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Fundamentals of the TC Duct and Pump-Controlled Flow Used on Sea-Bird CTDs

Scientists are interested in salinity and density, but CTD probes measure the pressure, temperature, and electrical conductivity of the ocean water. Because salinity and density are computed from the C, T, and P values, it is obvious that the C, T, and P measurements must be made on the same parcel of water, otherwise the computed salinity and density will be wrong and "spiking" will result (the pressure sensor can be above or below, so long as its physical displacement is taken into account).

Many CTD probes fail to measure C and T on the same water parcel because the C and T sensors are physically separated, or because the C and T sensors have different time responses. Especially, the time response of their conductivity cells depends on the CTD drop rate, with more time required to fill the cells at slower speeds. Unless the CTD profiling speed is known and constant (it almost never is constant because of ship motion), the response time of these systems' conductivity cells will be continuously changing, and serious spiking will result.

To reduce salinity and density spiking to the lowest possible level *without loss of resolution caused by data averaging*, Sea-Bird uses a TC duct and a pump. These two features ensure that the measurement of temperature and conductivity are made on the *same parcel of water* as follows:

TC duct: All the water sensed by both the temperature and conductivity cell must pass through a single small (0.4 cm) diameter opening.

Pump: The electronically controlled pump forces the seawater to flow at a constant 30 cm^3/second speed to ensure that the C - T time responses are constant.

The physical arrangement of the Sea-Bird T and C sensors with TC duct is shown in Figure 1. As the CTD descends, water is taken in at the duct opening (the opening points downward) and its temperature is immediately sensed. After a small time delay of 0.073 seconds during which the water flows through the duct, the water enters the conductivity cell. The 0.073-second delay is constant because the pumping speed is fixed. This delay is automatically corrected in real-time by the SBE 11*plus* Deck Unit.

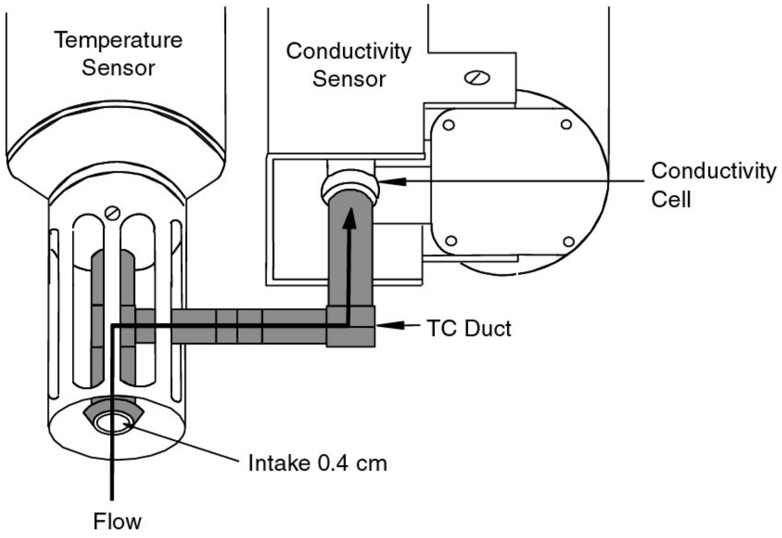

Figure 1. TC DUCT PHYSICAL ARRANGEMENT

Note that the downward exhaust of the pumped water (Figure 2) eliminates any "ram" effect that would cause the flow rate to be affected by profiling speed.

