TEMPERATURE MEASUREMENT ARRAY FOR INTERNAL WAVE OBSERVATIONS

L. M. Occhiello
University of California, San Diego
Marine Physical Laboratory of the
Scripps Institution of Oceanography
San Diego, California 92132

R. Pinkel
University of California, San Diego
Marine Physical Laboratory of the
Scripps Institution of Oceanography
San Diego, California 92132

Abstract

During the last six years the Marine Physical Laboratory has been engaged in a study of the internal wavefield in the upper ocean. Inasmuch as internal waves propagate horizontally, vertically, and in time, a four-dimensional (space-time) measurement was desired. To meet these requirements, a three-element temperature sensor system in an array 40 meters on a side, was created by mounting 3 booms on the R/P FLIP. Repeated temperature profiles were made from each of these booms. The system consists of temperature and depth profile sensors, winches to raise and lower the sensors, a computer to manage the data, and a central control unit. A vibrotron pressure sensor and two variable frequency thermometers are suspended from each of the booms. The first thermometer and the pressure sensor are placed at the bottom end of a 500 meter cable; a second thermometer is attached 188 meters up the cable. The cables are raised and lowered simultaneously by individual winches. Lowering the winch cable 220 meters provides sampling over a depth of 400 meters in the water column. The drop rate of the sensors is 4.5 meters/second. Vertical temperature resolution is 1 meter. Profiles are taken every two minutes by the three elements. The sensors are scanned by the computer while the elements descend. While the elements are being raised the computer is utilized for data display and initial analysis.

1. Introduction

Internal waves are one of the more mysterious of oceanic phenomena. Their role in the vertical transport of energy and momentum, the driving or dissipating of ocean currents, and in mixing processes has yet to be fully understood. Recently, great progress has been made in internal wave observational techniques. This paper will describe a measurement array deployed from the Research Platform FLIP, which has contributed to the overall effort to understand internal wave dynamics.

The design of the FLIP measurement system was strongly influenced by several factors. It was desired to make a four-dimensional measurement. Earlier observations had ascribed the motion in the internal wave spatial and frequency bands to internal waves, but had failed to establish that internal wave dynamics indeed governed the observed motions. Given the magnitude of the larger scale eddies and shears in the sea, it is quite possible that some other dynamic balance regulated the observed oscillations. The straightforward way to establish that the motions are internal waves is to verify that they obey the linear internal wave dispersion relation. The dispersion relation expresses the relationship between the horizontal, vertical, and temporal scales of the motions. Verifications of this theoretical relationship can only be accomplished using a three-dimensional array of sensors, sampled repeatedly in time.

2. Design Considerations

Although it was desired to construct as large a spatial array as possible, we did not wish to have the array anchored to the sea floor. We preferred an array which could drift with the mean currents in the upper ocean, while still maintaining the fixed relative positons of the sensors. This is due to the fact that the mean currents and lower frequency eddies in the sea advect the media through which the internal waves propagate. Any sensor which is not free to drift with the mean currents will produce Doppler shifted measurement of the internal wave field. Extensive Doppler shifting of the measurements would thwart the effort to compare the observed wavenumber-frequency relationship with that predicted by theory. This consideration precluded the approach of tri-mooring FLIP, and running arrays of sensors down each of the mooring lines.*

A final design requirement was to avoid sensors which produced "fine structure contaminated" measurements. Fine structure contamination refers to an error in deducing the

---

*FLIP is routinely tri-moored in water up to 4 km depth.

motion of water using fixed position sensors. The problem results from irregularities in the spatial gradient of the measured properties being advected past the sensor. This produces an irregular sensor output which is not proportional to the advection velocity alone. This effect can be illustrated simply in the situation where fixed position temperature fluctuation measurements are used to infer the vertical motion in the sea. The equation relating the observed temperature fluctuations, T, with the vertical position of the water, η is:

$$\frac{\delta T}{\delta t} = - \frac{\delta \eta}{\delta t} \frac{\delta T}{\delta z}$$

If there is a single frequency of vertical motion present

$$\eta = \sin \omega_0 t$$

but the vertical temperature gradient is significantly non-linear:

$$\frac{\delta T}{\delta Z} = A_0 + A_1 (Z - Z_0) + A_2 (Z - Z_0)^2 + \ldots.$$

then the fixed depth temperature sensor will output at many frequencies

$$\frac{\delta T}{\delta t} = A_0 w_0 \cos \omega_0 t + \tfrac{1}{2} A_1 \omega_0 \sin 2 \omega_0 t + \ldots..$$

