Inductive-Conductivity Cell

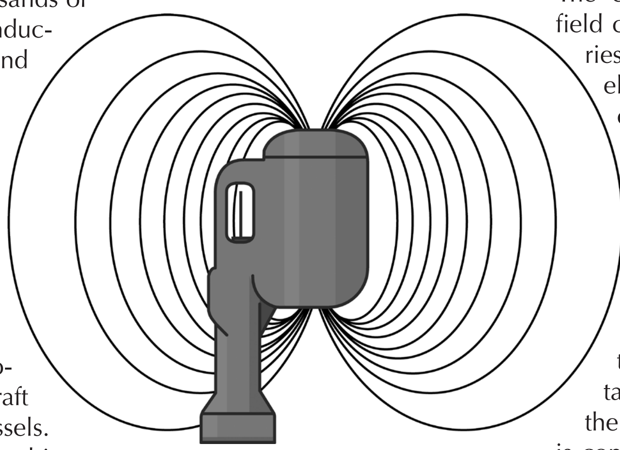
A Primer on High-Accuracy CTD Technology

By Dr. Mark Halverson • Eric Siegel • Dr. Greg Johnson

Conductivity, temperature and depth are core variables used by oceanographers and limnologists to study water properties and dynamics. RBR has been designing and manufacturing precise instrumentation for 45 years and introduced the inductive-conductivity sensor in 2000. Since then, thousands of RBR CTDs with inductive-conductivity cells have been built and deployed.

RBR CTDs have been deployed by major oceanographic centers worldwide into every ocean on Earth, and into the harshest environments, from the abyss to the poles. They have been deployed from many platform types: kayaks, ocean-going research vessels, aircraft and commercial fishing vessels. RBR CTDs have been integrated into ocean gliders, autonomous underwater and surface vehicles, and profiling Argo floats. They are frequently selected as the reliable solution for major citizen science programs.

This article focuses on the RBR CTD's inductive-conductivity cell, including operating principles, unpumped design, accuracy, resolution and stability.



Schematic of the RBR conductivity cell. The curved lines represent conceptual invisible lines of magnetic and electric fields surrounding the cell. The temperature sensor is co-located with the conductivity sensor to measure the same water parcel.

Operating Principles

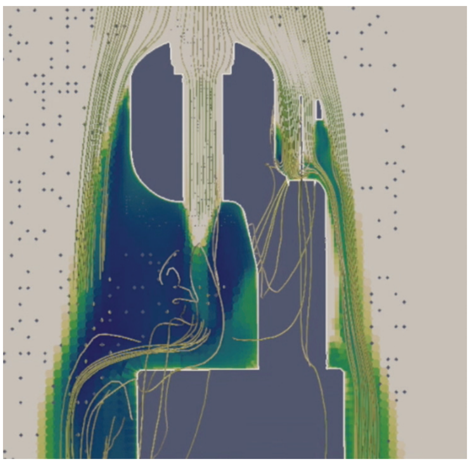
RBR's conductivity cells function according to Faraday's law of induction. Each cell contains two toroidal coils: a generating coil and a receiving coil. An AC signal is applied to the generating coil, producing a magnetic flux and a resultant electric field, and, finally, a current is induced in the seawater present in the center of the cell. The current in the seawater passes through the center of the receiving coil and induces a secondary current to flow in the receiving coil. The current in the receiving coil is proportional to the resistance of the water, which is inversely proportional to conductivity.

The current driven by the electric field can be conceptualized as a series of closed rings of current traveling through both coils in the conductivity cell, out into the water, then back into the cell. The current rings are most dense inside the cell, and they spread out with distance away from the cell.

Theoretically, the field induced by the conductivity cell extends an infinite distance from the cell. In practice, the majority of the measurement is constrained to the local proximity of the sensor. The high concentration of field lines within the center of the conductivity cell means that most (approximately 80 percent) of the conductivity measurement originates from this region. This local spatial extent of the electric field has implications both for calibration and deployment (described later in Proximity Effect).