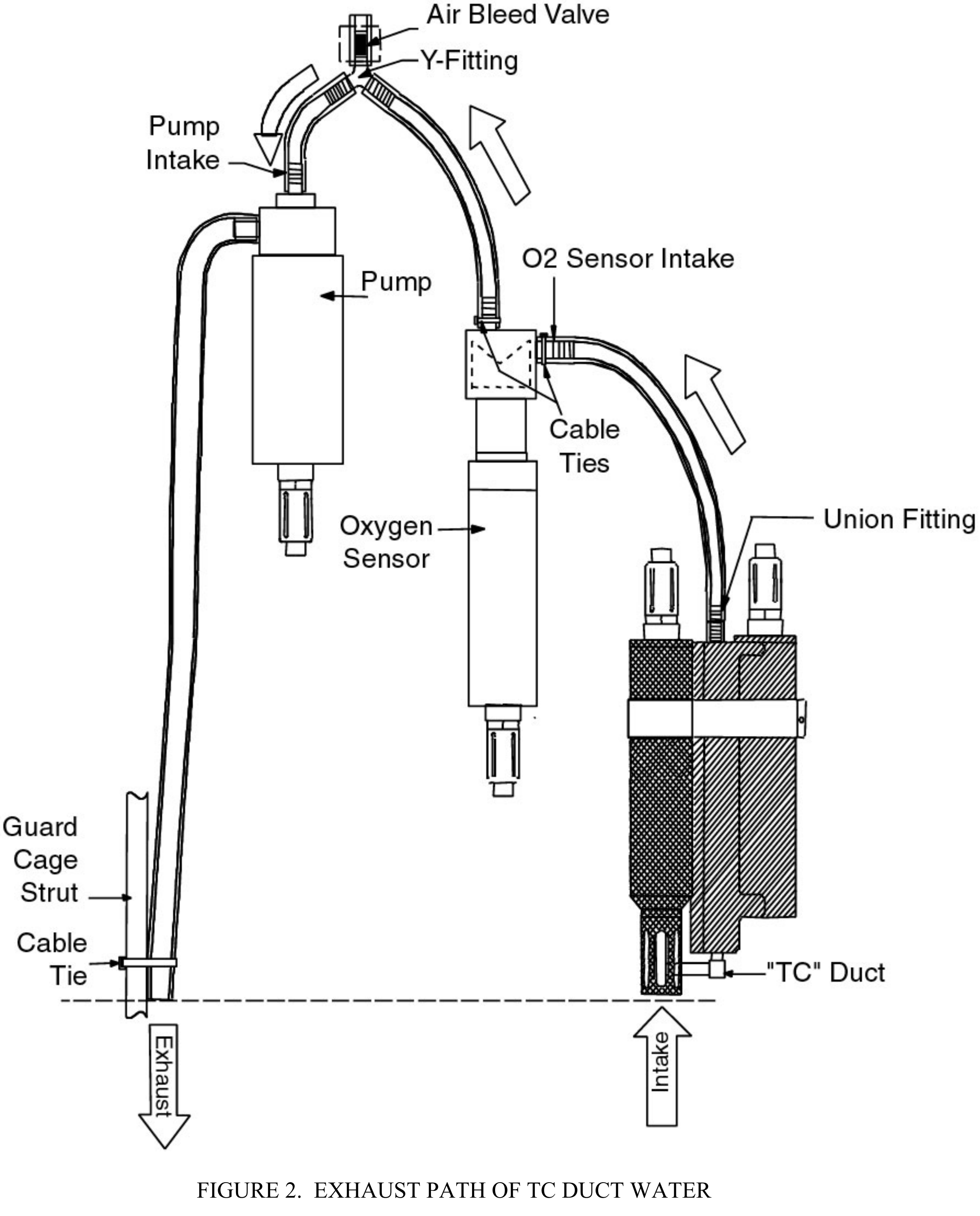

FIGURE 2. EXHAUST PATH OF TC DUCT WATER

Data taken with the Sea-Bird CTD show that the pumped and TC ducted temperature and conductivity sensors both exhibit the *same* time response of about 0.060 seconds. The Sea-Bird time responses have been measured and verified in a series of sophisticated and comprehensive field measurements by Dr. Michael Gregg of the University of Washington (Gregg's findings are supported by independent measurements in the North Atlantic by Dr. Thomas Müller of the Institute für Meerskunde / Kiel which demonstrate the 911plus CTD's fast and accurate responses (see below).

