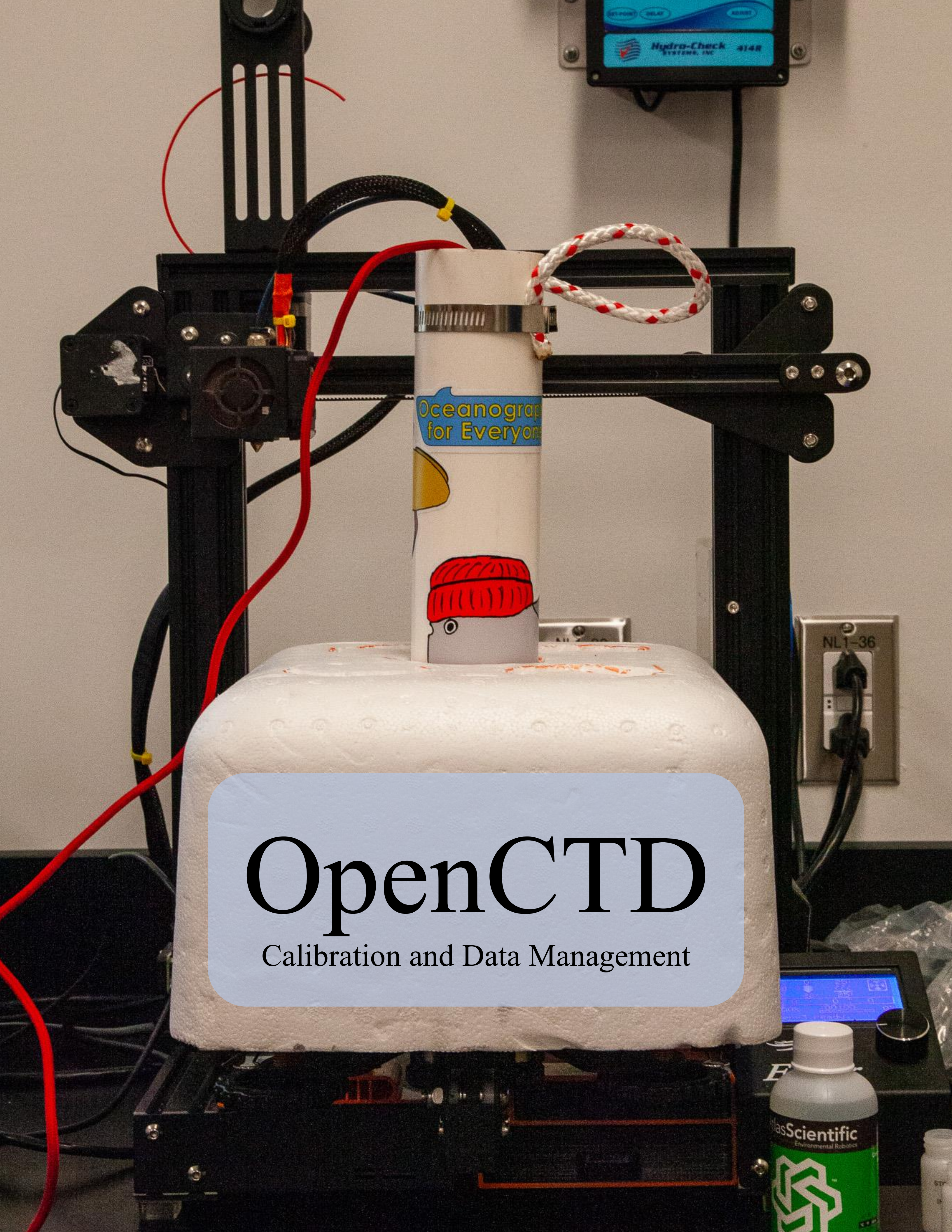

OpenCTD

Calibration and Data Management

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OpenCTD: Calibration and Data Management

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Cover photo by Allie Wilkinson.

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Introduction to Calibration and Data Management

The OpenCTD is a low-cost, open-source CTD designed intentionally for budget-restricted scientists, educators, and researchers working in nearshore coastal ecosystems. It was developed by a core team of marine ecologists in collaboration with a distributed community of scientists, engineers, makers, and conservation practitioners. It is assembled from components commonly available at large hardware stores or through major online retailers. An Arduino-based microcontroller controls a battery of sensors sealed within a PVC pipe. Power is provided by a standard 3.7V lithium polymer battery and data are stored in a comma-delimited text file accessed via SD card. All OpenCTD software is released open source with no restrictions on use.

