Columbia University in the City of New York

LAMONT GEOLOGICAL OBSERVATORY
PALISADES, NEW YORK

A DEEP-TOWED PROTON MAGNETOMETER

by
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Technical Report No. 7
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ABSTRACT

A proton precession magnetometer has been developed to measure the geomagnetic field intensity at the ocean floor. The instrument was built on short notice to support the search for the SSN Thresher and was operated at a depth of 1300 fathoms while being towed at two knots. A promising magnetic contact was made and verified by two subsequent crossings during about one hundred hours of operation and the instrument was not used further.

A brief description of the instrument construction and operation is presented and some salient design features of the electronics and deep-towed vehicle are discussed and illustrated.

CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

Prompted by the demand for instruments and techniques to aid in the search for the SSN Thresher, a proton precession magnetometer was designed and constructed to measure the magnetic field intensity at the ocean floor. The ability of a sensitive magnetometer to detect the presence of bodies exhibiting either induced or remnant magnetism is well known, making the instrument an ideal search tool - providing the sensing device can be placed sufficiently close to the vicinity of interest.

This report describes the construction and operation of a deep-towed magnetometer. The system was installed aboard the R/V Robert D. Conrad during the months of April and May 1963 and provided the necessary coverage for the search operation. Due to the short time available for design and test of this instrument major emphasis was placed on the selection of simple and reliable electronic circuitry, therefore a minimum of automatic features were incorporated.

A more sensitive bottom proton magnetometer using acoustic telemetry has been under development at this laboratory since early 1962 and will be operational in the near future. This instrument will be used primarily for the investigation of underwater time variation of the geomagnetic field and related phenomena. The simpler cable connected system herein described was chosen for its advantages in terms of time required to assemble and test an instrument of known characteristics which could be used with the maximum amount of existing equipment.

II. SYSTEM DESCRIPTION

The system utilized is essentially the standard proton magnetometer which has been in continuous use aboard Lamont vessels for several years. A block diagram of this system is shown in figure 1. Precision determination of the total geomagnetic intensity by measuring the frequency of free precession of protons was initially described by Packard and Varian (1954) and has since come into widespread use. Several sources are available which describe the instrument basic operation as well as various types of supporting electronics equipments. See, for example, Waters and Francis (1958), and Warren and Vacquier (1961).

Figures 2 and 3 show how the basic components have been distributed for deep-towed use. Briefly, the system employs a 20,000 foot length of coaxial cable as the connecting link between a towed vehicle containing the underwater electronics package, housed in a pressure cylinder, and the remainder of the equipment on shipboard. This package is in turn connected to the sensing coil via 210 feet of two conductor cable.

Coupled to the magnetometer cylinder is a second pressure cylinder containing a 12 kilocycle pulsed acoustic transmitter "pinger" which transmits once per second. The spacing in time between the directly received pulse and the bottom echo, as monitored on a precision depth recorder, is used to maintain the towed vehicle at the desired height above the bottom.

III. CIRCUIT DESCRIPTION

A. General - A description of the portions of the instrument which have been in use for some time will not be attempted. Instead, those items developed for use with the deep-towed instrument, or those of unusual interest will be described. The commercially available component equipments are listed in the appendix.

B. Input Circuit (Fig. 4a) - The input circuit consists primarily of the inductance and resistance of the sensing coil, and the tuning capacitors in the bases of the input transistors. Some additional elements, which by proper design can be neglected, are indicated in the figure. The three circuit elements, L, R_L and C_T comprise a series resonant circuit which provides a signal voltage output equal to the precession voltage induced in the sensing coil multiplied by the effective circuit Q. Circuit Q's of 100 or more are readily achieved and signal levels of 50 to 200 microvolts are typically available. The diode across the coil serves to damp out the destructive inverse voltage which would otherwise appear upon completion of the polarize cycle. The tuning capacitors are arranged such that they act as a differential signal source. Of the several types of input circuits studied and tested at this laboratory this arrangement is considered to be the simplest and the most efficient for this application.

C. Differential Amplifier (Fig. 5) - The differential amplifier consists of two transistors, Q201 and Q202 and their associated transformers. The transformer secondaries are connected series aiding. The circuit accepts a differential input with negligible loading and provides a nominal voltage gain of 25 db. It has a common mode rejection of greater than 40 db and delivers a single-ended output to emitter follower Q203.

D. Tuned Amplifier and Cable Driver (Fig. 5) - Two cascaded tuned stages provide most of the amplifier gain and selectively. Q301 and Q302 are identical tuned-collector stages providing over 60 db of voltage gain and a staggered-tuned 3 db bandwith of slightly greater than 150 cycles. Tuning capacitors C303 and C307 are selected for resonance at the expected precession frequency and contain proper ratios of ceramic and paper capacitors to minimize tuning drift with temperature. The cable driver stage, consisting of Q401 and T401, provides some voltage gain but serves mainly to couple the precession signal, at an appropriate power level, to the low impedance coaxial cable.

E. Programmer (Fig. 5) - An astable multivibrator serves as the timing device which establishes the length of time for which the sensing coil is polarized as well as the overall cycle time. Q101 and Q102 are used in a conventional saturating, free-running multivibrator. When Q102 is conducting it causes Q103 to conduct heavily operating relay K101. This transfers the coil to the polarize supply and begins a cycle of operation. During the off time of Q102, the coil is connected to the input of the tuned amplifier. R103, C102 and R105, C101 set the times as follows:

polarize time .... 2.5 seconds
amplify & quiescent time.. 9.5 seconds
total (cycle time) ...... 12.0 seconds

F. Power Supply (Fig. 4c) - The underwater electronics package is powered by a 12 volt, 12 amp-hour battery. The battery consists of thirty sintered plate nickel-cadmium cells arranged in a series/parallel arrangement. Ten cells rated at four ampere hours each are connected in series to give a nominal 12 volt supply; three of these banks are connected in parallel. One is tapped at midpoint to provide the six volts at 250 milliwatts required by the switching and amplifying electronics.

The life expectancy of this battery is determined almost entirely by the amount of current used to polarize the sample and the ratio of polarize to quiescent time for a cycle of operation. With the duty cycle employed, the battery provided as much as 19 hours of continuous operation at operating depth before becoming exhausted.

