Continued Development and Evaluation of the D-2 Inc. Hybrid CTD Sensor

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***Abstract*—Conductivity-Temperature-Depth (CTD) sensors, a mainstay of ocean observing, are routinely deployed from ships and fitted to autonomous instrument systems including moorings, profiling floats, gliders and AUVs. A recently-developed CTD sensor from D-2, Inc. is described and performance assessments based on laboratory calibration work and observations piggy-backed on research cruises are reviewed. The ocean observations were implemented using self-contained controller/data logger/battery units developed for this project; this subsystem is also documented. The work concludes with a discussion of further envisioned refinements to the CTD.**

Keywords—Conductivity, Temperature Depth (CTD) sensor, sea water salinity, physical oceanography

I. Introduction

Conductivity-Temperature-Depth (CTD) sensors (and predecessor STD systems) have been utilized in ocean science since they were first developed in the 1960's. Today, CTDs are routinely deployed from ships and are mounted on a host of autonomous instrument platforms including moorings, drifters, profiling floats, gliders and AUVs. Here a recently-developed CTD from D-2 Inc. - the Hybrid CTD sensor - is described and performance assessments presented. The latter involve laboratory calibrations of the temperature and pressure channels, and analysis of ocean profiles where self-contained D-2 sensor/logger units were piggy backed on the underwater frames of research vessel CTD/rosette packages. (Characterization of the dynamic responses of the CTD sensors in a test tank stratified with a sharp thermohaline step [1] will be reported elsewhere.) The CTD sensor and the data logger used in this program are described in Section II. Results from the laboratory work (Section III) and at-sea measurements are presented in Section IV, followed by a discussion of the next steps envisioned in the development

II. Description of the Sensor and Logger

Prototype Hybrid CTD units were constructed as stand-alone devices driven by an external power source and set up to stream measurements to an external logging system, Fig. 1. The CTD electronics are cased in a traditional single-open-end pressure

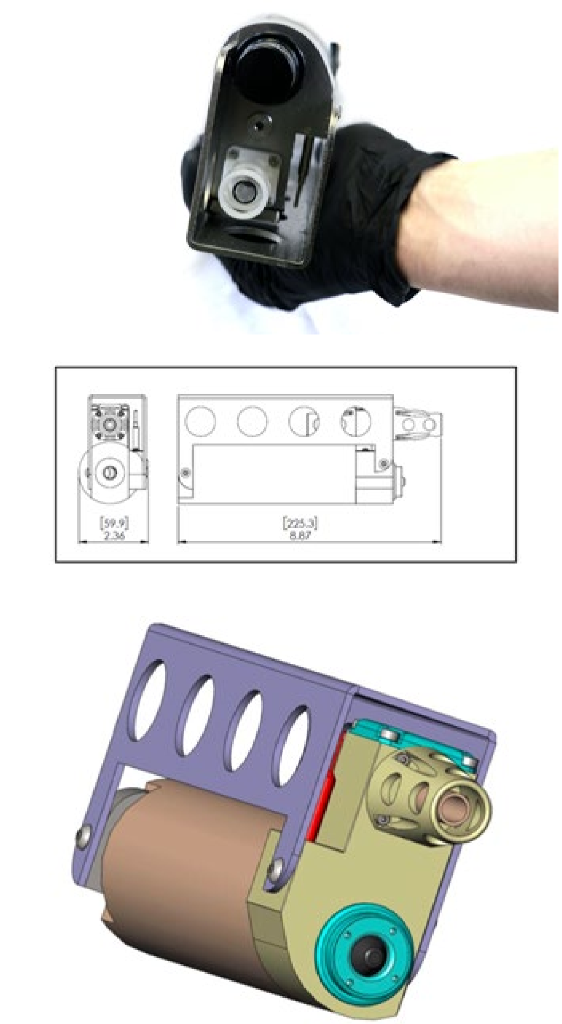

Figure 1. Photograph (top) and drawings (middle, bottom) of the D-2 Hybrid CTD built for this project. The dimensions given in the middle panel are in both centimeters and inches.