One of the most significant challenges with any open-source scientific instrument is ensuring accurate and precise calibration. Commercial CTDs often require expensive service contracts in order to maintain data quality. The OpenCTD can be calibrated and maintained by the end user, independent of any manufacturer.

While comprehensive validation of OpenCTD calibration requires access to professionally calibrated instruments maintained in a controlled environment, it is not necessary to do a full validation test for every instrument. This level of validation is for those for whom a high degree of confidence and extreme precision are needed. For environmental monitoring, ecology, conservation, management, and most other use cases, an OpenCTD calibrated against salinity standards and general-purpose temperature sensors is adequate.

As the community grows, validated OpenCTDs can be used to benchmark newly built instruments.

A Microsoft Excel and Google Sheets template is available in the OpenCTD GitHub repository. This template will take raw data from the OpenCTD and make the necessary conversions to create human-readable water column profiles.

The GitHub repository for the OpenCTD can be found here:

https://github.com/OceanographyforEveryone/OpenCTD

Calibration software, data management templates, and OpenCTD firmware can be found here:

https://github.com/OceanographyforEveryone/OpenCTD/tree/main/Software

1 Pressure (Depth)

The OpenCTD uses the MS5803 14-bar pressure sensitive chip from Measurement Specialties designed for SCUBA dive watches and depth gauges. This chip contains a pressure sensitive resistor embedded in a gel matrix. The pressure sensor is rated to 140 meters depth. A 30-bar chip, which can double the operating depth of the OpenCTD, is also available, though requires additional customization.

PRESSURE ERROR VS PRESSURE AND TEMPERATURE

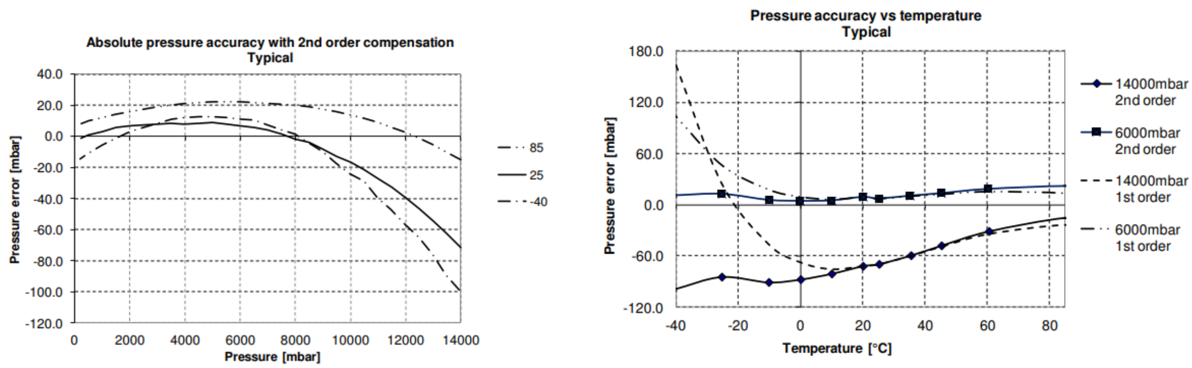

Figure 1. Pressure sensor error versus ambient pressure and temperature for the MS5803-14BA pressure sensor. Provided by manufacturer.

The MS5803 is a factory-calibrated pressure sensor capable of outputting absolute pressure up to 0.2 millibar resolution. No additional calibration is needed by the user. The pressure sensor outputs absolute pressure. At sea level, the average standard atmospheric pressure is 1013.25 mbar, though local weather and small changes in altitude will affect this baseline. To convert pressure in millibars to depth in meters, use the following equation:

$$D = (P_{(DEPTH)} - P_{(SURFACE)} * 100) / (G * 1000)$$

Where **D** is depth in meters; $\mathbf{P_{(DEPTH)}}$ is the pressure (in millibars) at depth); $\mathbf{P_{(SURFACE)}}$ is the pressure at the surface in millibars; and **G** is acceleration due to gravity, which for most field purposes can be assumed as 9.81 m/s^2 (Fofonoff and Millard Jr, 1983). For high-accuracy and high-resolution commercial CTDs, the latitudinal variation in gravity is considered in the pressure-to-depth conversion as these sensors often offer sub-centimeter accuracy.