This effect has been studied in great detail for the case of a stairstep temperature profile by Phillips (1971) and for vertical wavenumber band-limited spectrum by Garrett and Munk (1971). The problem can be avoided by using sensors which "follow" the vertical motion of the water. Although the temperature fluctuations at a given depth depend on the fine details of the temperature gradient near that depth, the depth fluctuations of specific temperatures depend primarily on the motion of the water. Vertical profiling sensors, which can follow the smooth evolution of an arbitrarily irregular vertical gradient field, are the straightforward means of reducing fine structure contamination problems.

3. Array System Description

Given these design considerations, it was decided to mount large light weight booms on FLIP, and make repeated profiles of temperature versus depth from sensors suspended from the ends of these booms. Specifically, three booms were constructed, forming a three-element array. The spacings between elements were 44 meters, 38 meters, and 38 meters, for the starboard-port, port-aft, and aft-starboard separations respectively. This was the largest array that could be safely handled from FLIP (Fig. 1, 2). Remotely controlled electric winches were located at the inboard end of each boom. These winches cycled the array elements down and up in unison, at a rate of 4.5m/sec. Winch operation, as well as data scanning, were coordinated by a timing unit mounted in FLIP's lab. A streamlined probe containing a vibrotron pressure sensor and a thermometer was suspended from the terminal end of each winch cable. A second thermometer was placed 188 meters up the cable. In normal operation, the upper thermometers were located at the base of the mixed layer (40-60 m typically) and cycled down to the depth where the lower probes started their descent (at 230 m typically). In this manner, the top 400 m of the water column was profiled (Fig. 3). Profiles were repeated every two minutes. Approximately 2100 profiles per day were collected. Data were scanned and recorded while the probes descended by a HP2100 computer system on board FLIP. While the probes were being raised, the depths at which a preselected set of temperatures was encountered during the drop were calculated by the computer (Fig. 4). Note that these isotherm depth fluctuations are a measure of the vertical displacement of the internal wavefield which is not contaminated by fine structure. In contrast, the time fluctuation of temperature at a preselected set of depths is a contaminated measurement. The difference in these two utilizations of the same data can be seen best in the displacement spectra (Fig. 5). The remainder of this paper will discuss the various elements of the measuring system in greater detail.

The winches used to lower and raise the probes were designed to operate at a 4.5 m/sec profiling speed with a 35 kg (70 lb) load (Fig. 6). The winch frame and drum were fabricated from aluminum, as topside weight is a prime restriction in determining the amount of equipment that can be carried on FLIP. Each winch was driven by a Reliance Electric 5 hp, 440 volt, three-phase electric motor/brake unit, connected through a 25 to 1 Boston reduction gearbox to the .95 m diameter drum. The rotation rate of the drum was 72 rpm. To assure level winding, the drum was grooved to accept the cable being used. During normal operation, there was only a single layer of wire on the drum.

The vertical position of the probes was sensed mechanically by means of sliding block threaded on a lead screw geared to the winch shaft. Microswitches at the extreme ends of the lead screw travel were activated by the sliding block. This information was used by a motor controller to start, stop and reverse each winch, and also by the central timing unit in FLIP's lab, which coordinated the operation of the winches. Profiling depth range was determined by adjusting the position of the microswitches with respect to each other along the lead screw.

It was desired to avoid the violent accelerations associated with the rapid transition from downward to upward travel at 4.5 m/sec. As the electric motor was capable of driving the winch at only one speed, the gradual