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housing with a 2.1” outer diameter and overall length of 9.0”. A bulkhead electrical connector is installed through the closed end of the case. The housing in this material is rated for operation to 6000 m water depth. The electronics are hard mounted to the end cap that additionally supports the three primary sensors: conductivity, temperature and pressure. The silicon bridge pressure sensor, built from Hastelloy® with an integral axial O-ring, is installed on the end cap from the inside with a retaining nut. A digital temperature sensor is added to the back side of the pressure sensor to facilitate (numerical) thermal compensation. The pressure port to the outside is routed to the side of the end cap to lessen velocity-induced hydraulic effects associated with movement of the CTD through the water. The pressure port accepts a standard-thread hydraulic connector to facilitate laboratory calibration of the pressure gauge.

The Hybrid CTD thermometer is housed in a 316 SS pressure protection sheath. A P20 (0.02” diameter glass bead type) aged thermistor is suspended inside the sheath which is filled with magnesium oxide powder that is sonically vibration packed after insertion to promote thermal connectivity to the surrounding water. The main body of the sheath is formed from a 2 mm OD standard hypodermic tube with 1 mm ID. The end is sealed with an electron beam weld. The sealed tube is in turn beam welded to a marginally-larger pressure housing designed to fit a small printed circuit board (PCB). The PCB provides a true 4-terminal connection to the measurement thermistor and facilitates the mounting of a high stability ionization resistor in close physical and thermal proximity to the measurement thermistor. The entire assembly is epoxy sealed for long-term stability.

The Hybrid CTD conductivity sensor is mounted in line with the main housing using two compression glands in a small cavity in the end cap. The tube passes through the drive transformer (see below) which is also located in the end cap cavity. Electrical connections to the conductivity sensor elements are routed through the end cap via glass to metal seals. The conductivity sensor drive core, sensor cavity and a compensator diaphragm are filled with synthetic silicon oil. So designed, the glass to metal seals of the conductivity need only support small differential pressures.

The hybrid cell employs precision bore low-thermal expansion borosilicate glass tube as the fundamental volume control element. The coefficients of thermal expansion and bulk compressibility of this material are of 3.3 x 10 6 °C-1 and - 9.57 x 10-8 dbar-1, respectively. To compensate for its relatively short length, sensitivity is gained in the electronics [2]. The cell tube is placed through a toroidal transformer that is used to generate the measurement current, Iw, inside the borosilicate tube. Annular electrodes E1 and E2, Fig. 2, on either end of the tube serve two functions: they provide a low impedance path around the drive transformer to form a single turn and, as they are shorted together, hold both ends of the tube at the same electrical potential. The latter renders inactive the external electrical conduction path around the outside of the sensor as there is no driving potential. Thus, the external resistance is effectively infinite and the electrical current that flows in the cell therefore depends only on the resistance of the sea water that is inside the borosilicate tube between the two electrodes. An electric current measurement transformer is placed around the

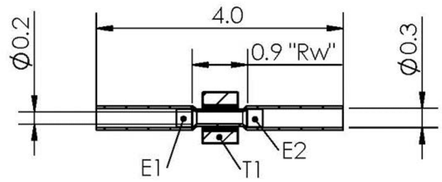

Figure 2. Mechanical drawings of the Hybrid Conductivity Sensor showing the glass cell and positions of the electrodes (E1,2) and drive toroid (T1). Rw indicates the total impedance of each cell with the annotations suggesting how it is distributed with distance along the cells. Dimensions are in inches.

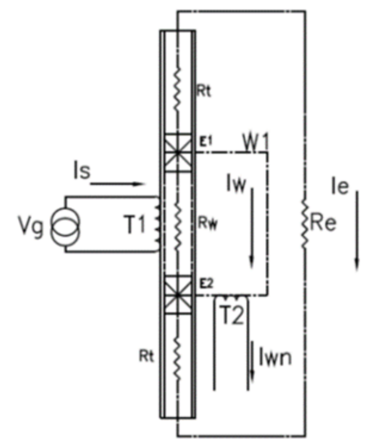

Figure 3. Electrical equivalent model Hybrid Conductivity Sensor. See text for definitions of the variables.

wire tied to the two electrodes to make a direct measurement of the current flowing between the electrodes. That current is determined by the driving potential of the drive transformer divided by the total impedance of the loop, which is overwhelmingly made up of the conductance of the sea water in the cell, the element of interest.