G. Cable Characteristics - The cable used to transmit the precession signal up to the ship is a coaxial line housed within two layers of spirally wound stress members. Some of its specifications are:

1.	breaking strength	7,200 lbs.
2.	attenuation @ 2.4 kc	1.34 db/n mi
3.	characteristic impedance @ 2.4 kc	100 ohms
4.	net weight in air	143 lbs/1000 ft.
5.	outside diameter	0.292 inches

The seaward end of this cable is terminated in a special fitting, insuring full use of the rated breaking strength and connects directly to the towed vehicle. The shipboard end is terminated in a slip-ring assembly, which is an integral part of the winch, permitting continuous instrument use during raising and lowering.

A two conductor shielded marine cable is used to stream the fish, containing the sensing coil, away from the electronics package. Here the most essential characteristic is complete freedom from magnetic effects of the conductors and shield. Some specifications of this cable are:

1.	breaking strength	800 lbs.
2.	conductor resistance	2.5 ohms/1000 ft.
3.	capacitance	
	a. between conductors	40 uuf/ft.
	b. conductors to shield	70 uuf/ft.

A 210 foot length is used which adds some 1.8 ohms (measured) in series with and 0.008 uf in shunt with the sensing coil.

H. Sensing Coil - The sensing coil consists of some 700 turns of #14 AWG enamel coated wire wound on a $3\frac{1}{2}$" diameter PVC cylinder coil form. The form is nominally 8" in length and the sample volume is well over 75 in^3. A neoprene diaphram allows for hydrostatic pressure equalization. A polarizing field of 150 oersteds is realized with about two amps. The inductance of this coil is 29 millihenries (measured at 1 kc) - its resistance is 2.6 ohms - the unloaded Q is nominally 170 at a precession frequency of 2.4 kc.

IV. TOWING AND OPERATION

On first inspection of the towing requirements of a deep magnetometer two avenues of approach seemed possible. One method which has been used in various experiments on a limited scale by Lamont workers employs a cable fitted throughout its length with free swiveling fairing to reduce drag. This permits operation with a minimum of required down force at the bottom of the cable. A dynamic depressor, or dead weight package, could be designed commensurate with the breaking strength of the cable and the expected speed of towing. 1,200 feet of double armor cable of .30" diameter has been used with rubber fairing along its entire length. A bottom dynamic depressor producing a down force of approximately 1000 pounds has been used and towing speeds up to eight knots have been achieved with the instrument at a depth of approximately 800 feet. This method was not practicable because cable fairing in the lengths required (10,000 - 12,000 feet) was not available on short notice, and a towed body with the required dynamic depression was not on hand.

Consideration was therefore given to an alternate method, which made use of an available double armored coaxial cable of .292" outside diameter, 20,000 feet of which was on hand. A study was made of the requirements for down force at the lower end of such a cable at various speeds commensurate with breaking strength of the cable. The following table reveals the expected values of speed, tension and amount of cable out for a towed system where the bottom terminus remained at a depth of 7,500 feet and the down force developed by dynamic or dead-weight methods was approximately 1000 pounds.

Speed (knots)	Tension (lbs.)	Cable Out (feet)
2.5	3,000-4,000	11,000
3	5,000	13,000
4	7,000	20,000

As can be seen, the configuration where a speed of 2.5 knots is developed by the ship, using 11,000 feet of cable, fell close to the most reasonable requirements. At this low speed a dynamic depressor would necessarily be of uncommonly large size. Therefore a dead weight depressor was considered most practical. With this configuration a trail distance of about 7,000 feet would be expected for the towed vehicle.

Following this brief comparison a vehicle was constructed consisting of the magnetometer underwater electronics package housed in a pressure cylinder 8 inches in diameter by 3 feet in length.

This cylinder and a somewhat smaller cylinder, housing an automatic pinger with self contained power supply, was mounted to a steel member and the entire assembly was placed in a faired sheet metal enclosure with a diameter of about 9 inches, a height of 3.5 feet and an overall length from leading edge to trailing edge of two feet. Below this package, which had a weight in air of some 200 pounds, a spherical weight of 750 pounds was secured on a short length of chain. Behind this unit, towed by 210 feet of cable, was the sensing coil in a PVC fish equipped with tail fins for stability. Figures 2 and 7 show the arrangement which finally evolved.

Electrical and mechanical connection was made between the towing cable and the towed vehicle through the use of a terminal fitting specially designed for the armored cable so that each stress member was securely gripped, while the electrical connections were brought through in a strain free manner and connected to the pressure cylinder cases using commercially available bulkhead connectors.

The following table, taken from the operating log, indicates some of the characteristics of this towed vehicle in operation.

Ship's Speed (knots)	Surface Cable Angle from Vertical (degrees)	Cable Out (feet)	Depth of Magnetometer (feet)
1.2	15	7,770	7,760
1.9	19	7,800	7,680.
3.5	44	8,770	7,680

Of the several procedures followed in the launching of the equipment the following was the most fruitful. With the towed vehicle on-board, the fish was streamed and the equipment was given a fully operational check. The 210 foot length of cable assured that a valid test was made with the sensing coil clear of the towing ship's magnetic field. The vehicle was then lowered to some several hundred fathoms and held there briefly to check for a clear bottom echo from the pinger and quality of the precession signal. The precession signal SNR was typically 15 db and its decay time greater than two seconds. The vehicle could then be lowered to operating depth at speeds up to 200 feet per minute.

The magnetometer operator was obliged to manually reset the digital counter upon seeing the precession signal on the monitor oscilloscope. With a data rate of five readings per minute this was a tedious task and automatic circuitry would be justified. At a speed of two knots made good over the bottom, a field measurement every forty feet was obtained. A second operator continuously monitored the precision depth recorder to determine the height of the towed vehicle above bottom and periodically advised the winch operator to adjust the amount of cable out such that the vehicle is held at the desired height. The vehicle was held 240 feet off the bottom which would then place the sensing coil nominally 30 to 60 feet above bottom. These heights were readily held to plus or minus 30 feet except during abrupt ship manuevering or when unusually strong currents were encountered.

