Appendix A. CastAway-CTD Principles of Operation

Most people probably think water is simply water. But if we dive a little deeper into the details, water is a complex fluid. It is arguably the most important molecule on this planet and quite possibly the most interesting. It exists in a variety of states from ice to steam and clouds to rain. It can dissolve rocks and minerals. You can walk on it when it's frozen, swim in it when it's liquid, and even drink it when you're thirsty. It sustains just about every life form on earth and it is an ecosystem unto itself. We've built spacecraft to look for it and submarines to explore it. It is no wonder that oceanographers and hydrologists dedicate so much of their time to studying water.

The CastAway-CTD will open new doors in the science of water. The small handheld size makes collecting data easy enough for a single person to do just about anywhere. The integrated LCD screen displays a simple yet comprehensive user interface along with instantaneous data feedback. You can view graphs and statistics from your casts without the need for a separate computer. The integrated GPS for precise location data completes the picture of a functional and field-friendly solution for capturing high quality data with a minimum of time and effort. Coastal and inland water profiling has never been easier.

A-1. Purpose

The CastAway-CTD Principles of Operation provides both experienced and novice users with a technical description of the CastAway-CTD and the data it records. It includes basic advice on methods for collecting the best CTD data and how to interpret your data. This document is intended to work in tandem with the CastAway-CTD Users Manual, which describes the details for operating the system.

A-2. What is a CTD?

A CTD measures conductivity and temperature profiles with respect to depth. The acronym CTD stands for Conductivity, Temperature, and Depth. For a CTD, profiling refers to a series of measurements collected as the instrument itself descends from the surface of the water to the bottom and back up again.

To collect profile data, a CTD is typically lowered from a boat or dock by hand or with a winch. Conductivity, temperature, and pressure are recorded while descending and ascending. This data provides a complete picture of water properties that change with respect to depth. Using these three measurements and applying the appropriate equations, we can calculate salinity, sound speed, density and depth to name a few of the more commonly sought parameters.

A-3. Who Uses CTDs?

The CTD is a versatile tool that is used by many different groups of people.

- Oceanographers studying and modeling the intricate details of seawater consider the CTD to be one of their most essential tools.
- Hydrographic surveyors use CTDs to characterize the speed of sound in water so that they can precisely calibrate the ranges of their echo sounding equipment.
- Hydrologists employ CTDs to detect salt water intrusion and other contaminants in rivers, lakes, wells, and reservoirs.
- Biologists in the aquaculture and fisheries industries regularly collect CTD data to ensure the health and well-being of the fish they monitor.
- Coastal engineers use CTDs in rivers, inlets, and estuaries to study local tides.
- Even fisherman use CTDs to locate parcels of water that are attractive to certain species of fish.

A-4. Water Layers: Temperature, Salinity, and Density

The water in almost every lake, river, estuary and ocean is stratified into different layers. The formation of these layers is usually driver by temperature, salinity, and/or and density. In general, cold water is denser than warm water while salt water is denser than fresh water. Denser water usually tends to settle near the bottom, while less dense water tends to float towards the surface – although there are exceptions to this.

Figure 37 is a graphic representation of intersecting layers of water where a freshwater river is flowing into the ocean. Because the fresh water is less dense, it floats near the surface as it enters the ocean. Fresh water wedges can extend out into the ocean for several kilometers and salt water wedges can migrate similar distances up rivers during high tides.

