FREE-SINKING TEMPERATURE AND SALINITY PROFILER FOR OCEAN MICROSTRUCTURE STUDIES

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Abstract

A free, slowly sinking profiler minimizes the velocity differences between its sensors and the structures which are sensed, allowing small scale features to be measured. Large quantities of data must be stored or transmitted acoustically with a free instrument. SCIMP, an acronym for Self-Contained Imaging Micro-Profiler, records 6 hours of conductivity, temperature, and pressure digitized to 16 bit accuracy every 400 ms. It sinks at rates of 3 to 10 cm/sec, photographing optical inhomogeneities for comparison with the temperature and salinity structures. Alternate sinking and rising or yo-yo stations have produced time series of microstructure profiles in essentially a single column of the ocean.

Introduction

A microstructure observing system comprising an autonomous sinking platform, a microstructure CTD and recorder, and an optical imaging system and camera has been used in four ocean experiments. The system is named SCIMP for Self-Contained Imaging Micro-Profiler. The autonomous platform, Autoprobe, was designed by Burt (1974), the microstructure CTD was designed by Brown (1974), I designed the optics, and Albro (1972) designed the optical and overall packaging of SCIMP. In this paper, I will describe the complete instrument system as well as elements of the system not described elsewhere, and engineering results based on 27 dives.

SCIMP

The principal requirement of the underwater instrument is to measure undisturbed microstructure, the salinity and temperature inhomogeneities with length scales where molecular diffusion may be important. These structures are generally smaller than 10 cm. At scales smaller than 1 mm, the lifetimes of the structures become too short to be of interest in the deep ocean, and I have made no attempt to resolve submillimeter scale structure.

The optical imaging system views a 5 cm diameter cylindrical volume which is 160 cm long. Periodic inhomogeneities (such as salt fingers) with wave lengths 2 cm to 2 mm, and gradient regions with thickness less than 2 cm can be measured with this technique. The microstructure CTD can measure, in a vertical column, finestructure and microstructure at vertical length scales greater than 5 cm. The vertical scales from 5 cm to 2 cm are not lost completely as the optical images can be overlapped to give a larger effective viewing aperture, but this is only useful for certain types of features (thick salt fingering interfaces for example).

The requirement that the observed microscale structure be undisturbed is severe. Cable lowered instruments are subject to vertical motion. Even if heave reducing techniques are used, such as line accumulators, spar buoy platforms, catenary decouplers, or fast lowering rates, horizontal velocity differences between the ship and the microstructure or between two depths in the water column may cause a cable lowered instrument to be dragged sideways.

I have reduced this kind of disturbance by choosing a free platform which sinks slowly enough (7 cm/sec) so that the horizontal component of its velocity with respect to the microstructure is always small. Autoprobe serves well as such a platform because it varies its displacement to achieve a slow, constant sinking rate. This is preferable in some respects to increasing the vertical drag to achieve slow sinking; for example the response to velocity shear is faster. Strictly, slow sinking is only a way of keeping the flow of water past the instrument vertical and minimizing the disturbance in the optical path.

Data measured on a free platform must either be transmitted acoustically or stored in the instrument. SCIMP only transmits enough data for tracking. All other data are recorded. The images are photographed on 16 mm film, 400 ft (122 m) of film recording 600 m of ocean. The digital CTD data are recorded on magnetic tape cassettes (Sea Data Inc. series 610 recorder); 7 hr of data (60,000 records) can be stored. The recordings are synchronized to the photographs through the tape record number which is displayed in the field of view of the camera. Each tape record contains four 16 bit words of record number, pressure, temperature, and conductivity.

The tapes are read into an 8K minicomputer through a microcircuit interface card from a 16 bit parallel-output tape reader (Sea Data model 10). Salinity, potential temperature, potential density, and dynamic height are computed from and plotted with pressure, temperature, and conductivity. Serial output is also used for quick-look analysis, when a computer is unavailable. In this case, two 8 bit segments of the 64 bit record are selected in a formatter and converted to analog voltages which are displayed on a strip chart recorder or plotted against one another on an X-Y recorder or on the screen of a storage oscilloscope. The sequency of CTD data handling is illustrated in Figure 1.