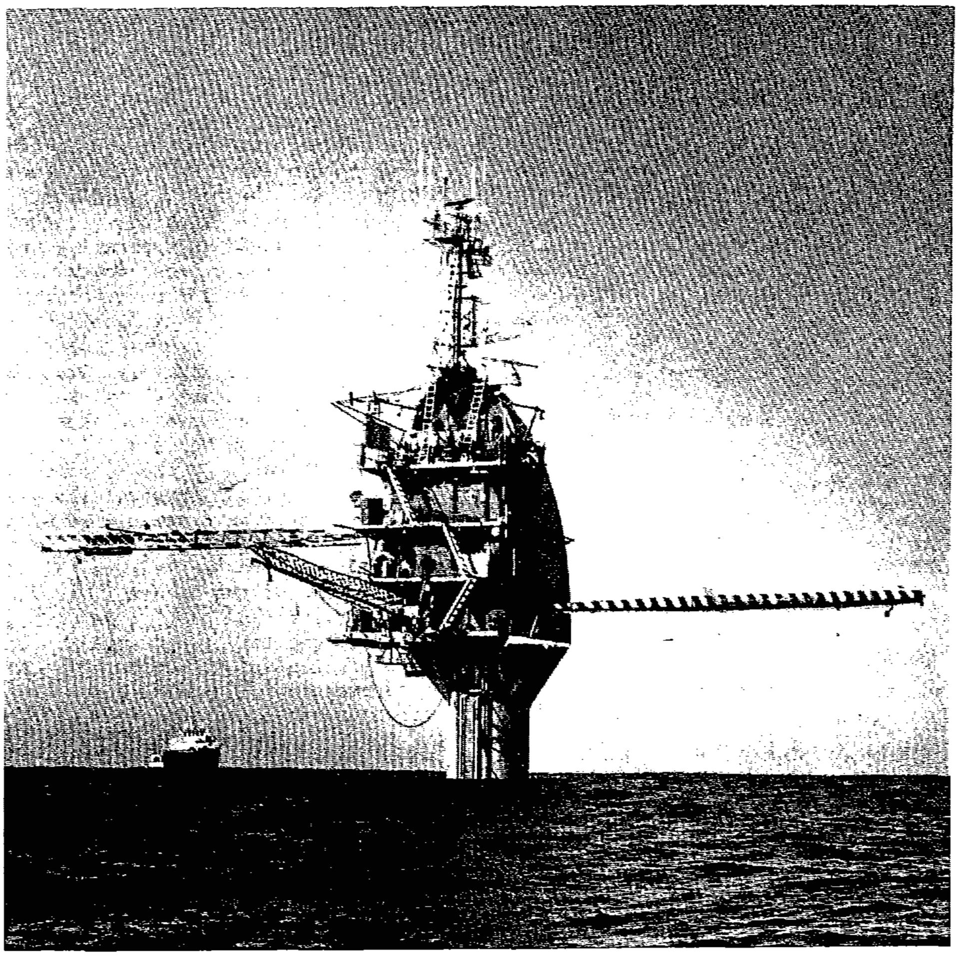


Fig. 1. Research Platform FLIP with temperature profiling array.

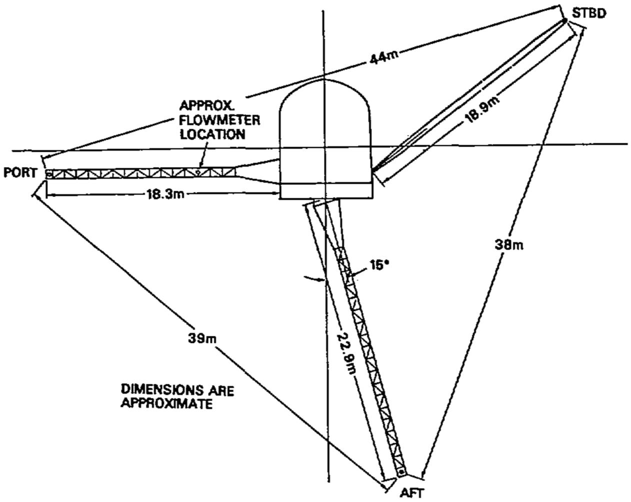


Fig. 2. Top view of temperature profiling array.

accelerations and decelerations were introduced through use of the motor brake and gravity. Specifically, three time delay relays were incorporated into the controller of each winch. The first relay provided a delay between the time the brake was released as the winch started down from the beginning of the drop to the time the motor was engaged. This allowed the winch to "free fall" gradually to 4.5 m/sec before the power was applied. The second relay provided a delay between the time the brake was applied to stop the descending probes and the time the motor was reversed and started to raise them. At the top of the drop the third delay occurred. The motor was turned off slightly before the brake was applied, allowing the winch to coast to a stop.

