The Underway Conductivity–Temperature–Depth Instrument

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ABSTRACT

The development of the Underway Conductivity–Temperature–Depth (UCTD) instrument is motivated by the desire for inexpensive profiles of temperature and salinity from underway vessels, including volunteer observing ships (VOSs) and research vessels. The UCTD operates under the same principle as an expendable probe. By spooling tether line both the probe and a winch aboard ship, the velocity of the line through the water is zero, the line drag is negligible, and the probe can get arbitrarily deep. Recovery is accomplished by reeling the line back in. Recovering the UCTD has some advantages: 1) the cost per profile decreases with increasing use, 2) sensors can be calibrated postdeployment, 3) the UCTD carries a pressure sensor so depth is measured directly, and 4) no hazardous materials are left behind. The design goal for the UCTD was to obtain profiles deeper than 100 m at 20 kt (typical of a VOS). This goal has been surpassed, as it is able to profile to over 150 m at 20 kt and to over 400 m at 10 kt. The first operational use of the UCTD occurred during a May–June 2004 cruise, the purpose of which was to examine the effect of internal waves and spice on long-range acoustic propagation. Over 160 UCTD casts were completed, resulting in a hydrographic section with resolutions of 10 km horizontally and 5 m vertically.

1. Introduction

Underway vessels are attractive observational platforms used in at least two ways. First, research vessels achieve rapid, purposeful, synoptic surveys at typical speeds of 10 kt (5 m s^{-1}). Second, vessels of opportunity are used as platforms for a variety of measurements. Such vessels range from research ships transiting between stations to commercial container vessels steaming between ports at speeds up to 20 kt (10 m s^{-1}). Observations of surface properties from underway vessels are relatively straightforward, but vertical profiles can be more challenging. At least three approaches to the problem of profiling exist: towed winged vehicles on fixed cables, "tow-yo" systems in which a shipboard winch repeatedly deploys and recovers cable, and expendable profilers. This paper presents a new approach that combines some of the properties of tow-yos and expendables. We call this system the Underway Conductivity–Temperature–Depth (UCTD) instrument.

Before presenting the UCTD, it is worthwhile to discuss briefly the characteristics of towed winged vehicles, tow-yo profilers, and expendable profilers. The advantages and disadvantages of each system in typical use are highlighted.

Towed, winged vehicles are most often used for purposeful surveying from research vessels. Perhaps the most well known and widely used system is SeaSoar (Pollard 1986). SeaSoar is controlled by adjusting the angle of attack of pivoting wings, which causes it to fly typically in a sawtooth pattern from the surface to 300–400-m depth at a tow speed of 4 m s^{-1}. With a cycle taking about 12–15 min, a horizontal resolution of about 3 km is achieved. As SeaSoar is towed on a conducting cable, data are communicated in real time. Wing control is active, so SeaSoar can be programmed to follow pressure or density surfaces, allowing horizontal resolution as fine as 4 m (Rudnick and Ferrari 1999; Ferrari and Rudnick 2000). The SeaSoar vehicle has a substantial payload, and all manner of sensors have been deployed successfully. Perhaps the major disadvantage of a SeaSoar system is its size and complexity. SeaSoar requires exclusive use of the ship while towing and a fairly large dedicated winch. Deployment and recovery is an involved, labor-intensive process, especially when using the rigid cable fairing required to

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achieve depths of over 300 m. In the final analysis, towed winged vehicles are the usual choice for purposeful surveying from research vessels.

The first underway surveys were accomplished with the bathythermograph (Spilhaus 1938). An early use was a survey near the Gulf Stream, where a continuous 175-mi section was made at speeds of about 7 kt, with horizontal resolution of about 3 mi, to depths of 120 m (Spilhaus 1940). The original bathythermographs had to be recovered to remove and replace the glass slide on which the data were recorded in the smoke of burned skunk oil (Snodgrass 1968). Modern tow-yo instruments are towed on conducting cables, so the data are available immediately. To profile, the tow-yo depends on a heavy weight to go down, with a winch that can pay out faster than the ship speed and recover quickly under tension. The main factor limiting depth is cable drag, because the cable paid out on descent must be recovered. Because cable drag increases as the diameter of the cable, while strength increases as the diameter squared, arbitrarily thick cable allows any desired depth and tow speed. With the benefit of sophisticated winches, tow-yo systems continue to be used today [e.g., the Moving Vessel Profiler (Herman et al. 1998)].

Expendable profilers offer an ingenious solution to underway profiling, as the connecting cable spools both from the probe and from the ship. That is, cable is left behind the probe as it falls through the water, and cable is left behind the ship as it steams away from the place where the probe was deployed. The velocity of the cable through the water is zero (cable drag is negligible), and the probe can go arbitrarily deep. The cable on an expendable profiler is a thin pair of conducting wires that transmits signal from the probe to the ship. When wire on the probe runs out, the wire breaks, and the probe is lost. Expendable profilers have been in use for over 20 yr, so their relative merits are well known. The chief advantage of expendable profilers is ease of use. Deployment involves dropping the probe in the water, and, because the probe is expendable, no recovery is required. Such variables as temperature [expendable bathythermograph (XBT)], salinity [expendable CTD (XCTD)], and velocity [expendable current profiler (XCP)] have been measured on expendable profilers. The main limitation of expendable profilers is that each sensor is used only once, with effects on the cost of operation and the quality of sensor calibrations (no postdeployment calibration is possible). Depth is determined by a drop-rate equation rather than through the measurement of pressure. Expendable profilers are the current tool of choice for commercial vessels of opportunity and for many applications on research vessels.

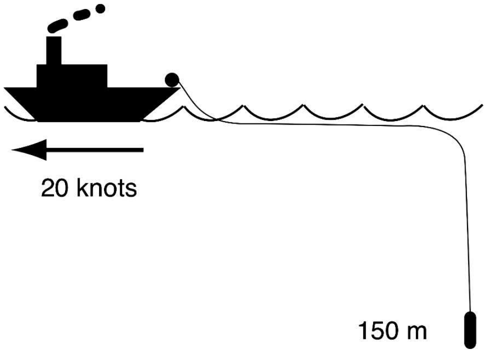

FIG. 1. A schematic diagram of UCTD deployment (not to scale). Line spools from the shipboard winch and the probe, so line shape is roughly as depicted. When the probe is fully deployed, the winch brakes and recovers line. On recovery, the probe follows the line back in as if there is a pulley where the line makes a 90° bend at the surface. This "water pulley" effect is a result of tangential cable drag being much less than normal cable drag.

The UCTD operates under the same principle as an expendable (Fig. 1). By spooling tether line from both the probe and a winch aboard ship, the velocity of the line through the water is essentially zero, line drag is negligible, and the probe can get arbitrarily deep. The challenge is to recover the probe, because the line velocity will then equal the ship speed, and line drag may become large. This has proven possible using a Spectra line commercially available for fishing. A number of advantages accrue because the UCTD is recovered rather than expendable. First, the cost per profile decreases as the probe is reused. Second, because the probe is recovered, sensors can be calibrated postdeployment, improving the quality of the observations. Third, the UCTD carries a pressure sensor, so depth is measured more accurately than by the drop-rate equation typical for an expendable. Fourth, plastics and other hazardous materials are not left behind.

The purpose of this paper is to present the design, construction, operation, and example data of the UCTD. A functional description of the UCTD is presented in section 2. Practical use of the UCTD is described in section 3. A recent successful deployment of UCTD to do science (as opposed to engineering tests) is presented in section 4. Section 5 concludes with a summary and some suggestions for future development.

