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OCEAN MAGNETIC MEASUREMENTS

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Geomagnetic measurements in the ocean utilize, almost exclusively, instruments which measure the total magnetic intensity such as the proton precession, optically pumped and monitored, and servo-oriented fluxgate magnetometers. The proton magnetometer measures the frequency of precession of proton in a sample of water or liquid hydrocarbons to determine the field intensity with a sensitivity and absolute accuracy of ±1 gamma. This instrument is used from survey vessels for mapping the field intensity which is by far the largest and only routine endeavor in ocean magnetic measurements. The optically pumped and monitored magnetometers are employed for their high sensitivity in special search, buoy, and gradient measuring applications. The information gained from all such measurements are used for geologic interpretation of the ocean floor, analysis of the secular variation of the field, petroleum and mineral exploration, salvage and underwater search, and finally for investigations of the time variations of the earth's field in oceanic areas.

1. INTRODUCTION

Of the many physical properties that are investigated in the ocean environment, only the gravitational and magnetic fields involve measurements of a geo-potential field. The geomagnetic field, in particular, originates, by and large, in the deep interior, or core, of the earth and is distorted by certain variations in the local environment. All of our useful knowledge of such variations that concern oceanography, we gain by mapping the perturbations in the geomagnetic field. In this paper we will concern ourselves simply with the nature and purpose of most of the present day ocean magnetic measurements.

In general the instruments that are used for these measurements are devices which indicate the total magnetic intensity, that is, the scalar magnitude of the earth's field. By definition, a scalar is a quantity which is independent of direction. All measurements in oceanography with the exception of those on bottom-moored stations are made on moving platforms with imperfect reference to any earth-based coordinate system. Thus, to monitor the geomagnetic field on these platforms with any precision, we must be content with observations of the total magnetic intensity.

The only instruments which measure the total intensity are servo-oriented component sensors such as the fluxgate magnetometer and the spin precession magnetometers. In the latter category are the proton precession and the optically pumped rubidium, cesium, and helium magnetometers respectively. The field is usually measured in a "fish" streaming behind a ship to be free of the error caused by the presence and change in orientation of the ferromagnetic properties of the vessel itself. A notable exception is the non-magnetic Soviet sailing ship, the "Zarja" which has onboard fluxgate and proton precession magnetometers. The elements of the sensor when in a fish, however, must have relative freedom from acceleration and vibration, a quality which is inherent in the proton precession sensor. For this reason and because of its absolute accuracy and simplicity, it is today the most widely used magnetometer on oceanographic vessels. The optically pumped magnetometers possess higher sensitivity than the other two types and have been tried with success in several unique oceanographic experiments but have not been adapted to routine marine magnetic surveys.

2. PRINCIPLES OF OPERATION

2.1 PROTON MAGNETOMETER

The proton free precession magnetometer was conceived by the late Russell Varian in 1954 (U.S.Pat. 23,769). In the proton magnetometer sensor, a uniform magnetic field is created by passing a few amperes of current through a coil about a sample of protons, usually the hydrogen nuclei in a small volume of water or hydrocarbon fluid. The spinning protons act as small magnetic dipoles and align themselves with the applied field. When the field is removed, the spin of the protons causes them to precess about the direction of the ambient field, i.e., the earth's magnetic field, at a rate proportional to the total magnetic intensity. This rate is determined by the value of the gyromagnetic ratio of the proton, 23.4875 cps per gamma, which, of course, is an atomic constant known to an accuracy of 8 parts per million. The precession frequency is independent of the direction of the spins with respect to the earth's field; only the signal amplitude varies being maximum when the spins are normal and zero when they are parallel to the direction of the earth's magnetic field. (The Overhauser-Abragam type of proton magnetometer produces a continuous precession signal by application of a particular radio frequency exciting field).

The precession signal is actually induced by the motion of the precessing protons in the coil used for polarizing the sample. Thermal agitation causes the signal to decay in a few seconds from its peak value of a few microvolts. The frequency of the precession signal in the average earth's field of 50,000 gamma (1 gamma = 10^{-5} gauss) is approximately 2000 cycles per second.

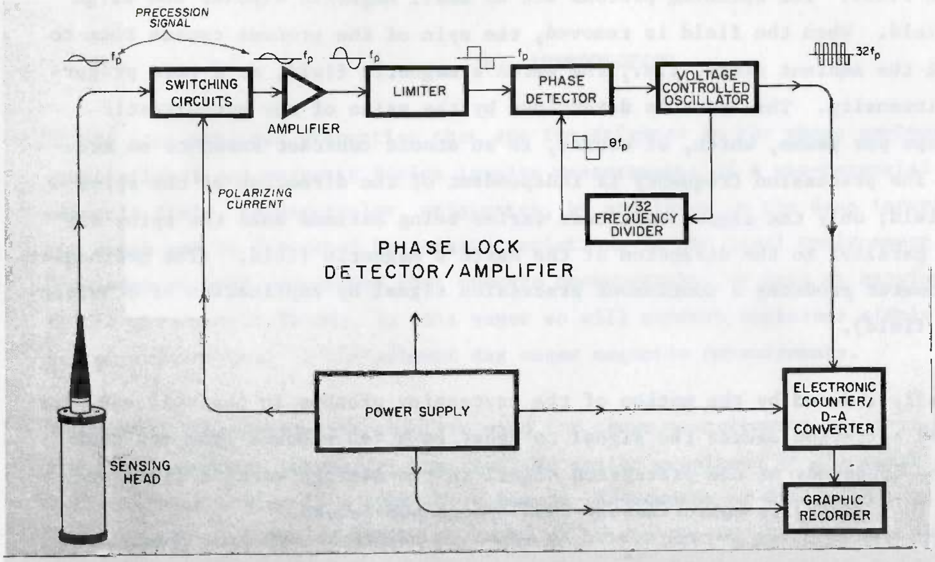
All that remains, then, to use this bottle of water and coil of wire as a magnetometer, is to measure the frequency of precession. In order to utilize the inherent accuracy of this technique, however, we must be able to measure this frequency to an accuracy of $\frac{1}{23.4875}$ cps for an accuracy of 1 gamma. In turn, this frequency measurement requires good signal-to-noise and an effective counting technique during the few seconds in which the signal persists.