The coordination of winch operation with data scanning was the function of the timing unit located in FLIP's lab. This unit produced a set of pulses, one every two minutes during typical operation, which released the probes on their downward profile. This "start pulse" was gated with the signals from the upper limit

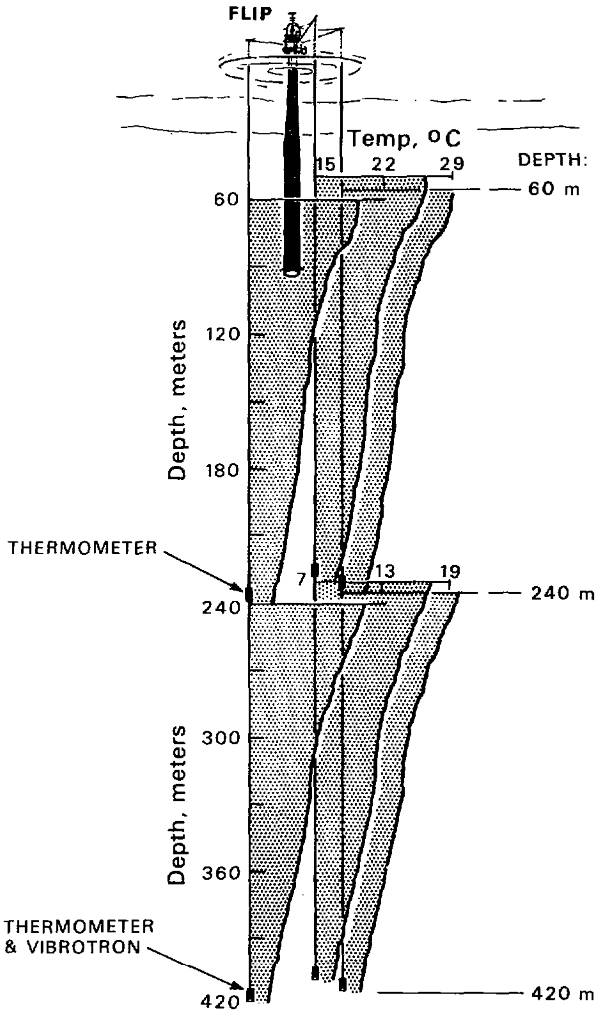


Fig. 3. FLIP temperature profiling array configuration.

switch of each of the winches, such that none of the probes would start down unless all had returned from the previous profile. This assured that the winches would operate in unison. Drop repetition time was adjustable from 40 sec to 180 sec in 20 sec increments. While the probes were descending, a second set of pulses was sent to the computer, initiating the scanning of the sensors. Typically, these pulses were generated every .2 sec, although the scan time was adjustable from .05 seconds to .4 seconds in .05 second increments.

To monitor winch operation in the laboratory, a potentiometer was connected to the lead screw on each winch. Winch drum rotation, as indicated by this potentiometer, was displayed in the lab. Also displayed was the output of a counter, which indicated the number of revolutions of each winch. This counter only functioned during descent of the probes, and was reset at the beginning of each drop.

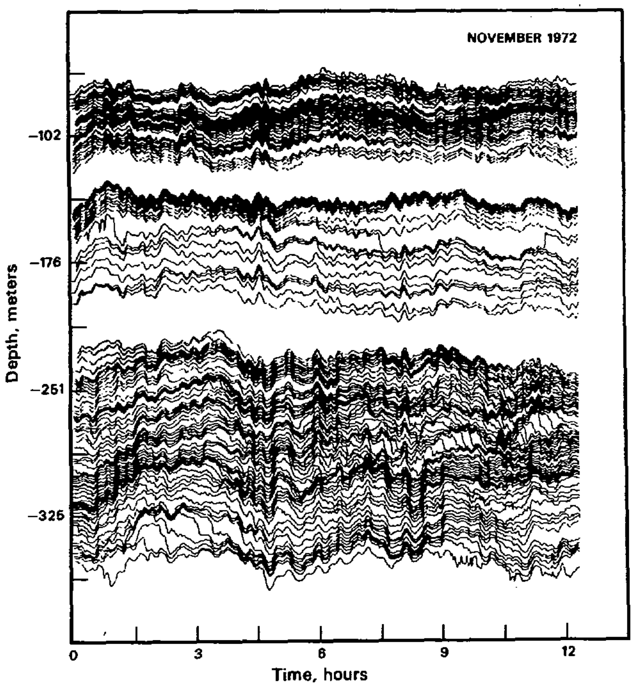


Fig. 4. Thirteen hour series of isotherm fluctuations data from the starboard profiler.