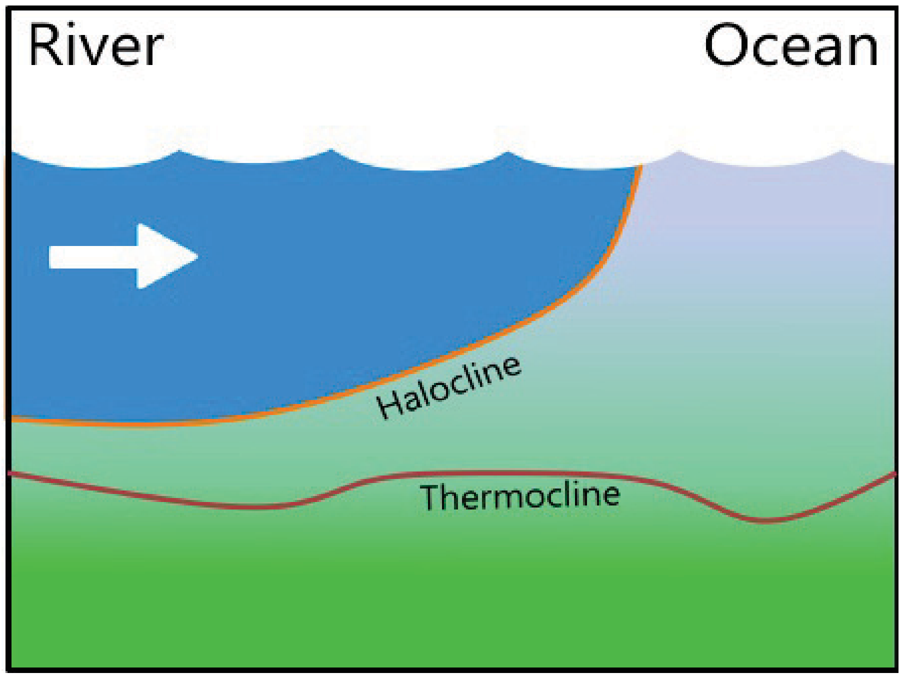


Figure 37 – Boundary Layers for a Fresh Water River Flowing into the Ocean

Temperature conditions in one layer may be notably different from conditions in another layer. The boundary between two layers with different temperature is called a thermocline. Water of different salinities will often be stratified in layers, especially where fresh and salt waters come together. The boundary where there is a notable change in salinity is called a halocline. Likewise a change in density is called a pycnocline. In coastal waters, the pycnocline usually coincides with the halocline because water density is directly related to temperature and salinity.

Underwater acoustics are widely used to map the depth of rivers, lakes and the ocean, as well as to measure physical properties of the water and its motion. Thermoclines and haloclines are areas of interest in the field of underwater acoustics because these boundaries have unique physical properties. They are capable of reflecting sound from acoustic instruments as well as changing the direction or path of an acoustic beam through refraction. The local change in water density creates this unique boundary. Thus measurements of different water layers can be essential for many studies using underwater acoustics.

A-5. CTD Measured Data

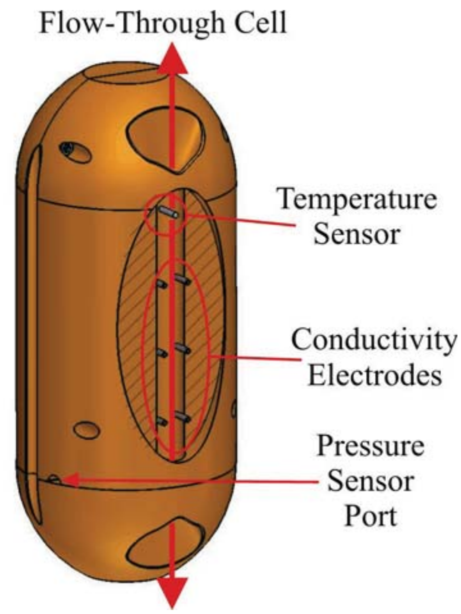


Figure 38 – CTD Sensors

The CastAway-CTD uses three sensors to profile conditions in the water: conductivity, temperature, and pressure. The conductivity and temperature sensors are located in the flow-through channel along the back of the CastAway-CTD housing, while the pressure sensor port passes through the housing at the top of the battery cap (Figure 38). The flow-through channel is designed to ensure a steady flow of water past the sensors when the system is descending and ascending through the water column.

Conductivity refers to the electrical properties of water, or specifically how much electricity the water conducts. Pure water has low conductivity while seawater has high conductivity. The conductivity of water is proportional to the concentration of ions in solution which carry the electrical current. The most common ion in seawater is chlorine, primarily from dissolved salts.

To measure conductivity, the CastAway-CTD has six electrodes in its flow-through channel. Although only two electrodes are required for a basic conductivity measurement, using six electrodes within the enclosed channel improves the accuracy of the conductivity measurement while increasing its immunity to calibration errors that plague many conductivity measurements. Two electrodes generate an electrical current and the remaining four are used to measure the resistivity of the water contained within the cell.