In the Varian Model V-4937 proton magnetometer[1] (See Figure 1), the precession signal is first amplified and squared. A phase detector applied to the signal is used to control the frequency of a voltage-controlled-oscillator which is then maintained at exactly 32 times the precession frequency. The VCO frequency is therefore a function of the precession frequency but has much improved signal-to-noise and is a much higher frequency which is therefore easier to measure accurately. This VCO signal is then counted on a frequency counter using a specially selected gate time so that instead of cycles per second, we have units directly in gammas. The output of the counter is then recorded on magnetic tape, punched tape or converted to an analog voltage for display on a strip-chart recorder with a sensitivity generally on the order of ±0.5 to ±1 gamma.

2.2 OPTICALLY PUMPED MAGNETOMETER

Optically pumped magnetometers represent a family of almost identical instruments based on the principles of optical pumping and monitoring.[2] Magnetometers based on the principle of optical pumping and using Rb^{85}, Rb^{87}, cesium, potassium, sodium, or metastable helium as the active element have been operated. Each element or isotope determines slightly different temperature, frequency, and absolute accuracy characteristics of the magnetometer. To accomplish the pumping and monitoring process in a rubidium magnetometer, for example, a Rb^{85} light is used as an energy source of photons (wavelength, 7948 angstroms), which are focused through a glass cell containing Rb^{85} vapor. The transparency of

1. Varian Associates, Proton Magnetometer, V-4937, Data Sheet, INS 1532, 1964
2. H. G. Dehmelt, Phys. Rev. 105, 1487, 1984, 1957



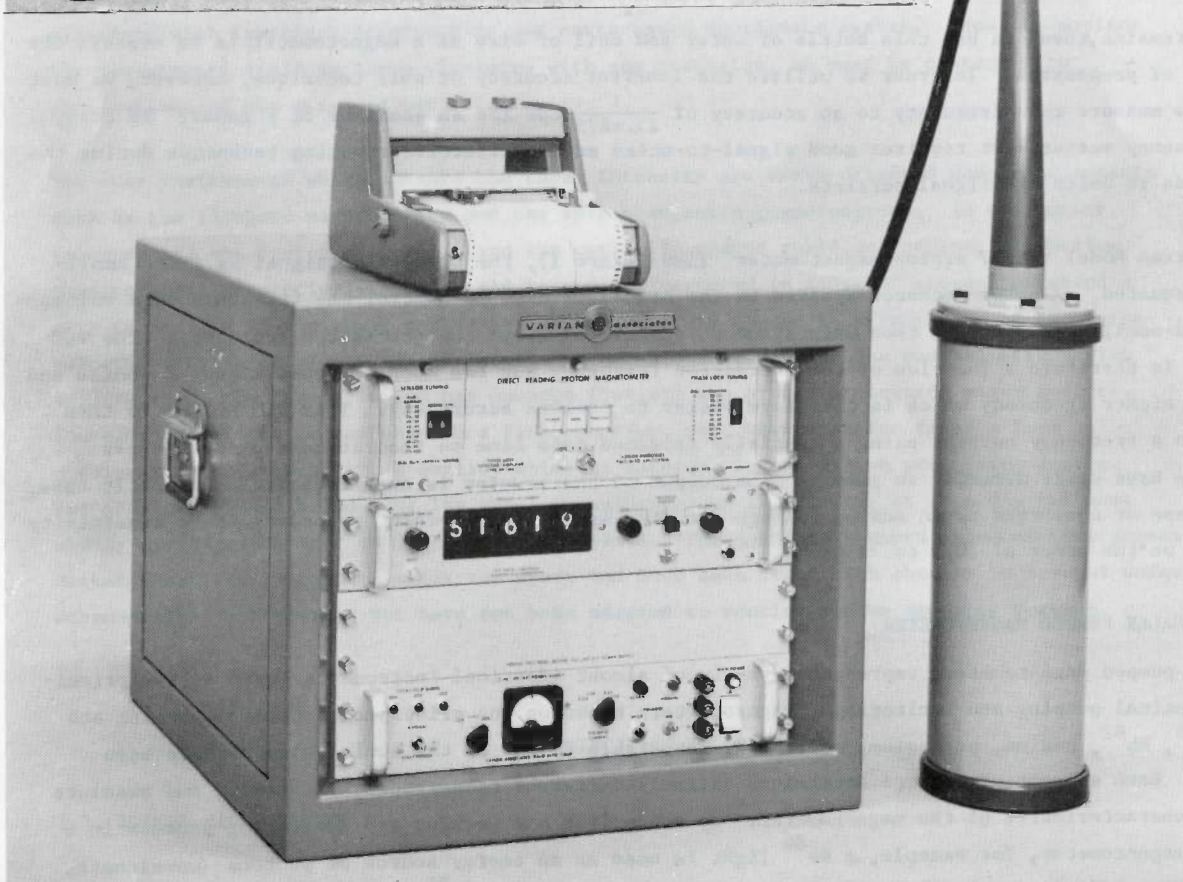


Figure 1. The Varian Model V-4937 Proton Magnetometer and Marine Sensor.

this cell is decreased, however, when the Rb^{85} photons are absorbed by the valence electrons of Rb^{85}; this absorption raises the electron's energy, causing the electron to rise from one of sublevels of the $^2S_{1/2}$ ground state to a specific sublevel of the $^2P_{1/2}$ excited state. The rise of the electron to the $^2P_{1/2}$ state must, by quantum mechanical rules, be accompanied by an increase of +1 in the corresponding sublevel. The absorbed photon energy is soon reradiated, and the electron drops back with equal probability to any one of the sublevels of the ground state, ready to absorb another photon. However, since there are the same number of sublevels in the ground state and in the excited state, the electrons in the highest sublevel of the ground state cannot rise to the excited state nor absorb additional photons. A large number of electrons are thus "pumped" into this highest sublevel of the ground state, and, because the photons pass freely through the vapor cell, the cell becomes transparent.

Sweeping the vapor cell with a weak alternating magnetic field disrupts this state and allows pumping to begin again. If one varies the frequency of the applied field and observes the light transmitted through the vapor cell, a sharp absorption is seen to occur when the applied field has a frequency given approximately by the equation $f = 4.667F$, where f = frequency (in cycles per second) for Rb^{85} and F is the total field intensity, in gammas. The electrons undergoing the transition between energy sublevels precess about the magnetic field at a Larmor frequency determined by the Zeeman splitting of the levels. Whereas the proton magnetometer operates discontinuously with a Larmor frequency of approximately 2000 cycles per second in a field of 50,000 gammas, with the rubidium magnetometer the Larmor frequency is continuous and approximately 233,000 cycles per second. The rubidium and cesium magnetometers can resolve short term variations in the total intensity as small as 0.005 gamma when in a fixed position.

