing research at sea. In the field of geophysics, several technological developments in the last five years have made it practical to collect large amounts of bathymetric, gravity, and magnetic information during a single cruise, and the reduction of these data involve the processing of a similar amount of navigational information. It is difficult for analysis to keep pace with the collection of data at present, and it will become increasingly so without comparable changes in analysis techniques. This situation clearly calls for the utilization of a modern data-processing capability. The goal is to accomplish at sea as much data reduction, analysis, and interpretation as possible in order to most effectively utilize ship time.

Thoughts of a concept for a shipboard system led to collaboration between the Geophysics Department, Woods Hole Oceanographic Institution, and Federal Systems Division, International Business Machines Corporation, and the development of what we now call Shipboard Oceanographic Data Processing System I (described by Bernstein and Bowin, 1963; and Bowin, 1964[1]). The experience gained from this system led to a second contact between the Woods Hole Oceanographic Institution and International Business Machines Corporation for the implementation of Shipboard Oceanographic Data Processing and Control System II (ODPCS) which is described in this paper.

System I had the capability of automatically sampling the ship's heading and speed, two inputs from a shipboard gravity meter, and later, an analog input representing the three low order digits of the earth's total-intensity magnetic field (a five-digit number). Water depth was entered by the manual setting of remote switches. Logic and peripheral equipment were developed to relate the gravity, magnetic, and water-depth data with time, date, and latitude and longitude; to reduce the raw input data to

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1 An earlier non-computer, card-oriented, data-acquisition system utilizing remote manually-operated switches, output typewriters, and a modified card-punch was experimented with aboard R/V CHAIN, August to September, 1961 (CHAIN Cruise 21). This experiment was conducted through the cooperation of the Federal Systems Division, International Business Machines Corporation, and the Geophysics Department, Woods Hole Oceanographic Institution, and was initiated by R. Melville of IBM.

gravitational acceleration, and free-air and sea Bouguer gravity anomalies; and to record the desired values on a typewriter output and on paper tape in real-time. The typewriter record was for immediate use in checking the system, planning the future progress of the cruise, and interpreting the scientific results. The paper tape record was for possible later reprocessing of the data by shore computer facilities.

System II was developed to provide expanded capability in several areas and to improve the performance of the system and the utilization of the data collected. Added to the system were three magnetic-disk drives, a card read/punch, remote input and output typewriters, and a digital plotter. Display, alarm, and control capabilities were implemented, and the core memory was expanded to 60,000 character locations The paper-tape reader and punch were removed.

SYSTEM FUNCTIONAL DESCRIPTION

General

System II performs all the functions accomplished by the first system, and many others in addition (Figures 1, 2, 3, and 4). A digital plotter automatically produces on-line, fully-annotated profiles of bathymetry, free-air and Bouguer gravity anomalies, gravity Browne correction, and the earth's total intensity magnetic field (Figure 5). A digital feedback-control system provides automatic control of the gravity meter. Previously,

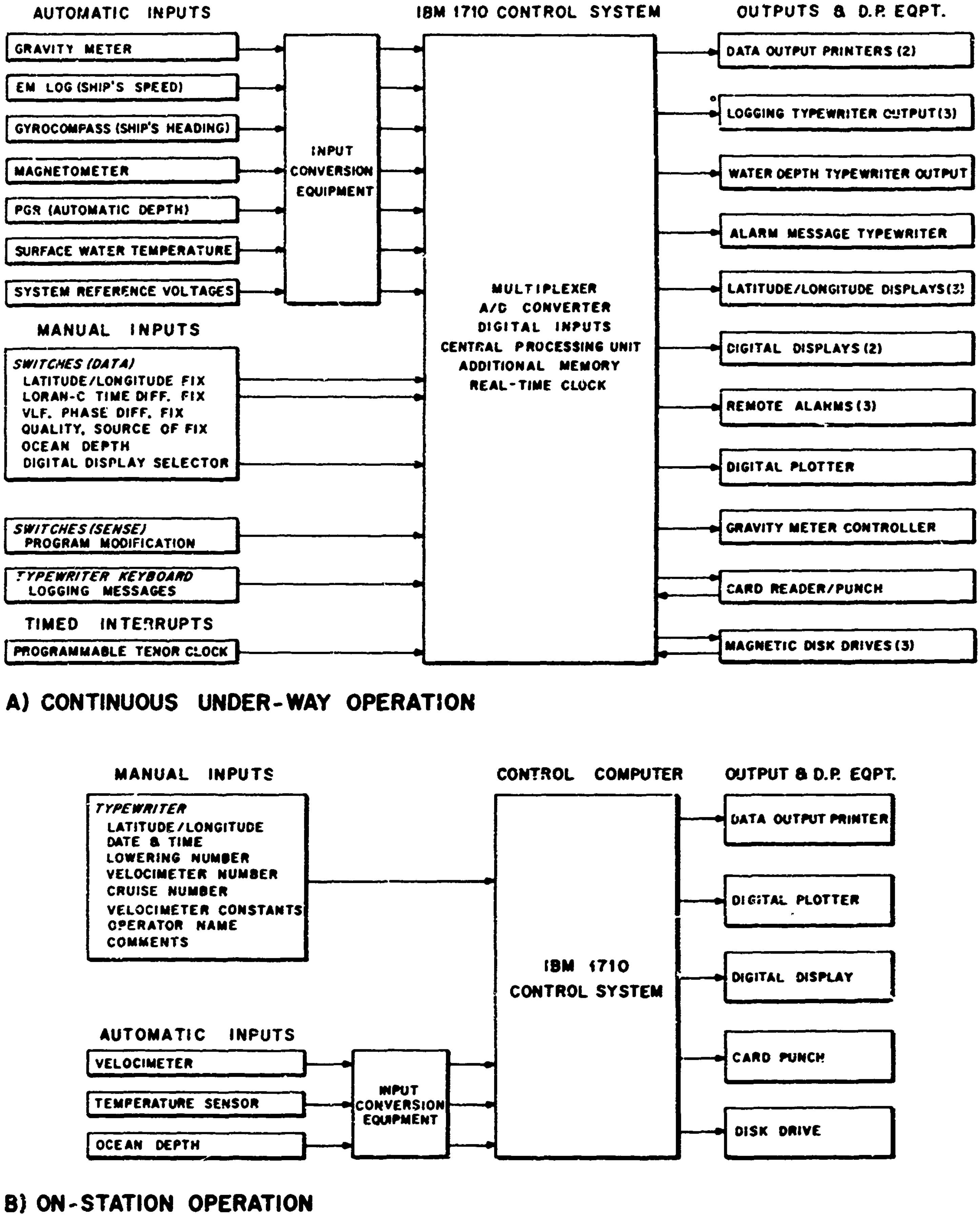

Figure 1. Block Diagram of the Oceanographic Data Processing and Control System aboard the R/V CHAIN.

