SEA·BIRD SCIENTIFIC
Application Note 82
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Guide to Specifying a CTD - Understanding Impacts on Accuracy

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INTRODUCTION

CTDs are used to measure Conductivity (C), Temperature (T), and Pressure (P, but commonly written as D for depth). Parameters such as salinity, density, and sound velocity are calculated from all of these measurements.

When specifying a CTD, you must:
- Define your needs in terms of what parameters are to be determined.
- Consider the application and conditions under which the measurements will be made, such as a moving platform like a profiling CTD or in a moored system.
- Define the accuracy required in the basic measurements to meet the scientific or engineering objectives.

The authoritative source of information regarding definition of oceanographic salinity and the derivation of oceanographic variables from the measured parameters of Conductivity, Temperature, and Pressure is The Practical Salinity Scale of 1978 (IEEE Journal of Oceanic Engineering, Vol. OE-5, No. 1, January 1980, page 14). Additional information is available in the following documents:
- UNESCO Technical Papers in Marine Science (No. 44) - Algorithms for Computation of Fundamental Properties of Seawater (www.jodc.go.jp/info/ioc_doc/UNESCO_tech/059832eb.pdf)
- Sea-Bird Application Note 14: 1978 Practical Salinity Scale (www.seabird.com/document/an14-1978-practical-salinity-scale)
- Sea-Bird Application Note 90: Absolute Salinity and TEOS-10 (www.seabird.com/document/an90-absolute-salinity-and-teos-10-sea-birds-implementation)

EVALUATING MANUFACTURER SPECIFICATIONS

I. Instrument (Sensor) Accuracy

Accuracy is generally understood as the ability of an instrument (sensor) to report the truth within a specified margin of error. The conditions under which a sensor's measuring capabilities are judged are created during calibration by comparing the instrument reading with a reference of known accuracy during a period where the reference and sensor are both in equilibrium (i.e., static accuracy). The instrument's response over the entire operating range is best judged by comparing responses at multiple points spanning the sensor's measurement range. This allows instrument non-linearity to be identified and permits mathematical fitting (linearization of response) by application of calibration coefficients, thereby minimizing errors that might otherwise exist between the points observed during calibration. CTD manufacturers' accuracy specifications are understood to be their claims for performance during initial calibration, unless specific explanation of a different meaning is provided.

II. Calibration Accuracy

The accuracy of a calibration is dependent on many factors, but primarily on the accuracy of the primary and secondary reference(s), the stability (degree to which it is unchanging) and homogeneity (degree of sameness at all points) of the test environment (i.e., bath), and the precision with which the comparisons are made. Sea-Bird uses physical standards as primary references, for example the Jarrett triple-point-of-water cell for temperature, and IAPSO (International Association for Physical Sciences of the Ocean) standard seawater for conductivity and salinity. Secondary reference sensors are carefully monitored for stability over time, and Sea-Bird calibrations are NIST-traceable (National Institute of Standards and Technology) back to primary references.

Given equal calibration accuracy, it is common to assume that two different instruments will perform equally well when used in the ocean. However, in a dynamic environment (e.g., profiling from a vessel) where several conditions are changing rapidly and simultaneously (temperature, conductivity, pressure, etc.), additional sources of error (dynamic error) reduce accuracy potential. **One cannot assume that equal calibration accuracy results in equal dynamic accuracy (i.e., the ocean is not a clean, well-mixed bath).** Instrument and sensor design play a significant (and sometimes dominant) role in achievable dynamic accuracy.

III. Dynamic Accuracy

Simply stated, dynamic accuracy is calibration accuracy degraded by errors associated with instrument use in a changing ocean, which are not found in the calibration environment. This impact is significant on moving platforms, particularly when transiting through gradients. The primary sources of dynamic errors in CTD measurements are:

- Turbulent wakes generated by the modulating effect of ship heave on the instrument motion through the water (known as *shed wakes*), causing contamination of temperature and conductivity measurements and resulting in *spiking* in salinity and density data.
- Unequal response times of Temperature and Conductivity (T & C) sensors.
- Measurements of T & C which are not well coordinated in time or space (i.e., measurements which are not made on exactly the same *piece* of water).
- Thermal mass error in conductivity cells.

These four factors account for the majority of error in CTD measurements and resulting salinity computation. The combined errors can range from many parts per million to many parts per thousand in severe conditions (e.g., 0.020 to 2.0 PSU Salinity). [1]

Shed wakes affect all profiling CTDs that are lowered from vessels, and a CTD's design is not the primary cause of shed wake error. Shed wake error is mentioned here because it is commonly unrecognized and often misinterpreted as CTD instrument error. Shed wake error is best minimized by:

- Careful physical arrangement of sensors on a given package to intake *clean* (i.e., undisturbed) water on the downcast (or on the upcast for some moored profilers and floats)
- Modifying the winch operation (when safely possible) to suit the sea conditions, generally increasing descent rate as ship heave increases.
- Using a pumped system that can maintain a nearly constant flow velocity through the sensor flow path.