In the actual instrument[3] shown in Figure 2, the modulation of the transmitted light is detected by a photocell. The current from the photocell is amplified, changed in phase, and used as a feedback signal to drive the alternating magnetic field about the vapor cell. This arrangement thus constitutes an oscillator whose frequency is proportional to the total magnetic field intensity at a rate fixed by an atomic constant, 4.667 cycles per second per gamma for Rb^{85} and 3.498 cycles per second per gamma for Cs^{133}. The signal from this oscillator is then either counted directly or mixed with a frequency from a fixed reference oscillator to obtain an audio frequency difference also proportional to the field intensity. The audio-frequency difference can either be made audible or transformed, in a frequency discriminator, to an analog voltage for display on a paper chart recorder.

3. THE NATURE AND PURPOSES OF OCEAN MAGNETIC MEASUREMENTS

3.1 LARGE SCALE MARINE SURVEYS OF THE EARTH'S MAGNETIC FIELD

The vast majority of the oceanographic ships equipped with marine magnetometers perform magnetic surveys for the primary purpose of mapping the total intensity at sea level in all the navigable seas of the world. This task is immense for the surveys have barely begun and the ocean covers five-sixths of the earth's surface. Even the land surface has not yet been completely mapped. International cooperative programs such as the International Indian Ocean Expedition, World Magnetic Survey, and the Pacific and Arctic Ocean surveys have all resulted in the mapping of large areas of the ocean.

3. Varian Associates, Rubidium Magnetometer, V-4938, <u>Data Sheet</u>, INS-1495, 1963

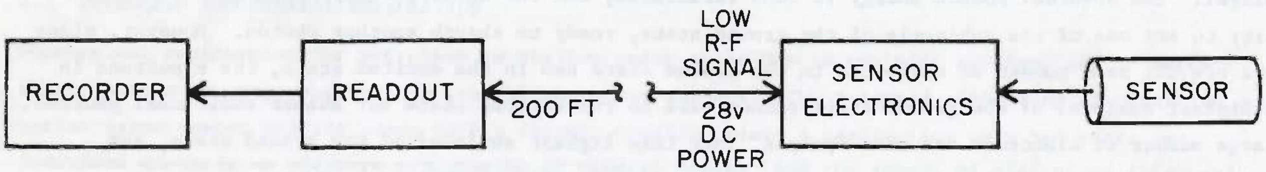


Figure 2. The Varian Model V-4938 Rubidium/Cesium Magnetometer

A survey ship may produce a map from a regular grid with a spacing of 5 to 10 miles if its principal purpose is to conduct magnetic surveys. If, on the other hand, a multitude of other observations are sought, the ship's track may be very long lines hundreds or thousands of miles long, the product of which is a series of a magnetic profiles to be correlated with bathymetry, heat flow, gravity, or possibly seismic profiles. When a large number of variables are recorded for subsequent correlation, the magnetic intensity from a proton magnetometer is usually recorded on magnetic tape or punched tape for automatic data processing. A V-4937 Varian Proton Magnetometer aboard the AGOR ship USNS SILAS BENT is perhaps the most outstanding example of such data acquisition, the magnetometer output being recorded along with almost all of the above data in this manner.

The earth's total field also varies in time usually between 25 and 75 gammas which generally occurs slowly during the day. These changes, known as diurnal variations, are not removed from the data. Often there is no fixed-base monitor near enough to be coherent with the variations in the survey area. Furthermore, the location of the ship itself is not known to enough precision to warrant such accuracy. Check lines are occasionally run to insure that the diurnal shift which occurred during a survey did not exceed certain limits which would certainly be exceeded by a large magnetic storm.

The ultimate analysis of the resulting total intensity maps is far reaching. For example, through proper interpretation of even the total intensity maps alone, we may deduce considerable knowledge of the geologic structure, thickness of sediments, magnetization and character of sea mounts, and perhaps what is the most striking interpretive example—the magnetic expression of the structural features in the Pacific such as in Figure 3 interpreted to be large transcurrent faults in the crust[4]. Such examples and the results of magnetic surveys over rift zones, mid-ocean rises, the deep ocean trenches, and arcuate structures bear heavily on the evidence for and against continental drift.

Knowledge of the value of the total field over a large number of points on the earth's surface allows us to use appropriate polynominal expressions for the sources of the main field of the earth, the more data points, the better the fit. In this way we learn more about the nature of the origin of the field, the orientation of the dipoles and higher order poles, and the contribution of extraterrestrial sources to the earth's field.

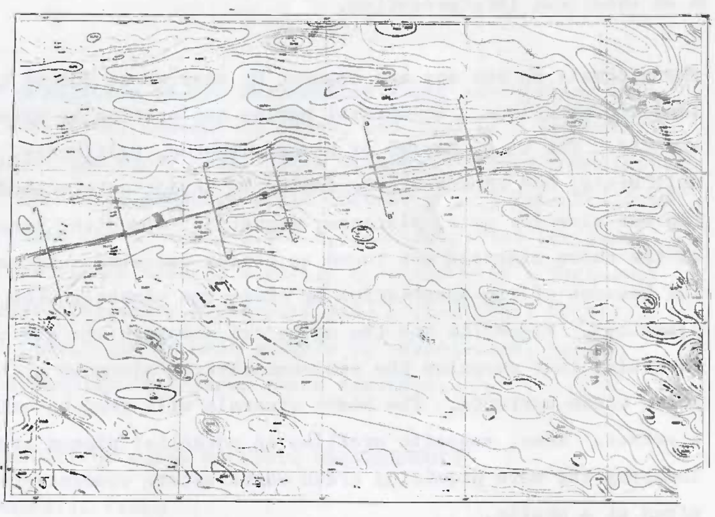


Figure 3. Total magnetic intensity map of area south of the Hawaiian Islands showing the magnetic expression extending across the entire map of a major rift zone in the ocean floor (Courtesy U.S. Naval Oceanographic Office).

4. A Marine Magnetic Survey south of the Hawaiian Islands, Technical Report, Aeromagnetics Branch Marine Survey Division, U. S. Naval Oceanographic Office, 1902.

Finally, the data obtained from the absolute accuracy of the proton magnetometers may be used to plot the secular drift of the field when traverses are repeated years later. Further knowledge of the variational behavior of the earth's main field is thus obtained and can be used to predict more accurate maps for the variation in magnetic declination used in navigation.

