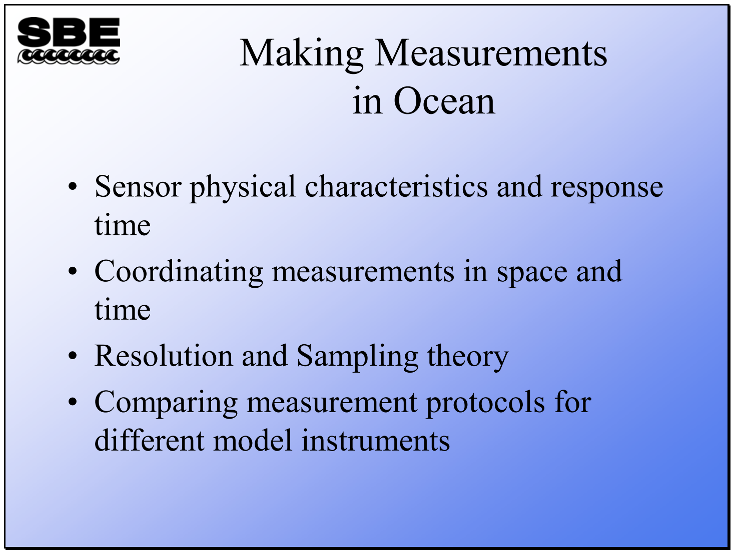
Module 6

Making Measurements in the Ocean

Overview



In this section we will take a close look at how measurements are made, in the environment in general and in the ocean specifically. We will discuss what to expect from measurements in terms of resolution and how to judge if we can make the measurements needed for our scientific purpose with the equipment at hand. Many common oceanographic parameters, such as salinity or density, require measuring multiple physical parameters, such as temperature and conductivity, to calculate the single new parameter. We will consider how measurement techniques impact the accuracy of these parameters.

At the end of this module, you should be able to:

- Determine what resolution your data will have, based on instrument sampling rate and descent rate in the ocean.
- Describe what a sensor is and how it operates.
- Explain the importance of correlating temperature, conductivity, dissolved oxygen, and pressure measurements in time and space.

Sensors Revealed

SBE

Sensor Components

- Device that allows a physical characteristic of environment to be converted into an electrical signal
- Composed of:
  - Active element having a property that changes in response to physical characteristic, and
  - Circuit that converts this change into a signal that may be measured by normal methods
- Normal methods mean frequency measurement or analog-to-digital conversion

Sensors convert a physical property of the environment into an electrical signal. Variations in the physical property are followed by variations in the signal. Consider a telephone, which converts the pressure wave that is sound into an electrical signal that can be transmitted through a wire. In similar fashion, oceanographic sensors convert pressure, temperature, conductivity, or some other physical parameter into varying electrical signals that are proportional to the value of the physical parameter. Typically, a sensor is composed of two parts:

- Active element

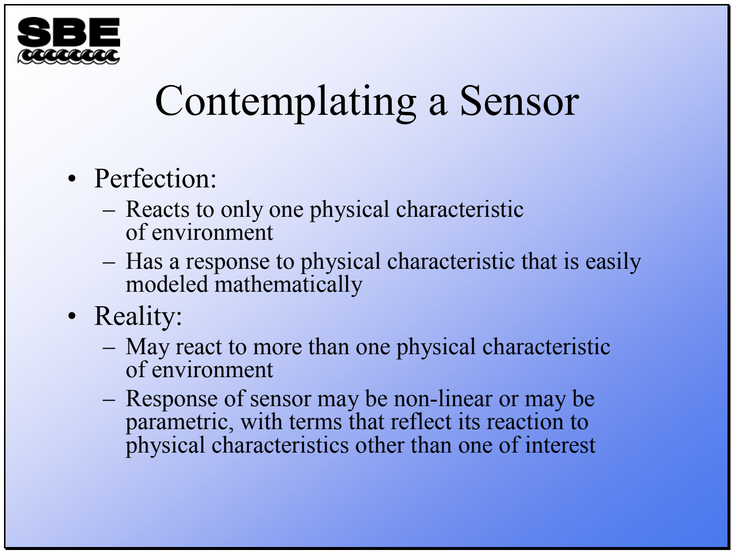
  The active element converts the physical parameter of interest into an electrical signal. To operate, the active element generates an electrical current or modifies an electrical current in response to changes in the value of the physical parameter.