For best overall results, users should look for instruments that are delivered with high quality calibrations, and that have design features that minimize dynamic errors. For example, Sea-Bird uses a pumped and ducted flow path as a design feature; see below for further discussion. In addition, Sea-Bird provides software data processing routines to make dynamic corrections to profile data and minimize salinity spiking.

DESIGN FEATURES THAT CONTRIBUTE MOST TO SUPERIOR SALINITY ACCURACY

I. Establishing Response Times for Temperature (T) and Conductivity (C) Sensors

The accurate computation of Salinity (PSS-78) requires accurate measurements of temperature and conductivity (and pressure) on the same water mass. If T and C sensors have the same response times and are physically co-located, the computation of salinity will be made correctly. If the response times are not matched, the salinity computations will contain errors displayed as spikes in the plotted data, particularly when the package transits through gradients in temperature and salinity. To the degree that sensor response times can be well matched, the potential for salinity accuracy is increased. Sea-Bird uses flow-controlled (pumped) sensors to control sensor response time.

Free-Flushed Sensors vs. Flow-Controlled (Pumped) Sensors

Of the three main parameters measured by all CTDs, conductivity is by far the most susceptible to error and is therefore worthy of the most attention. There are two types of conductivity sensors used on CTDs, electrode cells and inductive cells. Sea-Bird uses electrode cells that take the conductivity measurement entirely inside the cell, unlike inductive types that can have proximity errors due to changes in external electrical fields.
For more details, see Conductivity Sensors for Moored and Autonomous Operation (www.seabird.com/document/conductivity-sensors-moored-and-autonomous-operation).

In both types of cells, the sensor response time is determined entirely by the flow rate through the cell (faster flow = faster response). As the flow rate through the cell changes, the response time also changes. Conductivity cells on free-flushed CTDs lowered from a vessel will experience continually changing flow rates, primarily resulting from ship heave and the decreasing lowering speed of the winch as successive layers of cable spooled off the drum reduces the drum diameter. In contrast, conductivity cells on flow-controlled (pumped) CTDs use a constant volume pump that delivers a constant flow rate to the cell, forcing a fixed response time that is completely independent of the CTD motion through the water. This causes a dramatic reduction in salinity spiking.

Temperature sensor response times are largely determined by their physical size and construction, and the impact of flow rate in typical applications is minimal [2]. Sea-Bird optimizes the design in conjunction with the application, cost, and sampling rate for each CTD model. Faster sample rates require faster responding and thinner thermistors.
For example, the SBE 3*plus* temperature sensor used on the SBE 9*plus* is designed with a faster response time (1 Tau = 0.065 sec), while the SBE 19*plus* V2 thermistor has a slower response time (1 Tau ≈ 0.5 sec). The SBE 9*plus* samples at 24 times per second (24 Hz), while the SBE 19*plus* V2 samples at 4 times per second (4 Hz); the SBE 19*plus* V2 does not require response times that are faster than its sample rate. It is important to be aware of the response times in order to match temperature and conductivity data, as explained below.

II. Coordinating T & C Measurements in Space and Time

CTDs with design features that match the time response of their T & C sensors, use flow control to keep those time responses constant under changing dynamic conditions, and make the measurements of T & C on exactly the same *piece* of water, have a fundamental advantage in determining accurate salinity. For example, Sea-Bird CTDs incorporate constant flow pumps and a device known as a T-C duct. The T-C duct is a essentially a small pipe inside of which the T and C sensors are positioned in line, and through which water is pumped at a constant rate, forcing the measurement of T & C to be made on exactly the same water despite any physical separation of the T & C sensors and CTD motion. The chosen pump speed (flow rate) yields a conductivity response time equal to the temperature response time. The matched response times reduce salinity errors. For more details, see Application Note 38: TC Duct Fundamentals (www.seabird.com/document/an38-tc-duct-fundamentals).

III. Minimizing Thermal Mass Errors in Conductivity Cells

Conductivity is a function of both temperature and salinity, and temperature has a much larger impact on the magnitude of conductivity changes in the ocean. For example, the method by which conductivity cells are calibrated involves changing the temperature in a bath of a single salinity to yield a range of conductivities (e.g., from 2.6 S/m at 1°C to 6 S/m at 32 °C at an equal salinity of approximately 35 PSU). All conductivity cells have mass and therefore have the capacity to store heat. When a conductivity cell moves from warmer to colder water (for example, on the downcast), stored heat is lost to the surrounding water. Varying amounts of that heat actually warm the water within the measurement area of the cell, changing (raising) its conductivity. Because CTD temperature sensors are not located inside the conductivity cell, the temperature (assumed accurate) reported by the CTD will be slightly different (lower) than the actual temperature inside the conductivity cell. As a result, when those measurements of T & C are used in the salinity equation, the computed salinity will be in error.