2. Functional description

The development of the UCTD was motivated by the desire for inexpensive profiles of salinity from under-

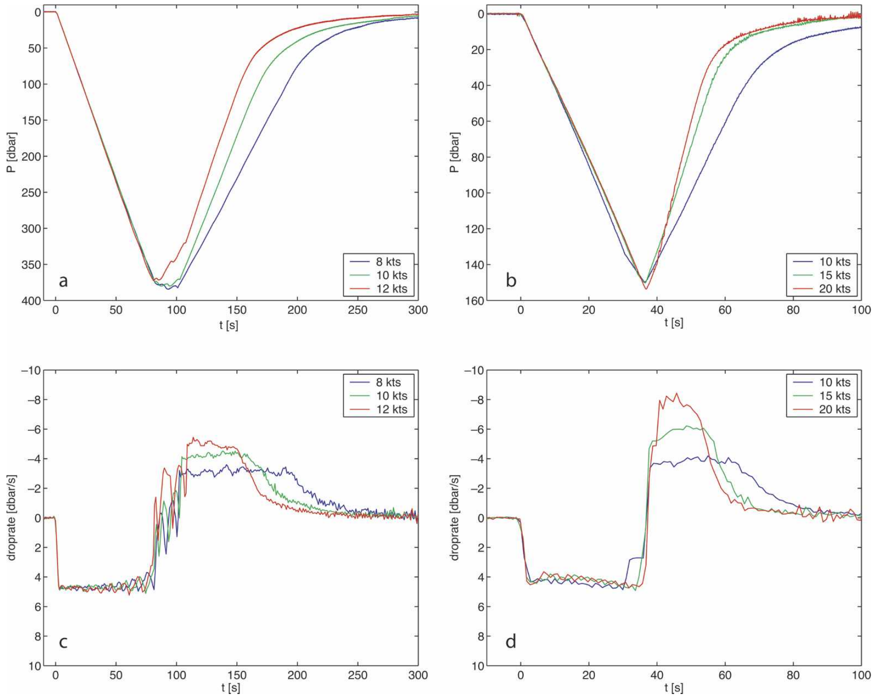

FIG. 2. UCTD pressure and drop rate as a function of time for drops at various ship speeds and using probes of different lengths. (a), (c) Deployments at 4, 5, and 6 m s^{-1} (8, 10, and 12 kt) were done with a probe of length 0.99 m; and (b), (d) deployments at 5, 7.5, and 10 m s^{-1} (10, 15, and 20 kt) were done with a probe of length 0.73 m. The nearly constant drop rate of each probe was independent of ship speed. The probes were thus effectively decoupled from the ship.

way vessels, including volunteer observing ships (VOSs) and research vessels. While XCTDs do provide the needed salinity profiles at present, their cost limits how many can economically be used. The temperature–salinity (*T*–*S*) relationship is most variable in the mixed layer and seasonal thermocline, where the ocean is in direct contact with the atmosphere. Deeper, climatological *T*–*S* relationships combined with XBTs are sufficient for observing the hydrographic structure that enters into momentum, heat, and salt budgets. Thus, the design goal for the UCTD was to obtain profiles to at least 100 m at 10 m s^{-1} (typical of a VOS). This goal has been surpassed, as the UCTD can profile to over 150 m at 10 m s^{-1} and to over 400 m at 5 m s^{-1}.

The UCTD system was designed to satisfy a number of requirements. First, line must be spooled on a probe and a winch aboard ship, and it must unspool freely from both. Second, the line and winch must be strong enough to allow recovery at ship speeds of up to 10 m s^{-1} and depths of 150 m; because tension is proportional to line out times the square of ship speed, this requirement theoretically allows casts of 600 m at ship speeds of 5 m s^{-1}. Third, a rewinding mechanism is required to respool line on the probe. Fourth, a conducting cable is undesirable because it adds drag but no strength, and the requisite slip ring on the winch adds complexity, so sensors for temperature, conductivity, and pressure must log internally to be downloaded to a computer on recovery.

The first challenge in the design of the UCTD was to prove that the probe could be successfully decoupled from the ship during deployment, to achieve a nearly constant drop rate, and therefore a nearly vertical profile. Pressure records and drop rates for UCTD deployments carried out at a variety of ship speeds, and using probes of different lengths, demonstrated this behavior (Fig. 2). A probe of length 0.99 m had a constant drop rate of nearly 5 m s^{-1} at ship speeds of 4–6 m s^{-1}, and down to pressures of about 380 dbar. A shorter probe (of length 0.73 m), which could accommodate less line, had a drop rate of about 4 m s^{-1} at ships speeds of 5–10 m s^{-1}, down to 150 dbar. The difference in drop rates for the two probes was a reflection of their different aspect ratios and resulting drag coefficients. The longer probe, with its lower drag, dropped faster.

The key finding was the uniform drop rates for each probe, regardless of ship speed, suggesting decoupling from the ship and a nearly vertical profile. Had the drop

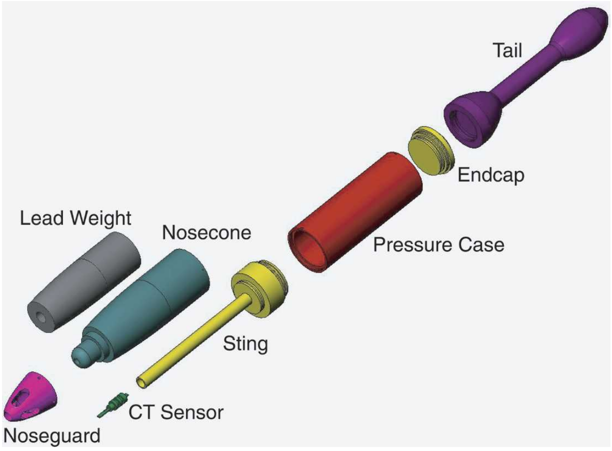

FIG. 3. Individual components of the UCTD probe, labeled and in an exploded view.

rates depended on ship speed, the probes would not have been decoupled from the ship, and profiles would not have been vertical. Upward profiles were dependent on ship speed, as the probe was pulled through the water by the ship. Achieving a uniform drop rate required attention to the design of the tail, because drop rate was influenced by friction as line was unspooled from the tail. The egg-shaped bulb on the end of the tail was the result of some trial and error (Fig. 3). Observed pressure gave the vertical position of the probe during the drop. Horizontal position was not obtained because of the difficulty of the measurement, precluding a detailed study of trajectory.

The recovery of the UCTD involved the retrieval of several hundred meters of line while underway. As the line was being pulled through the water at the ship's speed, a concern was whether the tension was within working strength of the line. We measured line tension during many of our test deployments to prove that the breaking strength of the Spectra line was much greater than tension during recovery. For example, peak tension ranged from 70 to 160 lb (32 to 73 kg) using 500-lb (227 kg) Spectra for towing speeds between 10 and 20 kt (5–10 m s^{-1}), and tension ranged from 60 to 120 lbs (27 to 55 kg) with 300-lb (136 kg) Spectra between 8 and 12 kt (4–6 m s^{-1}). Ship speed did not affect drop rate but did affect tension. As the relevant metric is ship speed through the water, a depth-independent head, tail, or cross current should have no effect on UCTD performance. However, a vertically sheared current may change performance. In practice, we have found that spooling the line smoothly on the tail is the key to consistent drops, while sheared currents play a relatively small role.

a. Deployment assembly

The winch had to be able to spool line out freely with little tension, have adjustable drag, and recover under high tension. Conventional big-game fishing reels were found to be uniquely suited to the application, as these requirements were similar to those of sport fishing. We used a Penn International II ST130 fishing reel, which we upgraded with more robust drag plates (Fig. 4). An electric motor (24–32 Vdc) for recovery was readily available from a third-party vendor. The Penn fishing reel was loaded with approximately 900 m of PowerPro 300 Spectra line. The line rating of 300 lb (136 kg) was confirmed independently by break tests performed in-house. A speed control for the motor and a manual level wind completed the reel setup. Power to reel was supplied either via 24-V batteries or a variable dc power supply.

