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A Towing System for a Sensing Package: Experiences and Plans[1]

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ABSTRACT

The development of a technique for towing standard oceanographic sensors (pressure, temperature, conductivity, and sound velocity) at intermediate depths of less than 1000 m is described. Data show the depth characteristics of the tow and the comparative output from each of the sensors. High-frequency variations in the tow depth, coupled with incompletely matched sensor response, are found to be a limiting factor in the resolution of the measurements. The capability of the system to delineate discrete patches of water and to make observations along an isopycnal surface is demonstrated. Plans for future simultaneous vertical-gradient measurements are discussed.

1. *Introduction.* In the last few years, continuous sensing of pressure, temperature, conductivity, and sound velocity has become a primary tool for observing the ocean. The lowering of these sensors has become a commonplace substitute for the Nansen-bottle cast when accuracy can be partially compromised or when a corollary measurement is necessary for greater vertical resolution. As a consequence, there is an increasing body of literature (e.g., Hamon 1967, Cooper and Stommel 1968, Tait and Howe 1968, Pingree 1969, Katz 1970, and Roden 1970) that describes medium-scale and small-scale structure in the water column as observed by continuous vertical lowerings. These very same sensors can be used to obtain continuous horizontal data of comparable detail. One technique of doing this is the subject of this paper.

The system described and the data discussed are the result of two tow experiments. The first experiment was performed in July 1970 when 550 km of towing were logged in the western Mediterranean Sea. The sensors, mounted in a faired housing, were attached to a weighted and faired cable and towed at depths of 100 to 450 m at speeds of 4 to 7 knots. Signals were recorded on digital deck equipment designed for vertical lowerings and an analog strip chart was substituted for the usual $x-y$ plotter.
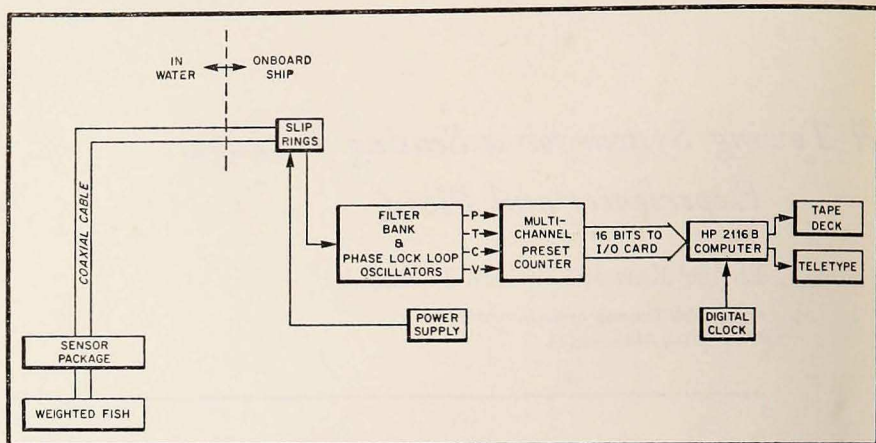
Figure 1. Components of the tow system.

The second experiment was executed in March 1971 in the western Sargasso Sea. An additional 750 km of towing were logged, but a more sophisticated data-acquisition system was used. From the first experience, we acquired confidence that the sensors were behaving well in the tow configuration. Tows down to 700 m were now accomplished and manual control of depth was introduced; with the tow cable only partially faired. A shipboard computer was employed for acquisition of the data, allowing for on-line computations. This latter capability was fully utilized when the depth of the tows was controlled to follow an isopycnal surface.

The results are divided into performance data and samples of overall results. Combined they provide a basis for evaluating the potential of the existing system in future work. Previously reported tow systems have concentrated on the measurement of temperature or, nearly equivalent, sound velocity. They can be classified as follows:

Observations at one depth

    (i) Voorhis and Perkins (1966) using a thermistor;
    (ii) Beckerle (1966) using a sound velocimeter;
    (iii) Katz (1969) using a quartz thermometer.

Isotherm following

    (i) Fuglister and Voorhis (1965) using a thermistor and bourdon gauge.