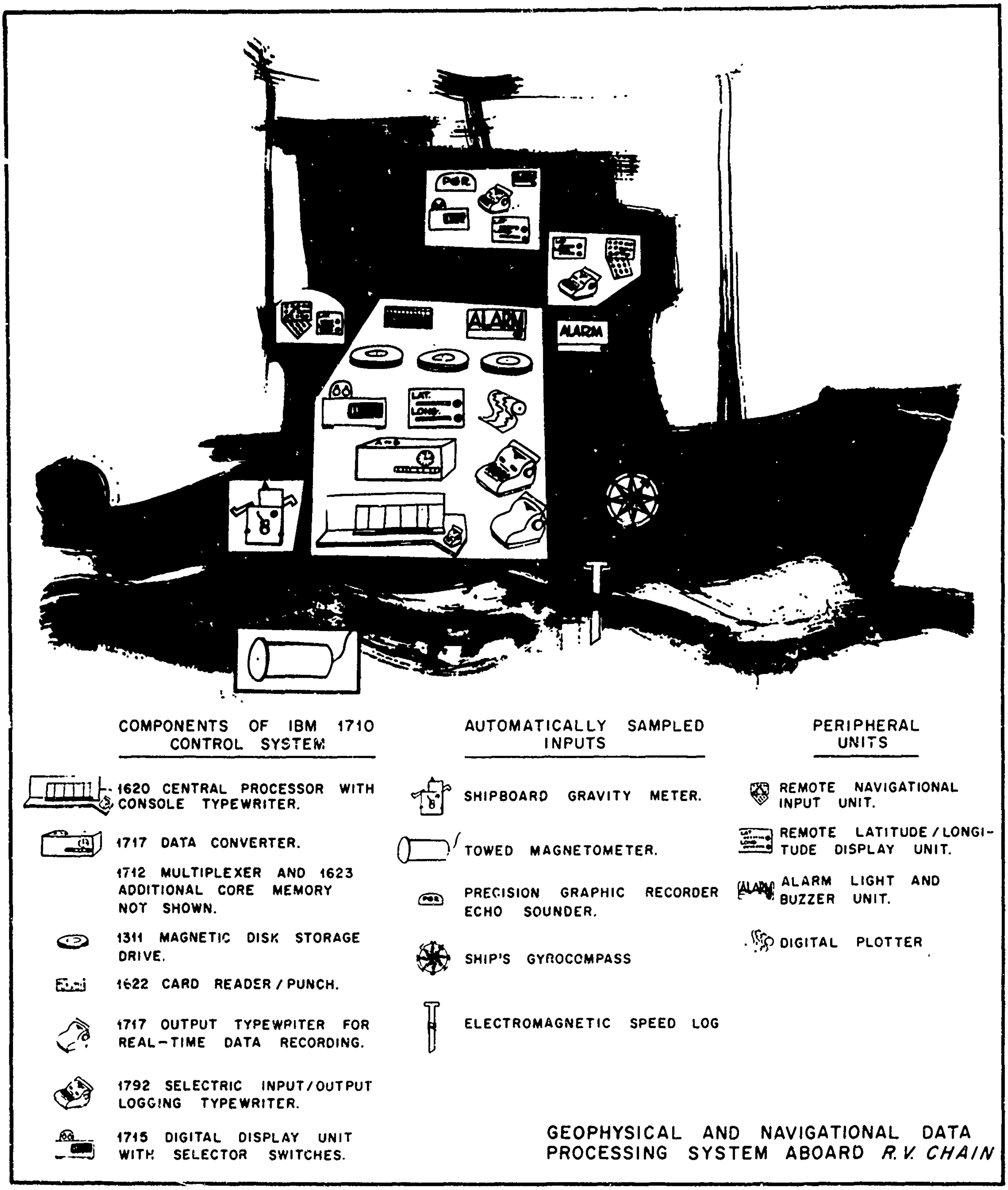

Figure 2. Diagrammatic Representation of the Oceanographic Data Processing and Control System aboard the R/V CHAIN Showing Relative Location of Components.

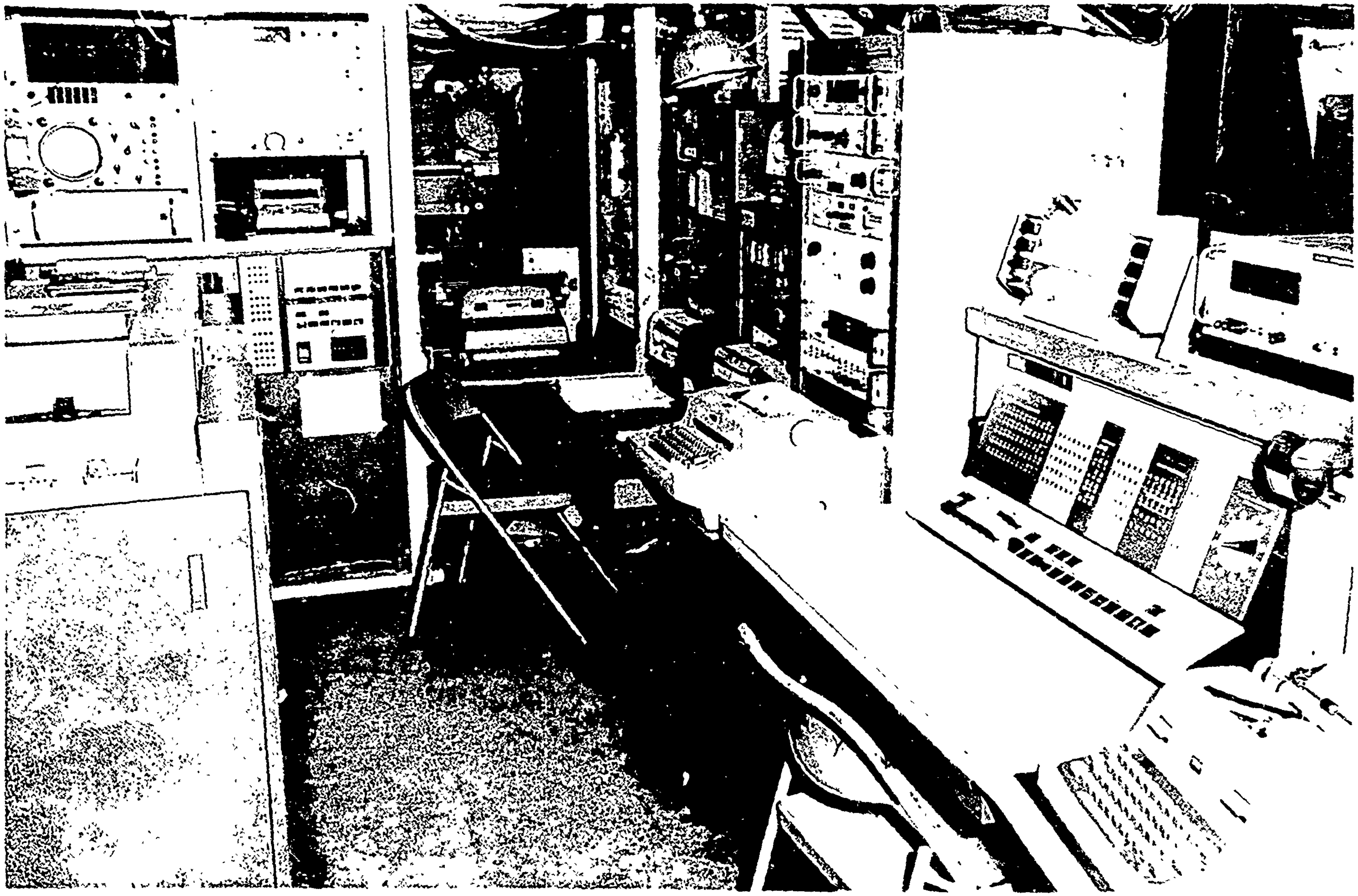

Figure 3. Photograph of System in Main Laboratory on R/V CHAIN.