Resistivity and conductivity are related by the following equation.

$$C = \frac{K}{R}$$

C is conductivity, R is the measured resistance in ohms and *K* is the cell constant.

$$K = \frac{l}{A}$$

l is the distance between the electrodes in centimeters and *A* is the cross-sectional area of the volume of water enclosed by the cell in square centimeters. The CastAway-CTD measures resistance in ohms and this is converted to conductivity, reported in units of microsiemens per centimeter (µS/cm).

Temperature is measured using a thermistor. Thermistors have a well known relationship between resistance and temperature; resistance of a thermistor changes as the temperature changes. The thermistor in the CastAway-CTD is calibrated to the ITS-90 standard following the recommendations of the Joint Panel on Oceanographic Tables and Standards and Saunders (1990).

The CastAway-CTD, like all CTDs, uses a pressure sensor to determine depth. It is important to note that depth is not directly measured; pressure is measured and depth is derived from this data. The calculation of depth is described later (§A-6.), but it is important to understand that although depth and pressure are related, they are not necessarily equal.

Scientists often use units of decibars for pressure because one decibar is approximately equal to a depth of 1 meter. This approximation gets worse the deeper you go. At a pressure of 100 decibars the depth in the ocean is closer to 100.5 meters while at 10,000 dbars the depth is about 9,700 meters. These depths vary slightly with changes in density caused by temperature and salinity differences.

The CastAway-CTD removes atmospheric pressure from the underwater pressure measurements; this is sometimes referred to as gauge pressure. The atmospheric pressure is measured before and after each deployment. During post-processing, the change in atmospheric pressure over time is removed from the entire sample using a linear fit.

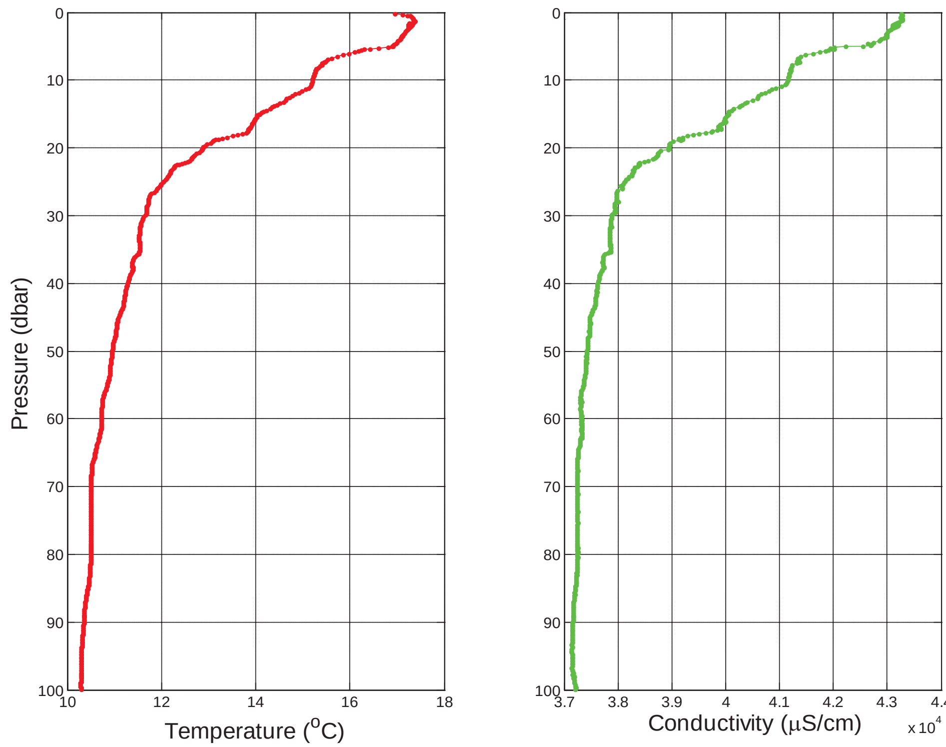


Figure 39 – Example Temperature and Conductivity Profiles

Figure 39 gives an example of the raw conductivity, temperature and pressure data collected by the CastAway-CTD; this data was collected in the Pacific Ocean near San Diego, California. In this data, a temperature gradient of about seven degrees exists in the upper layer of the ocean. The thermocline is located at a pressure of about 30 decibar (depth of about 30 meters). Below this, the temperature is much more stable. The influence of temperature on conductivity is seen in the nearly identical vertical structure of the two measurements. Since the salinity of the ocean is fairly constant in this area, the change in temperature is mostly responsible for the change in conductivity. To separate the influence of temperature on conductivity, scientists often use a derived parameter called specific conductivity (§A-6.).