Multidepth thermistor chains

    (i) Richardson and Hubbard (1959);
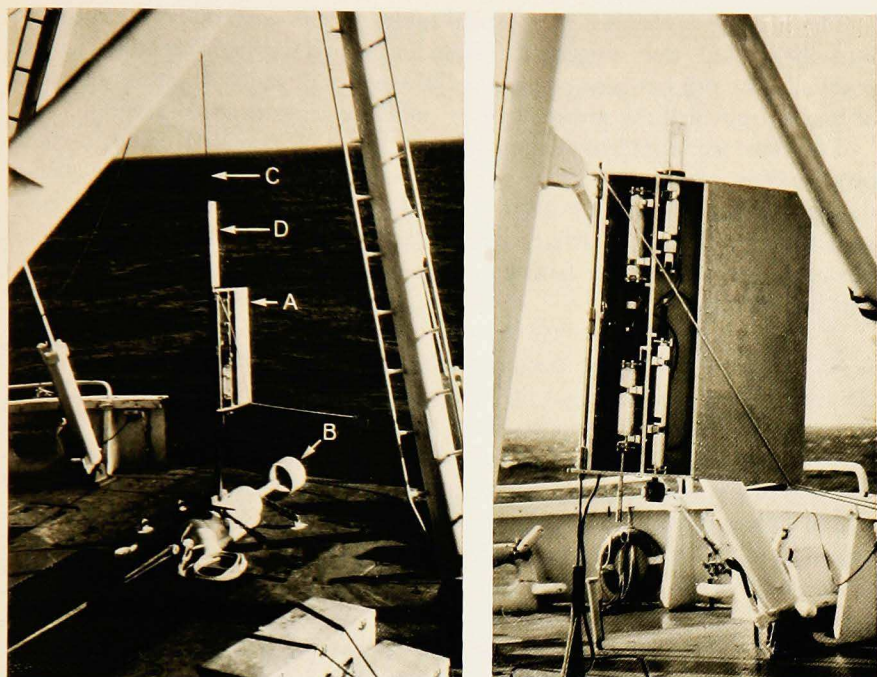   (ii) La Fond (1963).

Figure 2. In-water equipment on deck. Left photo shows the major components: A. Low-drag housing for sensors. B. Weighted (one-ton) fish. C. Multiconducting reinforced tow cable. D. A fairing. Right photo shows the four sensors (pressure, sound velocimeter, temperature, and conductivity) mounted in the housing.

The above investigations (and others not referenced) were of near-surface phenomena (0–300 m) and they described fronts and internal waves from the single parameter of temperature. The present system not only affords substantially deeper penetration of the water at reasonable speeds but includes a measurement of conductivity as well. The subsequent calculation of salinity and density yields a more precise description of both fronts and wave fields.

2. *The Tow System.* The components of the present tow system are diagrammatically illustrated in Fig. 1. Fig. 2 shows that part of the system that is operated under water. The sensor housing is aluminum with a fiberglass access cover; its cross section is an axially symmetric wing profile, 23 in. long and 5 in. (1 in. = 2.54 cm) across its beam, designed to keep the fin headed into the flow. The pressure, temperature, and conductivity sensors are components of the Bissett-Berman vertical profiler, model # 9006. The sound velocimeter is a model TR-4 of NUS Corporation design. All of these components are mounted vertically in the housing so that their sensing elements protrude into the water from both the top and bottom ends of the fin.

The housing is clamped to a coaxial cable. At the wet end of the cable is a lead-filled "fish" that weights the cable and keeps the housing in an upright position. The fish has been constructed of sections of standard pipes; its weight of 900 kg provided the greater part of the cable tension while towing.

The cable was faired with alternating S-shaped aluminum fairings; a major consideration in the use of fairings is their relative expense—roughly five times the cost of the cable per unit length. In the first experiment the cable was completely faired from 1 m above the fin to the surface. Operational and cost factors prevented complete fairing in the second exercise, and the consequences will be described.

A slip-ring connection at the dry end of the cable is an essential element for *in situ* calibration of the conductivity sensor during the raising and lowering of the fish. The signals, once past the slip rings, are separated by band-pass filtering and are applied to a phase-locked loop for the purpose of improving the wave shapes. The time of a selected integral number of cycles of each signal is determined by using a multichannel period counter (Fig. 3). The counting of all the signals is initiated simultaneously at a half-second repeat rate. By suitably adjusting the count-down ratio of the oscillator for each channel, the counting times can be extended over roughly the same time interval, despite the differences in frequencies and resolution requirements. In the present work, the time interval was about 0.01 sec. Such a short count time was not necessary and was thought to be a possible source of data noise. However, subsequent trials under comparable test conditions, with count times of approximately 0.25 sec, demonstrated that such was not the case. The half-second sample rate is a limit roughly set by the rated time response of the slowest responding sensor (about 0.33 sec for the temperature sensor).