For extra accuracy, use the absolute pressure at the surface of the water at the time of deployment by taking the last pressure reading before the conductivity probe contacted the water for $\mathbf{P_{(SURFACE)}}$. For deployments in alpine lakes and other high-altitude environments, be aware that surface pressure may be significantly less than 1013.25 mbar.

2 Temperature

The OpenCTD uses a DS18B20 digital thermometer potted in a stainless-steel cladding. These sensors communicate over a 1-wire protocol, which allows users to connect multiple sensors to the same data pin. The sensors have an operating range of -55 to 125ºC (with peak accuracy between -10 to 85ºC). The advertised accuracy is ±0.5ºC, however, in field trials using a battery of 3 sensors, we observed mean error as low as ±0.1ºC.

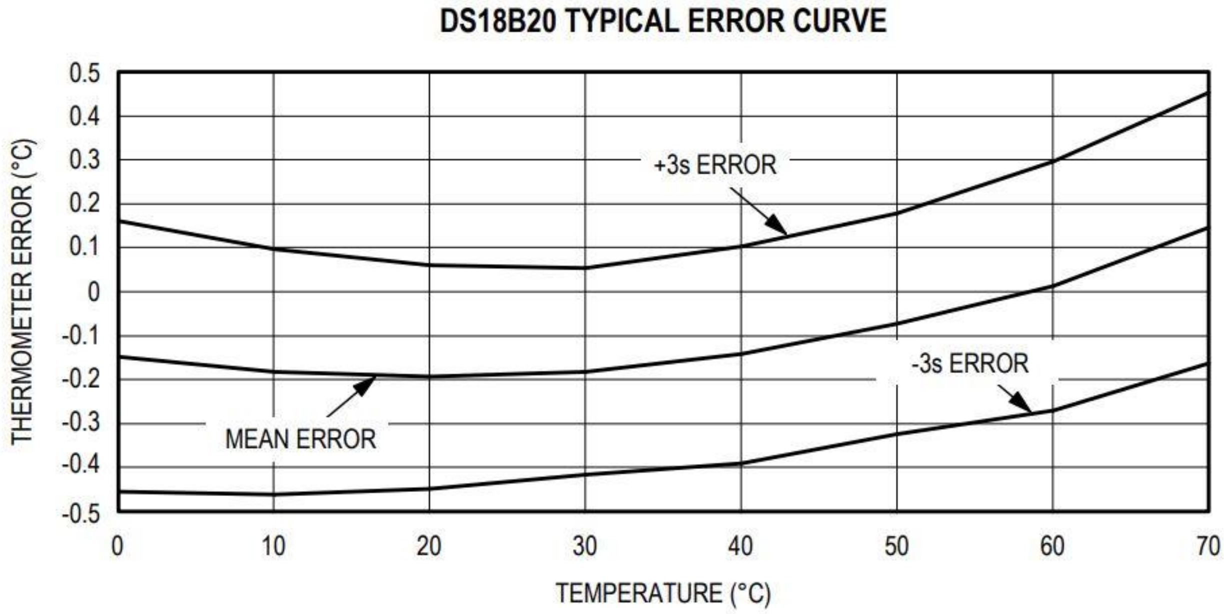

Figure 2. Typical error curve for DS18B20 digital thermometer. Provided by supplier.

Thermal time constant is a measurement of how quickly the thermistor responds to changes in ambient temperature. It is expressed as the time it takes for a thermistor to cool to 63.2% of the total difference between a stable high temperature and a stable low temperature. We determined the thermal time constant for two different designs of DS18B20 sensors in stainless steel cladding: flat-topped and hemispherical. For sensors clad in a flat top housing, the time constant was 5.7 seconds. For those clad in a hemispherical housing, it was 8.5 seconds.

We also determined equilibration rate for DS18B20 sensors. While equilibration rate is not a precise measurement, it is useful for making quick protocol adjustments in the field and gives a basic guideline for how quickly these sensors react to temperature changes. For transitioning from low temperature to high temperature, the equilibration rate was 1.2 ºC/s. For transitioning from high temperature to low temperature, the equilibration rate was 2.3 ºC/s.

The DS18B20 digital thermometer is factory calibrated but the user should perform a single-point or two-point calibration in cases where desired precision exceeds the error rate of ±0.1ºC. The sensor offset is, however, linear, which means that a single calibration constant can be used to correct the accuracy of the temperature measurements averaged across three sensors. A calibration constant can be established by plotting the average deviation between the OpenCTD temperature sensors and water of known temperature.