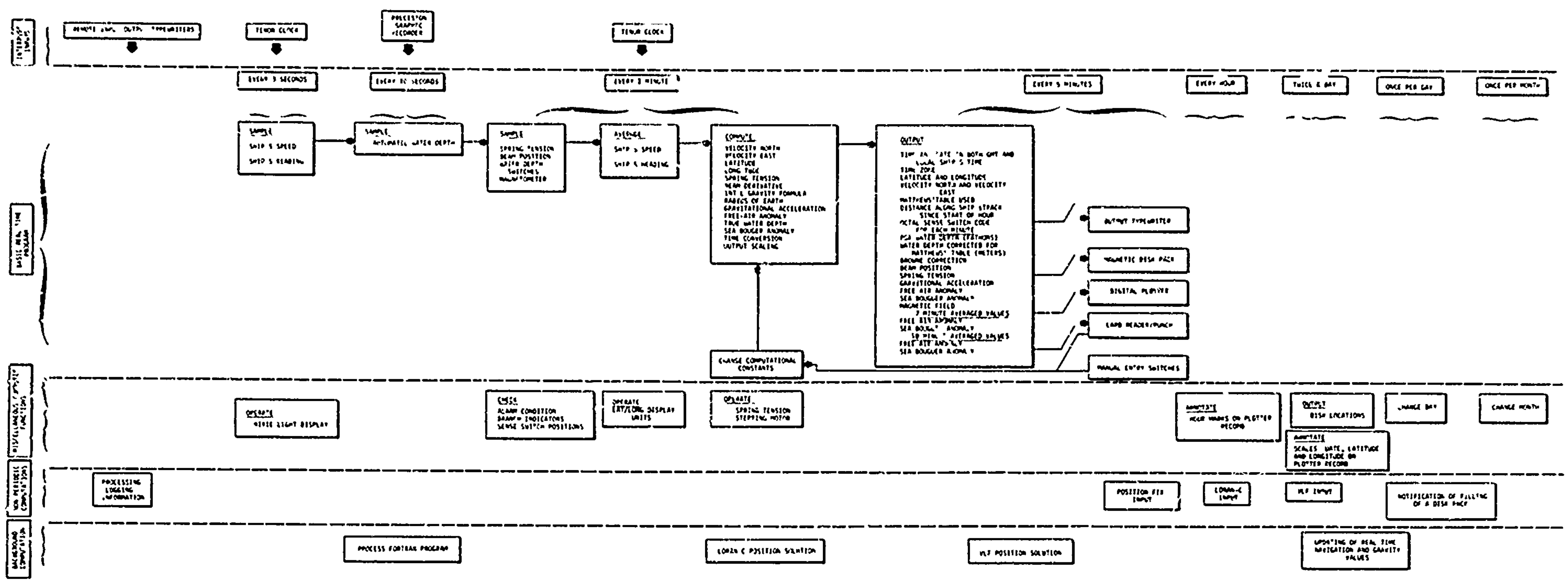

Figure 4. Outline of Computer Operations.

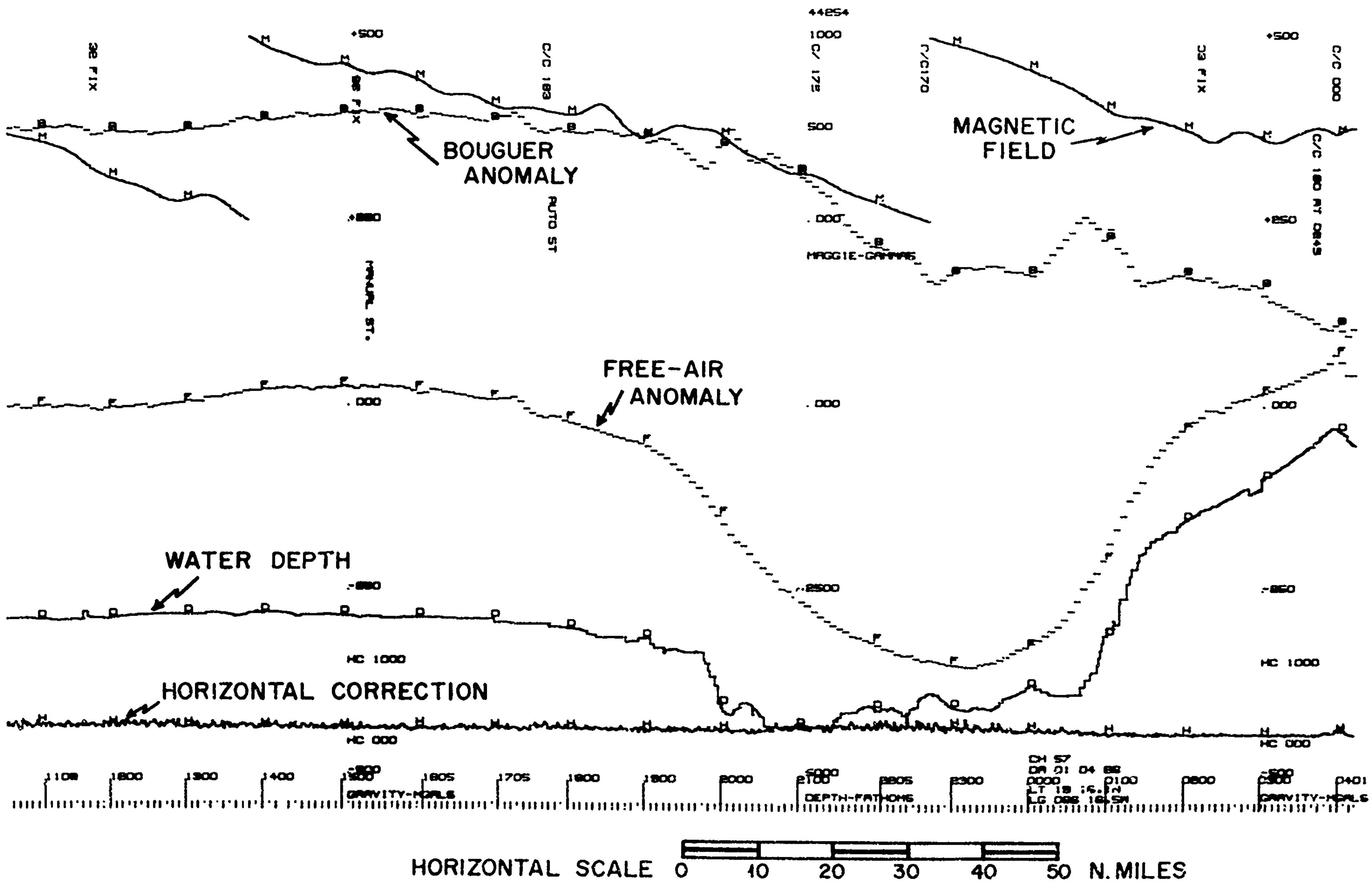

Figure 5. Example of Record Produced in Real-Time by Digital Plotter.

this function had to be performed manually and required the operator's periodic attention. Remote display of computed latitude and longitude has been added, and provisions for the display of any computer variable in real-time at other laboratory locations on the ship have been made. Three peripheral input/output typewriters situated at key locations on the ship serve as scientific log terminals and are used for the collection, coordination, and dissemination of scientific and navigational information messages logged during the course of the cruise. An output printer provides the display of computed data every five minutes (Figure 6), and these data are also recorded on a magnetic disk storage unit for later processing operations. A second disk storage unit is used for the storage of logged information, and a third serves as storage for the programming systems and makes possible a greatly expanded use of the computer's core memory, thus permitting the implementation of program time-sharing. Another output printer in a remote laboratory records the water depth in fathoms at one-minute intervals, and in fathoms and meters corrected according to Matthews' tables (Matthews, 1939). Erroneously entered water-depth values can be corrected at sea by the use of a special set of data insert switches. The console input/output typewriter is used for program initialization, recording program changes, and the type-out of alarm messages. The card read/punch is used for program and data loading and optional data output. The system includes an automatic malfunction-monitoring and alarm capability.