A-6. CTD Derived Parameters

In addition to conductivity and temperature, a number of valuable parameters can be derived from the data collected by a CTD. Using an advanced microprocessor, the CastAway-CTD provides four of the most commonly derived parameters after the completion of each cast: specific conductance, salinity, sound speed, and depth. In the **CastAway-CTD Software**, you can also view density.

To derive these additional parameters the CastAway-CTD uses established, internationally recognized methods. These methods have been compiled into something known as EOS-80 – the International Equation of State for Seawater (1980). The equations were published by UNESCO in 1983 (§A-11).

Specific Conductance

The CastAway-CTD measures the conductivity of the water, which is primarily a function of the concentration of ions in the water. However, conductivity is also affected by water temperature. To remove temperature effects, we derive a parameter called specific conductance. Specific conductance may be a more useful parameter for certain applications.

Hydrologist sometimes use specific conductance to identify pollution events in fresh water. Because pesticides and fertilizers increase the conductivity of water, agricultural runoff can often be detected by analyzing profiles of specific conductance in fresh water basins.

The calculation of specific conductance from conductivity is a fairly simple formula. This is the standard method for applying a temperature correction to any conductivity measurement; the slope depends on the material measured. The slope of 0.020 used here is for water.

$$SpC = \frac{C}{1 + 0.020 * (T - 25)}$$

Where:

- SpC = Specific conductance (µS/cm)
- C = conductivity (µS/cm)
- T = temperature (ºC)

Salinity

Prior to the 1970s, the salinity of water was measured primarily through the chemical analysis methods of titration and evaporation. In the mid 1960s, oceanographers began using conductivity meters to analyze water samples exploiting the direct correlation between the electrical conductivity of water and the amount of ions it contained. Since Chlorine from salt is the primary ion, the amount of ions can be directly related to the amount of salt in the water.

Historically, salinity was defined in terms of parts per thousand (ppt). A salinity of 35 ppt meant 35 pounds of salt per 1,000 pounds of seawater. In 1978, oceanographers redefined salinity in terms of the Practical Salinity Scale (PSS-78) based on the conductivity ratio of a sea water sample to a standard potassium chloride KCl solution at 15º C and atmospheric pressure. Ratios have no units, so technically the salinity given by PSS-78 has no units and it is not the same as ppt; a salinity of 35 PSS-78 is not equal to 35 grams of salt per litre of water. Ocean salinity general ranges from 31 to 39 PSS-78.

Using the EOS-80 equations, salinity can be directly calculated from temperature, conductivity, and pressure measurements (Millard & Fofonoff, 1983). The CastAway-CTD records these parameters and calculates salinity onboard after each cast.

Sound Speed

The speed of sound in water is a critical value for any application that makes use of underwater sound. These applications include bathymetric surveys done in harbors, estuaries, rivers, and coastal areas. Detailed knowledge of the sound speed profile is needed to convert the acoustic data to accurate water depth information.

Sound speed can be calculated from temperature, salinity, and pressure (Millard & Fofonoff, 1983). Since the CastAway-CTD measures and calculates these parameters with each cast, this data can be directly used for a variety of applications using underwater acoustics.

Density

Density is the mass of a given volume of water. It is important for converting pressure data to depth, and also can be used to predict density driven currents. Density can be calculated from temperature and salinity (Millard & Fofonoff, 1983).

Depth

A CTD does not directly measure depth, it measures pressure. To accurately determine depth from pressure data, we need several other pieces of information – all of which are directly available from the CastAway-CTD.

- The density of water, which can be calculated based on temperature and salinity.
- The location of the measurement, specifically latitude and altitude. This data is recorded from the GPS onboard the CastAway-CTD.

With the above data, we can convert pressure to depth with considerable accuracy.