The amount of thermal mass error is a function of flow rate and the sharpness of the thermal gradient that the CTD transits through. The less time water resides inside the cell, the smaller the error, and vice versa. In controlled-flow CTDs, thermal mass error for a given system is predictable and can be minimized in data processing. In free-flushed CTD systems, the constantly varying flow rate in the cell makes it extremely difficult to correct for thermal mass error.

A NOTE ABOUT PRESSURE SENSORS

Pressure sensor technology is sufficient in most CTDs to provide minimal contribution to salinity error. However, there can be significant differences in pressure sensor error from one manufacturer to another, based on their design, temperature compensation, and calibration. See Application Note 27D: Minimizing Strain Gauge Pressure Sensor Errors (www.seabird.com/document/an27d-minimizing-strain-gauge-pressure-sensor-errors).

SUMMARY

There are several factors to take into consideration regarding CTD accuracy. The accuracy of a measurement depends on both static errors (calibration accuracy and stability) as well as dynamic errors in the environment. Derived parameters such as salinity and density come from measurements of temperature, conductivity, and pressure, so any errors in these core measurements can propagate to this final calculation. Sea-Bird has design features like a pumped flow path and provides recommendations and data processing routines to help account for thermal transients, hysteresis, and to match sensor response times. With proper cleaning and maintenance protocols, careful data processing, and tracking of instrument stability over time using water bottle samples, routine calibrations and/or historical climatological data, end users can expect to obtain high quality Sea-Bird CTD data over time.

REFERENCES

- Larson and Pederson, Sea-Bird Electronics (1996), Temperature Measurements in Flowing Water: Viscous Heating of Sensor Tips. (www.seabird.com/viscous-heating-sensor-tips)
- Larson, N.G. (1993), “Calibration of Oceanographic CTD Instruments: Methods and Traceability”, Journal of Advanced Marine Technology Conference V7, 3-13.
- Lueck, R.G. (1990), “Thermal Inertia of Conductivity Cells: Theory”, JAOT V7(5), 741-755. (http://journals.ametsoc.org/doi/pdf/10.1175/1520-0426(1990)007%3C0741:TIOCCT%3E2.0.CO;2)
- Morison, J., R. Andersen, Larson, N., D'Asaro, E., and Boyd, T., “The Correction for Thermal-Lag Effects in Sea-Bird CTD Data”, Journal of Atmospheric and Oceanic Technology (JAOT), V11(4), August 1994, 1151-1164. (http://journals.ametsoc.org/doi/pdf/10.1175/1520-0426(1994)011%3C1151:TCFTLE%3E2.0.CO;2).
- Sea-Bird Electronics (2014), Measurement Accuracy at Triple Point of Water and Gallium Melt Point Supports a Total Measurement Uncertainty of 0.0006 degrees C. (www.seabird.com/document/measurement-uncertainty)
- Sea-Bird Electronics (2009), Conductivity Sensors for Moored and Autonomous Operation. (www.seabird.com/document/conductivity-sensors-moored-and-autonomous-operation)
- UNESCO Technical Papers in Marine Science, #44 (1983), “Algorithms for computation of fundamental properties of seawater”, UNESCO Division of Marine Science (Paris), 53pp. (www.jodc.go.jp/info/ioc_doc/UNESCO_tech/059832eb.pdf)
- Application Notes 14, 27D, 38, and 90 (www.seabird.com/application-notes)

FOOTNOTES

[1] If they cannot be nullified by instrument design and/or deployment methodology, the remaining secondary dynamic errors combined (e.g., viscous heating, pressure sensitivity, etc.) can induce salinity error ranging from approximately 0.005 to 0.020 PSU (5 to 20 parts per million).

[2] Regarding temperature sensors, flow rate does have a small influence on their response time due to viscous heating. As water flows past the sensor, friction with the water causes a small amount of heat that causes an erroneously high reading of order 1-2 millidegrees C at 1 m/sec flow (varies with sensor design). On free-flushed sensors where flow rates are constantly and unpredictably varying, the error cannot be removed from the data. In contrast, on flow-controlled CTDs, the error is a constant value and can be removed from the data, based on physically defensible criteria. See Temperature Measurements in Flowing Water: Viscous Heating of Sensor Tips (www.seabird.com/viscous-heating-sensor-tips).

Application Note Revision History

Date	**Description**
October 2005	Initial release.
April 2016	Update links to current pages on Sea-Bird website. Provide more details on the advantages of Sea-Bird CTDs.