FORMAT OF DATA RECORDED EVERY 5 MINUTES

CHAIN CRUISES 43, 44, 46, 47, 52, 53

R 28 09 65 1813 04	0423	00798	015	P1950	07402	979311.4	M047.2	M046.9	52387
30 16.1P 078 55.4P	0423	00798	015	P1943	07402	979312.5	M046.2	M046.8	52385
P01.06 M07.47 01.3	0423	00798	015	P1948	07402	979312.4	M046.3		52386
23 09 65 2213 12	0423	00798	015	P1948	07402	979312.4	M046.3	P013.2	52394
000124 M000 P00.41	0423	00798	015	P1953	07402	979311.3	M047.4	P013.1	52381

VALUES EACH MINUTE — TIME AVERAGED VALUES

R 28 09 65 1813 04	IDENTIFICATION CHARACTER, DAY, MO, YR, TIME, TIME ZONE
30 16.1P 078 55.4P	LATITUDE (P=NORTH M=SOUTH)---LONGITUDE (P=WEST M=EAST)
P01.06 M07.47 01.3	VELOCITY (P=N M=S), (P=E M=W)---DISTANCE ALONG TRACK
23 09 65 2213 12	GMT, DAY, MO, YR, TIME, DEPTH TABLE
000124 M000 P00.41	OCTAL CODE OF SENSE SWITCH POSITIONS---GRAVITY PARTIAL DIFFERENTIAL RATIO---BEAM DERIVATIVE

0423 0423 0423 0423 0423 — PGR READING UNCORRECTED FATHOMS

979311.4 979312.5 979312.4 979312.4 979311.3 — GRAVITY IN MILLIGALS

CORRECTED METERS — 00798 00798 00798 00798 00798

M047.2 M046.2 M046.3 M046.3 M047.4 — FREE AIR ANOMALIES

BROWNE CORR. — 015 015 015 015 015

FREE AIR
7 MIN AVE M046.9
10 MIN AVE M046.8
BOUGUER
7 MIN AVE P013.2
10 MIN AVE P013.1

BEAM POSITION — P1950 P1943 P1948 P1948 P1953

MAGNETOMETER VALUE IN GAMMAS — 52387 52385 52386 52394 52381

SPRING TENSION — 07402 07402 07402 07402 07402

WATER DEPTH

GRAVITY METER INPUTS

MAGNETIC FIELD

COMPUTED GRAVITY VALUES

Figure 6. Format and Explanation of Data Recorded every Five Minutes.

Normal ship's power is notoriously subject to extreme fluctuations of voltage and frequency as generators, winches, electric fryers, and other equipment are turned on and off by conditions beyond the control of the computer operator. Temporary failures of the ship's power also are not uncommon aboard a ship. To provide a stable and reliable source of ship's power for the system, a 10 KVA solid-state SCR inverter (Power Sources, Inc.) operating off the ship's main DC buss is used. This inverter has been modified to provide a Reeves-Hoffman crystal oscillator for external frequency synchronization, resulting in 60-cycle power to an accuracy of better than 1 part in 10^6. Thus, all synchronous devices, such as clocks, pen recorders, and timing devices, maintain an accurate time base. The inverter is also floated on-line with the ship's large battery bank (118 VDC, 1750 ampere-hours). Thus, should the ship's DC generators fail temporarily, current is immediately supplied to the inverters by the batteries, and the computer system is able to remain operative.

DATA ACQUISITION AND COMPUTATION

Date and Time Identification

An electronic real-time clock (RTC) of the IBM 1711 unit provides the system with the time of day to a resolution of one-hundredth of an hour. Since time in terms of hours and minutes is in more common usage, time data from the real-time clock is converted to these units. To avoid ambiguous identification, the real-time clock is set to Greenwich Mean Time (GMT), and the computer program uses GMT for all its computations. Local ship's time is computed and recorded on the basis of an operator entered time zone indication. The GMT date is set by the operator via manual entry switches, and the computer program updates the date by reference to the real-time clock.

The basic scan and computational cycles are initiated by contact closures occurring in a separate programmable interrupt clock. This clock (Tenor Clock) consists of a rotating drum with 31 columns of 60 holes around its circumference into which cams can be mounted. The drum is driven by a synchronous motor controlled by the precision 60 cycle AC power supplied by the 10 KVA inverter, thereby accurately making one revolution each minute. Thus, 31 independent timed signals with a resolution of one second can be generated. Cams have been positioned on three of the columns to generate a periodic three-second closure and a one-minute contact closure. The three-second closure provides an external interrupt signal to the 1710 that causes the operational program to branch to the analog input scan routine (see Figure 4). The one-minute external interrupt signal initiates the basic one-minute computational cycle. When five one-minute interrupt signals have occurred, the operational program initiates a five-minute output cycle, and all processed data is output on the typewriter, plotter, and disk.

Other columns on the Tenor Clock are used for control or display purposes. The magnetometer polarization cycle-time and duration is controlled by this clock, which synchronizes it to the basic program cycle. The reset of the quartz thermometer and various indicator displays for operator information are also actuated by this clock. Lights tell the operator of the gravity meter when he should manually change the spring tension so that the transient response equations used by the computer will be valid. Other lights indicate to the operator of the depth echo sounder that a one-minute scan and computational cycle is about to take place.

Navigation

Accurate navigational information is essential in locating the scientific measurements conducted during a cruise and in the subsequent reduction of gravity and magnetic information. This system performs dead-reckoning navigation by monitoring ship's speed and heading each three seconds, computing the incremental distance traveled north and east each minute, and updating the last ship's position by this incremental distance, taking into account the ellipticity of the earth. The ship's velocity components are also used to determine the Eotvos acceleration correction in the gravity computation. The computer's dead-reckoning position is periodically updated by manually entered position fix information. The incremental distance traveled is used in controlling the abcissa of the on-line plotted output, which then corresponds to the distance along the ship's track. The computer inputs for ship's speed and heading have been described previously by Bernstein and Bowin (1963). The linear potentiometer on the gyro repeater in the interface equipment has been replaced by a sin/cosine potentiometer, thereby reducing the computational load, and a calibration table for this potentiometer is stored in the computer program.

The dead-reckoning computation must be periodically reinitialized and checked against more accurate position information, which can be entered into the computer by the manual entry switches at the computer site itself, or from either of two remote input units. When fix information is received by the computer, it calculates the difference between this fix and the dead-reckoning position at the time of the fix, and outputs this information on the main-lab output typewriter and on the three remote input/output typewriters. These differences are used in judging the consistency of the fix in relation to previous fixes, and in helping the operator to decide whether or not to use the manually entered fix for updating the dead-reckoning navigation.

Latitude and longitude can be accepted by the computer from any source. Programs have been generated for the on-line processing of Loran-C and VLF microsecond delays, and the positions determined by these programs are similarily recorded on the output typewriters. This process is considerably faster and more accurate than manually plotting and reading Loran positions, and similar programming for Loran-A microsecond delays are in progress. All ship's position information which is processed by the computer is also stored on a magnetic disk, and these data disks may be later reprocessed using off-line programs to update the dead-reckoning navigation to agree with selected navigational fixes, thus improving the continuity of position information along the ship's track.