- Gravity is calculated using the WGS84 ellipsoidal gravity formula using local latitude and altitude measured by the GPS.
  - If there is no information from the GPS a default latitude of 30 degrees and a default altitude of zero are used. These defaults can be changed in the software (§5.5.1).
  - These calculations are taken from the WGS84 Ellipsoidal Gravity Formula, Department of Defense World Geodetic System, 1984.
- The depth is calculated from equation 25 of (Millard & Fofonoff, 1983), and includes a full integration of the geopotential anomaly over the entire cast to account for changes in water density.

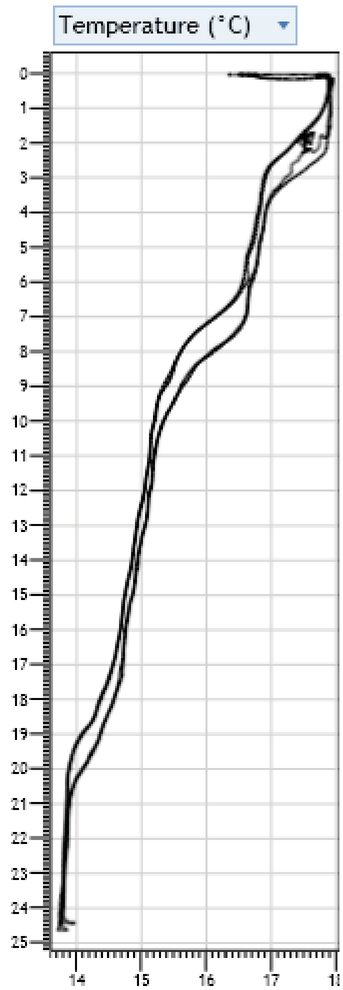
A-7. Best Measurement Practices

Making measurement with the CastAway-CTD is quite simple; the basic steps are described in detail in the Users Manual (Section 2 and Section 3). There are a few key items that should be kept in mind to ensure the best quality data.

- At the start of the cast, hold the system underwater near the surface for 5-10 seconds. This allows the temperature and conductivity sensors to adjust from air to water conditions, and avoids problems in the first part of the down cast.
- For the down cast, allow the system to free fall to the bottom.
  - The size, shape and weight of the CastAway-CTD has been specifically designed to free fall at approximately 1 m/s (3.3 ft/s).
  - Allowing a clean free fall ensures a steady flow of water through the flow-through cell and past the sensors.
- For the up cast, retrieve the system at a steady rate of about 1 m/s (3.3 ft/s).
  - A steady rate ensures a steady flow of water past the sensors for the best quality data.
  - Do not let the system rest on the bottom. Begin the up cast as quickly as possible.
- Do not pause during either the down or up cast.

A-8. Overview of Available Data

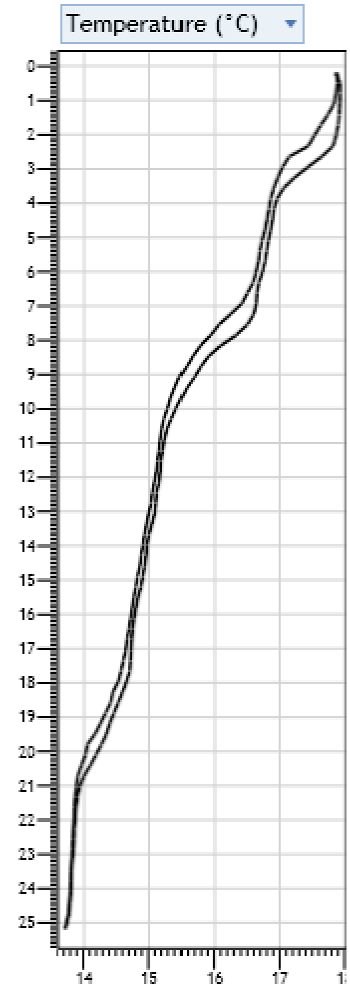
The user can view several types of data from the CastAway-CTD: **Processed**, **Down Cast**, **Up Cast**, or **Raw**. For most applications, we recommend using the processed data without additional modification. This section provides an overview of the different types of data available from the CastAway-CTD.