Calibrated instruments should remain steady for many casts, but it is always good practice to check your temperature calibration whenever you suspect that the calibration may have changed. We recommend checking temperature calibration at the beginning of each expedition or once per year.

3 Conductivity (Salinity)

The OpenCTD uses a graphite conductivity probe manufactured by Atlas Scientific. Electrical conductivity probes are relatively simple devices consisting of two electrodes of known surface area and known distance from each other. As conductive fluid passes between the two electrodes, they measure the resistance of the liquid. The Atlas probe has a response time of 90% within 1 second, a 343-meter maximum operating depth, and a 1 to 110ºC temperature range. The K 1.0 probes can measure conductivity from 5 to 200,000 µS/cm.

Salinity is derived following the formulas outlined by the 1978 Practical Salinity Scale (Lewis, 1980). Temperature and pressure are integral parts of this calculation; therefore, it is recommended that the user use this method for determining salinity instead of using the salinity value derived internally by the Atlas Scientific EZO-EC conductivity circuit. The accuracy of the calculated salinity value ultimately depends on the accuracy of each individual sensor.

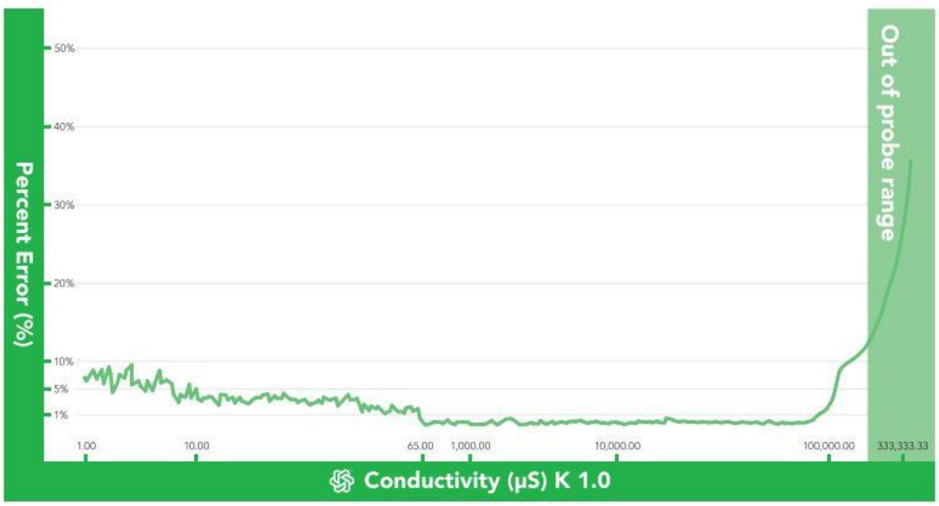

Figure 3. Accuracy of Atlas Scientific K 1.0 Conductivity Probe and EZO circuit. Data provided by Atlas Scientific.

The conductivity circuit requires a two-point calibration using solutions with a known and precise conductivity. Calibration solutions can be pre-mixed or ordered from a scientific supplier. Atlas Scientific sells a set of conductivity calibration solutions for their probes. Most calibration solutions are designed to be used at 25ºC but the Atlas EZO-EC conductivity circuit also allows for temperature compensation if maintaining a stable 25ºC temperature is not possible. While any clean glass or plastic container can be used to hold the conductivity solution standards, we recommend a small probe storage bottle to contain the fluid and minimize waste.

Do not return the conductivity solution to the original bottle once it has been used.

In order to clean the conductivity probe and whatever containers you are using to hold the conductivity solution between steps in the calibration process, you will need a source of either distilled water or water filtered through reverse osmosis. Distilled water is readily available in most grocery stores. Reverse osmosis is often used to purify drinking water from seawater and RO machines are often found on oceangoing vessels as well as a component of the filtration system of some high-end ground wells. Aquafina bottled water is produced using reverse osmosis and has no added minerals, making this brand a useful source of RO water.

We have developed a simple system for establishing a controlled, thermally stable environment for the calibration process that uses the hot bed of a low-cost 3D printer, coupled with a Styrofoam cooler, and a large ceramic thermal mass. A few hours before calibration, set the heated bed of the 3D printer to 25ºC and prepare the following setup.