3.2 PETROLEUM AND MINERAL EXPLORATION

Geophysical exploration for petroleum in shallow ocean areas has in the past involved marine seismic ships, bottom gravity observations, and aeromagnetic surveys. The relative simplicity of obtaining a marine magnetometer profile along with a seismic profile became a realization only two years ago. Increased emphasis on offshore exploration at greater depths, and the advent of continuous shipboard gravity measurements have accelerated the use of magnetics for oil exploration.

Magnetic profiles are, among other things, a function of the underlying geologic structure and represent an independent variable for correlation with seismic reflections. Faults, folds, basins, and domes may be expressed in the character of a magnetic profile. Recently, a Varian proton magnetometer with a sensitivity of ±1/2 gamma was used to record the profile over a large salt dome in the Gulf of Mexico. The time variations of the magnetic field were removed from the observed data using a near shore-based monitoring station. The regional gradient of the earth's field was also subtracted resulting in the profile shown in Figure 4. The small amplitude negative anomaly can be attributed to the diamagnetic properties of the salt which is also clearly expressed in the bottom topography. A bottom gravity survey which was also conducted[5] over the structure exhibited analagous profiles and resulted in an identical interpretation.

The minerals in the sea are thought by many to be one of the most important marine resources next to food and petroleum. Commercial marine exploration is being conducted for such minerals as diamonds and tin. The U. S. Bureau of Mines, Tiburon, California, the U. S. Geological Survey, Menlo Park, California, and others are beginning to investigate methods of exploration not only for diamonds and tin but also for gold, platinum, magnetite, ilmenite, manganese, and a number of other minerals. All of the above minerals are found as placer deposits. In many cases, the magnetometer may be found useful because of the association of these ore minerals with the common magnetic mineral, magnetite (or ilmenite). Magnetite and the above ore minerals are all heavier than the quartz, feldspars and rock particles that comprise the sediment carried along by streams to the river mouths and then by near-shore ocean currents. The heavy minerals will tend to exist together and the magnetite will serve as a marker. Thus, magnetic profiles in potential placer areas might save considerable time and effort in locating the more promising areas where nature concentrated certain minerals in sufficient degree to be mined at a profit.

In any magnetic exploration program, there is always a problem of interpreting the profiles or maps correctly. The most difficult procedure in the interpretation of profiles for placer deposits will be the separation of the normally occurring deeper-seated geologic/magnetic anomalies from the placer/magnetic anomaly. An attempt to facilitate this interpretation and at the same time provide higher sensitivity profiles has been made by Varian Associates and the Pacific Coast Marine Geology Branch of the U. S. Geological Survey.

5. L. L. Nettleton, Gravity Survey over a Gulf Coast Continental Shelf Mound, Geophysics Vol. XXII, No. 3, 630 (1957)

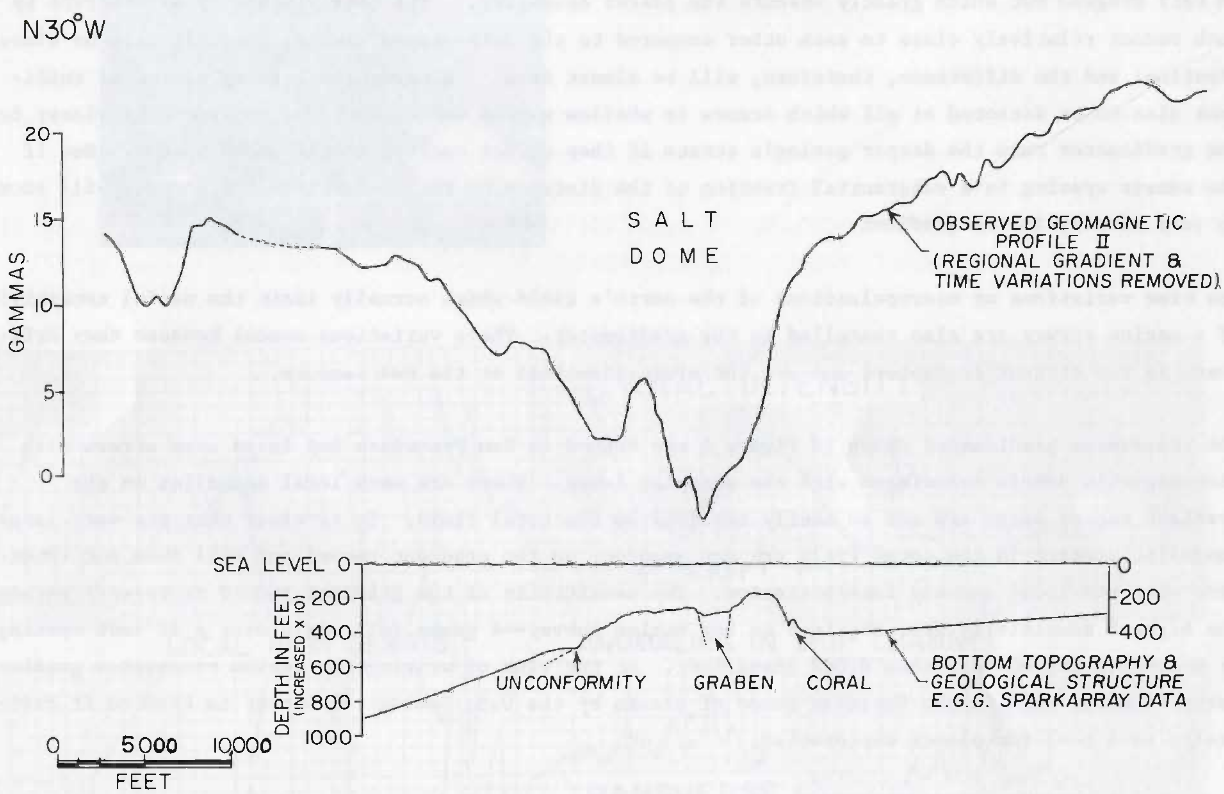


Figure 4. Total magnetic intensity profile over a large structure with a salt dome at its center in the Gulf of Mexico

Two high sensitivity cesium magnetometer sensors each capable of resolving less than 0.01 gamma were placed in fiberglas dinghies rigidly fixed to each other catamaran-style so that the sensors are separated by 12 feet. Their signals were then mixed to obtain the difference in their intensities, this arrangement being called a gradiometer. The dinghies were towed 100 feet behind a motor launch to remove the sensors from the magnetic effects of the launch (see Figure 5). In this manner, we obtained the gradient transverse to the profile. In addition, the total intensity itself was recorded from one of the sensors.