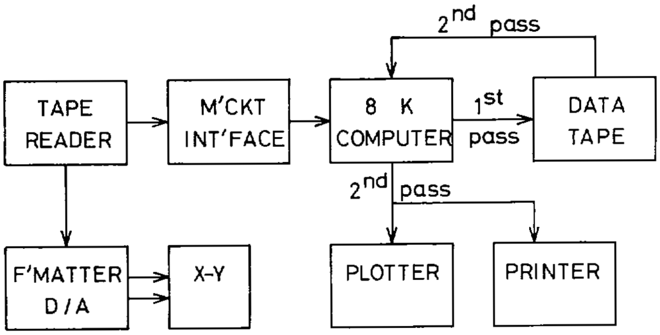

Figure 1. Block diagram of CTD Data Processing.

The film is developed at sea and viewed on a movie editor for interactive experiments as well as optical adjustment. Further analysis is done ashore on a time-motion study projector and by printing individual frames on copy film which are then manipulated.

The acoustic telemetry used to track the instrument is a pulse repeated precisely every 2 sec with time-delay encoded pressure and temperature pulses. The pulses are 10 ms and 20 ms bursts of 5 KHz (40 w input power) giving an acoustic range of 10 km barring poor refraction. A shipboard tracking receiver (Burt, Webb, Dorson, and Williams, 1974) indicates range to the instrument and displays the decoded pressure and temperature on chart paper. The ship is customarily released to other users after the instrument is launched and the telemetry informs the operator if the dive is going routinely. If the instrument requires control, the shipboard tracking receiver is used to transmit acoustic commands to the underwater command receiver. Commands are used to change from sinking to rising modes for yo-yo stations, and to speed ascent at the end of the dive if the ship is waiting. Range and bearing (from multiple towed hydrophones) help the operator to relocate the instrument for pickup.

While acoustic tracking is the primary relocation system, a flag and flashing light for visual contact helps when the ship approaches the instrument. The instrument is snagged with a hook-bearing line (Williams, 1974a) when the ship is within range.

The optical instrument, microstructure CTD, Autoprobe electronics, compressed gas tanks, variable displacement unit, recovery weight, syntactic floatation, and frame weigh about 320 kg. The frame ties these pieces together, provides lifting points and legs, and absorbs shocks when the instrument hits the ship. The 27 mm o.d. structural aluminum pipe sections of the frame are replaceable and the frame which is 3 m by 1 m square when assembled, breaks down into pipe and pinned couplings.

The rest of the shipboard equipment includes apparatus for recharging batteries, drying agent, and gas tanks, and alignment equipment for the optical unit. Only primative calibration equipment is carried for the CTD, spares having been calibrated ashore.

Internally Recording Microstructure CTD

The cable lowered CTD's normally perform a digitization every 32 ms (or in the three digitizer version, all three quantities are digitized each 32 ms). However the slow sinking rate and long data acquiring time of SCIMP allow a reduction to one digitization of all three quantaties every 400 ms. This interval is approximately the time constant of the platinum thermometer (Rosemount 171BJ) at such descent rates so only a small amount of temperature resolution is lost by such a slow sampling rate. The vertical sampling interval is about 30 mm (the same as the cable lowered CTD) which matches the estimated flushing length of the conductivity cell and the 50 mm resolution of the pressure measurement.

Two conductivity cells were used in the 27 dives, differing only in construction materials. The first was all ceramic and glass while the second was covered with urethane in one place (to seal the troublesome kovar-platinum welds used at the time). The first cell had a fast response compared to the thermometer. To correct for the response time difference, the next digitization of temperature was used with the present digitization of conductivity in the calculation of salinity. This simple correction is effective for all cases where the temperature gradient is uniform if the sampling interval equals the simple time constant of the probe. The second conductivity cell exhibited a thermal delay at slow descent rates, at which rates the cell walls warmed the water within the cell. The time constant of this process was longer than the time constant of the platinum thermometer. The flushing rate thus plays a role in the response of the second cell and an adequate correction to the data is still being sought to handle sharp steps in temperature. No problem is experienced at regions where the temperature gradients are slight.