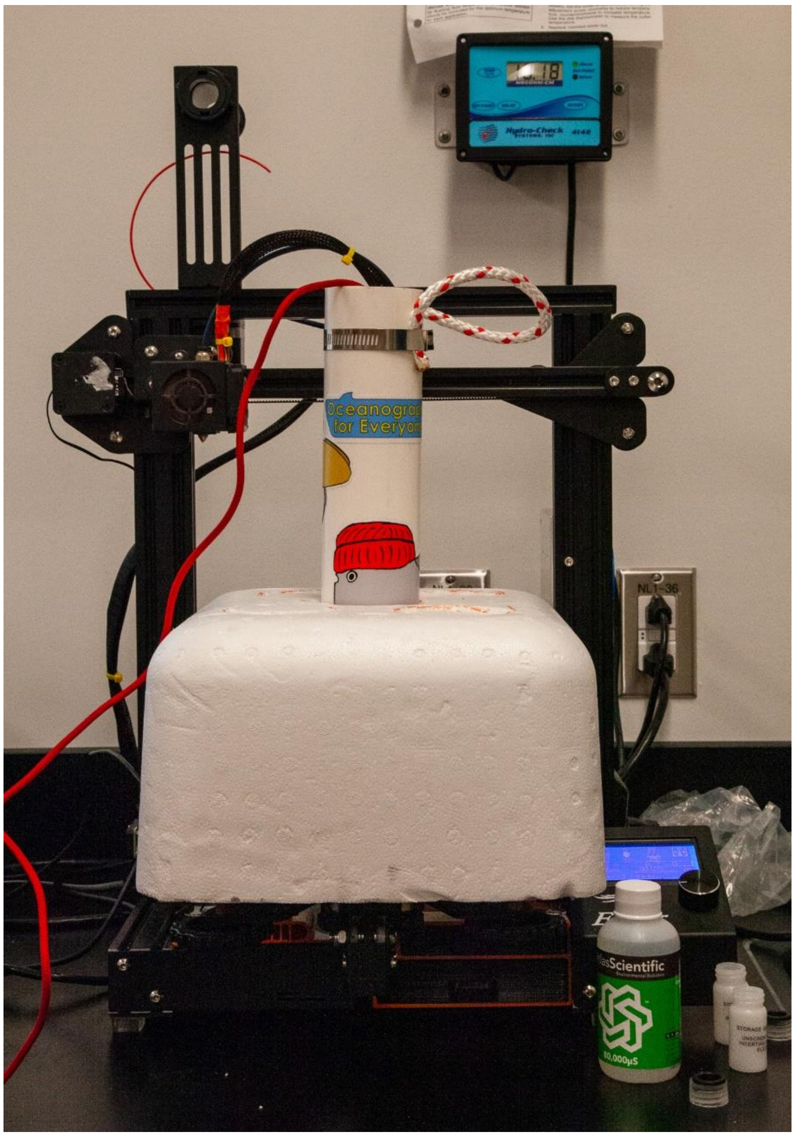

Figure 4. OpenCTD mounted inside a Styrofoam cooler on top of a 3D printer heat bed in order to maintain an ambient 25ºC temperature. Photo by Allie Wilkinson.

Find the largest thermal mass available that the OpenCTD housing can fit inside (a heavy coffee mug works well) and place it on the heated bed of the printer. Cut a hole in the bottom of a Styrofoam cooler large enough for the OpenCTD housing to fit snuggly inside. Place the inverted cooler on top of the 3D printer's heated bed such that the OpenCTD can be inserted through the hole and sit inside the thermal mass.

When you are ready to calibrate your OpenCTD, insert the device into the hole in the Styrofoam cooler such that it sits inside the coffee mug or other thermal mass, and allow it to reach equilibrium (usually 15 minutes or less).

We have determined through experimentation that even the least expensive 3D printers can maintain a very stable temperature throughout the calibration process. In cases where the ambient temperature is more than 5ºC cooler than 25ºC, you may want to store the conductivity solution on the heated bed as well. This process will not work for rooms where the ambient temperature is greater than 25ºC. Please reference the end of this section for alternatives to temperature compensate the OpenCTD during calibration.

Two-point calibration is facilitated using Serial_for_EC_Calibration_m0.ino (https://github.com/OceanographyforEveryone/OpenCTD/tree/main/Software/Support/Serial_for_EC_Calibration_m0) found in the OpenCTD GitHub repository. If only a single calibration standard is available, one-point calibration is possible, but not recommended. This software will also output the average temperature reading from the three temperature sensors.