The winch was mounted on a small davit, with a 2 ft by 2 ft (0.61 m by 0.61 m) footprint, the boom of which

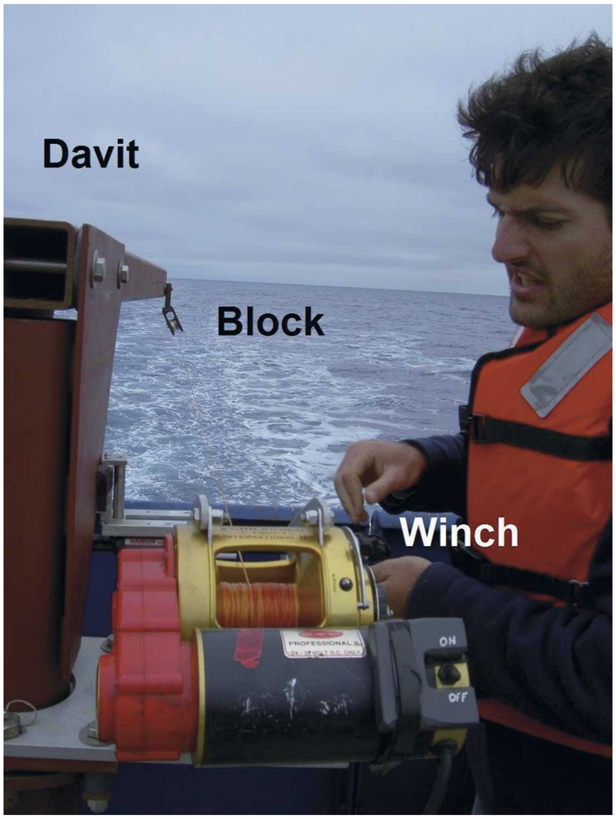

FIG. 4. UCTD winch and davit just after probe is fully deployed. The winch, davit, and block are labeled. The winch consists of a fishing reel connected through a chain (inside red case) to a motor (black housing). The davit is pointed directly aft, and the line running through the block is approaching maximum tension. The last several layers of line on the winch are colored red to remind the operator to stop paying our line.

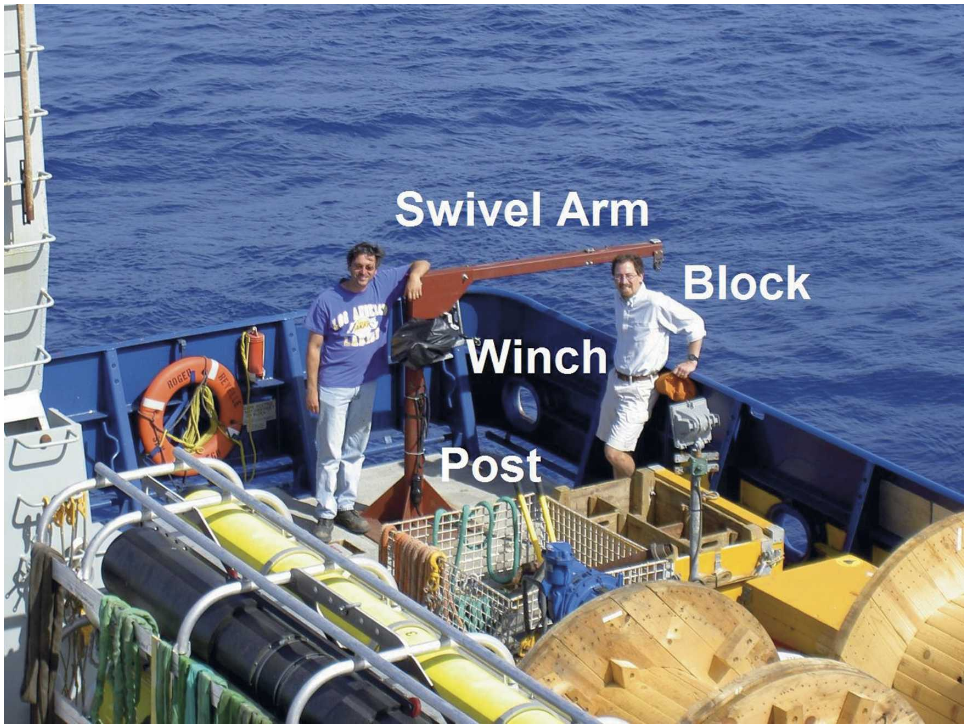

FIG. 5. UCTD davit on the fantail of the R/V *Revelle*. The swiveling arm, block, winch, and post are labeled. The davit is stowed pointed to port to keep it out of the way of mooring operations.

could pivot and extend (Fig. 5). Ideally, the davit was positioned as close to the centerline of the ship and as far aft as possible. Using the 2-ft hole pattern available on the deck of many research vessels, it was usually possible to mount the davit stand within 2 ft of the aft rail. On vessels that lacked such a hole pattern in the deck, other mounting options were possible. Inside the davit stand sat a post with a horizontal arm that could be extended to a maximum length of approximately 3 m. The post was designed to swivel freely around the fixed stand but could be locked in place in different orientations via a pin. The total height of the davit was slightly over 1.5 m. The Spectra line ran from the winch through a snatch block attached to the end of the horizontal arm. The block was fitted with plastic washers on either side of the pulley to protect the line from chafing.

For deployment, the horizontal arm was rotated to point straight aft and locked in that orientation with a pin. In this position, the block at the end of the arm cleared the stern rail of the ship. After the probe was launched, the drag wheel on the fishing reel was adjusted to allow free-spooling without slack in the line. As the probe descended, line from the reel was paid out at the rate of the ship's speed. When the probe reached a depth of 400 m (after approximately 80 s), the reel was put into strike mode. At this time, almost all the line was unspooled from the reel. Now the level wind was engaged and the motor turned on to reel the probe back in. Once the probe was within roughly 30 m of the stern of the ship, the retrieval speed was reduced and the probe was pulled through the wake of the ship for recovery. After trying several methods of retrieval, we found this method to be the simplest and safest.

b. *Tail rewinder*

Respooling of line on the tail was accomplished with a commercially available variable pitch level-wind mechanism, driven by a motor from a portable handheld drill (Fig. 6). Upon recovery, the tail was detached from the probe and installed in the level-wind unit. The davit was oriented toward the rewinder setup, and the empty tail spool was inserted between two mounts on the drive shaft of a modified battery-powered Milwaukee drill motor. One end of the tail spool fit into a mount made from a spare rear bulkhead of the probe. The tail pin end of the spool fit into a conically shaped mount at the end of a bearing-supported stainless steel rod. The tail pin mount was made of Delrin and its inside lined with neoprene rubber to protect the tail spool surface from scratches. A pull-ring spring plunger fit into a matching keyhole in the tail spool, preventing slippage of the tail spool with regard to the rear mount