The number of periods to be counted is preset into the counter, individually for each sensor. It is convenient to limit the clock count to a 16-bit binary word; this is made possible by allowing for unambiguous overflows. When all counters are filled, the computer is flagged to sequentially receive the data scan.

The computer is programed to begin by acquiring new data and accumulating a number of scans in a buffer. Once filled, the computer begins to fill a second buffer while simultaneously operating on the data stored in the first buffer. To proceed from the raw count to the engineering units, the overflow information and calibration data are preprogramed. All data, including a clock reference, are then preserved on digital magnetic tape for future analysis. For real-time control of the experiment, averages of each variable are computed each minute, with obvious miscounts excluded. Averaging the data over at least a 6-sec time span (in each minute interval) produces smooth results; the reasons for this will become apparent when we discuss the high-frequency motion of the tow body. Salinity, density, and sound velocity are also computed, and the combined results (seven in number) are put out on the teletype at the rate of one line per minute. Acquisition and computation (with the Hewlett Packard
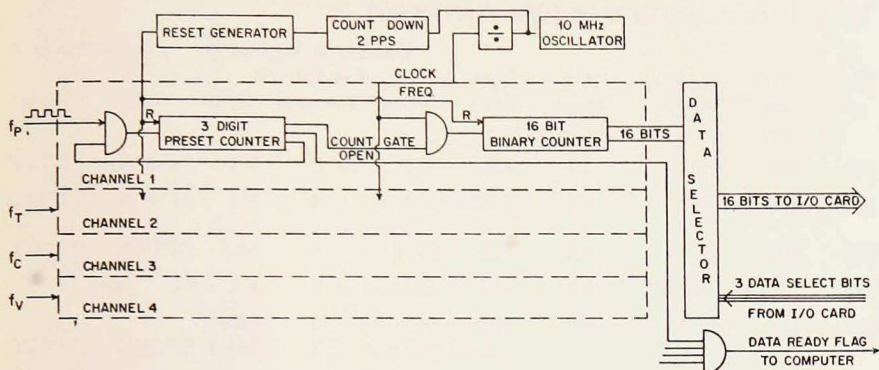
Figure 3. Block diagram of the counter.

2116B) occupies the computer for 19 sec, the type out requires an additional 7 sec. The remaining 34 sec of each minute is idling time (waiting for the next buffer to be filled) and is available for future program development. The same programing is used for vertical lowerings, but instead of averaging, the teletype output is one scan in every 5 sec.

A visual comparison between computed and sensed sound velocity is an up-to-date indication of the continual reliable performance of all four sensors, and the teletype output is monitored for that purpose.

3. *Performance Data.* The first experiment, which consisted of five tows at two different sites, produced 50 hours of data. The cable was completely faired and no attempt was made to control the depth of the tow. The particular value of the uncontrolled depth data is the information they provide on low-frequency depth variability.

With a 900-kg weight and with speeds in the five-knot range, tows down to 500 m are relatively efficient in their use of cable. Deeper than 500 m, either the speed must be significantly reduced or the weight must be substantially increased in order to avoid trailing excessive lengths of cable behind the ship. Data pertaining to five tows in the first experiment are summarized in Table I; continuous records of one-minute depth averages are shown in Fig. 4.

The general dependency of depth penetration on tow depth and tow speed was as expected. Also, there appears to have been another trend; the better the depth penetration, the more variable was the tow depth in the cycles-per-hour frequency band (cf. tow 102 with 101 and with 201; also, cf. the latter part of tow 202 with the earlier part). This dependency is explained by noting that, when the ship was heading into heavier seas, it had to be slowed in order to keep the cable laying properly. In tow 102, heading into the swell, the result was an estimated vertical motion of $\pm$ 5-m amplitude at a rate of some 5 cycles/hour. At the shallowest depth (tow 203), the comparatively stable tow

Table I. Summary of tows (first experiment).