An equivalent electrical circuit model of the cell has been constructed, Fig. 3. In the model, the sensor is driven by an AC generator represented by Vg, and the transformer, T1, which is placed around the sensor tube. The tube forms an enclosed volume of sea water. An AC current, Iw, flows through the sensor in direct proportion the resistance of the sea water represented by Rw. This current is confined by the sensor tube between the electrodes (E1 and E2), which are connected by a very low impedance wire W1. W1 is passed through a current sensing transformer T2 (that is located inside the instrument housing). The current flowing through T2 results in current Iwn, which is proportional to the sea water current by the turn’s ratio of the transformer T2. The current Iwn can be detected using traditional feedback systems so that T2 operates at zero flux, eliminating the effect of magnetic changes in this current sense transformer. The external path around the outside of the sensor is represented by resistance Re. The external current Ie is thus determined by the ratio of the external sea water path resistance to that of the direct current path represented by the resistance of W1 that can be made very small, <0.01 ohms. The ability of E1 and E2 to collect all the Iw current can be enhance by increasing the surface area of the electrodes by treating them with a gold or platinum black coating or other surface conductive enhancements. Re and its ratio with W1 may be augmented by extending the tube beyond the E1 and E2 electrodes, thus adding 2* Rt to the external path resistance.

The CTD electronics are mounted on 3 PCBs in a fixed chassis that is hard mounted to the end cap, Fig. 1: a CPU board, a Pressure/Temperature interface board and a Conductivity interface board. The latter two each have a transformer mounted; that on the Pressure/Temperature board is to isolate the drive signal and provide appropriate signal levels to match the sensor sensitivities. The transformer on the conductivity board is the current sensor coil that detects the electrical current flowing in the cell. As noted above, the conductivity drive toroid is mounted in the sensor head. The CPU card holds a Microchip PIC32 Microprocessor that controls the instrument. One unique feature of the prototype CTD systems built for this project is that the CPU supports three 24-bit A/D convertors that can be run synchronously so that conductivity, temperature and pressure are sampled over coincident time windows. The CPU controls the rate at which the A/Ds are operated; instrument sample rate can be varied from approximately 2 frames/second to 25 frames/second. The cards also incorporate additional auxiliary circuits such as the pressure temperature measurement, and have the capability to digitize an additional 8 analog channels. At the 2 Hz sample rate, the Hybrid CTD draws approximately 30 mA from a 12 V power supply.

Data from the 3 A/D's and auxiliary data constitute the data stream assembled by the Microprocessor in ASCII encoded counts spanning 0 – 16,777,216 for the primary channels and 0 – 4096 for the secondary channels (including the pressure transducer temperature). For the present project, the Hybrid CTDs were configured to automatically boot up when power was supplied and to stream these unscaled ASCII data to the data logger unit described below. CTD operations are terminated by removing power.

To control the operations of the Hybrid CTD during at-sea deployments and store the observations, self-contained data logger systems with battery packs were designed and fabricated at WHOI, Fig. 4. The logger pressure housing is a 15" long by 6.5" - diameter titanium pressure vessel rated to 6000 m; each unit was tested and certified by the WHOI pressure test facility to 10,000 psi. The top end cap has ports for a 5-pin sensor connector, an 8-pin Ethernet connector, a Prevco Titanium Dual Seal Vent Plug and an acrylic view port, Fig. 4. The bottom end cap is blank. Two Ethernet pairs are used for 100baseT offload connectivity while the other two pair are used for RS-232 console/wake and shore power. Visual feedback to the operator is provided by an RGB LED and a reed switch that is mounted directly behind the acrylic view port.

Figure 4. Photographs of the Logger system built for the current project, top, and closeup view of the end cap showing the two electrical bulkhead connectors, vent plug and the acrylic view port with LED status indicator. .

The logger electronics consist of a Technologic Systems Inc. TS-4200 Linux macro controller board (about the size of a credit card) mounted to a 4" x 6" carrier board that provides power conditioning and switching with self-resetting fuse, and brings out the controller serial ports to RS-232 transceivers as well as Ethernet and USB functionality. The Linux board uses a 4GB micro SD card for data storage. Also on the carrier board is a very low power supervisor micro controller that is used to monitor the reed switch and control the state of the RGB LED. Data offload capability is achieved with Ethernet connectivity.