The largest normally occurring anomalies originate in deep-seated geologic bodies of no real interest in this program but which greatly obscure the placer anomalies. The total intensity as observed by each sensor relatively close to each other compared to the deep-seated source, however, will be almost identical and the difference, therefore, will be almost zero. A magnetite-bearing placer of sufficent size to be detected at all which occurs in shallow marine waters would be considerably closer to the gradiometer than the deeper geologic strata if they do not outcrop at the ocean bottom. Now if the sensor spacing is a substantial fraction of the distance to the placer then the anomaly will show up very clearly in the gradient.

The time variations or micropulsations of the earth's field which normally limit the useful sensitivity of a marine survey are also cancelled in the gradiometer. These variations cancel because they originate in the distant ionosphere and are therefore identical at the two sensors.

The transverse gradiometer shown in Figure 5 was tested in San Francisco Bay in an area strewn with ferromagnetic debris associated with the shipping lanes. There are many local anomalies on the gradient record which are not so easily resolved on the total field. It is clear that the very large anomalies present in the total field are not apparent on the gradient record and will thus not interfere with the local anomaly interpretation. The sensitivity of the gradient record represents perhaps the highest sensitivity ever obtained on any marine survey—4 gamma full scale over a 12 foot spacing or a sensitivity of less than 0.002 gamma/foot. At the time of writing the cesium transverse gradiometer is being used in the Kotzebue Sound of Alaska by the U.S. Geological Survey to examine it critically as a tool for placer exploration.

3.3 SEARCH AND SALVAGE

There is an ever increasing demand for a capability of retrieving, detecting, or localizing man made objects on or under the sea bottom. Such objects might be sunken ships, artifacts, pipelines, cables, submarines, weapons or almost anything whose location is of interest to someone. A wide variety of instruments and techniques may be employed in such a search but the chief means are perhaps sonar, television, sub-bottom profilers, magnetometers, and, of course, divers.

When there is reason to expect there to be a quantity of ferromagnetic material associated with the object, a magnetometer would be an efficient tool in the search because it has a wide zone of coverage, has the advantage of being a remote sensor, and may operate as fast as one wishes. Two recent marine search activities, that of the lost hydrogen bomb and earlier the tragic sinking of the submarine THRESHER brought to light many of the problems associated with search activities. The bomb reportedly possessed very low ferromagnetic susceptibility so that the use of magnetometers would have been futile.

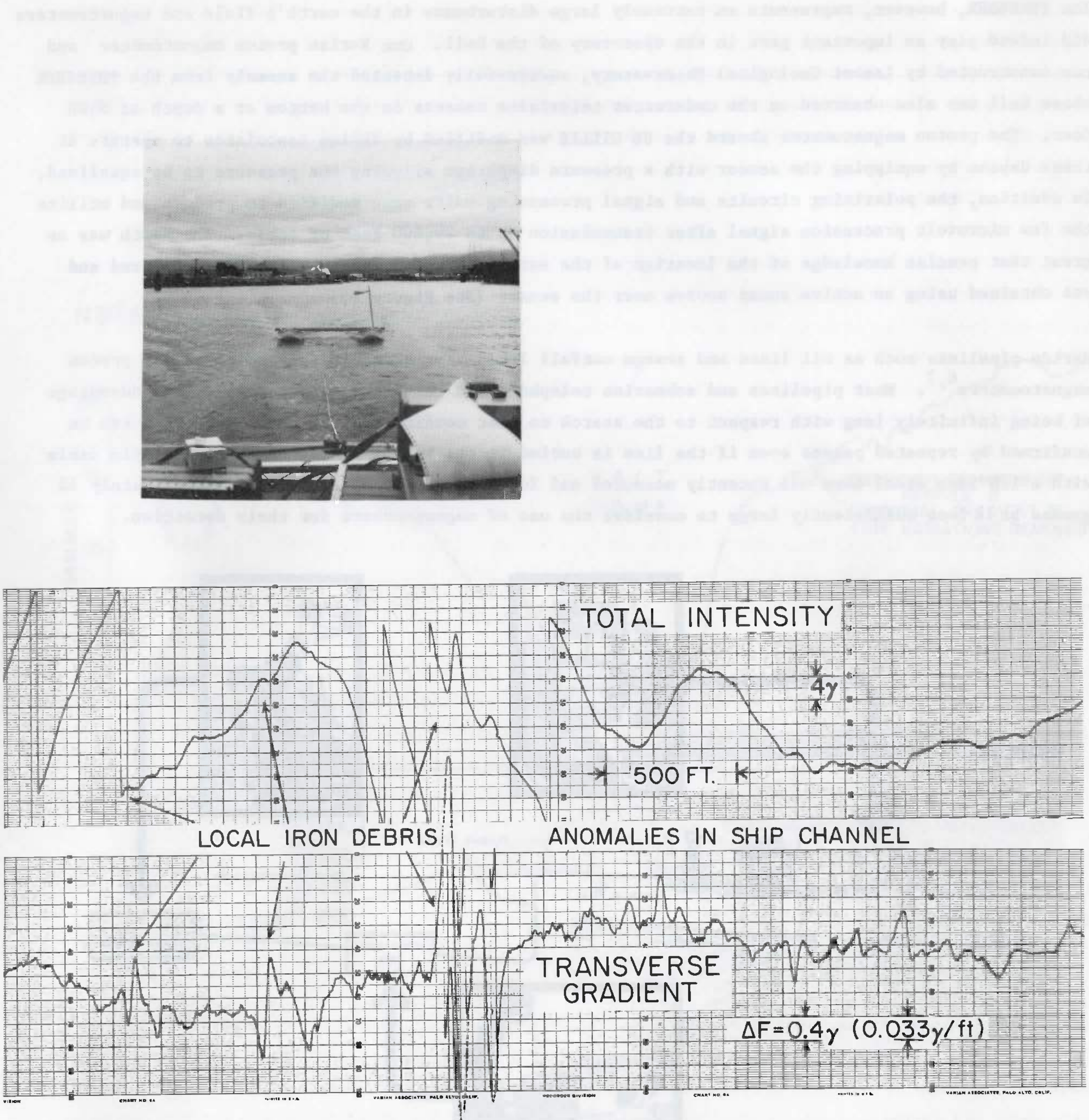


Figure 5. Cesium marine gradiometer for salvage and placer exploration. Above, twin hull platform for sensors. Below, recordings obtained in San Francisco Bay showing improved resolution of local anomalies on gradient record by removal of large anomalies apparent on total intensity record.