Tow #	Wire out (m)	Av. depth (m)	Av. speed (knots)	Tow direct.	Wind	Sea state	Swell	Lat.	Long.
					Weather at beginning of each track			Co-ordinates of track	
101	480	402	5.7	ESE	N4	3	N3	38°00'N	6°25'E
102	480	443	4.5	WNW	NW5	4	N4	37°48'N and	7°43'E
201	480	371	6.8	NE	SE4	4	SE3	38°10'N	11°50'E
202	310/285	266/277	5.3	SW	SE2	2	E2	and	
203	145	137	6.9	NE (end)	SE5 WSW2	3 2	SE3 SSE1	38°58'N	12°45'E

is the norm, having been obtained on numerous prior occasions at speeds of up to 10 knots.

In the second experiment, comparable data were not obtained. In order to follow an isopycnal, the amount of wire out was purposely changed as frequently as every five minutes to compensate for both the movement of the fish and the variable depth of the isopycnal being followed (560 to 680 m). Speeds of about 4 knots were maintained to a 10% tolerance under favorable sea
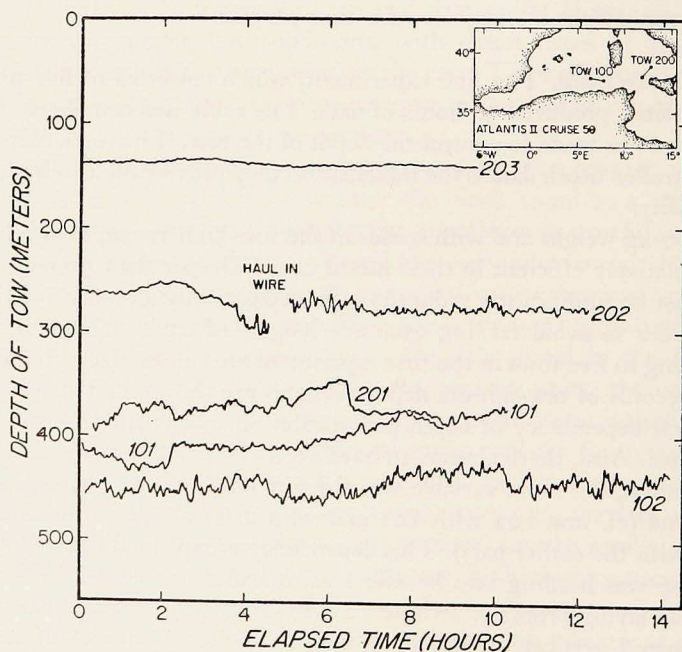

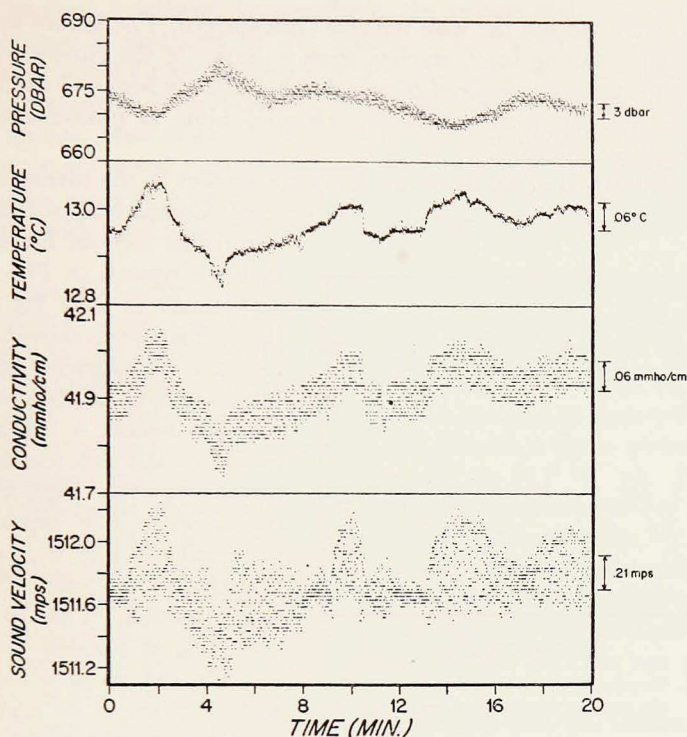Figure 4. One-minute averages of tow depth for five tows.