1. With the control unit powered on and connected to the sensors, upload Serial_for_EC_Calibration_m0.ino to the Adalogger M0. Make sure that the OpenCTD control unit power is also on, as the voltage differential between USB and battery power may affect calibration.

2. Open the serial monitor through the Arduino IDE. Make sure the dropdown menus in the serial monitor are set to "Carriage return" and "9600 baud". You should see a message with EC Board Info, a note to review this guide, and a reference list of useful commands.

3. Type **k,?** in the command line and hit enter. This will tell you what the K-value of you probe is set to. It should be set to K=1.0 for most use cases.

    a. If the K-value is something other than 1.0 type **k,x** (where x is the new K-value of the probe) in the command line and hit enter. This is useful if your EZO-EC conductivity circuit reads the incorrect K-value or if you are building an OpenCTD for freshwater deployments using a K 0.1 probe. If there is an error transmitting the command, the serial monitor will report *ER and you should send the command again.

4. To check whether the probe has been previously calibrated type **cal,?** in the command line and hit enter. If it reads ?CAL,0 the probe has not been calibrated.

5. Type **cal,clear** and hit enter to clear the previous calibration. It is good practice to send this command even if the circuit reports back that it has not been calibrated. If there is an error transmitting the command, the serial monitor will report *ER and you should send the command again.

6. With the probe dry (be sure there is absolutely no water on the electrodes) enter **cal,dry** in the command line and hit enter. This will dry calibrate the probe. If there is an error transmitting the command, the serial monitor will report *ER and you should send the command again.

7. Enable continuous monitoring by entering **c,1**. You will begin to see a steady stream of readings from the conductivity probe updating once per second. If the dry calibration was successful, those values should read 0.00.

8. Clean the probe with distilled or RO water and dry with a clean paper towel. Make sure there is no water trapped in the small hole between electrodes. Clean and dry the probe storage bottle with distilled or RO water and dry with a clean paper towel.

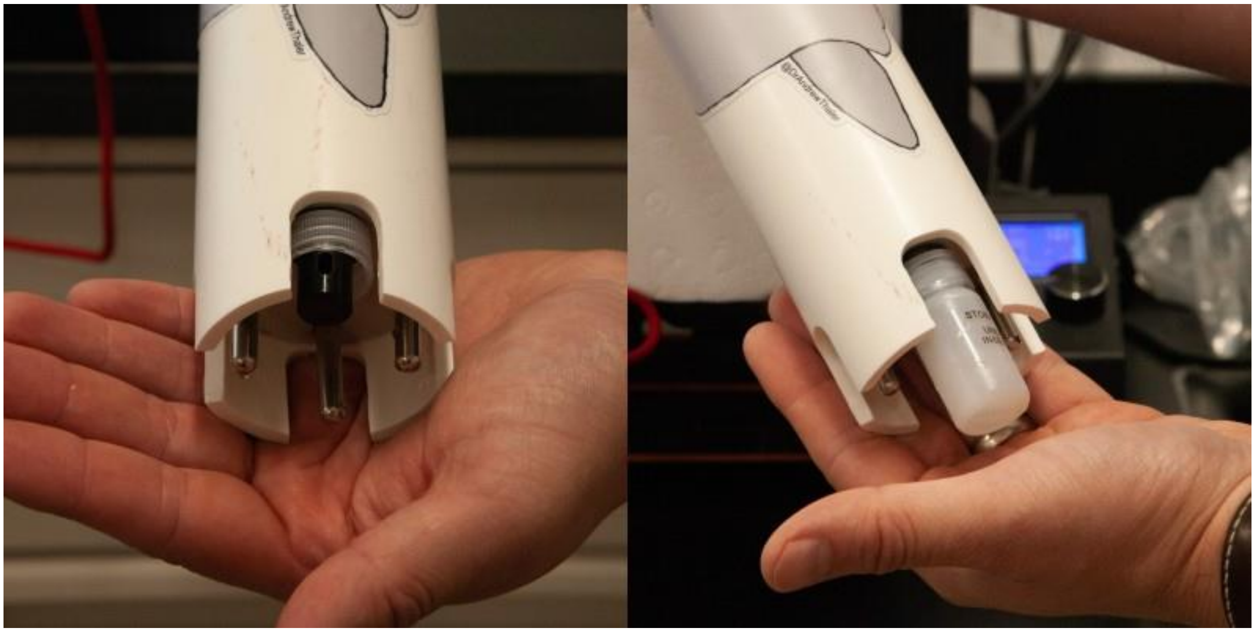

Figure 5. OpenCTD conductivity sensor with the cap ring of the probe storage bottle placed above the electrode opening (left) and with the conductivity probe completely submerged in the probe storage bottle. Photos by Allie Wilkinson.