The THRESHER, however, represents an extremely large disturbance in the earth's field and magnetometers did indeed play an important part in the discovery of the hull. One Varian proton magnetometer and two constructed by Lamont Geological Observatory, successfully detected the anomaly from the THRESHER whose hull was also observed on the underwater television cameras on the bottom at a depth of 8400 feet. The proton magnetometer aboard the SS GILLIS was modified by Varian Associates to operate at these depths by equipping the sensor with a pressure diaphragm allowing the pressure to be equalized. In addition, the polarizing circuits and signal processing units were modified to produce and utilize the few microvolt precession signal after transmission up to 20,000 feet of cable. The depth was so great that precise knowledge of the location of the sensor as towed from the ship was required and was obtained using an active sonar source near the sensor (See Figure 6).

Marine pipelines such as oil lines and sewage outfall lines have been detected easily using proton magnetometers[6,7]. Most pipelines and submarine telephone and telegraph cables possess the advantage of being infinitely long with respect to the search so that confirmation of their detection can be confirmed by repeated passes even if the line is buried in the bottom sands. A trans-Atlantic cable with a 1/8 inch steel core was recently measured and found to create an anomaly of approximately 12 gammas at 12 feet sufficiently large to consider the use of magnetometers for their detection.

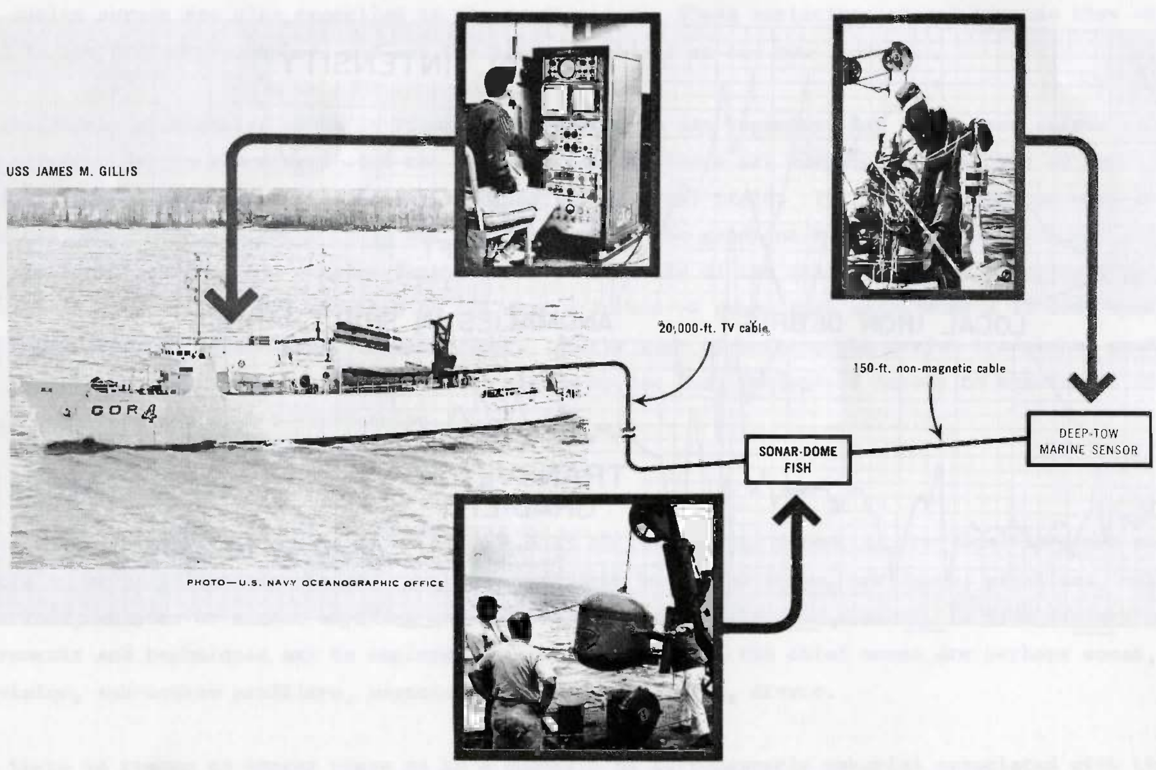


Figure 6. Varian proton magnetometer as modified for use in search for the submarine THRESHER.

6. Jack O. Hill, Marine Pipeline Pre-Lay Surveys and Right-of-Way Investigations, Offshore, p. 69, June, 1966.

7. Sheldon Breiner, Magnetic Search, An Example Involving a Submerged and Buried Pipe, Varian Associates Geophysics Technical Memorandum #13.

The availability of the high sensitivity rubidium, cesium, and helium magnetometers offer new possibilities in search and salvage work. Whereas the normal survey such as described earlier for mapping purposes would find no use for the higher sensitivity, the search applications can indeed utilize the higher resolution. In order to make effective use of the resolution we must first improve the signal-to-noise with respect to both time variations and geologic sources as described in application to placer exploration.

As a prelude to using an optically pumped magnetometer for high resolution archaeological exploration, a rubidium magnetometer was wrapped in an almost watertight cover and carried by a diver over the site of a Roman shipwreck near Taranto, Italy as shown in Figure 7. The feasibility of moving the sensor about and recording the variations was established. Consequently, a pressure-tight non-magnetic housing was constructed for the rubidium and cesium sensors and outfitted with a diving plane so that it could be towed while being manuevered underwater by a diver[8]. This arrangement was used in cooperation with the Council of Underwater Archaeology for mapping a portion of Drake's Bay, California, in search of evidence of the Spanish ship, the St. Augustine, which ran aground in 1595. The profiles showed a few large iron objects in shallow water most likely pieces of modern ships frequently found in that bay (see Figure 7). Subsequent trials were conducted off the coast of Florida by Mr. Ed Link detecting buoys, pipelines, and underwater cables[9].