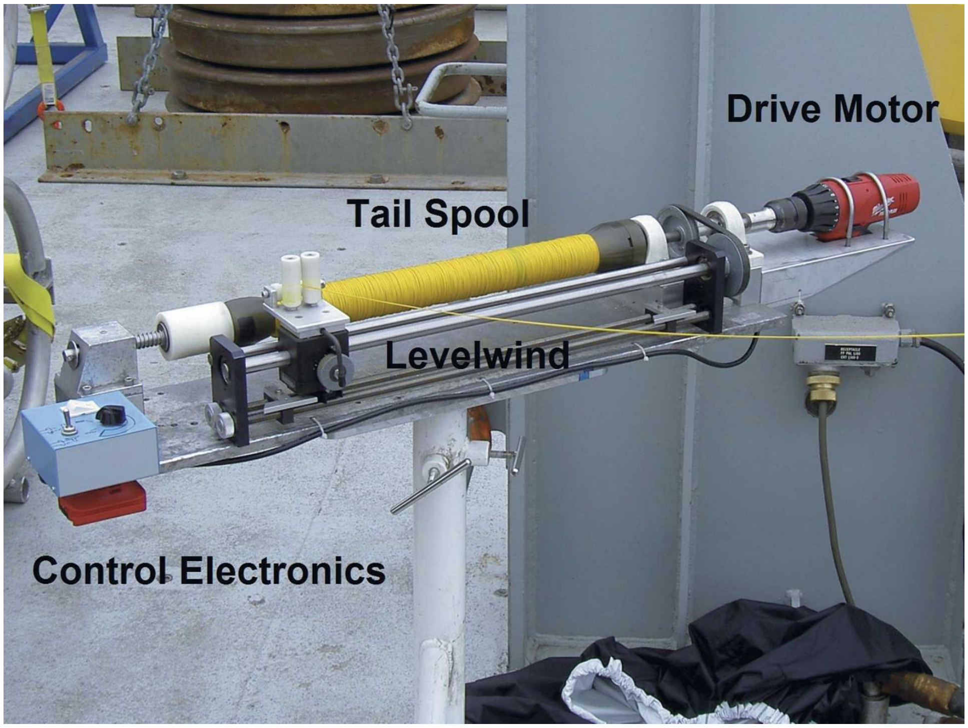

FIG. 6. UCTD tail installed in respooling unit, ready for the next deployment. The tail, level wind, drive motor, and control electronics are labeled. Yellow Spectra line (400 m) is wound onto the tail.

during the rewind. The direction of revolution and the speed of the drill motor at the end of the drive shaft were controlled manually from a switch box. The rewinder was powered by a standard 18-V Milwaukee rechargeable battery pack fit into a receptacle at the underside of the control box.

Originally, the level winding was done manually by moving a carriage on a guide rail. However, difficulties in maintaining a constant lead resulted in uneven spooling and, consequently, poor performance of the probe during the dive phase. To obtain consistent spooling of the spectra line onto the tail, we adopted an automatic level winder with a rolling-ring-bearing assembly. The shaft on which the level-wind carriage rides was coupled to the drive shaft via a pulley and a belt. In contrast to lead screw-based level-wind assemblies, only a single motor was required to drive both the tail spool and the level-wind carriage.

The lead of the carriage per revolution of the shaft was set with a dial on the carriage in the range 1.6–6.4 mm, with the fastest drop speeds and smoothest unwinding of the line occurring for a lead of about 3.2 mm. At the end stops, the carriage travel direction was reversed mechanically by flipping the orientation of the bearings inside the carriage with regard to the shaft. The tapered shape of the tail spool required an increased stroke length as the tail spool filled up with line. It was therefore necessary to move the end stops out with every layer of line wound onto the spool. Since the end stops were mounted on threaded rods, this was simply accomplished by turning the knobs at the end of the rods after every complete round trip of the carriage. The revolution direction of the drive shaft was alternated between consecutive rewinds to minimize the accumulation of twists in the line.

In order for the spectra line to unwind smoothly during the dive phase of the probe, it had to be wrapped tightly onto the tail. Therefore, it was critical to perform the rewind under sufficient tension. The line tension was set by adjusting the drag on the Penn reel. Typically, the whole rewind operation took about 2–3 min, and three to four rewinds could be completed on a single battery charge. The rewinder setup measured approximately 15 cm × 91 cm × 10 cm and weighed less than 10 kg. A telescopic mount facilitated height and orientation adjustment of the rewinder assembly for different operators and ships.

c. *Probe*

The probe consists of two main components that are connected securely via a threaded shaft: 1) the probe, with sensors, interface electronics, and data acquisition hardware; and 2) the tail spool that holds the line. The probe itself has a diameter of 6.4 cm and measures 0.46 m from the tip of the nose cone to the end of the rear bulkhead. Two tails were used depending on profile depth desired and ship speed, one tail of length 0.27 m, weight 0.78 kg, line capacity 500 m of 300-lb (136 kg) PowerPro Spectra; and one of length 0.53 m, weight 1.12 kg, and line capacity 150 m of 500-lb (227 kg) Spectra. The total lengths and weights of the assembled probes with short and long tails were 0.73 m, 5.2 kg, and 0.99 m, 5.5 kg, respectively. The end of the Spectra line was spliced into a loop and attached to the eye of a threaded stainless steel tail pin with a girth hitch. The tail pin was screwed into the end of the tail and secured with a set screw.

The probe carried a Precision Measurement Engineering conductivity–temperature (CT) unit with a four-electrode conductivity sensor and a Thermometrics thermistor, as well as a Druck pressure sensor. The assembly consisted of the rear bulkhead with data port, the main instrument pressure case, the forward bulkhead with sensor stem, and the nose cone with sensor guard (Fig. 3). The CT sensor was located at the forward end of the probe inside a stainless steel tube that was connected to the main pressure case through the forward bulkhead. The bulkhead also contained the port for the pressure sensor. This sensor–stem–bulkhead assembly was inserted into a lead-filled, tapered nose piece. A sensor guard was made of glass-reinforced epoxy protecting the fragile CT sensor at the tip of the nose cone. The CT sensor was molded into a cylindrically shaped plug and seated inside the stainless steel tube through which the sensor wires fed back into the main instrument compartment. The individual components of the assembly mated using bore seals combined with Ortman grooves in which monofilament fishing line [50-lb (23 kg) Trilene] was inserted. The probe assembly was pressure tested at 2000 psi (1379 dbar) for several days in the laboratory to ensure that the instrument was leakproof. Inside the main pressure case an embedded computer (Persistor CF II), rechargeable batteries, power supply, and interface electronics were mounted. Nine Li ion batteries (1.2 V, 0.35 Ah) connected in series provided power for up to 12 h of continuous operation. The embedded computer stored the software in its EEPROM, so the probe was operational—albeit in sleep mode—as soon as the battery pack was connected. The data acquisition was controlled from a host computer (in most cases a laptop) via serial communication through the data port in the rear bulkhead of the probe. Data from the sensors were logged at a frequency of 10 Hz to solid-state memory.

d. *Sensor calibration*

One of the advantages of the UCTD over expendable probes is the possibility to perform postdeployment sensor calibrations to allow monitoring of the long-term sensor drift. Calibrations were carried out in the laboratory, and reference checks were performed in the field.

The procedure to calibrate the pressure sensor was straightforward. A deadweight tester was attached to the probe's pressure port, and the pressure was sampled between 0 and 800 psi (552 dbar) in increments of 100 psi (69 dbar) for both increasing and decreasing pressures. Zero pressure readings were obtained before and after each calibration run to ensure that the sensor did not exhibit any hysteresis effects. For each pressure level, 500 samples were averaged and fitted to the known pressure values of the deadweight tester via linear regression, yielding the corresponding gain and offset. Although the Druck pressure sensor was rated to 1000 psi (690 dbar) absolute, the amplification of the digital acquisition electronics was chosen such to obtain maximum resolution for a maximum pressure of 870 psi (600 dbar). The resulting pressure resolution was on the order of 0.3 dbar.