A major problem which is still unsolved is the accurate determination of instantaneous ground speed. The best available source of ground speed is the ship's electromagnetic speed log, but since it will be in error through any ocean currents that may be present, sets due to wind, or water turbulence along the hull of the ship, the desired accuracy of 0.1 knot will not be achieved as surface currents are generally greater than that. Indirect determination of ground speed from two navigational fixes may yield accurate values of average ground speed if the time between the two fixes is sufficiently long. However, even if fixes with an uncertainty of 0.1 nautical mile are available, at least two hours between such fixes are required so that the error in determining ground speed is within 0.1 knot. There have been rare occasions, however, when the computer dead-reckoning did not differ from navigation fixes by more than three nautical miles for periods of up to twenty hours. Continuous 0.1 knot accuracy in ground speed, even with inertial navigation systems, does not appear to be practical at the present time, especially in areas of rough bottom topography (local deflections of the vertical are produced, causing erroneous accelerometer readings).

Navigational position information can be obtained aboard the R/V CHAIN by means of Loran-A, Loran-C, VLF experimental equipment, celestial sights, radar, and visual sights.

VLF refers to a relative navigational system operative in the "very low frequency" radio band. The signals emanating from several VLF transmitters located in diverse parts of the world are monitored by receivers aboard ship. The received signal is compared with the output of a very accurate oscillator carried on the ship, and the phase relations between the oscillator and the VLF transmissions are recorded. The change in phase relations (measured in microseconds) is used to determine changes in ship's position. The microsecond delay as indicated by the receiver-tracker is only relative, and must be determined with respect to a continuous tracking period. After any break in tracking, position must be determined by some other means, and the VLF delay time re-referenced (Baltzer, 1963; Stanbrough and Keily, 1964). A description of an experiment in precise positioning of a ship at sea utilizing VLF radio signals and the ODPCS system is in preparation (Ruppert & Bowin).

Ocean Depth Profiling

A Precision Graphic Recorder (PGR) is used to record ocean depths which have been determined by acoustical methods (Knott and Hersey, 1956). Briefly, the PGR records the total travel time an acoustic pulse takes in traveling from the ship to the ocean bottom and back. These reflections of the bottom are recorded on chemical facsimile paper, and are shaded in proportion to signal amplitude. Ocean depth and bottom terrain are readily apparent on the record. In addition to the dominant bottom echo, other reflections which can be recorded include echoes from scattering layers and sub-bottom sediment layers.

The PGR has the capability of range or record gating; that is, the introduction of an intentional blocking of the echoes when the desired signal is not expected, thereby resulting in a less cluttered record of the bottom echoes. Interpretation and correction of the multiple reflection is performed visually by the operator. The operator can manually introduce ocean depth data into the system after visually determining the ocean depth from the chemical facsimile recording. A manual Ocean Depth Input Unit is provided for this purpose.

The ocean depth can also be obtained automatically through the use of an electronic system which measures the time interval between the transmitted ping and the received echo (Hess, 1966). Midwater target reflections which might arrive earlier than the bottom echo are eliminated by an automatic range gate system. Integration of the signal allows the bottom return to be more reliably detected in the presence of spurious noise. The computer program can further eliminate inconsistent and poor data by the comparison of the input data with analytically smoothed data.

To perform an accurate conversion from the measured travel time to true depth, the computer refers to a table which is applicable to the particular region of the ocean (Matthews, 1939). Fifty-two tables are stored on the disk, and the operator must keep the proper table for the region in core storage to make an accurate depth correction.

Gravity Measurements

The LaCoste and Romberg gravity meter provides an uncorrected relative gravity data input to the system. This relative gravity data is corrected within the computer for gravity meter non-linearity by means of a stored calibration table for Eotvos acceleration and meter elevation. By a comparison with readings made at a dock site where the value of gravity is known, the relative gravity value is then converted to an absolute gravity value. The difference between the observed gravity and a calculated theoretical gravity is called the free-air gravity anomaly. By introducing ocean depth, the Bouguer gravity anomaly is also computed. A moving average of the gravity data is computed for five and ten minute intervals. This averaging eliminates the effect of vertical environmental accelerations that are superimposed on the sensed gravity values as they have a mean value of zero on a surface ship.

Three changes in the gravity meter inputs have taken place since the reports of Bernstein and Bowin (1963) and Bowin (1964). The first of these was the addition of a third potentiometer to supply spring tension information to the computer with a resolution of one milligal rather than of 10 milligals. In April of 1965, a Veeder-Root counter with contact points and divider networks was installed in the gravity meter console to replace the potentiometer device as the spring tension input-converter. A sense switch option allows the operator to choose between the two modes for entry of spring tension information. As of November 1965, the counter-converter is the normal input device used. The third change is the addition (November, 1965) of an alternate beam-position input to the computer which is not biased by a voltage proportional to the Browne correction which normally occurs. This new beam position converter utilizes an operational amplifier rather than a cathode follower. The new input is used for operation in the automatic spring tension controller mode, and the original input is used during manual spring tension operation.

Magnetic Measurements

Measurement of the earth's magnetic field contributes to a delineation and understanding of the earth's structure. The application of the nuclear induction principle to the measurement of a scalar field intensity has been achieved in the Free Precession Magnetometer (Varian Associates). The principle of operation relies upon the magnetic intensity of the earth's field affecting the nuclear precession frequency of the hydrogen atom (contained in a towed "fish"). These frequencies are proportional to the magnetic field strength, and are in the range of 1000 to 3000 cycles per second. The magnetometer converts the frequency into a higher pulse rate and introduces the signal into a counter.

The computer accepts the contents of the counter on an interrupt basis whenever the value has been changed, performs a scale factor adjustment and stores the resulting magnetic data. Magnetic measurements are generally made ry six to fifteen seconds and values are stored by the computer every minute.

Surface Temperature Measurements

The temperature of the water near the surface is sensed by means of an enclosed quartz thermometer (manufactured by Dymec, DY-2801) that protrudes nine inches beneath the hull of the ship. Temperature is measured by using a small disc of quartz as a piezoelectric resonator. The resonant frequency of the crystal changes with temperature. This frequency change is converted to degrees Centigrade and read out on a six-digit Nixie display.

This input was added to the system in November, 1965, and because of the lack of an additional digital input channel, the temperature data is converted to an analog voltage (Hewlett-Packard Model HP 580A) which is sampled by the computer each minute and recorded on the data disk pack. The resetting of the quartz thermometer is controlled by the Tenor Clock, so there is always a valid number in the counter at the time of sampling. Plans are underway to time-share one of the existing digital input channels and thereby read the temperature data directly as a digital number.

Ocean Speed of Sound Measurements

The speed of sound in the ocean is measured using a velocimeter operating on the "sing-around" principle. The velocimeter is lowered into the ocean to obtain a profile of sound velocity as a function of depth. The device contains a sonar transmitter and receiver which are mounted a fixed distance from each other on the velocimeter frame. The transmitter emits an acoustic signal into the water which then travels to the receiver in a time that is proportional to the speed of sound in water. When the pulse is received at the receiver, self-contained electronics cause the transmitter to emit another pulse into the water so that the resulting transmission frequency will be directly proportional to the speed of sound in water. A digital counter is used to determine the average period of the resulting frequency.

To obtain a velocity profile, measurements are recorded while the velocimeter is being lowered into the ocean (Figure 1b). Depth data can be obtained in two manners. The first records the time interval of an "upside-down-pinger". That is, the travel time of an independent acoustic source whose signal emanates from the lowered unit and is reflected from the sea surface. This depth measurement is automatic. The second method is manual, requiring an operator to enter the depth of the unit from a PGR record, which displays the depth as a function of time on a continuous basis.