The cesium marine gradiometer as described above for placer exploration provides the highest resolution for ferromagnetic objects in water less than a few hundred feet in depth both from a standpoint of natural background noise and instrumental noise. Figure 8a demonstrates the removal of background noise. The anomaly on the total intensity due to a nearby ship is indistinguishable from the anomaly due to a normal geologic body which exists at an estimated depth of 1500 feet. The gradiometer profile, on the other hand, clearly shows the ship but not the geologic effects. An added bonus is received by using the total intensity profile to obtain the longitudinal gradient, i.e., the gradient along the line of the profile (time derivative), and plotting the vector sum of this gradient and the observed transverse gradient from the difference between the sensors. It can be shown that the common intersection of the vectors is, to the first approximation, the location in a plan view of the center of the magnetic dipole of the object. The normally difficult task of obtaining the precise location can thus be achieved in a straightforward manner. An example of such a plot from an anomaly in San Francisco Bay is shown in Figure 8b. The anomaly is related to debris associated with the shipping lanes in the bay.

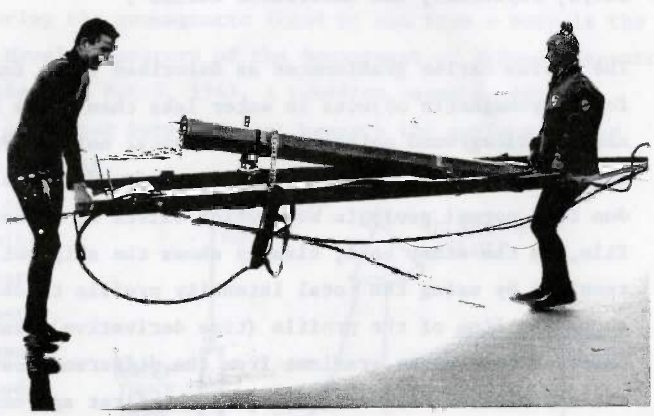
3.4 BUOY MAGNETOMETERS

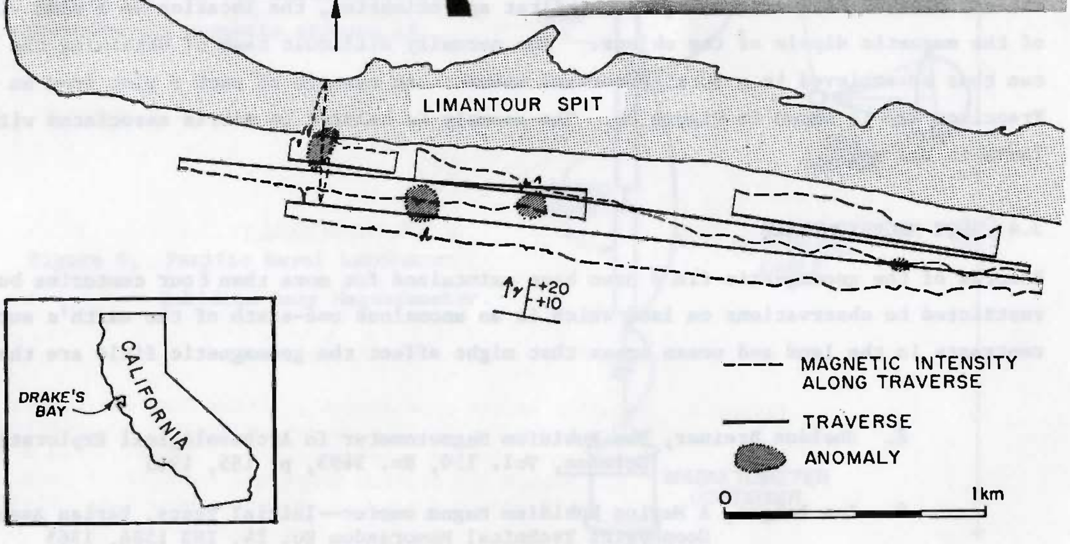
Records of the geomagnetic field have been maintained for more than four centuries but until recently restricted to observations on land which is an anomalous one-sixth of the earth's surface. Among the contrasts in the land and ocean areas that might affect the geomagnetic field are the large conducting

8. Sheldon Breiner, The Rubidium Magnetometer in Archaeological Exploration, Science, Vol. 150, No. 3693, p. 185, 1965

9. Lee Langan, A Marine Rubidium Magnetometer—Initial Tests, Varian Associates, Geophysics Technical Memorandum No. 24, INS 1586, 1965

Figure 7. Rubidium magnetometer in first trials as an archaeological exploration tool. Left, sensor hand carried by diver into the water over known location of Roman shipwreck at San Pietro, Italy, October 1964. (Courtesy Peter Throckmorton).
Below, sensor as installed in pressure housing and diving plane for diver-maneuvered boat-towed exploration of Drake's Bay, California. Anomalies are probably modern shipwrecks. (Courtesy John Huston, Council of Underwater Archaeology).