Figure 5. Simultaneous output of the four sensors (every, $1/2$ second scan) as recorded on magnetic tape; the predicted range of measurements for a 3-m variation in depth are shown at the right.

conditions (sea state 3 or less) for periods of 74 and 50 hours each. For the most part, 800 to 1000 m of cable were required.

It is impractical to continuously take off and put on fairings during a schedule such as that indicated above. Instead, only the bottom 350 to 400 m of the cable were faired. This arrangement resulted in the uppermost fairings (two strands of 25 each, separated by stopper clamps attached to the cable) being lost; they had been held against the cable by detent pins, which had chafed against the cable. The pins may have fallen out or the fairings may have broken as a result of the vibration of the cable. At the uppermost fairing, several outer strands of wire had been broken, causing permanent damage to the cable.

The section of the cable where the faired and unfaired sections meet is obviously subjected to greater vibration than elsewhere. On the second lowering of this second experiment, a somewhat different set of fairings was used for the upper 50 m of the faired section. These fairings were U-shaped, with a rectangular section cut out of their middle. In this cut-away, a stopper clamp was fastened to the cable to hold each fairing in place. During this tow, a couple

of fairings were lost but the wire remained undamaged. The failure was in the shearing of the fairing itself, starting from a corner of the cut-away; as evidenced by the topmost retrieved fairing that had already begun to shear. Thus, topping the fairings with individually clamped units to protect the pinned fairings has been effective.

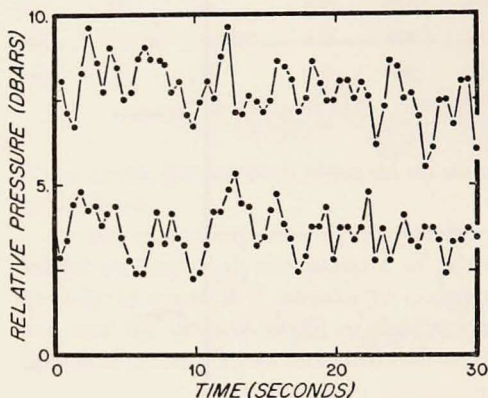For consideration of the performance of the sensors in the towing environment, a 20-min section of data has been selected. Comparison of this section with other sections has indicated that it is typical. In Fig. 5, every half-second of data for each of the four sensors is shown as it was recorded on magnetic tape. Note the dense band of observed values for each sensor. A partial explanation of this data scatter is suggested by the high-frequency oscillation in tow depth (shown in detail in Fig. 6), which is thought to be induced by the ship's motion. This oscillation, consisting of a period of a couple seconds and an amplitude of a meter or two, is an ever-present limitation to the quality of the tow results. Its effect on the other sensors can be predicted and compared with the observations.

Figure 6. Two half-minute samples of the output of the pressure sensor on an expanded scale.

For a comparison, recall that the data from each of these sensors are, for the most part, measurements of temperature. In the range of values observed over a small vertical scale in the ocean, salinity and pressure have only a second-order effect on conductivity and sound velocity. If we consider a 3-dbar depth variation and a vertical temperature gradient of 0.02°C/dbar, then we can derive expected bandwidths for the three remaining sensors. These are indicated in Fig. 5.

The band of conductivity measurements agrees with what is expected. The observed temperature band is decidedly narrow compared with what is expected, and the discrepancy is attributable to either the relatively slow response time of the temperature sensor or to poor flushing at the sensor head. Unless the mismatch in response is averaged out beforehand, difficulties in later computations must be expected. The need for this averaging, however, places a limit on the resolution of the observations.

The sound velocimeter has a variable scatter about its mean that cannot be the result of vertical motion alone. Although this sensor, which measures the time for a sound pulse to travel over a short reflected path, can be shown to

have a spurious sensitivity to crossflows, the nature and magnitude of the scatter cannot be explained by this artifact. The contractions in the scatter could be explained by intermittently poor flushing, but that leaves the bursts of excessive scattering unexplained. If the cause of the scatter is indirectly the vertical motion, then short-time averaging should eliminate it and, indeed, the difference in computed and sensed sound velocity after 10-sec averaging differs by an r.m.s. value of 0.05 mps. This is small compared with the directly in-duced bandwidth and can be ignored in the present application.[2]

4. *Results.* EXAMPLE 1. Tow 102 was made southwest of Sardinia in water that is 2800 m deep. The tow depth was chosen to nearly coincide with the core depth of the Levantine Intermediate Water, which flows through the western Mediterranean Sea from the Strait of Sicily to the Strait of Gibraltar (Wüst 1961, Lacombe and Tchernia 1960). According to those authors, the tow track would be in a main stream of this subsurface water movement and roughly parallel to it.