The logger housing also supports a lithium primary battery pack consisting of 12 Electrochem BCX85 DD cells in a 3S4P arrangement providing roughly 1300 W-hr of energy at 11.4 V after diode drop. The pack has a built-in 3-A fuse. The combined energy draw of the Hybrid CTD and logger averages just under 0.75 W; we predict that approximately 1750 hours of profiling time is available before the logger unit requires servicing. The shore power cable allows the Logger and Hybrid CTD to be operated from an external power supply while on deck or in the lab, saving battery power.

The design goal of a simple user interface was accomplished with the view port, RGB LED and reed switch. User control of the data collection is effected by magnet swipes across the end cap view port. When the supervisor micro controller detects the presence of the magnet via the reed switch, it turns on the blue LED. If the blue state is held for 2 seconds, the initiation command is passed to the Linux controller and the LED changes to green, notifying the watch stander that a logger session has begun. The Linux controller turns on power to the Hybrid CTD that in turn, automatically boots and initiates data collection and transmission. The green LED will continue to slowly blink green for the duration of the cast. To terminate the logger session, the magnet is again placed in front of the view port, which causes the supervisor to change the LED to blue. If this is held for 2 seconds, the blue LED turns to red notifying the user that the logger has received the shutdown command. This command is passed to the Linux controller that removes power from the Hybrid CTD, closes the log file and initiates a proper shutdown sequence. During the shutdown sequence, the LED will slowly blink red. At its conclusion, a message is sent to the supervisor to remove power from the Linux board. During this time, the red LED stays solid for 5 seconds and then goes out, signifying the end of a session. The function of the blue LED is to acknowledge the presence of the magnet at the reed switch. If it is not held in the blue state for the required 2 seconds and removed before another 2 seconds, the system will not transition to the green (recording state) or red (shutdown sequence state).

III. Laboratory Calibrations

At multiple times through the study period, CTD sensors were evaluated in a laboratory setting. Static laboratory calibration analyses were conducted for the pressure and temperature channels. (WHOI does not presently have the capability of conducting laboratory conductivity calibrations.) To characterize the CTD temperature channel, CTD units were fully submerged in fresh water temperature controlled baths (Hart Scientific, models 7041 and 7015) that were stepped from just above 0 ˚C to ~35 ˚C in 5 degree increments. Sensor digitizer counts and transfer standard readings were made at each check point after the bath temperature had stabilized. Bath temperature was measured with a Fluke 1594A Super Thermometer fitted to GE Thermometrics AS125 4-wire thermistor probes. The backup transfer standard in the laboratory is a Sea-Bird Scientific SBE-35. The Fluke system is regularly checked against a Gallium melting point cell, triple point water cells and a mercury freeze cell. The SBE 35 is periodically returned to Sea-Bird Scientific for recalibration. Hybrid CTD units were driven by a laboratory power supply with the serially-streamed data logged by a PC. Approximately 7 minutes of sensor data at 2 Hz were logged at each check point. For analysis, each set of sensor and standard readings were averaged and standard deviations estimated. Polynomials relating CTD temperature channel digitizer counts to the standard temperature data were then derived with least square regression. Polynomial fits were done for both the primary CTD temperature sensor data and for the temperature measurement on the pressure sensor interface board. (The latter is sampled to help characterize temperature sensitivity of the CTD pressure measurement, see below.)

The laboratory temperature calibration data consisted of average bath temperature and raw sensor counts at check points ranging between (just above) 0˚ C and 35˚ C. Polynomial regressions between raw counts and temperature were obtained at increasing order until the residuals of the fit were judged to be acceptable. Fifth order polynomial regressions typically yielded residuals of order 1 m˚C. Fits to the Steinhart-Hart form of the thermistor relationship between resistance and temperature [3] were no more efficient at relating raw counts to temperature than a high order polynomial. The standard deviation of the sensor counts at each of the check points ranged between 150 and 250 counts. This equates to a noise level of approximately 1 m˚C.