- Conditioning circuitry

  The conditioning circuitry provides any electronics required for the active element to work. The circuit might use changes in a property of the active element. For example, oceanographic thermometers often use a thermistor to measure temperature. A thermistor changes its resistance to current flow as its temperature changes.

  The circuit might also convert the active element's output into an electrical signal type and range that is more easily converted to digital format. For example, the dissolved oxygen active element has a cathode that reacts with O_2 to produce a weak electrical current; the conditioning circuit converts that current into a 0 to 5V sensor output.

Sensors Revealed (*continued*)



The best sensor has an active element that:

- Reacts only to 1 environmental parameter.

  This is a rather rare occurrence. *Almost any semiconductor or wet electrode will react to changes in temperature and pressure*. Response to multiple environmental parameters is referred to as *non-specific response*.

- Responds to changes in temperature and pressure in a fashion that is easily modeled.
- Responds instantly to changes in the physical parameter.

The problem of non-specific sensor response can be overcome with:

- The housing or mounting arrangement of the active element.

  For example, placing the thermistor of the SBE 3 in a fine needle protects it from pressure effects, but still allows it to react rapidly to changes in ocean temperature.

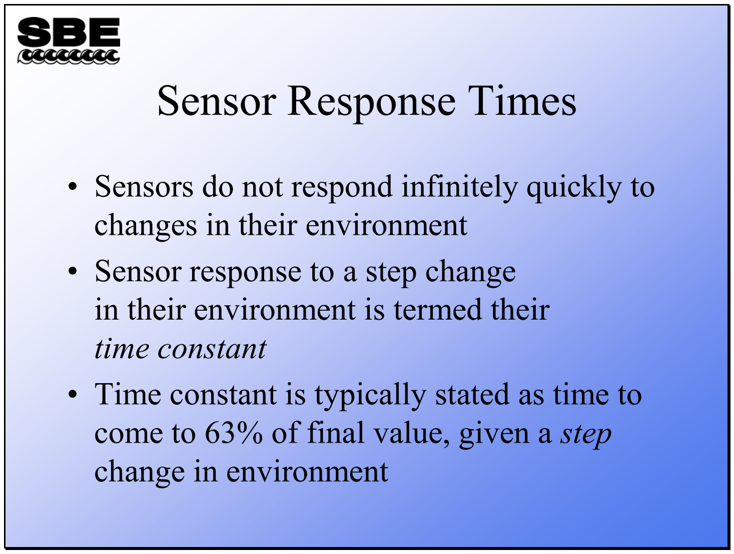
- The conditioning circuitry, which might have elements that compensate for temperature effects within the conditioning circuitry itself.
- The mathematical equation that converts sensor output to scientific units.

  For example, the SBE 4 conductivity sensor is affected by temperature as well as pressure; this is characteristic of the glass used for the cell. The best way to remove these effects is mathematically, turning the calibration equation into a parametric equation that has terms that depend on temperature and pressure.

- A second shielded sensor that compensates for non-specific response.

  For example, pH sensors have an electrode that is measured against a reference electrode contained within the sensor body.