9. Fill the probe storage bottle with the less conductive of the two conductivity solutions (12,880 µS if you're using the Atlas standard solutions). Slide the cap ring of the probe storage bottle onto the conductivity probe so that it sits well above the small hole between electrodes. Slide the probe storage bottle onto the probe and screw it into the cap so that it seals tightly, and the conductivity solution completely covers the small hole between electrodes. Tap the probe gently to shake out any bubbles.

10. Place the probe with the bottle attached in a thermally stable environment. Leave the probe suspended in the conductivity solution until readings stabilize (15 minutes is usually sufficient). The reading should be anywhere from 1% to 40% off from the conductivity solution. Even once they stabilize, there will be small fluctuations in value. If you leave the probe in for too long, it will ionize the water and the conductivity readings will begin to creep up. A gentle shake will return the solution to its baseline.

11. Type **cal,low,y** (where y is the known value of the standard. If you are using the Atlas conductivity solution, type **cal,low,12880**) in the command line and hit enter. The conductivity readings in the serial monitor will not update.

12. Remove the probe storage bottle, clean the probe with distilled or RO water, and dry with a clean paper towel. Make sure there is no water trapped in the small hole between electrodes. Clean and dry the probe storage bottle with distilled or RO water and dry with a clean paper towel.

13. Fill the probe storage bottle with the more conductive of the two conductivity solutions (80,000 µS if you're using the Atlas standard solutions). Slide the cap ring of the probe storage bottle onto the conductivity probe so that it sits well above the small hole between electrodes. Slide the probe storage bottle onto the probe and screw it into the cap so that it seals tightly, and the conductivity solution completely covers the small hole between electrodes. Tap the probe gently to shake out any bubbles.

14. Place the probe with the bottle attached in a thermally stable environment. Leave the probe suspended in the conductivity solution until readings stabilize (15 minutes is usually sufficient). The reading should be anywhere from 1% to 40% off from the conductivity solution. Even once they stabilize, there will be small fluctuations in value. If you leave the probe in for too long, it will ionize the water and the conductivity readings will begin to creep up. A gentle shake will return the solution to its baseline.

15. Type **cal,high,y** (where y is the known value of the standard. If you are using the Atlas conductivity solution, type **cal,high,80000**) in the command line and

hit enter. The conductivity readings in the serial monitor will update and should read very close to 80,000.

> **Alternative:** For 1-point calibration, suspend the probe in known calibration solution. Leave the probe suspended in the solution until readings stabilize. Enter **cal,one,y** (where y is the known value of the standard) in the command line and hit enter. Only do this if you do not have two calibration standards.

16. After calibration is complete, upload the OpenCTD software to the Adalogger M0.

If you do not have access to a system that allows you to maintain a temperature at a stable 25ºC, there are two alternatives for calibration. You can use the temperature compensation feature of the Atlas EZO-EC conductivity circuit to set a different stable temperature for calibration, provided that the environment around the probe is stable at that temperature. You can derive the compensation temperature from the OpenCTDs temperature probes, rounded to the nearest tenth of a ºC. Set the compensation temperature on the EZO-EC by sending the command **t,x** through the serial monitor, where **x** is the compensation temperature rounded to the nearest tenth of a ºC. Once temperature compensation is entered, continue through the above two-point calibration protocol. Temperature compensation will reset to 25ºC whenever the unit is powered down.

Review the Atlas EZO-EC Datasheet (https://atlas-scientific.com/files/EC_EZO_Datasheet.pdf) for more thorough instructions.