Pressure sensor calibrations were conducted at multiple temperatures. Hybrid CTD units were placed in a temperature-controlled bath with the port of the CTD pressure sensor(s) plumbed together with a Ruska 2480 deadweight table hydraulic system with calibrated masses and a Paroscientific Digiquartz 760-10K transfer standard. The Paros gauge is periodically returned to the manufacturer for recalibration. Up to three D-2 CTD sensors could be evaluated at the same time. Once bath temperature was stable, pressure was ramped up from atmospheric pressure to 6245 dbars in 400-600 dbar increments and then stepped back to atmospheric pressure. Pressures were applied by placing platters of known mass on the deadweight table's piston. D-2 CTD and Paros transfer standard data were logged at each check point for ~30 seconds; the observations from each check point were subsequently averaged and standard deviations estimated. Readings from the Paros gauge were consistent to within 1 dbar with the pressures inferred from the calibrated mass of the platters and the local gravitational acceleration. In similar fashion to the analysis of the temperature calibration data, polynomial regressions were developed between sensor counts and standard pressure values for each bath temperature.

The laboratory pressure calibration work yielded sets of average standard and sensor count values at a series of check points between atmospheric pressure (0 dbar) and 6245 dbar at each of 3 bath temperatures. Temperature sensitivity of the pressure sensor is manifested by differences in the relationships between sensor counts and standard pressure. Akin to how the temperature data are treated, polynomial regressions of increasing order were made between sensor counts and standard pressure at each bath temperature. Third order polynomials yielded residuals that were less than 1 dbar across the oceanographic range. The standard deviation of the pressure sensor data at each of the check points ranged from 20 to 140 counts. This equates to a noise level in physical units of less than 0.1 dbar.

Digitizer counts from the temperature sensor mounted on the back of the pressure gauge were also logged during the laboratory temperature calibrations. In similar fashion to how the external temperature data were treated, polynomial regressions of increasing order were derived between the pressure temperature counts and standard temperature. The linear fit yielded residuals of ± 20 m˚C that reduced to less than ± 10 m˚C at order 3.

IV. Assessment of Ocean Observations

Performance of the Hybrid CTD sensors in open ocean conditions were evaluated by piggy-backing systems on research vessels conducting standard hydrographic observations. Self-contained Hybrid CTD units with companion data logger units were mounted on the vessel hydrographic frame, typically using hose clamps and available structure. As detailed earlier, logging was initiated manually by swiping a magnet across the end cap of the logger unit. Another magnet swipe at cast end terminated the logging. Sensor data from each cast (acquired at approximately 2 Hz, with each scan tagged with time by the logger controller) were archived to separate files whose names included the date and time that logging was initiated.

Comparisons with calibrated vessel CTD data were conducted by aligning the Hybrid CTD time series (after applying the laboratory-based calibrations to the pressure and temperature data) with those obtained by the ship's system. The calibrated vessel data were kindly provided by the cruise chief scientists. Ship observations of sea water temperature, salinity and pressure were interpolated to the time of each Hybrid CTD scan using the times associated with each data scan. As the clocks in the logger units are set manually, alignment of the two time series sometimes required an offset of a few seconds to one of the series. The temporal offsets were done manually by examining the ship roll signals in the respective pressure time series.

After aligning the data from the two CTD systems in time, it was straightforward to compare the pressure and temperature data from the Hybrid CTD systems with the ship CTD observations. In situ calibrations of the Hybrid CTD conductivity data were obtained by regressing the conductivity channel digitizer counts against sea water conductivity obtained by inverting the vessel CTD temperature, salinity and pressure observations. Drift of the Hybrid CTD conductivity sensor calibration over time was inferred by using a single in situ conductivity calibration for a cruise.

Preliminary ocean observations with D-2 Hybrid CTD sensors were obtained on cruises to the western subtropical N. Atlantic aboard *R/V Endeavor* in spring and fall 2019 and spring 2020 and *R/V Armstrong* in fall 2019, and from the subpolar N. Atlantic in fall 2020, also from *Armstrong*. After sensor modifications to address issues revealed by the ocean observations, this study focuses on observations from the western subtropical N. Atlantic in conjunction with the Global Ocean Shipboard Hydrographic Investigations Program (GO-SHIP [4]) reoccupations of sections A20 and A22 aboard *R/V Thompson*. The GO-SHIP system was installed and operated by personnel from the Scripps Institution of Oceanography Ocean Data Facility.