SYSTEM OUTPUT DEVICES

Four types of devices are used for recording and displaying the data processed by the computer system. These are a digital plotter, magnetic disk packs, a card read/punch, and several printers or typewriters.

Digital Plotter

A CAL-COMP digital plotter (Model 565) provides the system with a computer controlled on-line plot of selected system variables and alphanumeric annotation of the plotted record. The plotter consists of a carriage mounted pen with a single degree of freedom (y-axis), a rotating drum (x-axis), and a pen-up and pen-down control (z-axis). The carriage and pen steps are 1/100 inch in length, and operate at the rate of 300 steps per second. The x and y movements allow the construction of eight line segments which plot the desired variable or character.

Figure 5 shows an on-line, real-time plot of free-air and Bouguer gravity anomalies, magnetic intensity, and ocean depth as a function of distance along the ship's track over the Puerto Rico Trench north of San Juan, Puerto Rico. The variables were plotted by drawing a straightline segment corresponding to the five-minute instantaneous value or average of the variables. The horizontal scale (time), the vertical scale (gravity anomaly, magnetic intensity, and ocean depth) and the plot identification (cruise number, date and time, latitude and longitude) are all under computer control.

The plotter has been very beneficial to scientific analysis as it not only displays long term trends, but it also permits the correlation of one variable with another; such as the free-air gravity anomaly with ocean depth. Unusual or unexpected results are detected almost immediately, as are malfunctions in the system components.

Magnetic Disk Packs

Three IBM 1311 Magnetic Disk Drives with removable disk packs of storage capacity of 2 x 10^6 characters are used with this system. The first disk pack is used to store the IBM 1620 Monitor I system which includes the supervisor program, the FORTRAN II-D compiler, the SPS II-D assembler, and the 1620 Disk Utility program. The supervisory program provides control for the IBM 1620 Monitor I system as well as input/output routines. This disk pack is also used to store the Operational Program and subroutines, and up to nine time-shared programs. The second disk pack is used exclusively for storing the on-line acquired and computed data for later processing and listing. This capability allows recomputation in the event that better navigation data or calibration factor is available at some later time. Further, any off-line program can perform some specialized operation on the data such as contour plotting or correlation computation. At the present rate of data accumulation (500 characters per five-minute output cycle for 24-hour operation), a disk pack is filled in about 14 days. The third disk pack is used to record the logged data and messages which are entered by the ship's scientists and officers. This data can then be sorted by the computer for messages or data of desired subject matter.

Card Read/Punch

An IBM 1623 Card Read/Punch is used for a number of off-line and on-line functions. The off-line functions are the initial entry of the Operational Source program and time-shared programs, and for normal data processing I/O functions. The on-line functions include changes of system parameter values such as the spring tension proportional, derivative constants, and control interval; the initial entry of Loran-C and VLF station locations and propagation constants or for the selection of new stations; and for the provision of a data and control input terminal for time-sharing operation. The card punch is used for operational program data output in the event of a disk drive failure, and for data output during time-share operation. The cards are then interpreted by an IBM 870 Document Writing System which includes an output printer for listing the data on cards.

Printers

Two output printers and an I/O console typewriter are used for the typeout and display of data and malfunction messages. The first output printer is used to type out all accumulated and processed data relating to the operational program. This typeout is a fixed format (an example of on-line data with identification is shown in Figure 6), and includes all pertinent data necessary for both analysis and monitoring purposes. The column organization format has been particularily useful in that variables are easily identifiable.

SYSTEM DISPLAYS

The following paragraphs describe briefly the latitude/longitude displays, digital displays, malfunction indicators, and status indicators controlled by the system. These units have been designed to aid the operation and monitoring of the system, and to provide scientific and navigation information at remote locations of the ship.

Latitude/Longitude Displays

Five counter-type latitude and longitude displays are used at various locations to display the ship's present position. The computer updates the position every minute, and provides a convenient indication of ship's position to the ship's scientists and crew. The counters (Veeder-Root) contain hemispheric indicators (NORTH-SOUTH, EAST-WEST) and display latitude and longitude to a resolution of one-half a minute of arc.

Digital Displays

Numeric Digital Display Units are used to display any computer variable selected by an operator. The displays are four numeric digits plus a sign. A Display Selector terminal has provisions for the selection of any one of 98 commonly observed variables, and any other variable can be selected by entering the memory location of the variable to be displayed via the card reader and setting the Display Selector to either of two unique numeric positions. The computer will update the display unit every three seconds or every 30 seconds, at the option of the operator.

Malfunction Indicators

The system has self-monitoring and malfunction detection capabilities to assist the operator in evaluating the performance of the system. Conditions that are monitored include potentiometer reference voltages, scientific instrument power supplies, relay and stepping motor power supplies, analog to digital converter (ADC) reference voltage and a short circuit line. The check of the ADC provides an immediate indication of a need for recalibration. The continuous check of the system eliminates the possibility of operating the system for an extensive period of time under unobserved improper operating conditions. When a detected malfunction occurs, the system will turn on flashing lights, audible alarms, or both, at the option of the operator. Three Alarm Units are placed at strategic locations on the ship for this purpose. The system also types out on the console typewriter the cause of the malfunction indication, and in some cases instructions to the operator for remedial action.

Status Displays

A number of console lights are provided to indicate the current status of the system which are used during the operation of the program and for testing purposes. The indicators inform the system operator that a position fix has been entered from a remote input unit, of an automatic-depth data failure, when a manual depth input is sampled, whether the system is in the manual or automatic-depth mode, when position data is entered, and when the data has been accepted.

Data Logging Capability

Three computer I/O typewriter terminals at key locations on the ship are used to implement a coordinated data logging system. The terminals serve as log stations, and the computer and the magnetic disk pack as master log book. In the past, scientists and ship's officers each had a log book into which they recorded their observations and data. Various scientific equipment was also assigned log books into which the equipment operators wrote entries. At the end of a cruise, the log books were collected and then made available to people requiring the information. Copies for individual scientists necessitated photo-copying or some other duplication scheme.

Observations or data typed into any typewriter terminal are also typed at the other terminals as well as being permanently recorded on a magnetic disk pack. Each message is identified by a typed code, and the place and time of entry. Thus, at any later time, all messages of a given characteristic can be selectively sorted from the disk, giving any individual scientist a complete record of his experiment or observations.

To prevent the scrambling of messages, entry of a message on one I/O typewriter inhibits the entry of data from any other typewriter until the first message has been completed. Since the messages are accepted and repeated one character at a time, operators at the other terminals are aware that a terminal is in service.

On the average, a magnetic disk pack is filled with logged data in about 60 days.

Digital Feedback Control System

A digital feedback control system has been designed to provide automatic control of the gravity meter. The problem of control is in maintaining the gravity meter beam near its null condition, with zero slope (rate of change of beam position) for changing gravity and acceleration conditions. This results in meter operation over the most linear operating region and increases the accuracy of the gravity measurements and computations.

The controlling variable is the gravity meter spring tension. Sampled variables are the spring tension and the averaged, or filtered, beam position. The function of the programmed digital control filter is to determine the proper corrective exitation pulses that must be applied to the stepping motor, which are mechanically engaged to and control the spring tension, such that a desired control strategy is satisfied. Since the controlling processes and the stepping motors are discrete in nature, the controller is represented by a digital filter or sampled data transfer function. The derivation and discussion of this digital control system is given by Bernstein (1966).