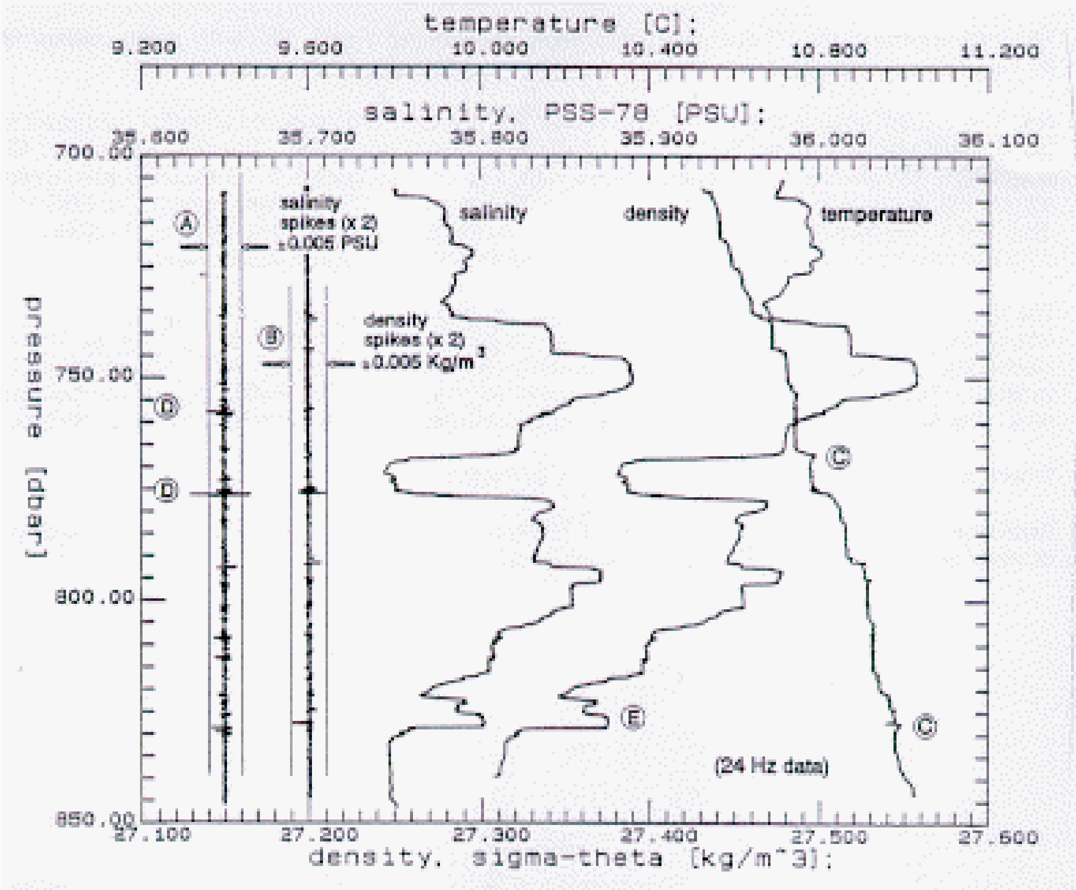

FIGURE 3. FIELD MEASUREMENTS PLOT

Containing very sharp temperature and salinity gradients that are stably stratified in density, the Mediterranean Outflow in the North Atlantic Ocean presents one of the world's most demanding challenges to CTD dynamic performance. It was here that the Institut für Meereskunde (Kiel, Germany) conducted CTD intercomparisons demonstrating the dynamic accuracy and resolution of Sea-Bird's *911plus CTD*.

The Sea-Bird's superior performance was confirmed by:

A salinity spiking errors less than ± 0.005 PSU throughout the profile and rms spiking error less than 0.001 PSU;

B corresponding density spikes of less than ± 0.005 Kg/m^3;

C density inversions in the entire record that are always less than 0.003 Kg/m^3;

D two prominent features identified by an algorithm as salinity spikes that are in fact signatures of active oceanographic mixing and not salinity or density error;

E sensor time-responses of 0.060 seconds (± 0.010) that are confirmed by the spatial resolution of the sharpest TS steps in the record.

The 24 Hz data (processed with SEASOFT 4.0) have been time aligned and corrected for cell thermal mass. No other filtering, averaging, or editing was performed and no data have been replaced or removed.

The following questions are often raised about the operations of the Sea-Bird CTD:

1. Does the TC duct act like a filter?

   On conductivity there is a small filtering effect that increases the conductivity time response from 0.035 seconds to 0.06 seconds. The effect of the TC duct on temperature is to improve its time response slightly (also to 0.06 seconds) and make it completely independent of profile rate.

2. The total volume of the TC duct and conductivity cell is about 6 cm^3. Since the pump volume rate is 30 cm^3/second, isn't the conductivity time response about 6/20 (0.20 seconds)?

   No. The 2.2 cm^3 volume comprising the TC duct and the short length of cell ahead of (upstream from) the first cell electrode is not part of the cell's active measuring region. The time required to fill this volume (2.2 cm^3 divided by the pump volume rate of 30 cm^3/second) is 0.073 seconds and represents a delay that is constant for all conditions, including variations in CTD profiling speed. The SBE 11 CTD deck unit automatically subtracts this delay so that the conductivity and temperature data passed to the computer are correctly aligned in time and truly represent the same parcel of water.

   The *time response* of the cell once the water has reached the first electrode is determined by the time rate of filling of the cell's 2 cm^3 active volume which comprises only the part of the cell *inside* the outer electrodes. The time to completely fill the active volume is only 2 cm^3 /30 cm^3/second or 0.067 seconds. The water in the 1.8 cm^3 upper (downstream) volume of the cell is beyond the cell's active area. The filling of this volume plays no role in the determination of the conductivity sensor's response.