The thermometers used were of a type developed by Mr. Earl Squier at the Marine Physical Laboratory. Each thermometer was a phase shift oscillator, with three thermistors used in the shifting network (Fig. 7). It generated a frequency which was proportional to the temperature. The temperature data was transmitted up the same pair of wires through which the sensors were powered. By the proper choice of the capacitors and thermistors used in the shifting network, the thermometer could be tailored to a variety of temperature-frequency ranges. The lower thermometers, used in the probe, were adjusted for IRIG channel E; the upper thermometers were spread over channels 10 thru 13. Separate sets of thermometers were required for central Pacific and California coastal operations, as the difference in temperature of the upper ocean was enough to force any single thermometer out of its band. The thermometer electronics were assembled between printed circuit discs .675" in diameter. After testing and calibration the electronics were placed in a 7/8 inch diameter p.v.c. pipe, six inches long, and potted with epoxy (Fig. 8). The three thermistor beads projected from one end of the potted tube. A two pin connector was cast in the other end.

The completed thermometers had a rise time of .25 sec. This corresponded to a rise distance of 1.1 meters of water at the 4.5 meter per second fall velocity. They were sensitive to .001°C temperature change, with

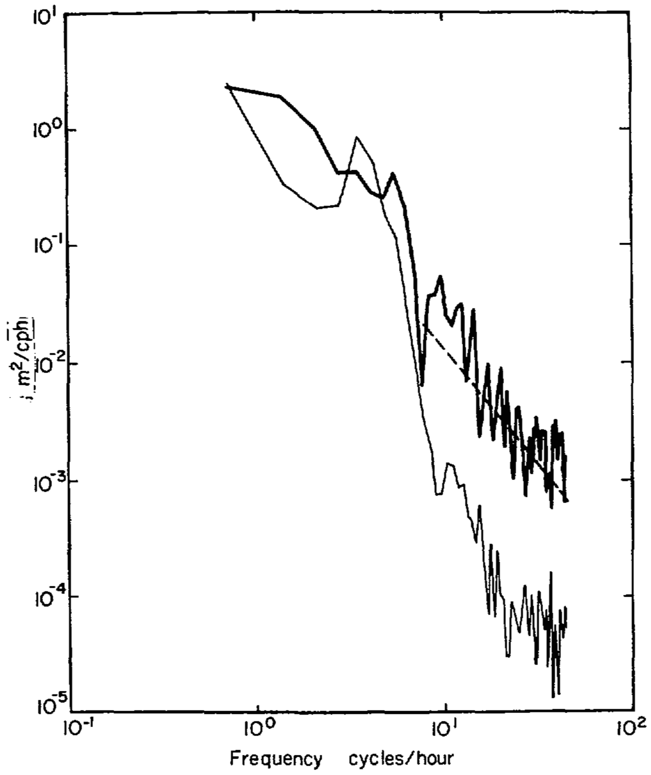


Fig. 5. Comparison of contaminated and uncontaminated spectra. An isotherm displacement spectrum (light line) is plotted with a fixed depth temperature fluctuation spectrum (heavy line) taken at the same time and same mean depth. The dashed line gives the approximate level of fine structure contamination noise.

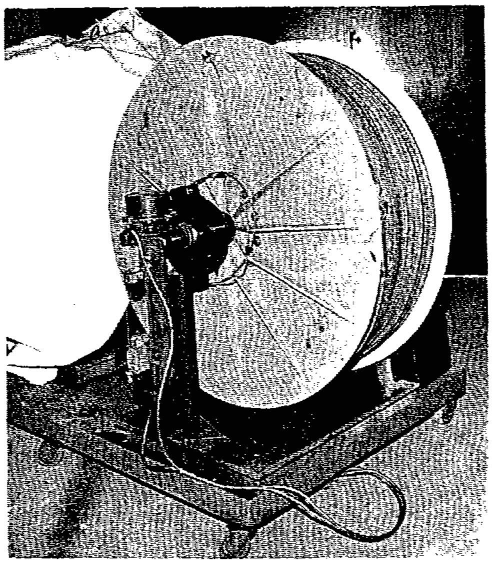
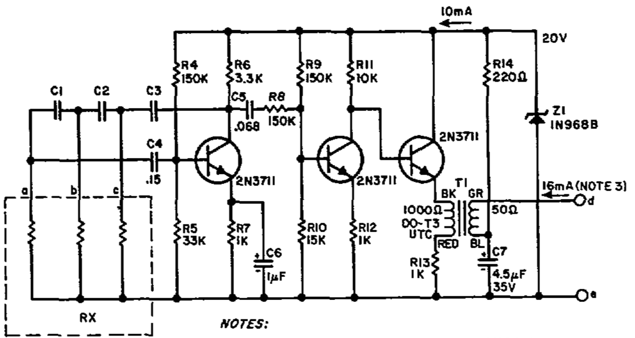


Fig. 6. A profiling winch used in this experiment.