The calibration of the temperature sensor was a two-step process. Once the calibration constants for the digital data acquisition electronics of each probe were obtained, up to six CT sensors were calibrated at once in a single water bath. Separating the calibrations of the interface electronics and the actual thermistor allowed for replacement of a (broken) CT sensor without the need to recalibrate the probe. The first step involved the determination of the parameters of the voltage divider circuit of the digital acquisition electronics. Eight different resistors with values in the range from 100 to 300 kilohms, corresponding approximately to a thermistor temperature range from 0° to 35°C, were used to obtain the three parameters and an error estimate. In a second step, the thermistor was calibrated in a freshwater bath. A cooler was used for thermal insulation, and temperature stability was maximized by constant stirring. With this setup a drift of less than 0.001°C min^{-1} was achieved. The bath was heated electrically from slightly above 0°C to almost 30°C in steps of 5°C. For each step, the temperature readings of the thermistor and a high-resolution thermometer (TS8901) were logged. These data were fitted to a nonlinear thermistor model. A minimum of four temperature steps were needed to yield the three model parameters and a temperature error estimate. The temperature calibra-

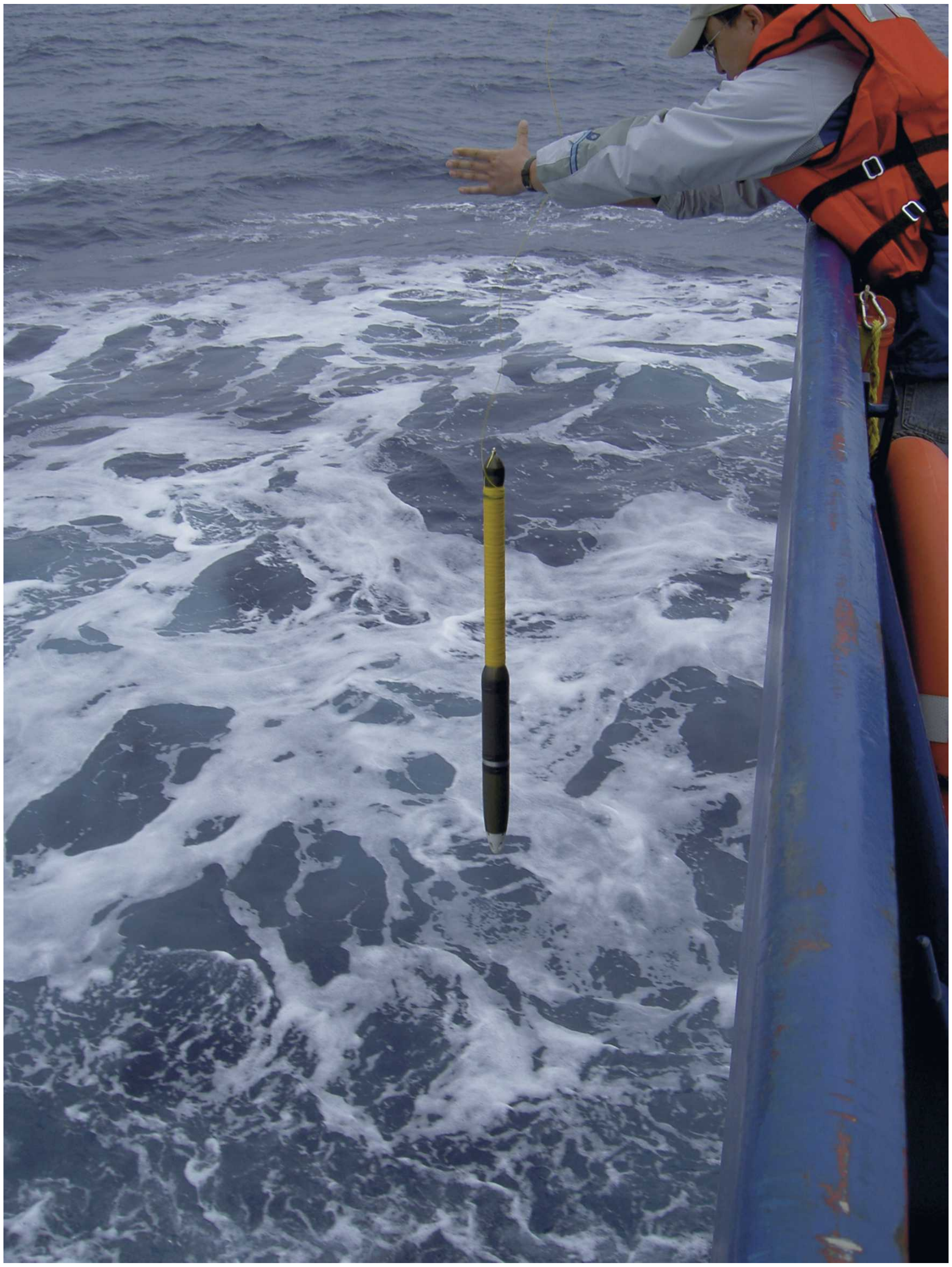

FIG. 7. UCTD probe being deployed by dropping off the stern. The first coils of yellow Spectra line are beginning to unwind from the tail.

tions of the sensors were found to be extremely stable, with uncertainties of less than 0.01°C over the course of a year.

During initial salinity calibrations we found that an accurate calibration was quite involved, because of an inherent "start-up" time constant in the conductivity sensor, requiring careful conditioning of the probe. Specifically, it was necessary to pre-wet the electrodes of the conductivity sensor in order to obtain repeatable calibrations. Therefore, the probe was stored in seawater for several hours prior to any measurement or deployment. For calibration, the probe was immersed in different, well-mixed water baths with salinities ranging between 0 and 35 psu while both temperature and conductivity were recorded internally. Simultaneously, two Sea-Bird 19*plus* SEACAT profilers and an SBE 4 conductivity probe logged temperature, conductivity, and salinity in 15-s intervals. The data records from the different instruments were then synchronized with regard to time and fitted via linear regression to yield the gain and offset for each sensor. This method provided salinity calibrations consistent to within about 0.02 psu.

3. Practical use

The UCTD operation was carried out easily and safely on an underway vessel, making no demands on vessel operators other than space on an aft quarter to put the equipment (Fig. 5). A typical cast scenario proceeded as follows. Prior to the initial deployment, the probe was stored in seawater for several hours in order to wet the CT sensor and prevent a relaxation-type behavior of the conductivity sensor during the first few profiles. The internal clock of the embedded computer was synchronized with GPS time at this time to allow for precise referencing of the drop location. Once the data acquisition was started, conductivity, temperature, and pressure sensors were sampled continuously at 10 Hz for up to 2 h. Then the communication/charging cable was removed, the data port sealed with the boss plug, and the instrument end connected to the tail spool. The unit was then ready for launch. The UCTD was deployed by dropping over the stern (Fig. 7) while letting the winch free spool. Because the fall rate was approximately 5 m s^{-1}, a 400-m profile took 80 s. At a ship speed of 5 m s^{-1} (10 kt), 400 m of line was pulled off the winch. The total of 800 m of line deployed at the conclusion of a profile took roughly 15 min to recover.

Once the probe was retrieved from a cast, the tail spool was removed from the rear bulkhead of the probe and placed in the rewinder for respooling. In the meantime, the data from the probe were downloaded to a laptop computer, verified, and copied to backup media, and the probe's batteries were recharged. Profiles were then plotted to verify the integrity of the data. Although it was not necessary to download and archive the data after every cast—up to four casts could be stored internally before the memory of the CPU was filled up—it took only a few minutes and was therefore routinely done. Rewinding the tail and downloading data took about 10 min, so consecutive profiles could be done as rapidly as every 30 min.

4. Example results

The first operational use of the UCTD was on a cruise in May–June 2004, the purpose of which was to examine the effects of internal waves and density-compensating thermohaline variability (sometimes called spice) on long-range acoustic propagation. The cruise resulted in over 160 successful UCTD casts. The primary goal of the cruise was to deploy four acoustic moorings on a 1000-km path (Fig. 8) in the central North Pacific subtropical gyre. The UCTD was used while the ship steamed at 10–13 kt between moorings, with a strict requirement not to affect ship operations.