A lightweight, demountable, aluminum sensor head carries the thermometer and conductivity cell (and certain electronics) as illustrated in Figure 2. The sensors are close to the endcap with this design but are not in the wake of the endcap. This arrangement is possible because the case lies horizontally. When sinking, the water reaching the sensors is undisturbed, but when rising, the sensors are in the wake of the syntactic floatation which reduces the resolution of the ascending measurements.

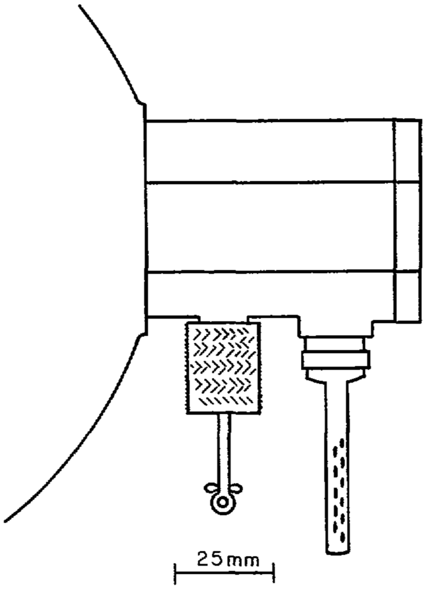

Figure 2. CTD Sensor Head. The conductivity cell and platinum thermometer are mounted near the endcap.

The electronics and sensor head are secured to one hemispherical endcap of a 152 mm i.d. aluminum pressure housing (collapse depth, 3000 m). The other endcap is removed to replace the battery, tape, and dessicant.

In the free instrument version of the CTD, a serial shift register is loaded with record number (which is also transferred to the photographic unit), pressure, temperature, and conductivity. On completion of the last transfer into this register, the tape recorder starts to shift the 64 bits at 2.5 ms/bit onto the tape (blocked into 4 bit characters). The shift is finished before the first quantity is again fully digitized. A single clock is used for both the CTD and recorder to ensure synchronization. See Figure 3.

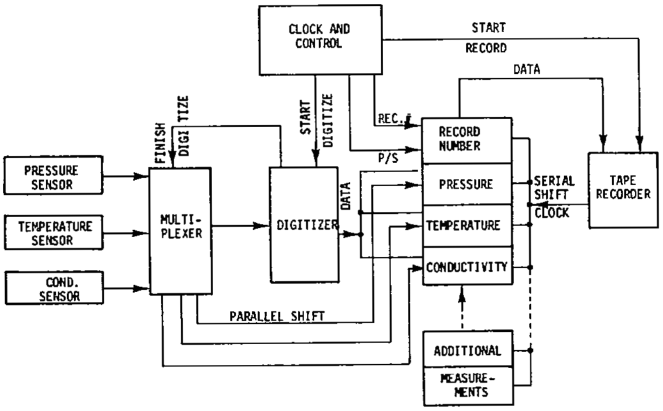

Figure 3. Block diagram of CTD and Recorder. Additional data can be recorded as indicated.

The CTD and recorder are powered by an 18 V, 2.3 ah, NiCd battery. Most of the stored energy is used by the tape transport in filling a single cassette.

The CTD and recorder perform well. Unrecoverable tape errors are rare. The data are apparently reliable (and in agreement with STD measurements made at the same time within the accuracy of the STD calibration) with two exceptions. On dive 8, the conductivity cell developed an electrical leak and on dive 9, it failed which made salinity doubtful or worthless on two dives. The second difficulty was experienced with the pressure measurement where sensitivity to moisture was exhibited by the sensor circuitry. Our mode of operation, in which we changed tapes and batteries out on deck, aggrevated this problem. Generally the intermittant pressure record which resulted could be patched on the computer adequately for our purposes, and the problem disappeared with careful drying.

Optical Imaging System

Microstructures refract light because they contain index of refraction inhomogeneities. Collimated light is focused by parts of these structures. At some distance from the inhomogeneity, a shadow of the structure can be detected. In SCIMP, a telescope shortens the required distance and projects the image on a ground glass screen. Sixteen light emitting diodes at the side of the screen display the binary record number of the CTD digitization. This number is serially shifted from the CTD to the optical unit each time a digitization is recorded. The number is parallel shifted into latches which drive the LED's when the serial shift is complete. Serial shifting is used to minimize the number of underwater connections. Latches are needed to ensure a complete number is displayed when the shutter is open.