Raw Data

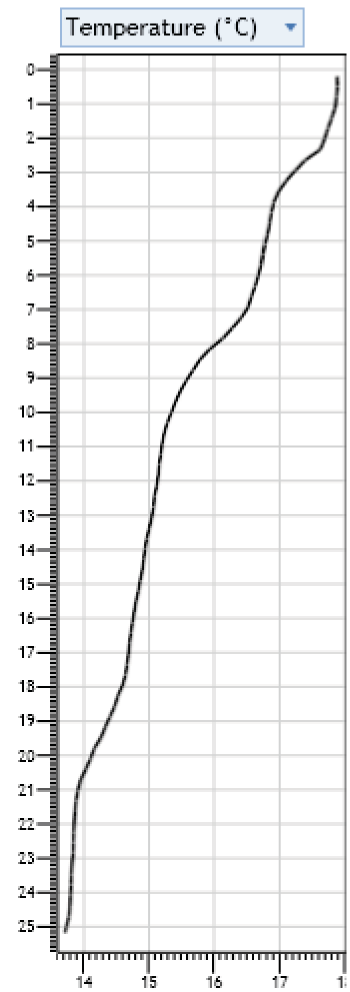
- Raw data is exactly that – the raw samples of conductivity, temperature, and pressure data versus time.
  - No derived parameters (specific conductivity, salinity, sound speed, density or depth) are available.
- Pressure data has been corrected for atmospheric pressure using data collected in the air at the start and end of the cast.
  - This sets pressure at the water surface to zero.
- Raw data is used only for specialized applications. In most cases, it is better to use either the **Processed** data, or the **Down / Up Cast** data.
- Raw data includes all data during the entire cast: in air at the beginning, at the surface, down cast, at the bottom, up cast, and in the air at the end.
- The figure to the right shows raw temperature data from a sample cast (collected in a reservoir in San Diego, California).
  - Notice the variation in temperature at the top – indicating some of that data was collected in air. This data is removed by the CastAway-CTD processing.
  - Notice the temperature at the bottom. When the system first hits the bottom the temperature is accurate. As the system sits on the bottom motionless, the thermistor begins heating the water around it. This only occurs when the system or the water is not moving. This heating is a result of the electrical current that is required to read the temperature sensor. This data is removed by the processing.

- **Down and Up Cast**
  - Converting raw data to down and up casts takes several steps.
  - Pressure data has been corrected for atmospheric pressure using data collected in the air at the start and end of the cast.
    - This sets pressure at the water surface to zero.
  - We calculate the rate of change of pressure versus time, which is the vertical speed of the system through the water. We use this to eliminate data collected in the air or while stationary at the surface or bottom, as well as to separate the down and up casts.
  - We then combine the raw data from the down and up casts into vertical bins based on pressure. All samples within a bin size of 0.3 decibars are averaged into a single value, giving profile data with regular spacing for easier post-processing.
  - When looking at data from the down or up cast, only the bin-averaged values from the desired cast are shown. Data when out of the water, waiting at the surface, or waiting at the bottom have been removed.
  - The figure to the right shows temperature data from the down and up cast for the same file shown in **Raw** data.
    - The difference between the two casts are likely caused by internal waves propogating along the different temperature and density layers.



When you first view the data difference between the up and down cast in this data set, it may appear that there is a problem with the sensor. However, there are many factors that can influence the distribution of measured parameters in the water column. Internal waves are certainly one phenomenon to be aware of, but more often the differences will be from the CTD moving through different columns of water. Even though you may be stationary during your measurements, the water could be moving. Even enclosed bodies of water have thermally driven currents that you can't see from the surface. As a result, your down cast and up cast could be through two different volumes of water. Changes in water temperature and conductivity can be abrupt, especially near merging bodies of water like lakes and rivers or rivers and oceans. These areas will often produce interesting data.

- **Processed**
  - This is the most common form of the data from the CastAway-CTD, and is what we recommend for the majority of our users.
  - In this form, data from the down and up cast have been combined to give the best possible measurement of the true profile.
  - The simplest description of CastAway-CTD data processing is that **Processed** profile is a weighted average of the down and up casts based on fall velocity. Up Casts are more heavily weighted near the surface and down casts are more heavily weighted near the bottom.
  - Details of how data are processed to produce the final profile are given in section A-9.
  - The figure to the right shows an example plot of processed CastAway-CTD data, using the same data shown for **Raw** and **Down/Up casts**.



A-9. Data Processing Algorithms

When processing data from the CastAway-CTD, we take a number of things into account.