NOTES:

1. RX - 3 EA. THERMISTORS, VALUES CHOSEN FOR SELECTED FREQ. - TEMP. RANGE.
2. C1, C2 AND C3 CAPACITOR VALUES CHOSEN FOR SELECTED FREQ. - TEMP. RANGE
3. DO NOT EXCEED 25 mA.

Fig. 7. Schematic of variable frequency thermometer (After Squier 1967).

.05°C long term drift. The electronics were initially calibrated prior to potting, using precision resistors in place of thermistors. Final calibrations were performed in a temperature controlled bath.

The thermometers underwent an initial calibration shift, as much as .3°C, when they were first subjected to high pressure (~1000 psi). After this initial calibration shift no further pressure dependence was observable.

The pressure sensor used was a 1000 psi vibrotron operating in IRIG channel A. The vibrotron was powered by an amplifier also developed by Mr. Earl Squier of MPL. Like the thermometers, it sent its signal up the same wires from which it received its power. In this manner, the three sensors on each cable shared the same two conductors.

The outputs from all sensors were passed through decoupling circuits in FLIP's Lab. There the signals were filtered and clipped. These conditioned signals were scanned by a period counter at a rate determined by the timing unit. The digital data was then transfered to the computer for preliminary analysis and recording on magnetic tape.

4. Operational Problems and Solutions

During the development of this project a number of difficulties were encountered. It was desired that the azimuthal orientation of the array remain fixed for long periods of time. Only with time series measurements made while FLIP's heading was fixed could the directional properties of the waves be deduced. The orientation control system on FLIP consisted of hydraulically powered propellors mounted off axis on FLIP's hull and controlled automatically by the ship's gyro-compass. The propulsion supplied was adequate for normal FLIP operations, but the additional windage caused by the booms used in this experiment would overpower the system in winds greater than 10 knots. A compromise strategy was adopted, whereby FLIP was allowed to orient in

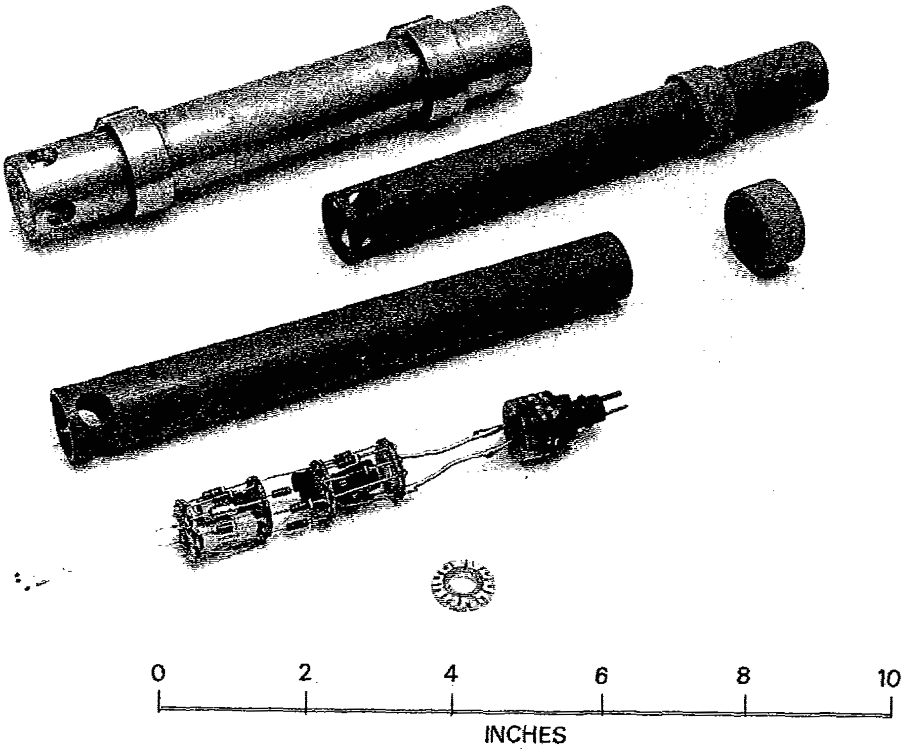


Fig. 8. Variable Frequency Thermometer

her equilibrium position, with the wind twenty degrees to the right of the keel. The orientation system was then used to damp our oscillations about this mean. During normal operation, FLIP's heading could be maintained to within +5° for several days at a time. Major wind shifts or squalls would necessitate repositioning of the array.