Examples of images photographed from the ground glass screen are shown in Figure 4. These images are prints of single frames of the 16 mm film. The upper images show turbulence associated with a nearshore environment at a strong mean gradient, and a structure-free region for comparison. Presumably, velocity shear has stirred the water to produce this mixing event. The lower images show salt fingers and a structure-free region nearby. The fingers are vertical, counterflowing columns of water which exchange heat (which diffuses rapidly) but not salt (which diffuses 10^{-2} as fast as heat). The salt finger image was taken where the temperature and salinity decreased rapidly over 24 cm in depth. The salinity inversion at such an interface provides the driving force, balanced by viscosity, to produce the flow. For more about salt fingers see Turner (1967) and Williams (1974b).

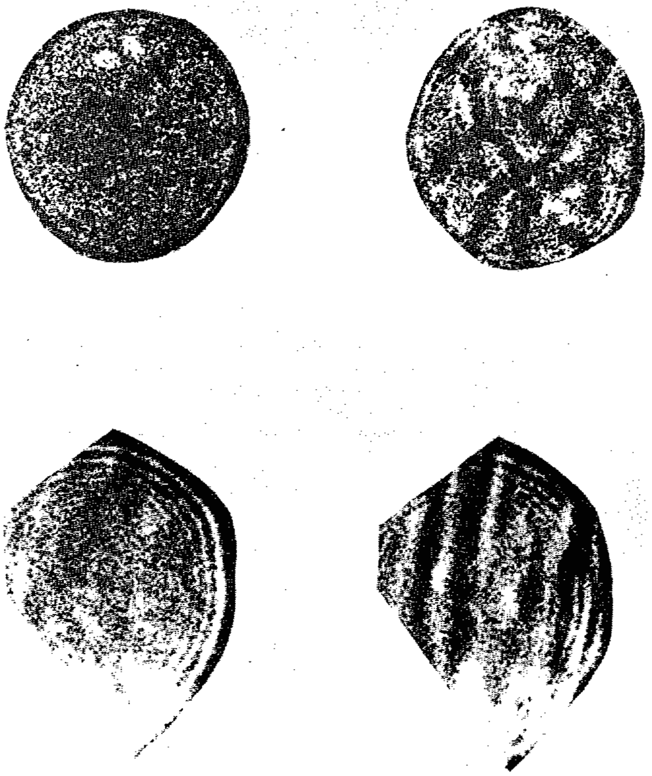

Figure 4. Images of Microstructure. The upper right photograph is a turbulent structure compared to a quiet region (at the left) on the same dive. The lower right photograph is a salt finger field. The lower left photograph was taken above the fingering interface.

Autoprobe

Autoprobe is useful as a platform for microstructure work. In SCIMP, it carries the optics and CTD. Autoprobe seeks a constant descent rate and generates a displacement correction signal which is equivalent to the difference between the desired and the actual descent rates. Actually two values of desired descent rates are used, one for sinking and one for rising, and the appropriate mode is selected by acoustic command. In the proportional control range, the applied correction is linear with error. The drag of the instrument varies with the square of the velocity so a linear relation will not match every rate. For SCIMP, a rate of 5 cm/sec is matched.

Control is limited to 85 cc/min. To reverse direction from 10 cm/sec sinking to 10 cm/sec rising requires a change of displacement of 2500 cc which would take 30 min under automatic control, so the acoustic command is used as a manual override to hold the control valve open as long as the command is received. Displacement can be changed 1000 cc/min by command. When the rate is close to the target, the automatic system is left in either the sinking or rising mode as is appropriate.

The compressed gas supply which powers the variable displacement system is stressed by deep dives and by large vertical excursions. The tanks hold 2000 liters at STP of nitrogen gas compressed to 200 bars. The volume of the variable displacement system which must be pressure compensated by this gas is about 1/3 as large as the tanks so this limits the maximum working pressure to 150 bars or 1500 m depth. In practice the limit is found to vary from 1200 m to 1400 m depending on the initial ballast and thus the volume of the displacement unit which requires gas compensation.