Design

The primary RBR conductivity cell has a co-located temperature sensor and thus is frequently referred to as a "combined CT cell." There are three versions of the combined CT cell, each rated for a different maximum pressure: 1,000 dbar; 2,000 dbar; and 6,000 dbar. The 1,000-dbar version is made from polyoxymethylene and



(Top) RBR combined conductivity-temperature cells (combined CT cells), with sculpted heads to optimize natural flow and co-located temperature sensors (titanium fitting on the right of each cell). Shown above are the three models, rated for maximum pressures of 1,000 dbar; 2,000 dbar; and 6,000 dbar (left to right). Shown below is the RBR*concerto*^{3} CTD. (Bottom) Reynolds-averaged Navier-Stokes simulation of natural flow through unpumped conductivity cell and temperature sensor at 30-cm/s profile rate.

ceramic, while the 2,000-dbar and 6,000-dbar models use engineered polymers and ceramic.

The combined CT cell was designed to optimize natural water flow through the measurement volume and over the temperature sensor so no pump would be required to circulate water. The thermistor is co-located with the conductivity cell, and the design is sculpted to be hydrodynamically smooth; temperature and conductivity measurements are of the same water parcel. The design features improve the measurement performance in dynamic applications such as profiling through gradients. RBR performed a Reynolds-averaged Navier-Stokes simulation and lab experiment in the Woods Hole Oceanographic Institution double-diffusive interface tank to demonstrate the combined CT cell design is flushed naturally and does not need a pump in order to circulate water.

Proximity Effect

The proximity effect is the phenomenon that objects close to the conductivity sensor may affect its calibration and the accuracy of its measurements. Conductivity, as measured by the inductive cell, is a weighted average of conductivity over the volume occupied by the current loops, with conductivity being most sensitive within the center cylinder and becoming less sensitive with radial distance. Objects near the outside of the central cylinder may affect the calibration and, therefore, accuracy of the conductivity measurement.

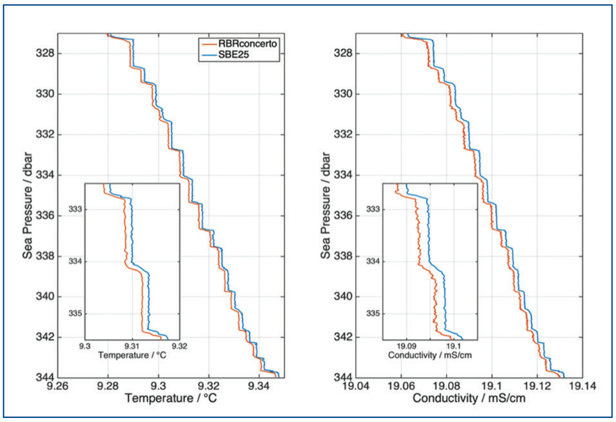
Laboratory experiments at RBR show that an object must be within 15 cm of the conductivity cell before any measurement accuracy is affected. Conductive objects (such as metal deployment frames) closer than 15 cm may bias the conductivity reading higher. Nonconductive objects (such as insulated mooring lines) may bias the conductivity reading lower. The amount of bias is related to the proximity, the relative volume of the material, and the relative difference in conductivity compared to the ambient water.