- The sensors work best when they have a steady flow of water through the cell.
  - A higher flow of water through the cell provides the best measurements.
  - The measured temperature will increase slightly with time when the water or the CTD is stationary.
  - Thus when combining measurements, we weight the measured data based on the vertical speed of the system – which is determined by monitoring the change in pressure.
- For near surface data, the up cast is weighted more heavily than the down cast. This is because the up cast will have been moving at a steady rate for some time, while the down cast has just started moving – providing more reliable data.
- For near bottom data, the down cast is weighted more heavily than the up cast. This is because the down cast will have been moving at a steady rate for some time, while the up cast has just started moving.

Below is a step by step description of the data processing steps used to convert **Raw** CTD data into the **Processed** profile.

- Pressure is corrected for the ambient atmospheric pressure.
  - Pressure data is collected at the start and end of the cast, while the system is in the air.
  - This air pressure is subtracted from the raw pressure data to get a measure of water pressure only. If there is a difference in the start and end air pressure, a linear correction is applied over the course of the cast.
- Next we calculate how pressure changes with time.
  - We calculate the rate of change of pressure versus time for each sample in the data file. The rate of change in pressure can be thought of as the vertical speed of the system through the water.
  - We set a minimum value for the rate of change of 0.025 decibars/second. If the rate of change of pressure is less than this, we consider the system to be stationary.
  - The sensors and flow-through cell are designed for measurements while the system is in motion; while processing the data, we discard any samples where the system is considered to be stationary.
- The conductivity data is de-spiked. This is to remove erratic measurements near the water surface that can be caused by air bubbles trapped in the conductivity flow cell or measurements made when the system is only partially submerged.
  - Using a one second moving window, the standard deviation of the conductivity measurements is computed.
  - If the center measurement in the window is more than 3 standard deviations from the mean value of the windowed samples, this spike is replaced with the mean of the windowed measurements.
  - After filtering, conductivity samples measured when the pressure is less than 0.15 decibars are replaced with the nearest conductivity measurement in time taken at a pressure greater than 0.15 decibars. This is to preserve as much of the cast as possible before measurements in air contaminate the data.
- To separate the down and up cast, we monitor the change in pressure to determine:
  - When the system first enters the water.

- When it starts the down cast.
- When it reaches the bottom (maximum pressure).
- When it starts the up cast.
- When it reaches the surface and leaves the water.
- The downcast is defined as measurements made before reaching the maximum depth.
- The up cast is defined as measurements made after reaching the maximum depth.
- There is only one down cast and one up cast for each CTD cast. If multiple up and down motions are contained in a sample period, the up and down casts are separated by the point of maximum pressure.
- The maximum pressure is the maximum pressure measured while the fall velocity is greater than 0.05 decibars/second. This sets the maximum pressure to the measurement taken just as the system hits the bottom or the end of the casting line.

- Based on the maximum measured pressure:
  - An array of pressure bins is created from the surface downward.
  - Each bin has a width of 0.3 decibars.
    - The center of the first bin is located at 0.15 decibars, the second at 0.45 decibars, the third at 0.75 decibars, and so on.
  - The reported pressure is always the center of the bin except for the last (deepest) bin.
  - The reported pressure in the last bin is set to the maximum measured pressure.
- The temperature and conductivity from down cast samples and up cast samples are averaged separately into 0.3 decibar bins.
  - If the absolute value of the fall velocity of the system is less than 0.025 decibars/second during a down cast, this sample is not used for the bin average.
  - If the absolute value of the upward velocity of the system is less than 0.025 decibars/second during an up cast, this sample is not used for the bin average.
  - All samples in the up and down portions of the cast that take place within a given 0.3 decibar slice of the water column are averaged together using the fall velocity as a weighting function. Faster velocities have more weight in the average.
  - If there should be no measurements in a bin after filtering based on fall velocity, a linear interpolation is applied to fill in missing samples in both the up and down casts using the adjacent bins that contain data.
  - If the surface bin or the last bin near the bottom is empty, the next nearest value from the cast is used to fill that bin. This is applied to the up and the down cast data separately.
  - The conductivity and temperature from the deepest two bins in the up cast are replaced with the measurements from the deepest two bins from the down cast to remove the effects of thermistor heating while resting on the bottom.