The temperature and salinity traces obtained during this tow are shown in Fig. 7. By comparison with the pressure trace, reproduced from Fig. 4, it can be established that there is no strong correlation between the immediate depth of the tow and the variations in temperature and salinity. Additionally, the earlier pass along this track, tow 101, showed the same major temperature and salinity features as this recent track, despite the fact that the tow was 40 m shallower on the average.

In comparing the data from these 110-km traces with the information that has been previously compiled from hydrographic stations, the range in tem-perature and salinity values over the track (and their often discrete change) is most remarkable. Thus, where Wüst (1961) has inferred a distance of over 300 km between core waters having salinities of 38.7°/oo and 38.5°/oo, such core waters with the appropriate temperatures are found here to be within 5 km of one another. Excluding the western end of the traces (where salinities below 38.45°/oo, coupled with temperatures above 13.2°C, are most likely shallower than the core maximum), the range in observed temperature and salinity all overlay Wüst's T–S correlation for the core water. Moreover, the range of these values, 13.95°C and 38.7°/oo to 13.2°C and 38.45°/oo, includes the greater part of the range that Wüst found throughout both the Tyrrhenian and Balearic basins (nearly the entire western Mediterranean). The special

2. Subsequent trials have added two additional observations. By mounting the sound velocimeter on the tow body itself, the disturbing pulsations of the observational scatter were effectively eliminated. Thus, it appears that the problem arose from either the rotation of the fin about the wire or the vibra-tions of the wire itself. The second new result to be added concerns the fact that, under similar sea con-ditions, the amplitude of the high-frequency motion of the tow depth was reduced by a factor of two. The only known major difference in performing the two data exercises was in the ship: from the R/V KNORR, which has a cycloidal propulsion system and a noticeable fantail motion in even calm seas, to the R/V CHAIN. If, as suspected, this motion of the tow body is attributable to the ship's motion, then the characteristics of the ship constitute another factor to be considered.
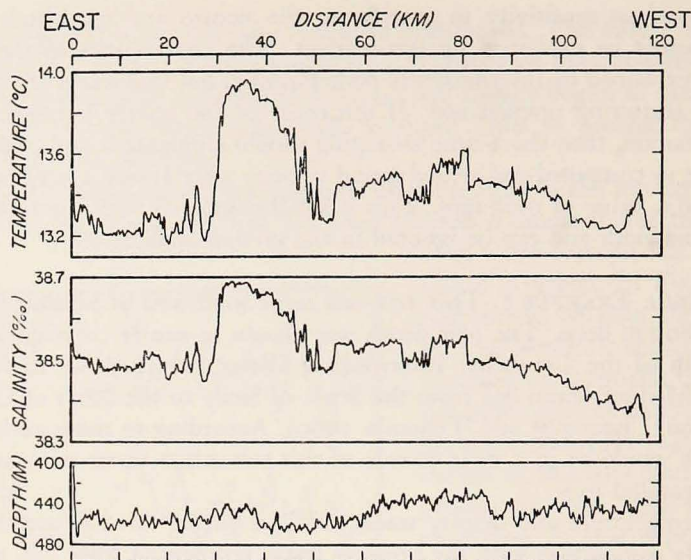
Figure 7. Salinity and temperature in the core of the Levantine Intermediate Water (tow 102) during July 21–22, 1971. The traces are one-minute averages. Track co-ordinates, etc., are given in Table I.

meteorological conditions in the region of this tow have been previously noted and related to changes in the flow of the surface waters (Ouchinnikov and Fedoseyev 1965). The tow illustrates possible consequences to the subsurface waters as well (Katz 1972).