Because the winches operated unattended and were of open construction, they presented a great safety hazard. Problems with any component in the lead screw-micro switch assembly would lead to violent mechanical failure. Emergency shut-off switches were installed on each winch and in FLIP's lab. To prevent personnel from becoming entangled in the winches, safety covers are currently being fabricated. The danger associated with the automatic operation of this machinery became evident only after the equipment was constructed. The importance of considering safety in the initial design phase of a system such as ours cannot be over emphasized.

The cables used on the winches were U.S. steel type 3H18RB and Rochester type 3-H-0, a 0.187 inch diameter double armored 3 conductor cable. Only 2 conductors were used, with the third being kept as a spare. The cable was run over a 10 inch diameter sheave at the end of the boom. This was the minimum diameter bend that the manufacturer recommended. After one to two weeks of constant operation the outer armor tended to stretch and form baskets (Fig. 9). After the wires had stretched to a certain point they would break. Some removal of these outer strands was tolerated, however, the cable was usually replaced when more than two or three strands had been broken. Discussions

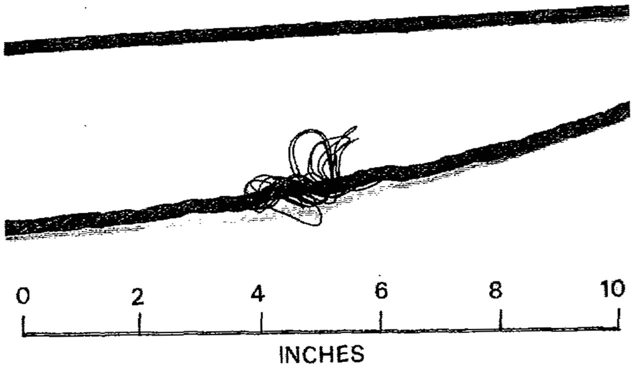


Fig. 9. Typical Cable Failure.

with the cable manufacturer confirmed that this was indeed a severe test of the cable and this type of failure was not unexpected. The manufacturer suggested using a larger diameter sheave and modifying the sheave groove in order to cut down on the cable wear. New large sheaves have been built and are awaiting a long sea trip for life testing of the cable.

One of the more unusual problems arose when operating off Hawaii. Large game fish tended to "strike" at the upper thermometers. They would sometimes miss and bite the wire between the thermometer and the cable termination. A long piece of spiraled plastic tubing and lots of black tape were used to cover the exposed wire. After covering the wire no further problems from fish bites were encountered.

5. Conclusions

In spite of these difficulties, the system has proven to be a comparatively reliable method for obtaining long term detailed information on the upper ocean temperature field. Approximately six months of data have been collected to date, from cruises in the central Pacific and off the California coast. During many of these operations wind velocity, barometric pressure, surface wave amplitude, ocean current and sound velocity profiles were also monitored. This data is currently being analyzed, with the objective of determining possible generating mechanisms of the internal wave field.

Acknowledgements

The authors wish to thank Mr. Bill Davy and his crew for their untiring efforts in the construction of the booms and winches. Our thanks also go to Mr. Earl Squier for his initial system design and his continuing advice and help over the past few years. This research was supported by the Advance Research Projects Agency of the Department of Defense and was monitored by ONR under Contract No. N00014-75-C-1023.

References

Garrett, C.J.R., and W.H. Munk, Internal wave spectra in the presence of fine structure, J. Phys. Oceanogr., 1, 196-202, 1971.

Phillips, O.M., on Spectra measured in an undulating layered medium, J. Phys. Oceanogr., 1, 1-6, 1971.

Squier, E.D., A variable frequency thermometer, Tech Memo 183, Mar. Phys. Lab., Univ. of Calif. San Diego, 1967.