An interesting minor feature that proved helpful is the supply voltage/PRF characteristics of the programming multivibrator. As the battery nears exhaustion its voltage falls slightly causing the multivibrator to speed up perceptibly providing an unambiguous indication that a battery change is called for.

Sensitivity of the deep-towed instrument is degraded from that obtained when the fish is towed near the surface at normal survey speeds. This is to be expected because of the reduced dynamic stability of the fish at low speeds. In the ideal case sensitivity is limited only by the one count ambiguity inherent in a digital counter. For the parameters used, i.e.: clock rate of 100 kc; gate time of 2,000 precession cycles, in a 55,000 gamma field each clock pulse has a value of 0.7 gammas. A spread of six to eight counts was usually observed resulting in an uncertainty of nominally five gammas. A conservative estimate of worst case operation would be ten gammas (plus or minus 5) error.

V. CONCLUSIONS

The deep-towed magnetometer proved to be a most useful tool during the recent search operation. On three occasions, distinct magnetic signatures of similar character were obtained while crossing over the same point on the ocean floor.

The instrument evolved in a comparatively short time and is accordingly somewhat primitive. Some modifications which could make the system easier to work with as well as more effective are: a) incorporate automatic circuitry to relieve the requirement of manually resetting the counter; b) devise a fish with a higher degree of stability at low speeds, this could improve instrument sensitivity significantly; c) substitute silver-zinc cells for the nickel-cadmium banks, this would extend normal operation for as much as three days, or employ a much smaller battery and supply a trickle charge down the coaxial cable to maintain zero float conditions; d) use the high percentage of coaxial cable dead time between readings for some alternate measurement; e) make the system more flexible by sending orders down the coaxial cable to effect mode changes such as duty cycle speed ups or changes in amplifier gain or tuning.

ACKNOWLEDGMENTS

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Waters, G. A. and Francis, P. D.; "A Nuclear Magnetometer", Journal of Scientific Instruments, vol. 35, 88-93, March 1958.

Warren, R. E. and Vacquier, V.; "A Ship-Towed Proton Magnetometer", Marine Physical Lab. Tech. Memo 120, 1961.

APPENDIX - COMMERCIAL EQUIPMENTS

1. Polarize Power Supply	Electro Products Laboratory Chicago, Illinois Model NFBR
2. Monitor Oscilloscope	A. B. DuMont Laboratories Clifton, New Jersey Model 304-AH
3. Counter	Hewlett-Packard Company Palo Alto, California Model 5212A
4. Digital/Analog Converter	Hewlett-Packard Company Palo Alto, California Model 580A
5. Strip Chart Recorder	Leeds and Northrup, Inc. Philadelphia, Pennsylvania Speedomax H, Type S
6. Armored Coaxial Cable	American Steel and Wire New York, New York Amergraph Type 2-H-1
7. Marine Cable	American Steel and Wire New York, New York LGO Special