EXAMPLE 2. The second experiment was an attempt to obtain for the first time a continous trace of an isopycnal surface in the main thermocline. The observations were made over the Bermuda Rise, due south of Bermuda. A north-south track of the density surface, observed for a distance of over 500 km, is shown in Fig. 8. A tow such as this is not actually on the surface but is as close to it as is possible. The data shown in Fig. 8 are those obtained when the observed density was within the range $\sigma_t = 26.91 \pm .05$, with the depth corrected by assuming a vertical density gradient of 3.75 dbar/0.01 units of σ_t. The latter number was derived from an average of the data and is not necessarily the correct gradient at any specific point. The data scatter of about 5 m is comparable to the estimate of what resolution could be expected after averaging over one-minute intervals. Of the one-minute averages, 85% was within the ± 0.05 criterion, or within less than ± 20 m, of the desired depth.

The depth of the isopycnal varies over a 120-m range. A small-scale oscillation of 10 to 20 m in amplitude and of 20 km in length is present throughout. Besides obtaining the depth of the isopycnal, the temperature and salinity changes on the surface can be studied for evidence of diffusion.
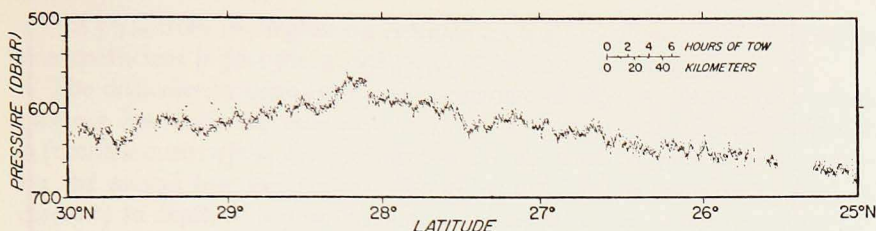
Figure 8. Profile of an isopycnal in the main thermocline along the meridian 65°W. The output of each sensor has been averaged for one-minute interval prior to making the computations. Each point is one such average when σ_t is within the range 26.91 ± 0.05, with the pressure corrected for the mean vertical-density gradient (see text). The tow was made continuously during March 7–10, 1971, from south to north at an average speed of 4.2 knots. The average temperature and salinity for those points that are nearly on the surface (26.91 ± 0.01) are 13.3°C and 35.7°/$_{oo}$.

The track was completed in 74 hr with an average speed of 4.2 knots. Temporal distortion of the apparent spatial scales is an inherent difficulty; the same problem is encountered in interpreting vertical sections.

5. *Future Development.* The data derived from these two experiments provide ample material with which to evaluate the tow system. Development in two areas that should improve the results are: (1) better stabilization of the tow depth and (2) measurement of simultaneous vertical gradients to correct for inevitable depth fluctuations.

The stability of a tow has proved to be a limiting factor in the resolution of the observations. In particular, the high-frequency oscillations are too fast for the response of the sensors, and possibly for their ability to properly flush. This has led to time averaging that introduces an ambiguity in the results because of changes in the mean depth of the tow body over the averaging period. It is not obvious how to improve the tow stability with the present system. An alternative solution worthy of investigation is the replacement of the weighted fish with a lighter tow body having a controllable fin similar to that recently developed at the Bedford Institute of Oceanography (Canada).

No matter what system is used to obtain the most stable tows, it will still not continuously maintain a tow exactly on any particular isopleth. If the local vertical gradients were known, then the optimum condition of towing on an isopleth could be relaxed.