We focus initially on representative data from Hybrid CTD SN 1563 obtained on the 2021 GO-SHIP cruise in comparison to preliminary 24 Hz time series data from the primary vessel CTD system. The A20 leg station taken east of Barbados at roughly at 12.5˚N, 52.3˚W is interesting as it sampled a salt finger thermohaline staircase [5]. For this analysis, the offset in time between the start of the Hybrid CTD time series and that of the vessel CTD was estimated by matching the ship roll signals in the respective pressure data. The ship data were then interpolated onto each Hybrid CTD scan to directly estimate the pressure, temperature and conductivity differences. The station occupation was typical: the hydrographic frame was lowered at relatively uniform rate to within 10 m of the sea floor. During the up-cast, the frame was held at selected depths to capture water samples.

The pressure data obtained by the Hybrid CTD, after applying laboratory calibrations, agrees with the data from the SBE system to better than 2 dbar, Fig. 5. For this comparison, the Hybrid CTD laboratory pressure calibrations done at 0˚, 15˚ and 30˚ C were linearly interpolated based on the sea water temperature estimates. A combination of external and internal temperatures might improve the agreement. The saw toothed signal in the pressure difference plot seen in the up cast might be due to hydrodynamic effects influencing one or the other (or both) of the pressure sensors.

Temperature, conductivity and salinity plots were constructed for this station, Fig. 6, showing data over the full depth span and a close-up of the thermohaline staircase stratification. Here the Hybrid CTD temperature data have been corrected assuming a 1 s response time but no corrections were done to the conductivity data apart from scaling for the bulk compressibility of the glass cell and applying a linear scaling of digitizer counts to physical units derived with reference to the vessel CTD data. On the scale of these figures, the Hybrid CTD data are consistent with the vessel CTD observations. Even though the response adjusted T and calibrated C data look reasonably like the vessel data, some spiking in the derived salinity is observed (Fig. 6). More work is needed to quantify and correct the response mismatch of the T and C sensors. Interestingly, the Hybrid CTD cell appears to flush well at ship winch lowering/raising speeds and we find no evidence of thermal mass contamination of the conductivity data.

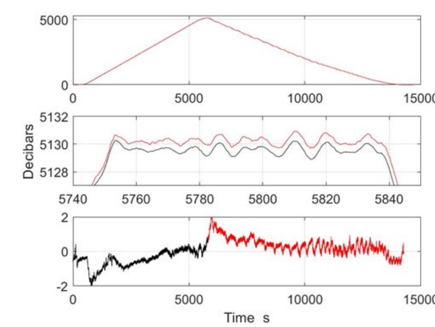

Figure 5. Comparison of pressure estimates. The upper shows the full time series of the station with data from the shipboard CTD in black and those from the Hybrid CTD in red. (The two curves are indistinguishable on this scale.) The middle panel is a blow up of the bottom of the cast demonstrating the matching ship roll signals and a small offset between the two pressure readings. The bottom panel shows the full cast of pressure difference (Hybrid minus ship) with the downcast in black and the upcast in red.