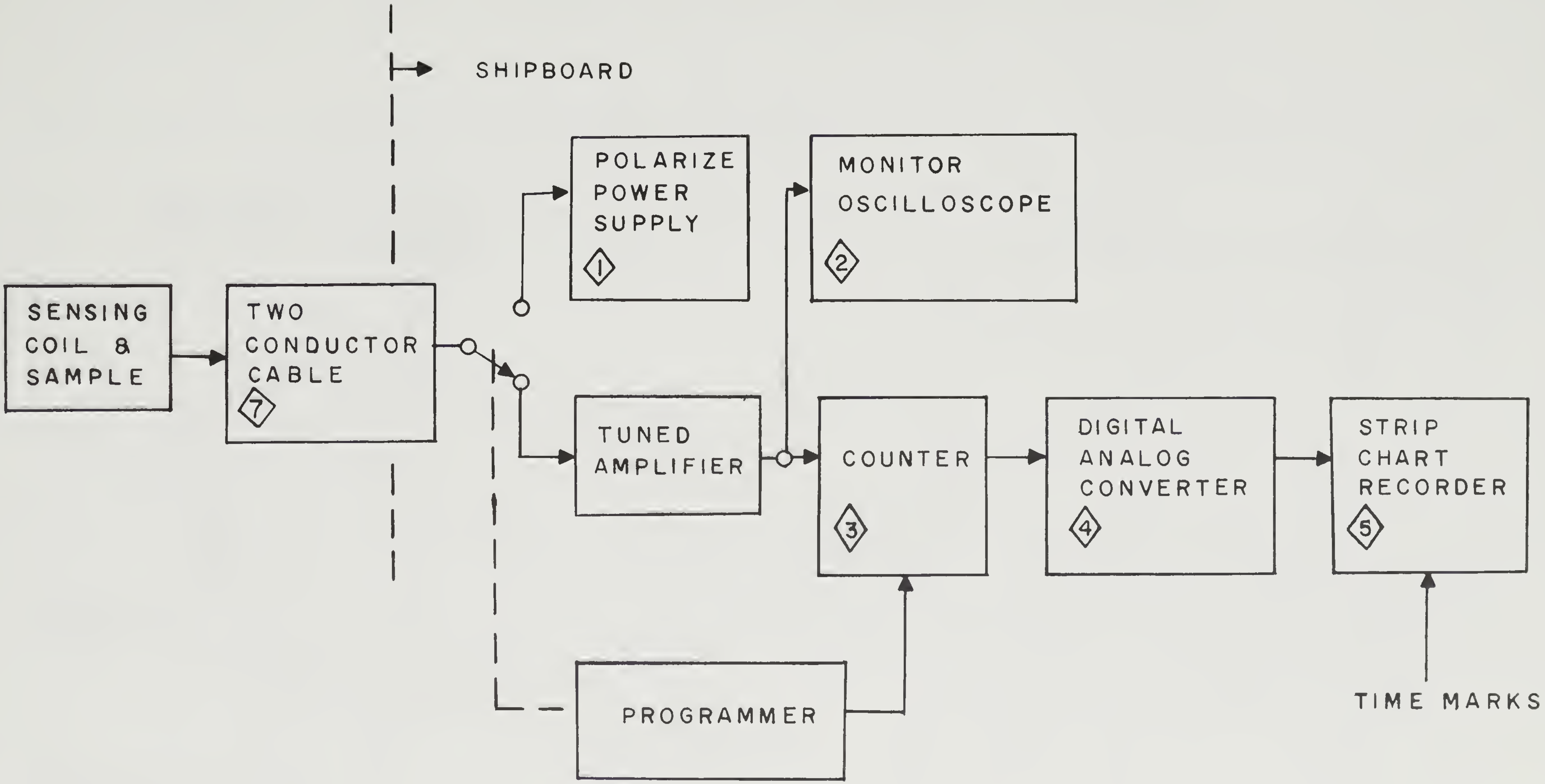


FIG. I SHIP-TOWED MAGNETOMETER BLOCK DIAGRAM

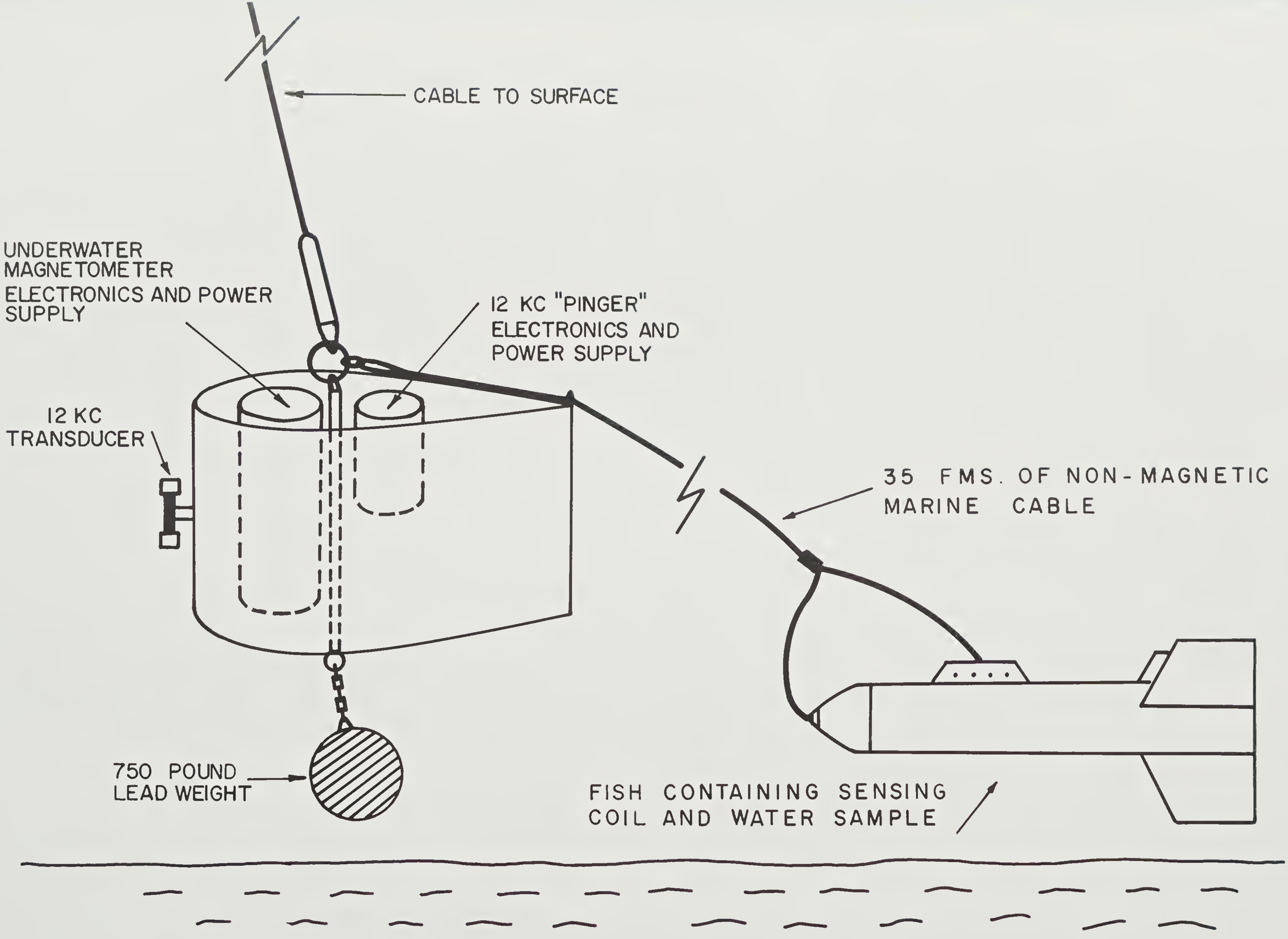


FIG. 2 DEEP-TOWED MAGNETOMETER PICTORIAL