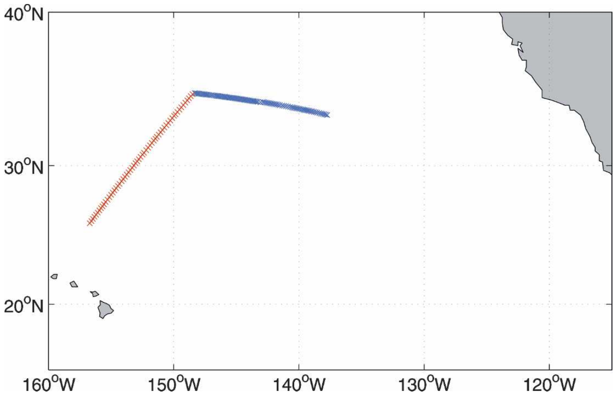

FIG. 8. Locations of UCTD casts during the North Pacific Acoustics Laboratory Spice04 cruise in May–June 2004. The blue line is actually made up of 97 crosses, signifying UCTD casts at about 10-km resolution.

a. Postcruise calibration

For most CTDs, the conductivity and temperature sensors have different temporal responses. Even small differences in these responses cause large spurious changes in inferred salinity, because conductivity is dominated by temperature. This effect, usually called

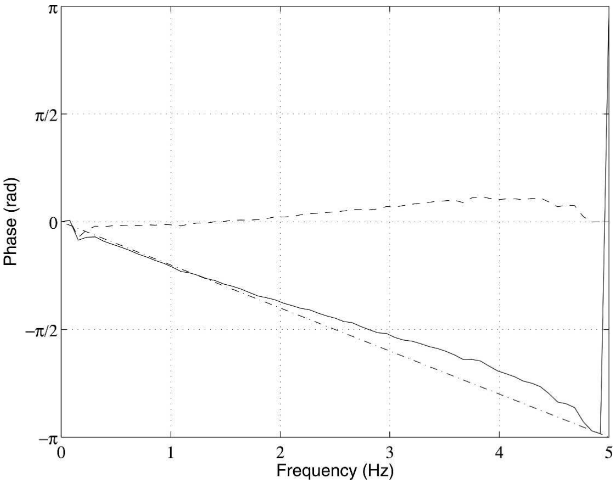

FIG. 9. Phase between the temperature and conductivity sensors, determined from a cross-spectrum of the raw data (solid line). A simple 0.1-s lag (dash–dot line) produces a phase between the corrected temperature and raw conductivity sensors (dashed line) close to zero to frequencies as high as about 2 Hz.

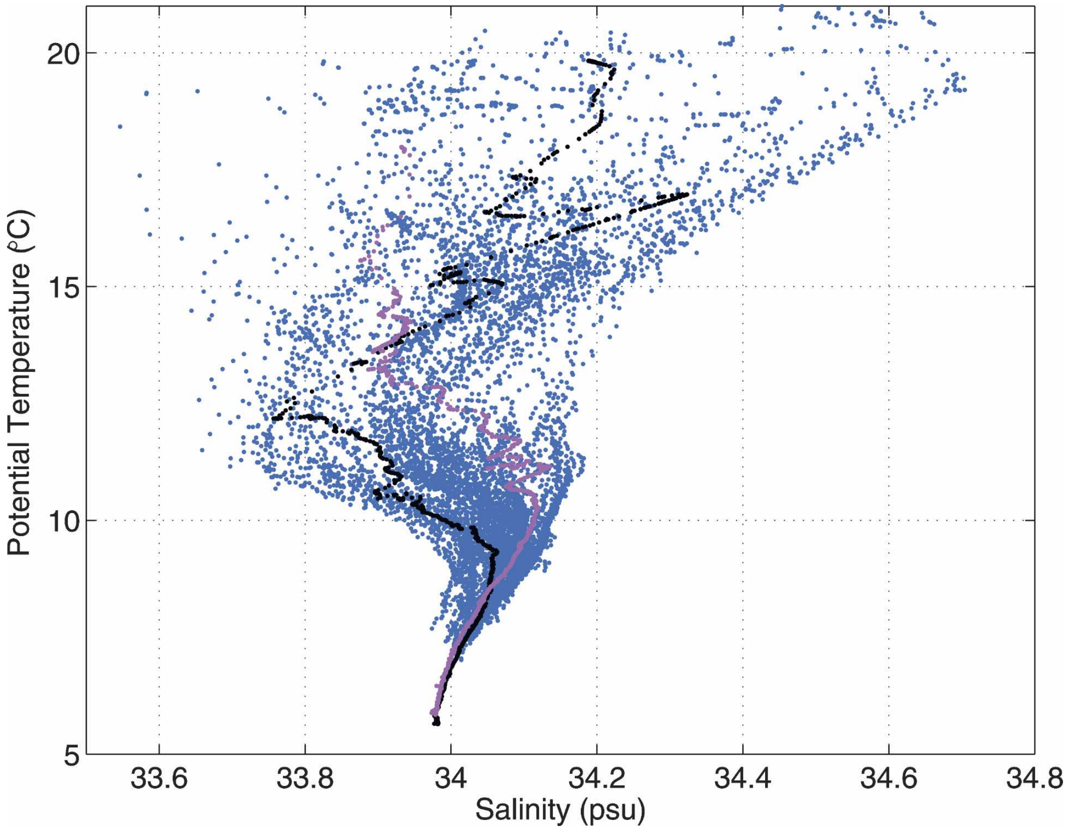

FIG. 10. Potential temperature–salinity (θ–S) scatterplot from UCTD casts (blue) and two CTD stations (black, magenta) on either end of the 1000-km section. The spread in salinity where the θ–S relationship is tight (about 8°C and colder) is a measure of the accuracy of UCTD conductivity.

"salinity spiking," is correctable in processing the data, often by lagging the output of the temperature sensor relative to that of the conductivity sensor (e.g., Lueck and Picklo 1990; Rudnick and Luyten 1996).

Salinity spiking was present in UCTD data and was corrected as follows. The cross-spectrum between temperature and conductivity was calculated using 10-Hz data from 52 casts, and the resulting phase was plotted (Fig. 9). The phase of a cross-spectrum may be interpreted as the phase difference between temperature and conductivity as a function of frequency. Consistent with a simple lag between the conductivity and temperature sensors, the phase (solid line) was nearly linear in frequency. If the relationship between conductivity and temperature were perfectly described by a lag, the phase would be $2\pi fL$, where f is frequency and L is lag. Such a model phase, with $L = 0.1$ s (one sample in 10-Hz data), is plotted for comparison (dash–dot line). This simple model provided a reasonable description up to a frequency of 2 Hz. The final correction was to use temperature one sample later than conductivity in calculating salinity. The phase in the final dataset (dashed line) was close to zero, especially at frequencies lower than 2 Hz. Because the goal was to obtain data at 1 Hz (or 5-m vertical resolution), this correction was adequate.