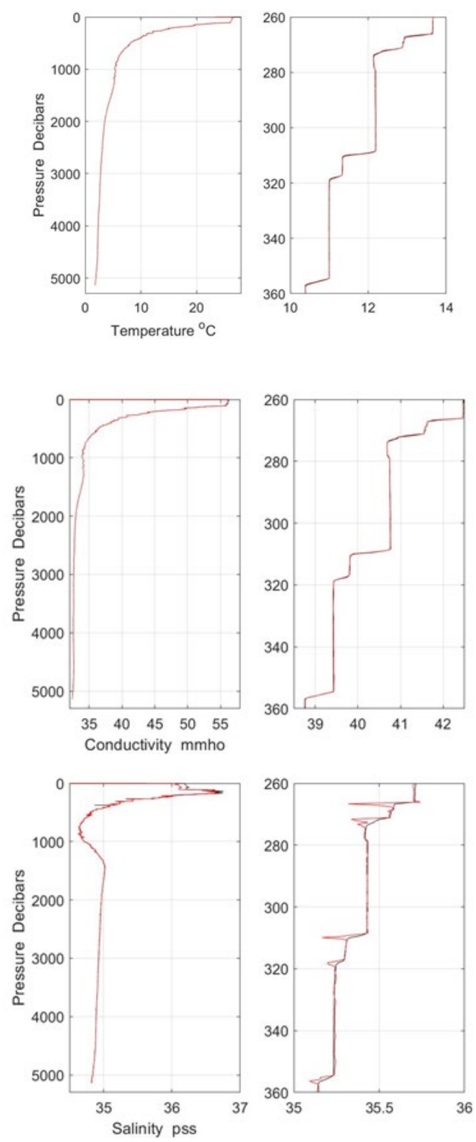

Figure 6. Comparison plots of temperature (top panels), conductivity (middle) and salinity (bottom) profiles obtained with a Hybrid CTD (red curves) and a the vessel CTD system (black curves). In each pair of plots, full depth profiles are shown on the left and a blow up of a thermohaline staircase is shown on the right.

A key attribute of any CTD sensor is the stability of the sensor data over time. Sensor stability was investigated through repeated laboratory calibration work over time and by comparisons to vessel CTD data from the piggy-back cruises. The Hybrid CTD temperature and pressure channels appear reasonably well behaved, though more work is needed to refine the correction of the pressure data for temperature dependence. The A20/A22 GO-SHIP observations document significant drift in the conductivity estimates from Hybrid CTD SN 1563, Fig. 7. Subsequent laboratory analysis attributed the conductivity drift to changes in the permeability of the transformer core due to pressure cycling. During the design cycle for the Hybrid CTD, the size of the magnetic material used in the conductivity sensor drive core was estimated based on historical data for the initial permeability of cores built in the USA. The supplier subsequently moved production of the cores offshore. During prototype construction, it was noted that the cores produced offshore have an initial permeability some ~20% less than the design specification. The lower performance of the core material impacted the induced impedance of the drive cores sufficiently that the drive core winding resistance became significant in ratio to it. Magnetic cores under hydrostatic loading have a tendency to increase their inductance due to isotropic compression, resulting we believe in the observed drift towards larger conductivity from cast to cast. Subsequent testing in the laboratory by simulation confirmed that the sensor slope change was due to isotropic compression changes on the cores permeability and the effect this has on induced drive current in the conductivity sensor sea water path. This effect has been addressed in a revision to the Hybrid CTD electronics by the introduction of a “sense” winding on the drive core that allows continuous measurement of any variation in the drive performance. An alternate solution would be to enlarge the drive core, however, it is felt that the present core size provides a better overall sensor performance with minimal thermal mass impacts. This work has been completed and we expect to field trials with modified instruments to commence shortly.

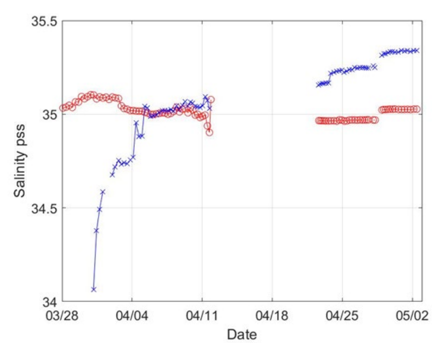

Figure 7. Time series of salinity estimated on the 4.5˚C potential temperature surface during the 2011 GO-SHIP occupation of sections A20 and A22. Data from Hybrid CTD SN 1563 are shown in blue while vessel CTD data are plotted in red. An empirical conductivity calibration for the Hybrid CTD conductivity data was derived with reference to the vessel data obtained on April 6, 2021 (accounting for the close agreement between CTD products around that date). The large gap in mid April is the break between the two cruise legs. The step change in SBE salinity in late April marks the transition from stations in the Gulf of Mexico to those in the open ocean. The drift in the Hybrid CTD derived salinity is due to variation in the conductivity cell calibration as the CTD experienced pressure cycling by repeated station occupations.

V. NEXT STEPS

For the next round of deep ocean trial deployments, the conductivity drive strength will be sampled in parallel with the sea water pressure, temperature and conductivity and used in post-cast processing to correct the conductivity measurement. In future, this correction could be done in sensor firmware in real time (along with scaling raw digitizer counts to physical variables.)

Longer term, to reduce the power drawn by the Hybrid CTD, the sampling electronics could be modified to use a single A/D and multiplex the sensor readings.

Data from the initial sea trials of prototype Hybrid CTD sensors show promise for their use in ongoing and future ocean observing systems. Results from deep ocean deployments of the revised CTD units will be reported when available.

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