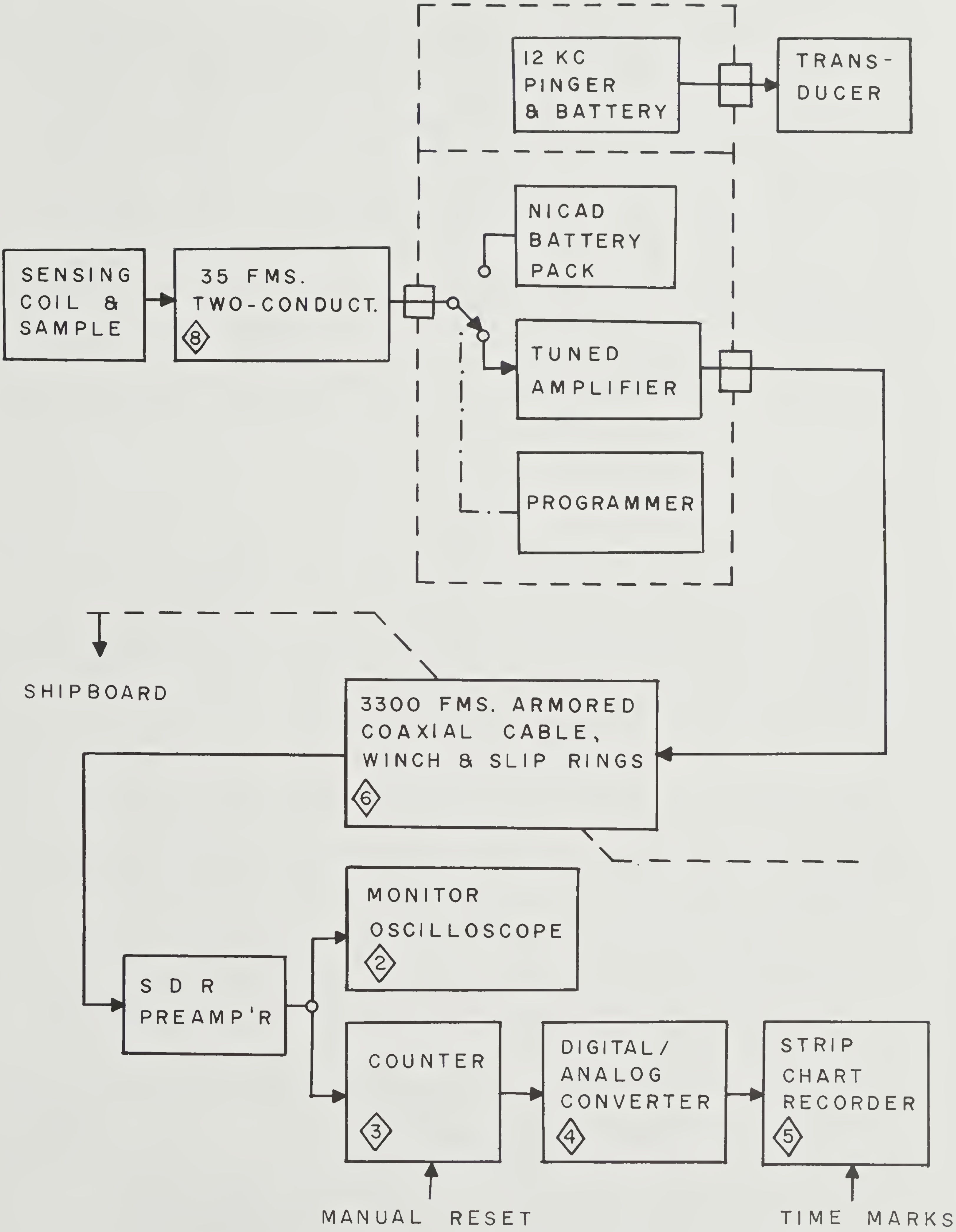


FIG. 3 DEEP-TOWED MAGNETOMETER BLOCK DIAGRAM

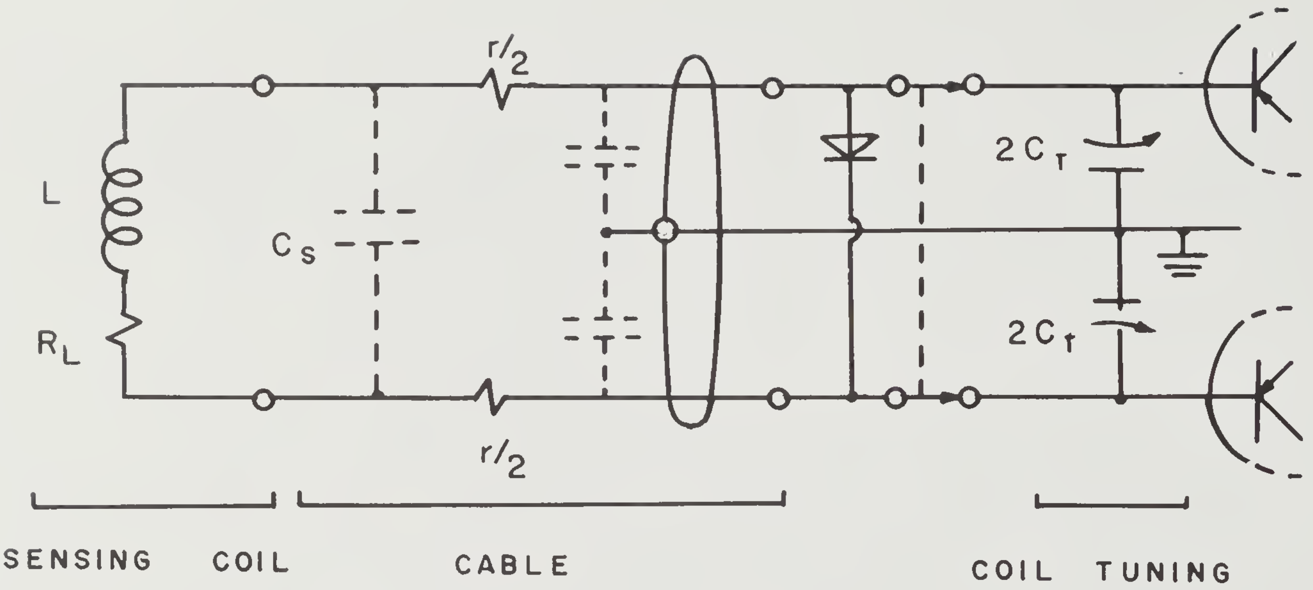


FIG. 4 (a) INPUT CIRCUITRY - SIMPLIFIED SCHEMATIC