A vertical excursion from 1200 m to 600 m rejects half the gas in the compensated volume so the next turning point should not be below 1050 m, etc. Autoprobe performs well within these restrictions. SCIMP has been carried on several yo-yo cycles to 900 m as illustrated by Burt (1974).

On deep dives, the variable displacement system free-floods and rate control is no longer obtained. However, the sinking rate can be roughly adjusted by ballasting before launch and a rate of 14.5 cm/sec was achieved on a dive to 1800 m. Recovery of the instrument in this case depends on release of a weight which is a triply redundant operation.

Autoprobe also carries SCIMP quickly to the working depth, then turns on the camera and the automatic control system, and finially terminates the dive at a second depth or after a certain time.

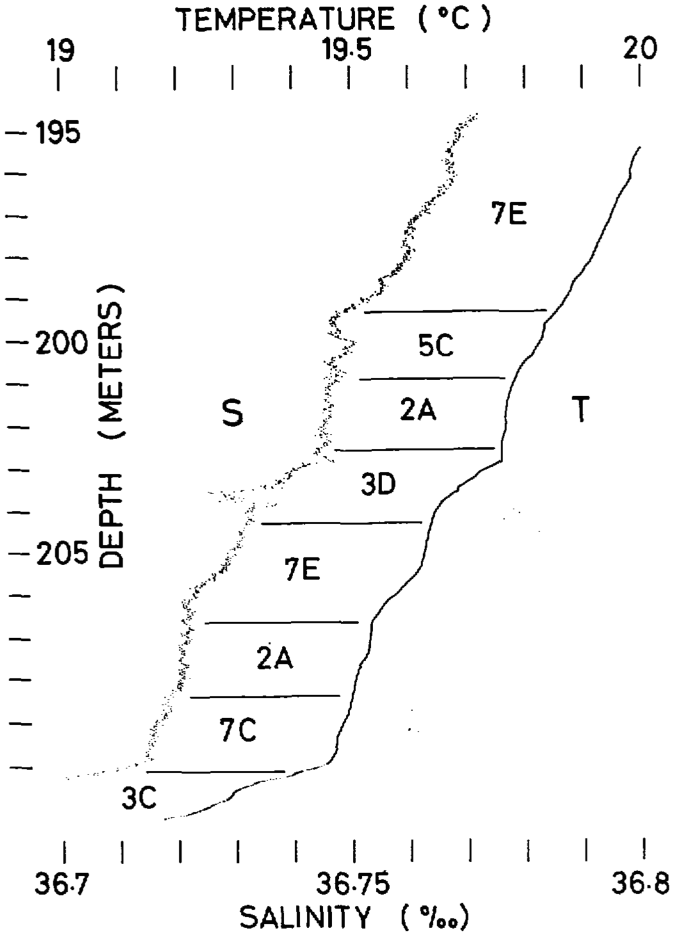

Figure 5. CTD Profile from 1.5 km south of Puerto Rico Shelf. The images have been encoded and correlated to this profile. Contrast is coded from A, high; to E, low. Number of lines in image is coded from 1, many; to 7, few. Figure 4 upper left would be 7E while the upper right would be 3A.

Performance

SCIMP was initially deployed in the Caribbean 1.5 km south of the Puerto Rican shelf. Dives were made to 600 m with optical adjustments between dives. Turbulent sequences of 1 to 5 m intervals were common to a depth of 200 m and occasionally down to 600 m. Salt fingers were observed on one dive at several depths. This was the first observation of salt fingers in the ocean.

The images of turbulence were not expected - perhaps because the profiles did not show large amplitude, small scale gradients. In fact, the strongest images of turbulence occurred at relatively low gradient regions within a thick (30 m) large gradient region. The temperature profile was smooth, the salinity profile showed small oscillations with 20 cm wavelength while the images implied there were centimeter scale inhomogeneities of large magnitude. Figure 5 illustrates one such region.

A staircase structure of temperature and salinity was studied in the Tyrrhenian Sea north of Sicily. Layers homogeneous to 10^{-3} °C potential temperature and 50 to 100 m thick were separated by 6 m thick interfaces at which the temperature dropped 0.1°C and salinity dropped 0.02 ‰. Figure 6, a station where SCIMP made 8 profiles in 12 hr, shows the changes of microstructure on the interfaces between the layers. Half meter steps came and went as the 6 m interface was stretched and compressed by internal waves.