A second calibration issue was a slow drift that existed in the conductivity sensor. This drift was correctable using standard CTD stations occupied during the cruise. Data from the UCTD were compared with data from a Sea-Bird CTD used on the stations to affect this correction (Fig. 10). A multiplicative correction was applied to laboratory-calibrated UCTD conductivity to minimize the difference between UCTD and Sea-Bird salinities for potential temperatures between 7.9° and 8.0°. This range of temperatures was chosen because the temperature–salinity relationship was relatively tight, and it was shallow enough to be within range of typical UCTD casts. Multiplicative constants used were 0.9979 and 0.9967 for the two sensors whose data are shown in Fig. 10.

b. *Final data*

Raw data were in the form of profiles (Fig. 11). This cast, with the ship steaming at 10 kt, achieved a depth of

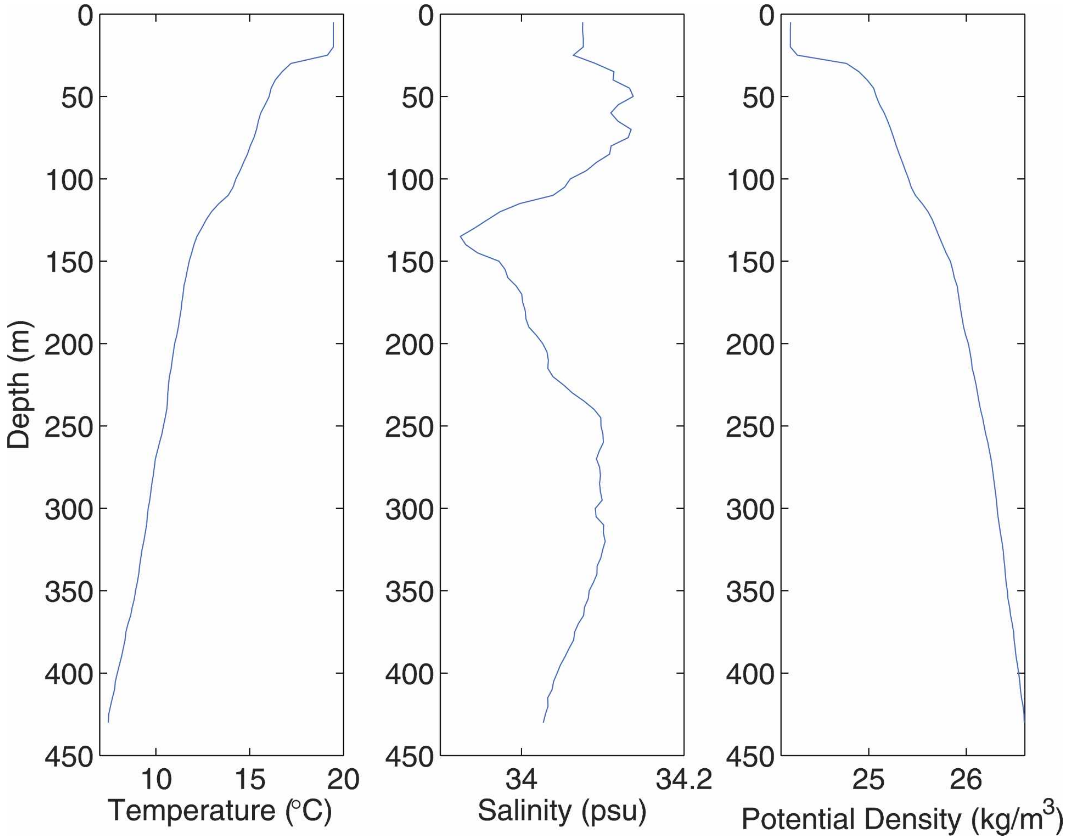

FIG. 11. Temperature, salinity, and potential density profiles from UCTD data for cast 80, in the western half of the section.

about 430 m. Oceanographic features typical of the region include a surface mixed layer of about 20-m thickness, with a sharp mixed layer base beneath. Moving downward, a region of reduced stratification marks the previous winter's relic mixed layer and a relic mixed-layer base at about 120 m. Observations then continue down into the permanent thermocline.

A plot of potential temperature against salinity (θ–S) is useful to evaluate the accuracy of sensors and to gauge oceanographic variability (Fig. 10). UCTD observations from the east–west section (blue crosses in Fig. 8) are plotted as blue dots, and standard Sea-Bird CTD stations on each end of the section are plotted in black (east) and magenta (west). At depth, the Sea-Bird station data agree well, suggesting a tight θ–S relationship and accurate sensors. Where the Sea-Bird data are tight, the UCTD data are more scattered, suggesting an error of about 0.03 psu in salinity. Shallower, there is great variability in station and UCTD data, consistent with increased ocean variability. The experiment was intended to quantify this variability, and the UCTD is sufficiently accurate for the task.

The east–west section (Fig. 12), covering 1000 km, comprises a total of 97 casts, which were completed in two separate 1-day transits, each traveling half the distance. Casts were separated by about 30 min in time and 10 km in distance. All except one of the casts returned complete data, with the one failure caused by a faulty connector in the pressure sensor electronics. The section was carried out from east to west, and the changing depth of the profiles was directly related to ship speed. During the first quarter of the section ship speed was 11–12 kt, the second quarter 12–13 kt, and the second half 10 kt. The one very shallow cast near a longitude of –141° was caused by a poorly rewound tail. Over the second half of the section the casts were mostly greater than 400 m, with the deepest ones greater than 430 m. This consistency in the depth of casts was maintained for the remainder of the cruise, including the transit toward Hawaii (red crosses in Fig. 8).

Oceanographic mesoscale and finescale structure is resolved by the UCTD observations. A shallow mixed layer underlain by a sharp base is prevalent throughout the section (Fig. 12). The relic winter mixed layer is bounded below by a stratified region at 100–150-m