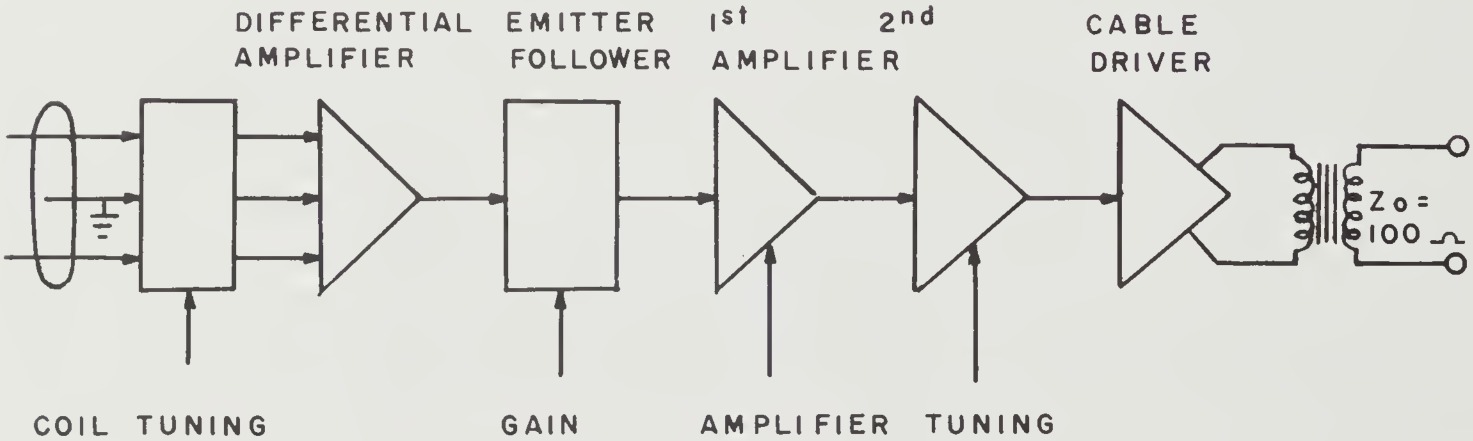


FIG. 4 (b) HIGH GAIN TUNED AMPLIFIER BLOCK DIAGRAM

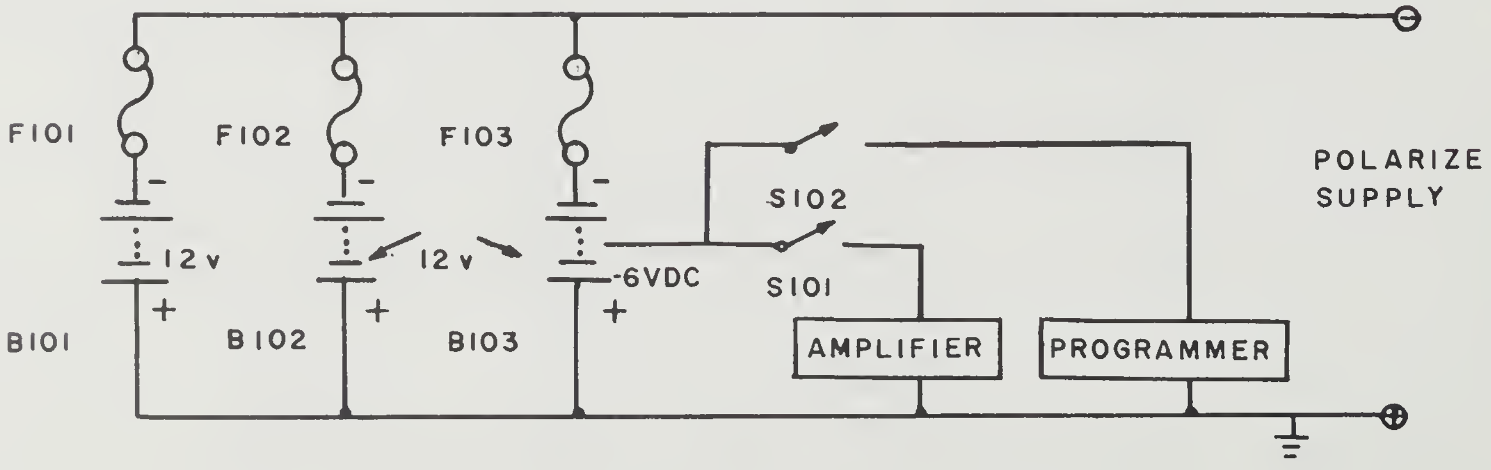
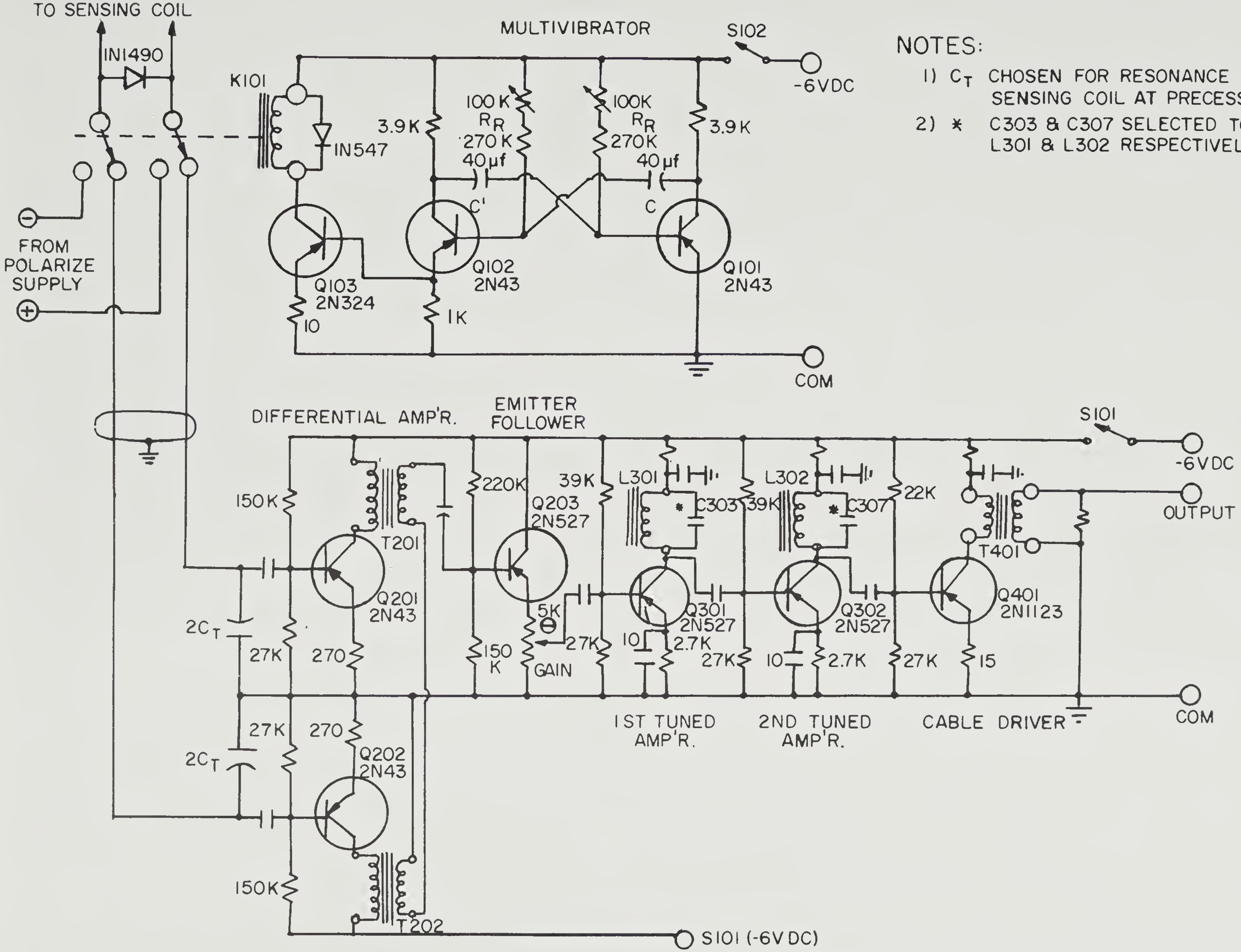