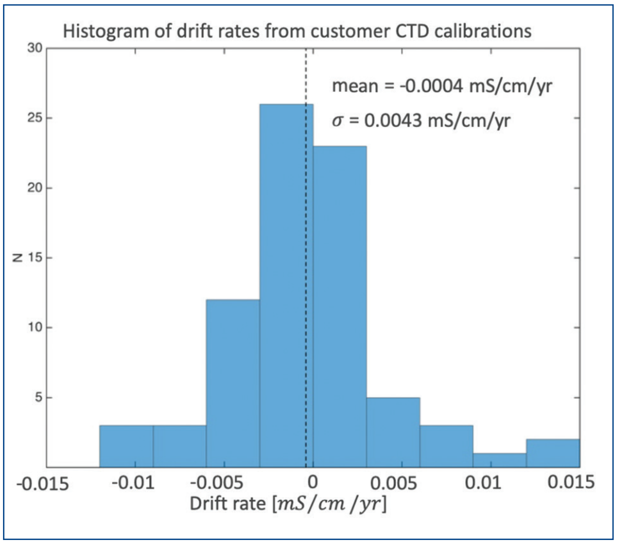
The proximity effect changes the calibration coefficients of the conductivity cell. The change induced manifests as a scale factor (a multiplier), rather than an offset (an addition or a subtraction). As a point of reference, a standard 0.25-in. (6-mm) insulated steel mooring line located 7.5 cm from the inductive conductivity cell (within the 15-cm zone) changes the conductivity calibration by -0.002 mS/cm at 35 psu. This small amount is still within the initial accuracy specification of ±0.003 mS/cm.

Permanent (static) objects in the near field of the sensor can be calibrated with those objects present, negating their effects. This is routinely done for instruments built with sensor guards, instruments which have numerous sensors mounted near the conductivity cell, instruments mounted in stainless-steel cages, and conductivity cells mounted on Argo floats with a nearby antenna. When static objects (such as other sensors or guards) are included in the conductivity calibration, the achieved calibration is always within the specified accuracy of ±0.003 mS/cm. RBR provides mounting clamps to offset the CTD more than 15 cm away from the mooring line.

Advantages of a Naturally Flushed Cell

No Pump Required. Accurate measurement of conductivity, particularly when vertically profiling, requires the sensor to measure the local water parcel. Electrode-based conductivity cells typically have a high-aspect-ratio (tall and narrow) measurement cell and require a pump to actively circulate water through the cell. Without a pump, water tends to move around the outside of the high-aspect-ratio cell, rather than through the central measurement volume of the cell. The RBR inductive-conductivity cell is designed with a low-aspect-ratio cell





(Top) Temperature and conductivity versus sea pressure graphs from profiles in Powell Lake, British Columbia, Canada, which exhibits a thermohaline staircase structure. The insets on each graph focus on two steps to emphasize the fine structure and low noise. (Bottom) Histogram of conductivity drift rate for customers' CTDs returned to RBR for calibration. The mean drift rate is -0.0004 mS/cm/yr; an order of magnitude smaller than the specified accuracy.

(short and wide) and is sculpted to be naturally flushed. Therefore, the RBR conductivity cell does not require a pump to mechanically circulate water through the measurement region. The temperature sensor is co-located in vertical position with the conductivity cell to measure the same water at the same time for improved derivations of salinity and density.

Low Power. The natural flushing of the RBR conductivity cell allows the RBR CTD to be operated with much lower power compared to a pumped CTD. When sampling at 1 Hz, a pumped CTD requires about 175 mJ of energy per sample, while the RBR CTD requires 18 mJ per sample—90 percent lower power consumption. The lower power enables more measurement opportunities, such as faster sampling and longer deployments, particularly on platforms that have limited power, such as ocean gliders and Argo floats.

Near-Surface Measurements. Electrode-based cells require contact between the sensing electrodes and the water. Measurement accuracy may be affected by even microscopic amounts of fouling or coating of the electrodes, such as by surfactants and oils commonly occurring in surface waters. To reduce the risk of contaminating the sensing electrodes, the standard operating procedure for electrode-based CTDs is to turn the pump off before the CTD reaches the top several meters of water. The RBR inductive-conductivity cell is not affected by microscopic amounts of fouling or coating, so it can measure substantially closer to the air-water interface.

Silent Operation. The inductive conductivity cell has no moving parts: it is silent. The silent operation can improve co-located passive acoustic listening measurements, and the absence of a vibrating pump can improve measurements of turbulence.