PROGRAMMING SYSTEM

The programming system developed for the Oceanographic Data Processing and Control System (ODPCS) encompasses three major functions (see Figure 4 and Table 1): operational program, time-shared program capability, and off-line programs. During real-time operation, the program exercises an executive function in controlling the normal execution as well as the time-shared function. At all other times, the system is available for off-line programs under control of the IBM 1620-1311 Monitor I System. Off-line programs include those written specifically to aid data collection and reduction as well as those written to perform any desired computing function.

Operational Program

The Real-Time Section of the Operational Program is the nucleus of the system. This section collects, reduces, and outputs bathymetric, gravity, magnetic, and navigation data as well as providing a control of the On-Line Section (Table 1). The Real-Time Section also monitors all interrupts[2] originating from any source in the system. Some sources of interrupts are the Tenor Clock, the automatic depth equipment, and output devices requesting data from the program. Program operation is controlled by the occurrence of these interrupts, and the decision of what function should be performed is based on the external device requesting attention. For example, a signal from the Tenor Clock tells

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2 The IBM 1710 possesses the capability of suspending its normal processing function temporarily upon the occurrence of an interrupt signal from an external device, and to service this interrupt signal.

TABLE 1

OCEANOGRAPHIC DATA PROCESSING AND CONTROL SYSTEM PROGRAM FUNCTIONS

OPERATIONAL PROGRAM

Real-Time Section

Normal Gravity Computations
Automatic and Manual Depth
Magnetometer Reading
Plotting of Computed Data
Automatic Spring Tension Controller
Malfunction Monitoring and Alarm
Fix Entry and Acceptance
Dead-Reckoning Navigation
Latitude/Longitude Displays
Digital Displays
Normal Data Input/Output
Logging System
Date and Time Computations
Priority Interrupt
Control for On-Line and Time-Shared Programs

On-Line Section

Loran-C
VLF
Updating

OFF-LINE PROGRAMS

Monitor 1 Programming System

Plotting
Updating
Velocity Data Acquisition
KAC Determination
Spring Tension Converter Check
Long Distance Calculations
Reduction of Land Gravity Measurements

the program to scan various analog input points and perform certain calculations, or, an interrupt from the printer causes the program to type another character.

The Real-Time Section also controls the execution of programs in the On-Line Section. These programs were written specifically to aid navigation and to reduce real-time data shortly after it is collected. There are three programs available in this section, namely, Loran-C Time Difference Reduction, VLF Phase Difference Reduction, and Updating of Gravity and Navigation Data. The two navigational programs are called directly by the Real-Time Section whenever the operator enters data requiring reduction. The Updating program is called by the operator using the same procedure as a Time-Shared Program. Once an On-Line Program is called, it executes in the same manner as a Time-Shared Program except that the navigational programs return to a specific area of the Real-Time Section which formats the results for later use. This return is internal and operator intervention is not required for the performance of this function.

The Real-Time Section occupies all of the 60,000 core locations available on the IBM 1710 and also uses approximately 15,000 locations of disk storage. In addition, each of the On-Line Programs has 20,000 locations reserved for it on the disk, and space is available for nine other

Time-Shared Programs. Certain areas of the disk are used for temporary program, table, and constant storage, bringing the total disk area reserved for ODPCS to 410,000 locations; about 20% of one disk pack. The remainder of the disk pack is used for the Monitor I System and all Off-Line Program storage.

Approximately one-third of the Real-Time Program is made up of constants, and this area is kept in core at all times. Whenever an On-Line or Time-Shared Program is to be executed, the first 20,000 locations of the Real-Time Program are saved on the disk and the requested program is read into this area. When the entire Real-Time Program is required, it is read in and the Time-Shared Program is saved. When the Real-Time Program is finished, it is exchanged with the saved program, and Time-Shared execution resumes. On termination of the Time-Shared Program, the Real-Time Program is restored to its original status. During this entire process, all interrupts are recognized and serviced, just as if the Realtime Program were alone in core.

Logically, real-time operation breaks down into three basic cycles:

1. three-second interrupt servicing
2. one-minute interrupt servicing
3. five-minute output cycle

The three-second and one-minute interrupts are generated by the external clock. When they are recognized, control is passed to the appropriate routine. During the three-second interrupt, speed and heading are scanned and averaged, the digital displays are activated, fixes may be accepted, and a Time-Shared Program may be started. During the one-minute interrupt, all inputs are scanned, all gravity and navigational computations are performed and the values are placed in the output blocks. During the fifth one-minute interrupt, the five-minute output cycle takes place. At this time, the data from the last five minutes is printed, written on the disk and plotted. Any or all of these output options may be selected. Every hour, the present date, cruise number and disk addresses for data and logging information are typed on all typewriters of the logging system.

Whenever any of the above functions requires a program segment which is on the disk, it is read into core, executed, and replaced with the normal core program. All synchronous interrupts such as the logging system and the automatic depth equipment are handled whenever they occur, regardless of other system activity at the moment. If the data disk drive is inoperable, the program is still able to operate. The data may be punched on cards, although certain operations must be eliminated.

Time-Shared Program Capability

The computer is able to execute disk-stored non-process programs interleaved with the normal operational on-line program. Thus the system has a time-sharing program execution capability, which allows the computer to be used as a general purpose data processing system while at the same time performing its normal on-line, real-time function. Since the computer is actively performing data acquisition, computation, control, or data outputting only 50% of the time, the computer is thus available for use as a general purpose data processing system about one-half of the time. Scientists are thus able to develop and test data analysis programs a[illegible], and use the on-line computer for executing these programs. Programs that have been used for this purpose include the conversion of radio navigation data to ship's position, and the updating of collected data based upon position fixes. The computed data is output on the card punch, and listed using the 870 Document Writing System.

Any non-process program which is error-free and is less than 20,000 locations long can be executed using this system. The program is first translated into machine language and then written onto the disk by a special loader program. A Time-Share Program Card is punched which indicates the source language of the program and its storage location on the disk. To execute this program during real-time operation, the Program Card and any data cards are placed in the card reader. The operator then activates a switch indicating that he wishes to execute a program. The Program Card is read, the program is loaded and execution is started. If the operator wishes to terminate the program manually, he activates a switch and execution is terminated at the next three-second interrupt.

Off-Line Programs

Off-Line Programs may be executed only when real-time operation is halted. All Off-Line Programs, whether writtenespecially for ODPCS or not, are executed under control of the IBM 1620-1311 Monitor I System. This is a system consisting of a FORTRAN II-D Compiler, a Symbolic Programming System (SPS) II-D Assembler, and a Disk Utility Program for performing various data manipulations involving the disk drives. The system allows stacked input jobs and a variety of output processing options. Programs may be stored permanently on the disk and called into core for execution in a very short time. Large programs may be segmented into many core loads providing a big machine capability on a relatively small machine.

Some of the ODPCS Off-Line Programs are:

1. Off-Line Plotting Programs
2. Off-Line Updating Programs
3. Velocimeter Data Acquisition Program
4. KAC Gravity Meter Calibration Program
5. Spring Tension Converter Check Program

Each of these programs is described in the following sections:

Off-Line Plotting Program

There are two versions of this program, one for disk input and the other for card input. The purpose of these programs is to provide a plotted record, on an off-line basis, of data previously collected during real-time operation. The plots a: e annotated identically to the real-time plots, except that comments may not be put on the graphs. In addition, if the data is from an updated disk, the letter "U" is appended to the cruise number.