Before attempting to directly measure vertical gradients between two sets of temperature and conductivity sensors attached to the tow wire, it is useful to first estimate the results to be expected on the basis of the data already in hand. In Fig. 9, the data from 596 pairs of temperature and computed salinity observations are plotted. Each pair is a six-second average observed during a single 65-min segment of the second experiment when the tow depth was relatively steady between 628–645 dbar. For discussion, the temperature meas-
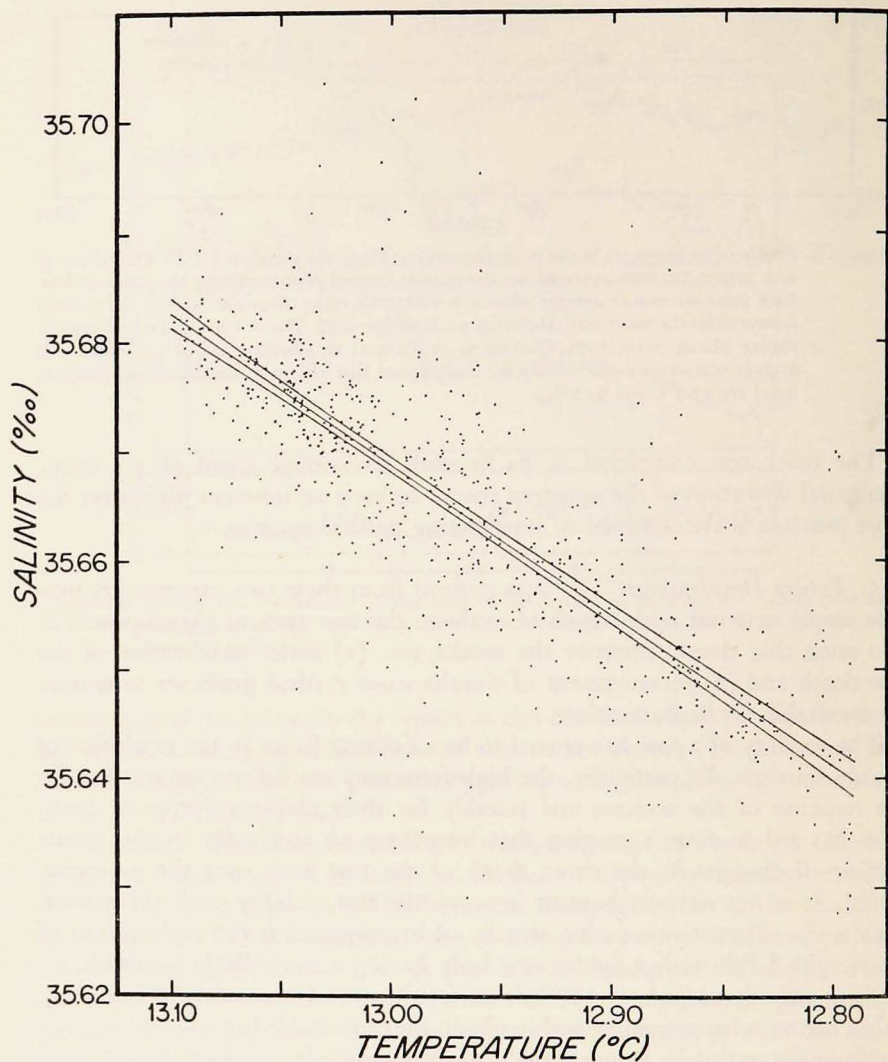
Figure 9. Regression of salinity on temperature and its 95% confidence limits. The data are six-second averages collected near 26°30′N, 65°W.

urement is assumed to be exact and it is further assumed that, had there been no observational error in the salinity computation, the correlation of salinity to temperature would be both exact and linear over the small temperature range and distance involved. Due to observational error, then, the standard error of the mean value of salinity for a given temperature is 0.008%/₀₀. The 95% confidence limits of the regression line, shown in Fig. 9, is within

±.0015⁰/oo from the regression estimate for a given temperature. The regression coefficient is [0.1380 ± .0084]⁰/oo/°C with 95% confidence.

The difficulty in comparing two computed salinities to determine a salinity gradient lies with the estimated error in making a single measurement, or ±[0.008 + 0.0015]⁰/oo for each sensor. In the mean vertical salinity gradient for the second tow experiment, this estimated error is equivalent to an uncertainty in depth of ±3 m. This may be considered an acceptable error for a single measurement, but the error in computing a gradient over an interval of 10 m, or even 20 m, is excessive.

An alternative approach is to use the T–S information from one pair of sensors to establish the local T–S relationship in the above manner. This correlation function could then be used to deduce the salinity at *both* sensing depths, making unnecessary a second conductivity sensor. The mean value of the salinity at each depth is then assumed to be known to better than ±.0015⁰/oo from the observed temperatures. Furthermore, the salinity gradient is known to 6% (0.0084/0.1380) independent of the vertical separation, as the two temperatures (and their separation) are assumed to be known exactly. In this manner, estimates of the vertical salinity and density gradients can be made with the addition to the present system of only a single temperature sensor. They could be spaced as closely as is possible to resolve the temperature gradient.

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