- The down cast samples and up cast samples are combined to get the final **Processed** data:
  - For bins with pressure greater than two decibars and less than 0.9*Maximum Pressure, the up and down cast temperatures and conductivities are averaged to get the final **Processed** data.
  - For bins with pressures less than two decibars, the down cast is weighted by the square of half of the bin pressure before averaging with the up cast. This is an exponential decay weighting function on the down cast data near the water surface.
    - This weighting function is shown for temperature below; the same formula applies to conductivity.

$$DownCast, P < 2dbar, T_{Processed} = \frac{\left(\left(\frac{P}{2}\right)^2 * T_{Down} + T_{Up}\right)}{\left(\frac{P}{2}\right)^2 + 1}$$

  - For bins with pressures greater than 0.9*Maximum Pressure, only the down cast data is used.
- After the final **Processed** temperature and conductivity profiles are computed:
  - The derived parameters of specific conductance, salinity, sound speed, density and depth are calculated for each pressure bin.
  - Algorithms for these derived parameters are taken directly from Millard & Fofonoff 1983, using the 1980 International Equation of State for Seawater (EOS-80).
  - Temperatures are multiplied by 1.00024 to convert from ITS-90 to ITPS-68 before computing the EOS-80 derived parameters.
  - The up, down, and processed output temperatures are in ITS-90, the conversion to ITPS-68 is only applied for EOS-80 calculations.
- The final step is to convert the pressure bins to depth bins:
  - Gravity is calculated using the WGS84 ellipsoidal gravity formula using local latitude and altitude measured by the GPS. If there is no information from the GPS a default latitude of 30 degrees and a default altitude of zero are used. These defaults can be changed in the software (§5.5.1).
  - The depth is calculated from equation 25 of Millard & Fofonoff 1983 and includes a full integration of the geopotential anomaly over the entire cast to account for changes in water density.

A-10. Data Processing for Point Measurements

Previous sections (§A-8 and §A-9) describe data processing for a CTD cast in detail. Some of the same methods apply to a CTD point measurement, although the processing is simpler since only a single point is being measured. A summary of processing for a CastAway-CTD point measurement is below.

For a point measurement, only two data types are available; selecting the **Down/Up Cast** data shows the same data as selecting **Processed** data.

- **Raw Data**
  - Raw data is exactly that – the raw samples of conductivity, temperature and pressure data versus time.
    - No derived parameters (specific conductivity, salinity, sound speed, density or depth) are available.
  - Pressure data has been corrected for atmospheric pressure using data collected in the air at the start and end of the measurement.
    - This sets pressure at the water surface to zero.
  - Raw data is used only for specialized applications. In most cases, it is better to use the **Processed** data.
  - Raw data includes all data during the entire measurement: in air at the beginning, in the water, and in the air at the end.
- **Processed** (same as **Down and Up Cast**)
  - Pressure data has been corrected for atmospheric pressure using data collected in the air at the start and end of the cast.
    - This sets pressure at the water surface to zero.
  - We calculate the rate of change of pressure versus time, which is the vertical speed of the system through the water. We use this to eliminate data collected in the air.
  - We then look for the point where the change of pressure is greater than 0.15 decibars from the first recorded point. This typically occurs when the system is first submerged into the water.
  - We wait 2 seconds and take one sample of conductivity, temperature and pressure. This single sample is used as the point measurement.
  - After the **Processed** temperature, conductivity and pressure sample is selected:
    - The derived parameters of specific conductivity, salinity, sound speed, density and depth are calculated.

A-11. References

International Temperature Scales of 1948, 1968 and 1990
http://www.ices.dk/ocean/procedures/its.htm [4/28/2010 7:24:44 PM]

Millard & Fofonoff, "Algorithms for computation of fundamental properties of seawater", UNESCO technical papers in marine science 44, 1983.

WGS84 Ellipsoidal Gravity Formula, Department of Defense World Geodetic System 1984, NIMA TR8350.2, 3rd edition amendment 1, January 2000, Technical Report pages 3-5 to 4-2.

It is worth noting that a new standard for CTD calculations has been proposed to the scientific community; the Thermodynamic Equation of State of Seawater (TEOS-10). However, the methods shown in the UNESCO 1983 publication are still the most commonly used calculations and are the only ones supported by the CastAway-CTD. Users interested in applying the TEOS-10 equations can export raw data from the CastAway-CTD to perform these calculations.