Off-Line Updating Program

The Off-Line Updating Program is used to recompute gravity data and to update the scientific data for position, based upon the position fixes. This is accomplished by assuming that the deviation between selected fix points and the dead-reckoning position is due to current and wind set. The average "drift" is then computed and this velocity term is added to the ship's velocity vectors obtained since the previous position fix.

Velocimeter Data Acquisition Program

The velocimeter program is used to acquire, compute, display, and record ocean speed of sound data as a function of ocean depth.

The original and processed data is stored in its entirety on a magnetic disk pack for later additional processing. A numeric digital display is used to monitor the incoming and processed data while the system is operating. The on-line digital plotter is used to plot the speed of sound data as a function of depth. This provides a visual indication of the sensor outputs, which are used to monitor sensor performance, and also aids immediate interpretation of the measurements.

KAC Gravity Meter Calibration Program

An off-line program is used to calibrate the LaCoste and Romberg Gravity Meter. This is accomplished by periodically introducing under computer control a fixed spring tension change into the gravity meter and measuring the resultant change in the meter beam position. The beam position voltage is sampled by the computer five minutes after a spring tension change has occurred (to allow transient to die out), and then used to compute the calibration factor. The calibration factor is the ratio of the rate of change of beam position to the applied excitation. Each time the spring tension is changed, the calibration factor is computed, averaged with previously determined factors, and the information is typed out. A very accurate and reliable calibration factor is thereby determined automatically, and subsequently used by the operational program in the computation of gravity from the gravity meter data.

Spring Tension Converter Check Program

This program is an off-line program used to calibrate and check the performance of the spring tension converter unit. On operator request, the program samples the converter potentiometer output voltages, computs the corresponding spring tension component values, and types out the input data and the computed spring tension. The alignment of the unit is thus reduced to setting the spring tension to a predetermined value, and adjusting the potentiometer such that the proper voltage is read out. The program is stored on the program data disk, and is read into memory on an operator request basis.

SIGNIFICANCE OF A SHIPBOARD COMPUTING SYSTEM

The primary purpose of taking a computer to sea is to collect, process and store data, and to present the information, concurrent with its collection, to scientists on shipboard. There are two prerequisites: the data must be interrelated to the other scientific and navigation information, and it must be in a form suitable for later processing or analysis. These needs are satisfied by a centralized data acquisition system. First, the data is output in a format permitting its correlation with other scientific observations and with relevant data such as position and time, and, second, by placing it in a digital form requiring no conversion for subsequent processing. The automatic acquisition of data is faster and more accurate than manual means.

Data which has been collected must undergo a certain amount of processing or reduction to be meaningful. In some applications, the data may require a scale factor change, averaging, or complicated mathematical operations before it can be used. Commonly, the data is correlated with data from another source. A researcher generally cannot evaluate data concurrent with its acquisition; this task is usually performed ashore, either manually or with the aid of a computer. Thus, scientifically interesting or significant regions may be discovered only after the data has been reduced ashore, often necessitating a return trip at great expense. On-line computer processing of the raw data eliminates this delay and expense, and allows scientists to monitor, assimilate, and evaluate the data at sea. In this way, the scientist maybe able to make preliminary hypotheses from the data at sea, and, he may modify the planned experimental schedule to include more extensive investigations. Reports of data collection, and, on rarer occasions, scientific papers, might be written at sea, significantly reducing the long delay between data collection and publication of the analyses.

Some data collected may prove worthless on reduction at the shore facility. This may be avoided, to some extent, by periodically checking important equipment voltages or parameters. Thus, many routine chores on a research ship involve the continuous monitoring and periodic control of equipment. However, these operations can sometimes be done more quickly and efficiently by the computer. With the necessary interface, the computer can be programmed to control scientific or navigational instruments, check important voltages periodically, compare these voltages with an expected range of values, and signal the operator when a detected abnormality exists. Thus, the scientist is released to plan and direct the current research, and to interpret results. Also, by reducing the data on-line, incorrect or unreasonable data is immediately obvious, and a prompt check of the scientific instruments can be made.

A computer is also useful on board a ship for general-purpose computation. Experimental data processing can be done, such as computations and rearrangement of data so that contours can be plotted, or the sorting or merging of data from various sources to detect marginally observable phenomena. If time-sharing is available, these non-process tasks can be done while the on-line program is underway.

RECOMMENDATIONS

During the three and one half years of its use, the digital data processing system aboard the R/V CHAIN has collected information along 170,000 km of ship's track, amounting to roughly 100,000 gravity values, each averaged over a 10-minute interval, or, 226,750,000 total bits of information. It would not have been practical to have calculated all of them without the assistance of a computer.

This is only the beginning of automating the recording and collation of oceanographic information collected at sea. The Geophysics Department at the Woods Hole Oceanographic Institution has under consideration the addition of the following capabilities: satellite navigation computation; automatic sampling, computation, and recording of continuous seismic profiling information, data from a deep-towed log, data from a thermistor chain, and meteorological information; computation of regional magnetic intensity values from spherical harmonic coefficients; a ship safety monitor system; possible automatic ship control; chart plotting on a second digital plotter eventually leading to automatic contouring of the collected information aboard the ship; and complete time-[illegible]ing facilities, including the ability to compile and assemble off-line programs without interrupting the operation of the real-time program. As these capabilities become realities, others will become of interest. Additional chemical, physical, geophysical, biological, acoustical, electromagnetic propagation, and water motion information is yet to be incorporated into an oceanographic data processing system.

Our experience over the last four years has suggested some basic requirements for a future shipboard data processing system. The successful and rapid processing of oceanographic information suggests that the need for a shipboard computer system with the capacity of a large machine (IBM 7090-type) is not far off. Versatility and flexibility of design are extremely important if the ability to follow up on experience is desired. Multiprogramming capability is essential, including the ability to time-share real-time and off-line programs. Programs should be written with a modular construction in a Fortran-like language with sampling and thereby permitting greater flexibility to modify and expand the program. Core memory should be made as large as practical; the tendency is for the best estimates to be too small. Equipment and programs should be developed that will prevent failures in peripheral units or external input units from halting or destroying the operation of the computer system.

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13. ABSTRACT In June of 1962 a digital computer (IBM 1710) was placed aboard the Research Vessel CHAIN of the Woods Hole Oceanographic Institution for real-time reduction of measurements of the earth's gravity and magnetic fields. This system has made it possible to automatically sample, compute, and record data concerning the ship's heading and speed, latitude and longitude, water depth, gravity in terms of total acceleration, free-air and Bouguer anomalies, and the magnetic field of the earth. The system was expanded in November 1963 to provide on-line plotting of bathymetric, gravity anomaly, and magnetic field profiles; computer control of gravity meter spring tension; processing of surface temperature measurements and ocean sound velocity measurements; display of ship's position and numerical data at remote stations aboard the ship and malfunction detection and alarm message generation. Experiments are being made using three remote input/output typewriters to improve collection, dissemination, and availability of scientific and navigational information logged during the course of a cruise. Three magnetic-disk storage units are used for data and program storage and provide the ability to merge real-time, on-line computations with background off-line computations (time-sharing).

The advantages of a shipboard computing system are: the automatic acquisition, computation, and recording of data; the availability of reduced data in real-time for use aboard the ship, thus providing increased opportunities for the development of scientific hypotheses at sea; provisions for automatic control of, and performance of checks on, scientific instruments, thereby saving scientists' time for creative work; and providing general purpose computation facilities aboard the ship.

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