FIG. 4 (c) PRESSURE CYLINDER INTERNAL WIRING



NOTES:

1) C_T CHOSEN FOR RESONANCE WITH SENSING COIL AT PRECESSION FREQ.

2) * C303 & C307 SELECTED TO TUNE L301 & L302 RESPECTIVELY

FIG. 5 HIGH GAIN TUNED AMPLIFIER SCHEMATIC

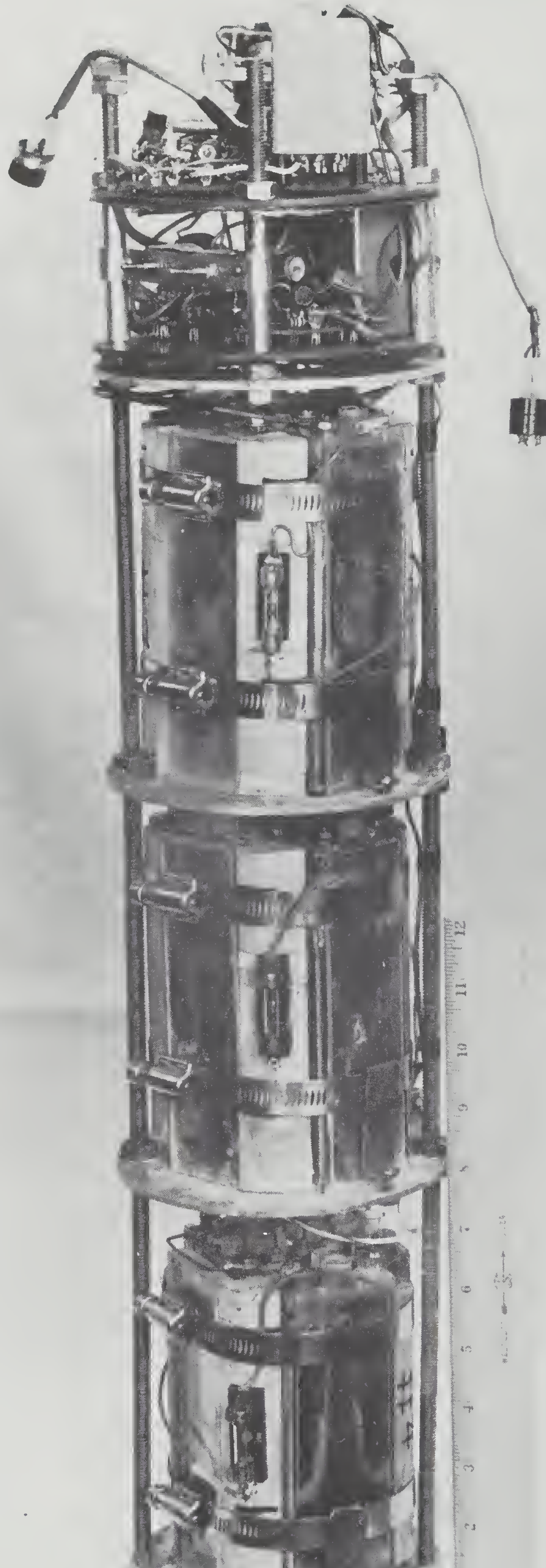


Fig. 6 UNDERWATER ELECTRONICS PACKAGE

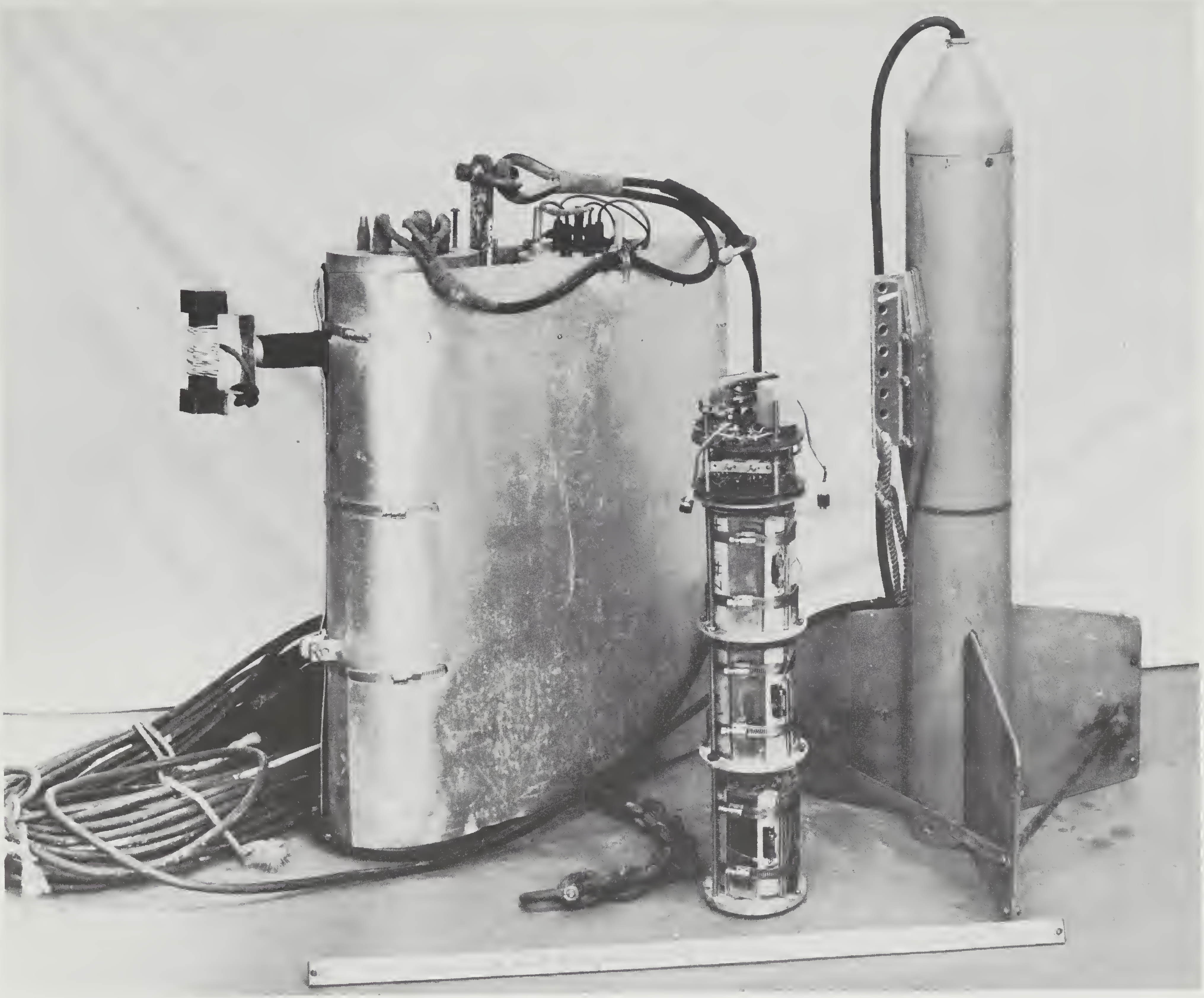


Fig. 7 DEEP-TOWED VEHICLE AND FISH

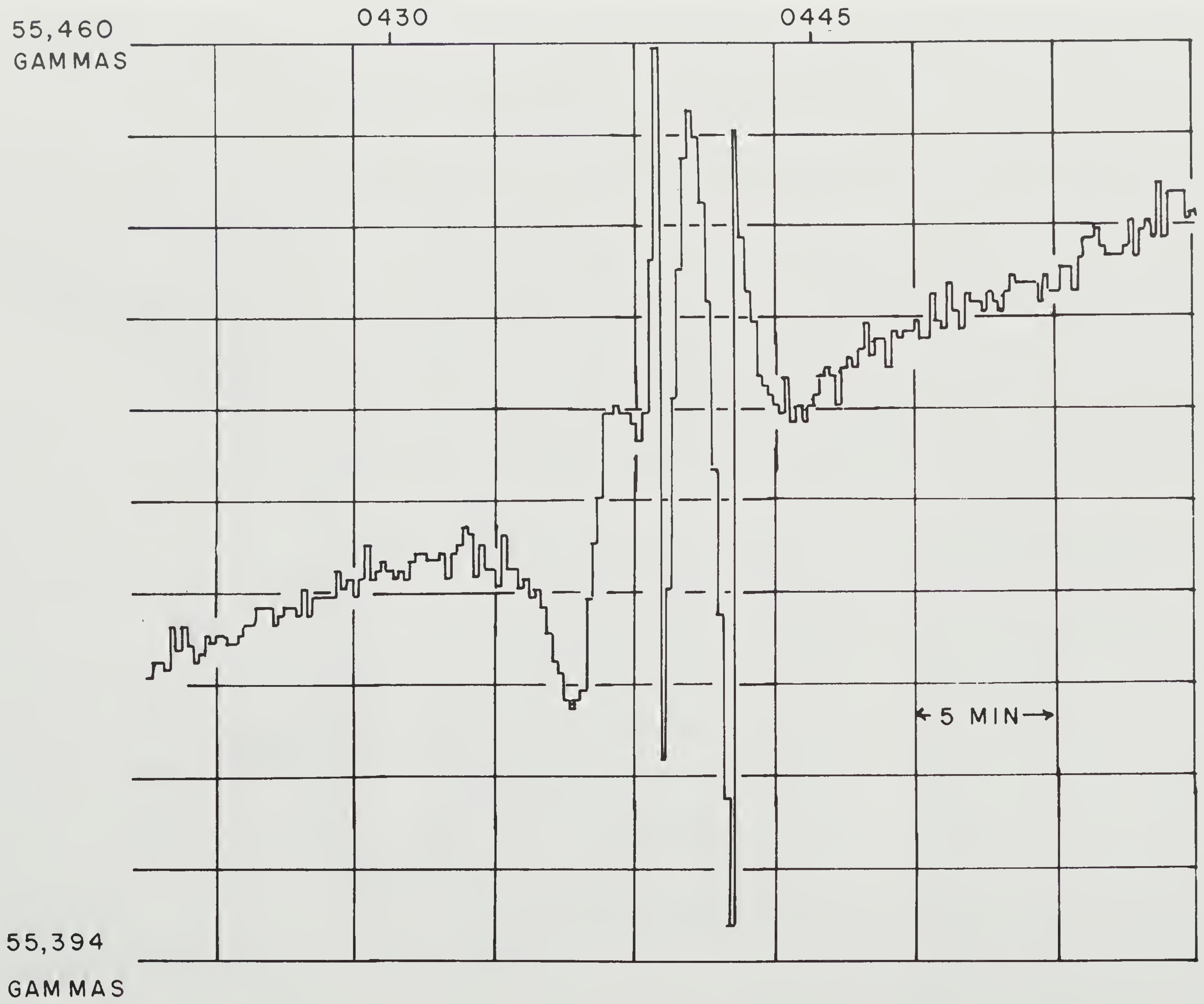


FIG. 8 - SAMPLE ANALOGUE RECORD SHOWING LOCAL ANOMALY