3. Where does the water taken in by the TC duct come from?

   Each 24 Hz scan measured by the SBE 911 CTD represents the conductivity and temperature of a "rod" of water immediately underneath the TC duct inlet (see Figure 4).

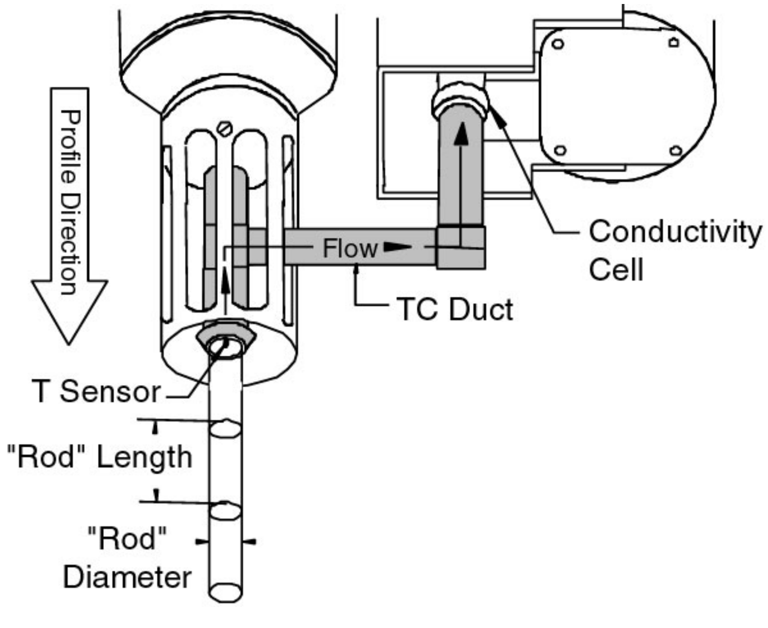

FIGURE 4. SOURCE OF WATER MEASURED BY TC DUCT

The dimensions of the rod depend on CTD profiling speed and are shown in the table below.

Profiling Speed (m/s)	Rod Diameter (cm)	Rod Length (cm)
0.25	1.24	1.04
0.50	0.88	2.08
0.75	0.71	3.13
1.00	0.62	4.20
1.50	0.50	6.25
2.00	0.44	8.33

Using the TC duct, the Sea-Bird CTD provides better spatial resolution than any other CTD.

While the analytical description of the flow is somewhat complicated, the simple cylindrical geometry is easily understood by the following argument: If the pump draws water into the TC duct at exactly the CTD drop speed, then water entering the duct must come from a cylinder having a diameter exactly equal to the inside diameter of the TC duct intake (0.4 cm). The CTD in this case "sweeps" new water at just the rate that its movement downward is causing new water to be "presented". The CTD can also be thought of as falling down a long 0.4 cm diameter "rod" extending from the surface of the water column to the bottom. The volume of water taken from the "rod" each second must equal the volume flow rate imposed by the pump. In the SBE 9 CTD, this volume is 30 cm^3/second. As speed of the CTD changes, the diameter of the "rod" will become larger or smaller to meet the water volume demanded by the pump.

All water that enters the TC duct comes from inside this cylinder and none comes from outside the cylinder. In addition, it is easy to see that for the Sea-Bird's 24 Hz sample rate, each measurement corresponds to a cylinder of ocean water with a length that is 1/24 of the distance that the CTD moves in 1 second. As shown in Figure 4, *Sea-Bird conductivity measurements taken using the TC duct correspond to discrete cylindrical samples of about 0.6 cm diameter stacked end-to-end along the path of the CTD*. Each data scan generated by the Sea-Bird CTD thus represents the true temperature and conductivity of a parcel of water typically less than 1 cm in diameter and less that 5 cm long.

4. Why don't other CTD systems use a TC duct and pump?

The conductivity cells (electrode and inductive types) used on other CTD systems have partly external electric fields. Any object (such as a duct or tubing leading to a pump) brought near these cells will cause large errors in conductivity. The designers of other CTD systems were not completely aware of the importance of time response matching and therefore chose cell configurations that are not compatible with TC ducts and pumping.

5. What happens when the Sea-Bird CTD is not moving? Doesn't the pump stir up the water?

Not very much. Even after 15 minutes, the most distant water taken in by the TC duct will be from less than 20 cm away. At-sea results obtained by the Institute für Meerskunde at Kiel show the Sea-Bird CTD to be very accurate and sensitive (providing quiet, low-noise data), even when held at one depth for 40 minutes. Other CTD systems were shown to be less stable and less quiet.