Robust Construction. RBR's inductive-conductivity cell is robust. It can be frozen into ice and thawed without damage or changing the calibrated accuracy. Because it is made from composite materials and a ceramic center cylinder, it can withstand shock and impact forces. The robust construction has enabled extreme measurement opportunities such as operation in high-latitude freezing conditions and air deployments of profiling floats.

Performance

Lab Calibration. RBR conductivity measurements are calibrated to a static accuracy of ±0.003 mS/cm, a resolution of 0.001 mS/cm and a precision estimated at ±0.001 mS/cm. When combined with temperature measurements accurate to ±0.002° C, an RBR CTD will provide a salinity measurement accurate to within ±0.003 psu. The accuracy specifications for conductivity and temperature are valid over the range of 0 to 85 mS/cm and -5 to 35° C, respectively.

Demonstrated Accuracy. In 2018, two RBR*concerto*[3] 2,000-dbar CTDs and a Sea-Bird Scientific SBE-9 CTD were cast simultaneously on a rosette during a Fisheries and Oceans Canada cruise in the North Pacific Ocean. Comparing instruments profiled on the same rosette removes uncertainty about whether the two instruments measured the same water mass.

The difference between the two RBR*concerto*[3] CTDs and the SBE-9 CTD, when averaged over a range of 800 to 2,000 m, was -0.00074 mS/cm and 0.0013 mS/cm (both within the stated accuracy specification for RBR and SBE). The agreement in terms of the pressure-averaged values is reinforced by low dispersion in the differences. In both cases, the dispersion in terms of the standard deviation is less than 0.001 mS/cm.

Demonstrated Resolution. To demonstrate the resolution of the RBR CTD, a profile was taken of the fine-scale thermohaline staircase structure near the bottom of Powell Lake, a deep lake on the west coast of British Columbia, Canada. The lake is filled with relic seawater from the last ice age and is characterized by a series of uniform temperature and salinity layers of approximately 70 cm, separated by approximately 10-cm stratified interfaces. The typical temperature and conductivity difference between adjacent steps are 0.005° C and 0.002 mS/cm, respectively, making this natural laboratory effective for demonstrating the CTD's resolution.

An RBR*concerto* CTD was mounted onto a protective cage containing a Sea-Bird Scientific SBE-25 CTD. The whole package was profiled to observe the very small gradients in temperature and conductivity through the water. The temperature and conductivity measurements from the RBR*concerto* CTD revealed the same detailed staircase structure as the SBE-25 CTD.

Demonstrated Stability. All oceanographic sensors experience some drift in calibration over time. In a conductivity sensor, the way the cell couples electrically with the water is an important factor for stability. Inductive cells are electrically isolated from the water, providing immunity from corrosion and making them insensitive to contamination from surface oils. Another factor that impacts measurement stability is cell geometry. RBR uses materials with stable geometry over wide ranges in pressure and temperature.

In-situ data from profiling Argo floats provide an estimate of the RBR conductivity cell's long-term stability. Analysis of an RBR CTD deployed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in 2015 on an Argo float in the Coral Sea shows an average annual drift rate of 0.002 psu/yr when analyzed with standard Argo data quality-control methods. Analysis from more recent Argo floats with RBR CTDs deployed in the Pacific Ocean in the last four years shows even lower drift rates (study to be presented at the American Geophysical Union Ocean Sciences Meeting, 2020).

RBR CTDs have demonstrated high stability in long-term laboratory and field experiments. Nearly 100 RBR CTDs were considered in an analysis for stability using laboratory calibration data. RBR calculated drift rates using the change in calibration over the time since the CTDs were last sent to RBR for calibration. Over this sample size, the mean conductivity drift was calculated to be -0.0004 mS/cm/yr, an order of magnitude lower than the specified accuracy, proving the stability and durability of the technology. **ST**

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