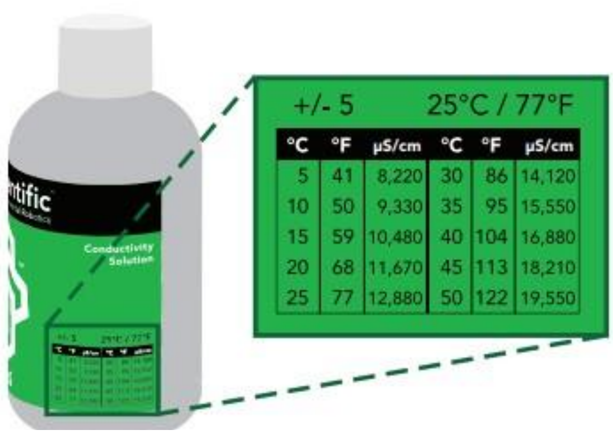

Figure 6. Location of conductivity temperature offsets. Image from Atlas Scientific.

If you cannot maintain a consistent thermal environment, there is one alternative that will result in a rough calibration of the probe acceptable for educational programming or for applications where precise salinity measurements are not essential. On the side of bottles of conductivity solution provided by Atlas Scientific and others, there is usually a table of compensation values in intervals of 5ºC. You can calibrate against the value closest to ambient temperature. This method should only be used when there are no alternatives.

Conductivity should not need to be calibrated again once the calibration protocol is complete, however it is practice to check calibration at least once per year or whenever components are changed. For more detailed explanation of the calibration process and for an explanation of temperature compensation, refer to the Atlas EZO-EC Datasheet (https://atlas-scientific.com/files/EC_EZO_Datasheet.pdf).

Each control unit is calibrated to a specific sensor package. Control units are not interchangeable between OpenCTDs without recalibration.

4 Data Management

The OpenCTD outputs data as a comma delimited text file which can be read by any standard spreadsheet program. It outputs the date and time followed by pressure in mbar, each of three individual temperatures in ºC, and conductivity in µS/cm. In order to convert those values into human-readable oceanographic data, we have produced Microsoft Excel and Google Sheets templates that take the raw data and outputs depth in meters, average temperature, and practical salinity units and generates a basic water column profile.

The template will also average readings in batches of 60 to simplify data presentation. It has fields for calibration constants so that users can input the absolute pressure at sea level at the time of deployment and the temperature offset of the OpenCTD temperature probes determined experimentally during the calibration process.

Although the SD card reader is built into the Adalogger, Arduino M0 microcontrollers do not provide data passthrough. This means that the SD card cannot be read directly from the Adalogger. Data is accessed post-deployment by removing the SD card from the Control Unit and connecting it directly to a computer.

Importing into Excel or Sheets: Open the Excel or Sheets template and navigate to the Data Input sheet in the lower left corner. You can copy-paste the desired data points directly into this sheet.

Data clean-up: Depending on when you started and stopped the OpenCTD, you may have dozens to thousands of rows of data from the surface that you don't need. Using the reading from the pressure sensor and conductivity probe, remove any date that appears to be from the surface (pressure readings around 1010 and conductivity readings at or near 0).

Water column profile: Select the data that you want to analyze and copy/paste it into the "Paste RAW data from OpenCTD" columns on the Calculations sheet. The water column profile graph should update but you will have to edit the source data fields in order to cover all of your data. You can save the water column profile as an image to embed in presentations or download the cleaned and processed data for more analysis. For long deployments, the final columns average the data over 1-minute intervals.

5 Additional Resources

Works Cited

Fofonoff, N.P., Millard Jr, R.C., 1983. Algorithms for the computation of fundamental properties of seawater. UNESCO Tech. Pap. Mar. Sci. 44. https://doi.org/10.25607/OBP-1450

Lewis, E., 1980. The practical salinity scale 1978 and its antecedents. IEEE J. Ocean. Eng. 5, 3–8. https://doi.org/10.1109/JOE.1980.1145448

Tools and Materials

- Atlas Scientific Conductivity Calibration Solution:
  - https://atlas-scientific.com/calibration-solutions/conductivity-calibration-k-1-0-set/
- Probe Storage Bottle:
  - https://amzn.to/43DcMcq

Sensor Specifications

- MS5803-14BA Miniature 14 bar Module:
  - https://cdn.sparkfun.com/datasheets/Sensors/Weather/ms5803_14ba.pdf
- DS18B20 1-Wire Digital Thermometer:
  - https://datasheets.maximintegrated.com/en/ds/DS18B20.pdf
- EZO-EC Conductivity Circuit Datasheet:
  - https://www.atlas-scientific.com/_files/_datasheets/_circuit/EC_EZO_Datasheet.pdf
- EC K 1.0 Conductivity Probe Datasheet:
  - https://files.atlas-scientific.com/Mini_EC_K_1.0_probe.pdf