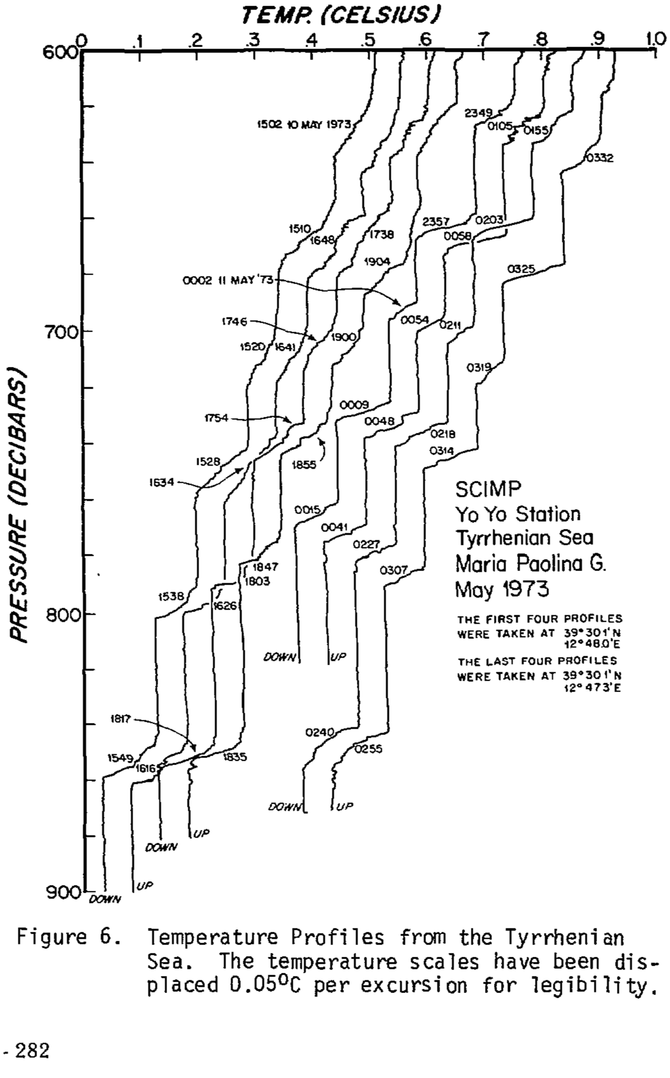

Figure 6. Temperature Profiles from the Tyrrhenian Sea. The temperature scales have been displaced 0.05°C per excursion for legibility.

Faint salt fingers were seen at the small steps but did not extend over the whole interface. The mean gradients were too small to produce strong fingers over a 6 m interval.

Dives were made to 1300 meters while yo-yo stations were made to 900 m.

A similar staircase was studied in the Mediterranean Outflow beneath the 1200 m salinity maximum. One strong salt fingering interface was imaged at the bottom of a high salinity intrusion (Williams, 1974b). On subsequent dives, staircases were observed in which the mixed layers were 12 m thick and the interfaces were 0.2 to 0.5 m thick with temperature steps of 0.1°C and salinity steps of 0.02 ‰ as in the Tyrrhenian. Close inspection of the images taken at the staircase interfaces (each of which exhibited fingers) revealed that, as in the Tyrrhenian, there were smaller interfaces of 10 or 20 cm thickness at which the fingers actually occurred.

Dives in the Mediterranean Outflow went as deep as 1800 m. No yo-yo stations were possible at those depths.

Summary

SCIMP, containing a microscale temperature and salinity profiler, an optical imaging system, and a telemetering autonomous platform, has observed two kinds of microstructure - salt fingers and optical turbulence - for the first time in the ocean. These features have been related to the larger scale features of the profile. An internally recording, free system of this type has facilitated these measurements.

Acknowledgements

This research was supported by ONR contract N00014-66-C0241; NR 083-004. The Mediterranean Outflow cruise was supported by the Oceanography Section of the National Science Foundation, NSF grant GA-37767. This is Contribution No. 3357 from the Woods Hole Oceanographic Institution.

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