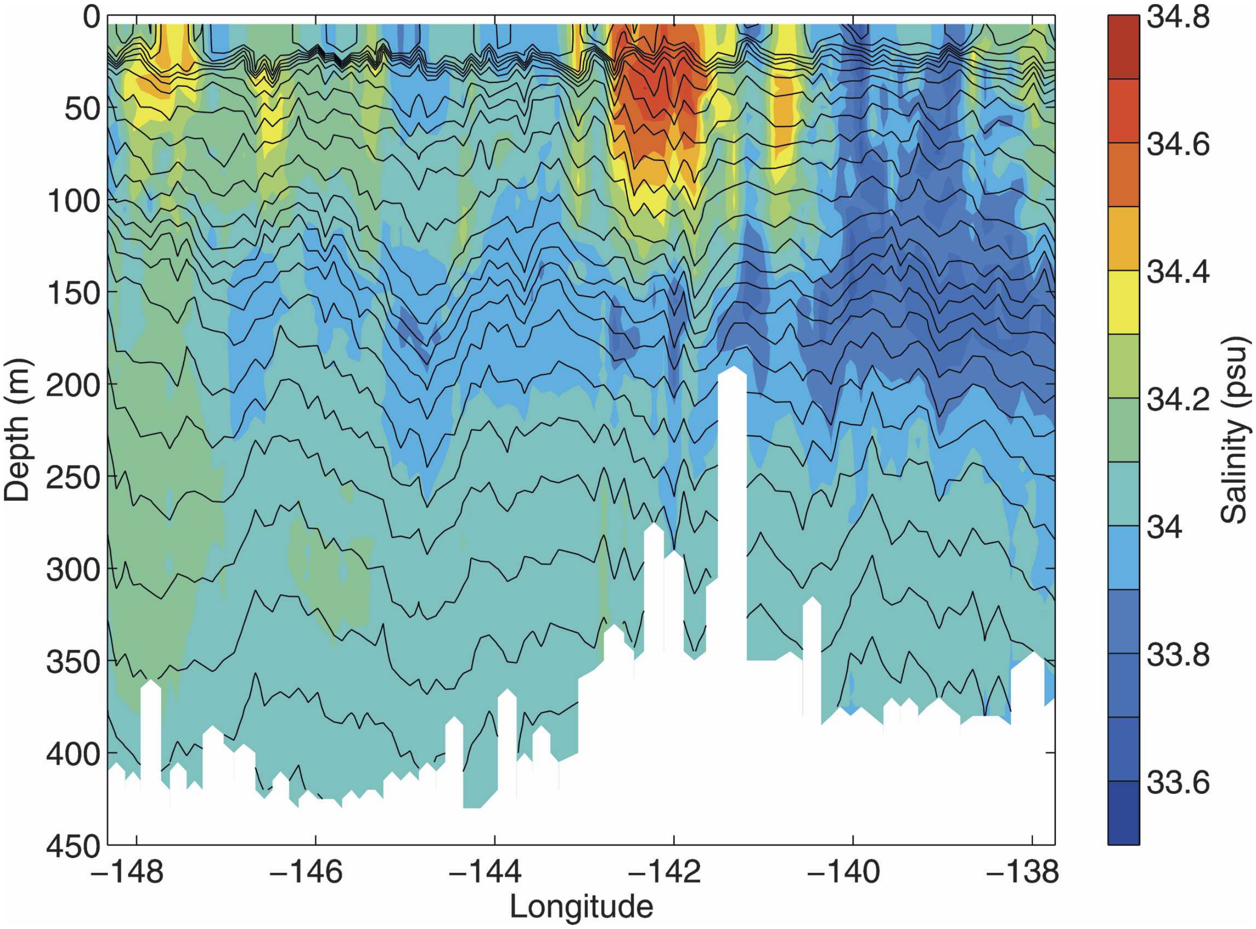

FIG. 12. UCTD section of salinity (color image) and potential density (black contours, interval 0.1 kg m^{-3}). The section was done east to west, and the varying depth was directly related to ship speed. During the first quarter of the section ship speed was 11–12 kt (5.5–6 m s^{-1}), the second quarter 12–13 kt (6–6.5 m s^{-1}), and the second half 10 kt (5 m s^{-1}). The spring 20-m-deep mixed layer is evident, as is the 100–150-m depth of the remnant winter mixed layer. Salinity features span the depth of the winter mixed layer.

depth. Salinity structure is apparent throughout the relic mixed layer. Salinity structure such as this, which varies along isopycnals, and is therefore compensated by temperature, has come to be called spice (Munk 1981). Readily seen in the section are vertical excursions of isopycnals, caused by mesoscale motions and internal waves. Assessing the relative effects of these processes on acoustic propagation is one of the goals of the experiment.

One important application of hydrographic surveying is the measurement of sound speed. The sound speed section (Fig. 13) demonstrates UCTD capabilities for this application. Sound speed variability related to heaving isopycnals and spice is identifiable by comparing features in sound speed to corresponding features in salinity. These data are being used to interpret acoustic data from the moorings and in numerical simulations of acoustic propagation (Rudnick and Munk 2006).

5. Conclusions

The UCTD fills a need for profiles of temperature and salinity from underway vessels. A complete prototype system has been tested and used operationally on a research cruise. Continuing development is addressing ease of use and, especially, the long-term accuracy of the conductivity sensor. A goal is to make the UCTD available to the community through the private sector.

Additional sensors could be mounted on the UCTD, with the primary limitation being physical size; some optical sensors may currently be appropriate. To date, we have not attempted any such enhancements to the UCTD. However, the barrier to additions is not high, because lengthening the UCTD to accommodate new sensors is a relatively simple matter. The nearly constant fall rate of UCTD should provide benefits for measuring some variables.

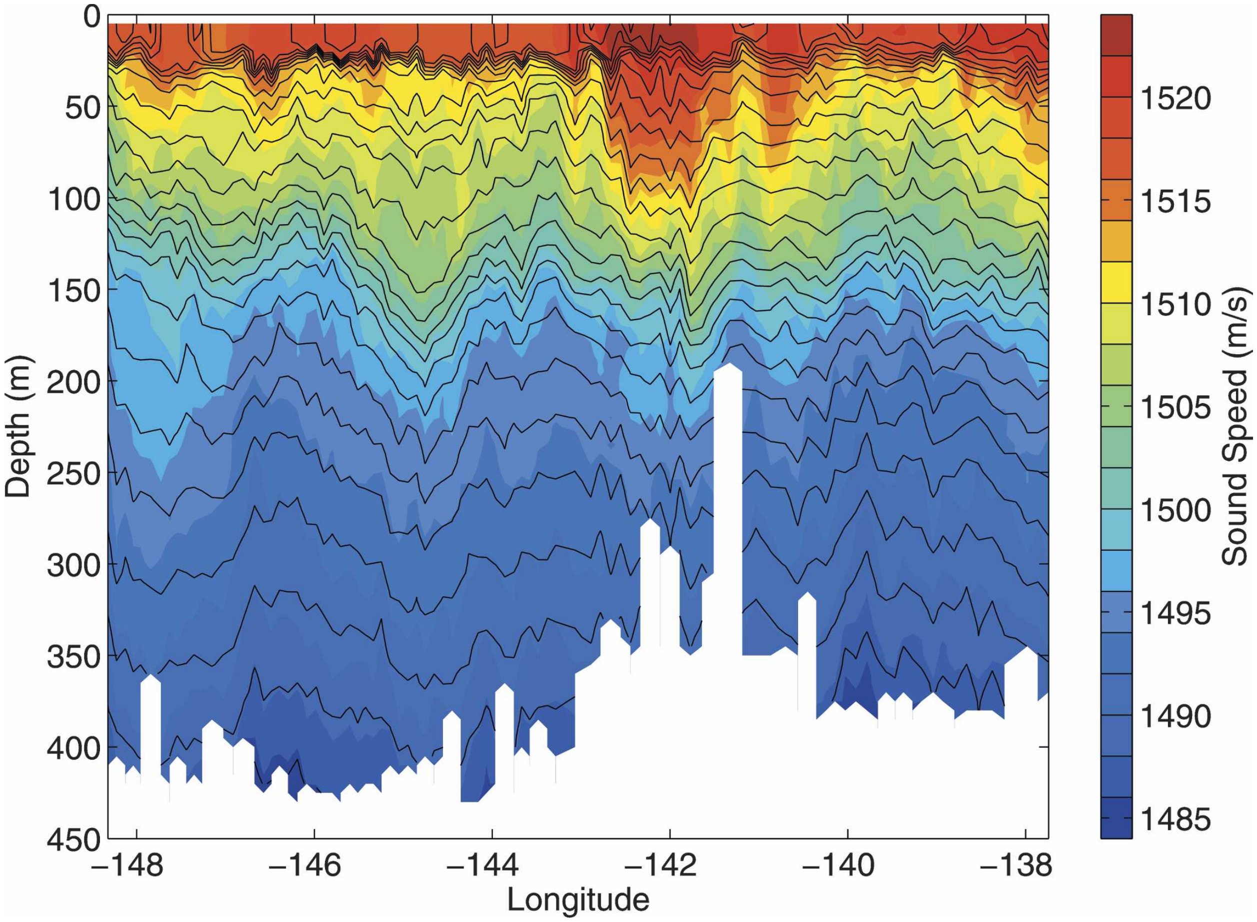

FIG. 13. UCTD section of sound speed (color image) and potential density (black contours, interval 0.1 kg m^{-3}). Horizontal variability in sound speed is caused by heaving of the isopycnals and by spice (θ–S changes along isopycnals).

The development of the UCTD was originally motivated by the need for rapid, accurate, economical profiles from underway vessels. With increasing attention given to human effects on the environment, an additional motivation is that the UCTD is recovered, as opposed to expendables. No plastics or other potentially harmful materials are left behind, which may be especially desirable in certain environmentally sensitive areas.

The data presented here represent only one of the operational uses of the UCTD. As part of the same acoustics experiment reported here, another use of the UCTD occurred in September–October 2004 by a group of scientists unconnected to the development effort. This cruise resulted in over 170 successful UCTD casts, which we consider a reasonably positive beta test. Scientists at the National Oceanic and Atmospheric Administration (NOAA) Fisheries conducted a test of the UCTD in January 2005, with the purpose of evaluating the UCTD as a replacement for expendable probes. Another effort was a UCTD tow-yo section on a ferry operated between San Pedro, California, and Santa Catalina Island. In this application, depth was not as important as horizontal resolution, so the tail on the UCTD was not respooled for each cast; rather the UCTD was winched in and out. The section was being repeated every 2 weeks, with results posted on the Web (http://www.icess.ucsb.edu/iog/uCTD/). As the UCTD is made widely available, more applications are expected to arise.

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