When the CTD is not moving (for example, hanging above the ocean bottom waiting to close a deep salinity bottle), the water entering the TC duct comes from a collapsing sphere centered on the duct intake. This point-sink flow pattern is well documented in fluid dynamics texts (Batchelor, 1967) and has been verified for the TC duct by dye tests in a laboratory tank. The flow field can be visualized as a set of concentric spheres collapsing on the duct intake at a volume rate equal to the pump rate.

Tests conducted in the North Atlantic by Dr. Müller of IFM/Kiel demonstrate that *the pump and TC duct do not cause errors on a non-moving Sea-Bird CTD*. The CTD was suspended under the ship at a depth of approximately 4635 meters for 43 minutes. All 62,000 measurements of temperature and salinity during this test are plotted in Figure 5 and show that the measurements are within +/- 0.002 °C and +/- 0.0012 PSU of the local mean gradients.

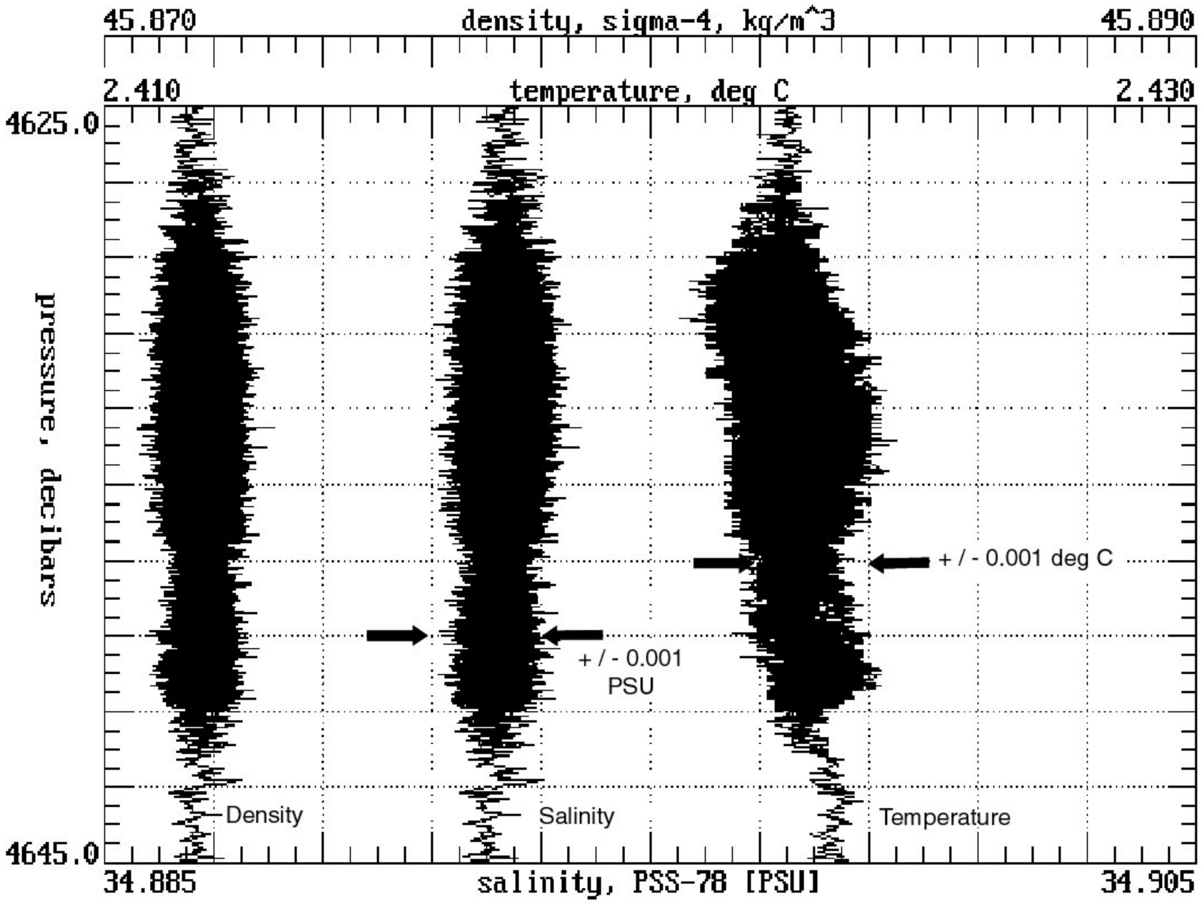

FIGURE 5. QUIET DATA WITH SBE 9 STATIONARY