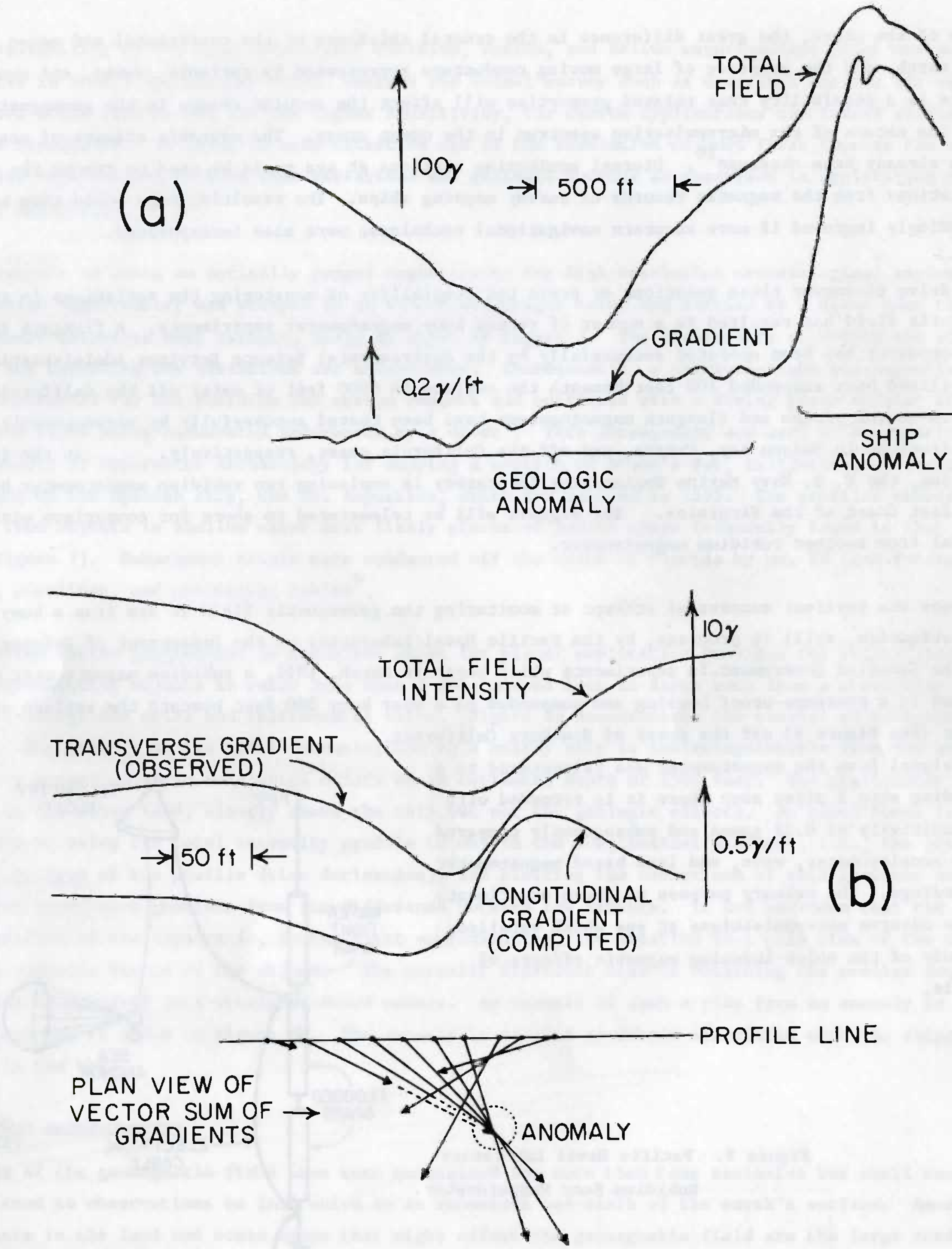


Figure 8. Cesium marine gradiometer profiles from San Francisco Bay as they apply to salvage and underwater exploration. A) Resolution on gradient trace of anomaly from a ship. B) Method for precise graphical solution of location of anomaly from one pass by recording both total field and the transverse gradient (See text).

body of the ocean, the great difference in the crustal thickness of the continental and ocean areas of the earth, and the presence of large moving conductors represented by currents, waves, and swells. There is a possibility that related properties will affect the secular change in the geomagnetic field and the nature of the micropulsation spectrum in the ocean areas. The magnetic effects of ocean swells have already been observed[10]. Diurnal monitoring stations at sea could be used to remove the time variations from the magnetic records of survey mapping ships. The resulting maps would then be correspondingly improved if more accurate navigational techniques were also incorporated.

The drive to answer these questions or prove the feasibility of monitoring the variations in the geomagnetic field has resulted in a number of recent buoy magnetometer experiments. A fluxgate component magnetometer has been operated successfully by the Environmental Science Services Administration in a stabilized buoy suspended 100 feet beneath the surface in 4000 feet of water off the California coast. Bottom-moored proton and fluxgate magnetometers have been tested successfully by oceanographic institutions in Hudson Bay, Canada, and off the California coast, respectively. At the time of writing, the U. S. Navy Marine Engineering Laboratory is emplacing two rubidium magnetometer buoys off the East Coast of the Virginias. The signals will be telemetered to shore for comparison with the signal from another rubidium magnetometer.

Perhaps the earliest successful attempt at monitoring the geomagnetic field at sea from a buoy is the investigation, still in progress, by the Pacific Naval Laboratory of the Department of Defense Research of the Canadian Government. In experiments which began in March, 1963, a rubidium magnetometer was placed in a pressure-proof housing and suspended on a spar buoy 300 feet beneath the surface of the water (see Figure 9) off the coast of Southern California. The signal from the magnetometer was telemetered to a standing ship 2 miles away where it is recorded with a sensitivity of 0.02 gamma and subsequently compared with accelerometer, wave, and land based magnetometer recordings. The primary purpose of these experiments is to observe micropulsations at sea which entailed a study of the noise-inducing magnetic effects of swells.

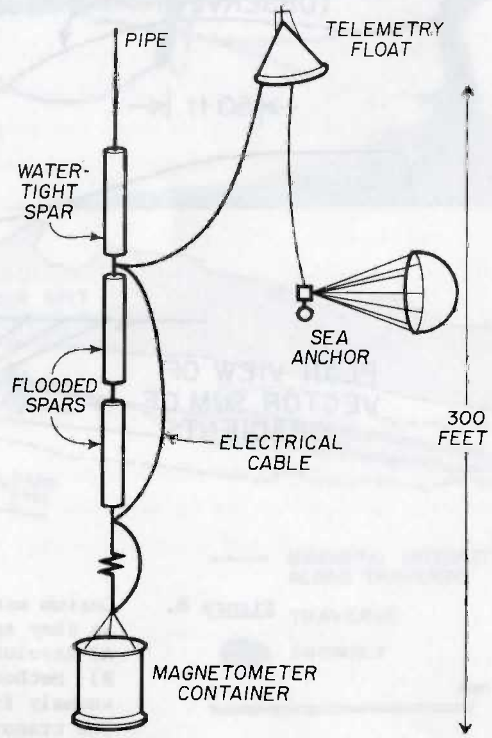


Figure 9. Pacific Naval Laboratory Rubidium Buoy Magnetometer.

10. K. C. Maclure, R. A. Hafer, and J. T. Weaver, Magnetic Variations Produced in Ocean Swell, Nature, 204, p. 1290, 1964.

4.0 CONCLUSION

Geomagnetic measurements in the ocean environment encompass a wide variety of configurations depending upon the particular application of the data. The type of sensors in common use, however, are very few in number being limited almost entirely to the proton precession and optically pumped and monitored magnetometers.

The purposes for the measurements may be archival in nature, research oriented, or direct exploration for salvage or natural resources. The subject of military applications of geomagnetic measurements does not lend itself to free discussion of its goals or methods because of its restricted nature and they were not discussed. The entire history of ocean magnetic measurements is only two decades old so that most of the measurements are unique or experimental, the only routine measurements at present being general survey mapping and petroleum exploration.