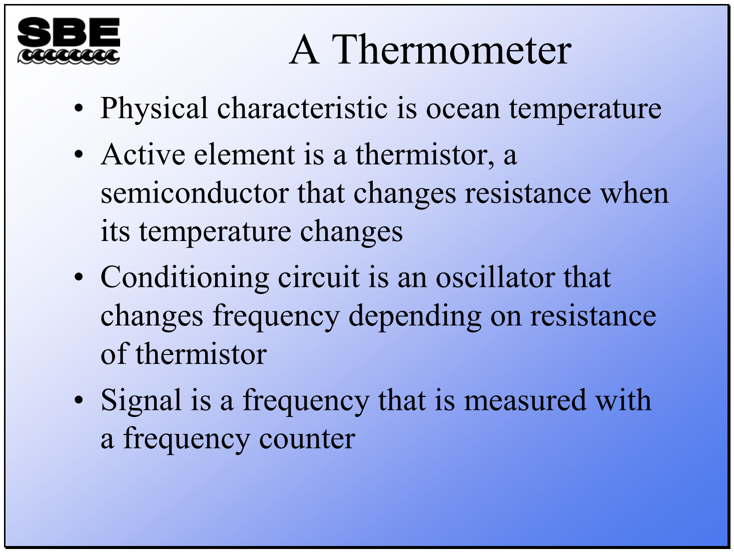
Sensor Response Times



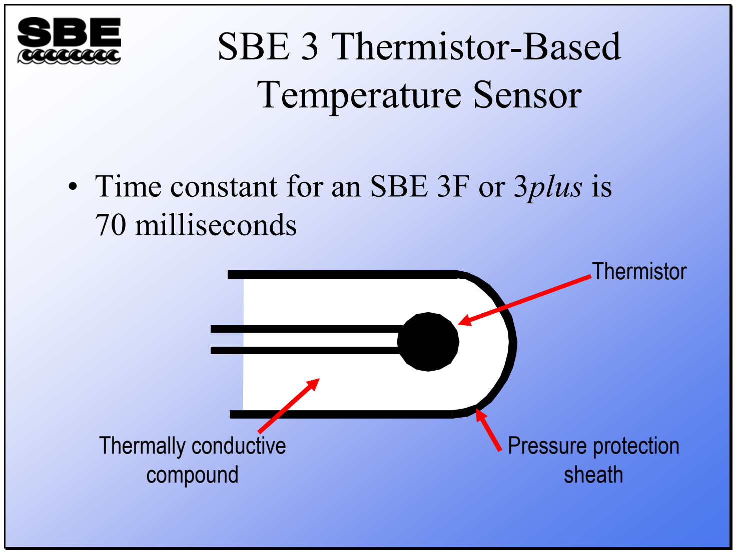
Sensors do not react infinitely quickly to a new environmental condition. For example, let's look at a 2-box ocean, with the top box at 20 °C and the bottom box at 0 °C. If our CTD moved from the top to bottom box, we would see a temperature signal that changed very quickly from 20 °C to 0 °C, but not as a perfectly sharp jump. *The reason for a slower response time for sensors is often found in the packaging of the active element of the sensor.*

For example, a thermistor is housed in a thin metal sheath; the delay in response to a sharp change in temperature from warm to cold is due to the time required for the heat in the thermistor to diffuse into the environment. For a conductivity cell, there is flushing time of the cell. For a dissolved oxygen sensor, there is the time required for the concentration of O_2 near the electrode to equilibrate with the environment. *The time constant, or τ, of the sensor is expressed as the time for the sensor to come to 63% of its final value given a step input.*

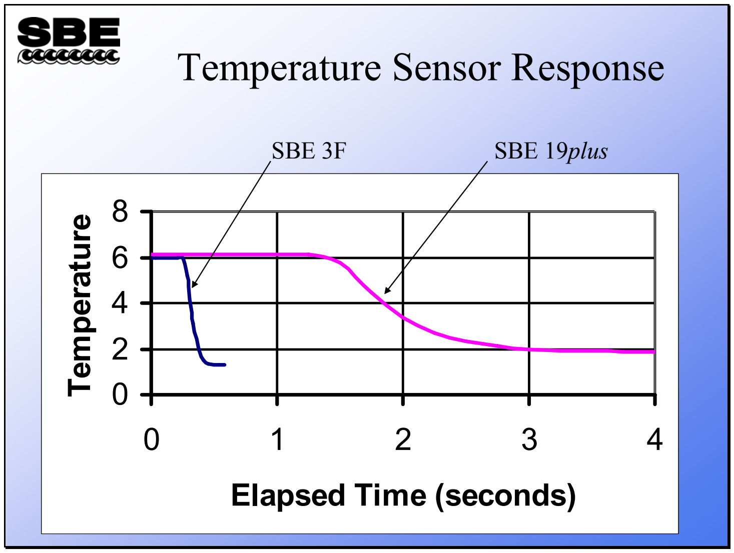
Sensor Example: a Thermometer



Sensor Example: a Thermometer (*continued*)

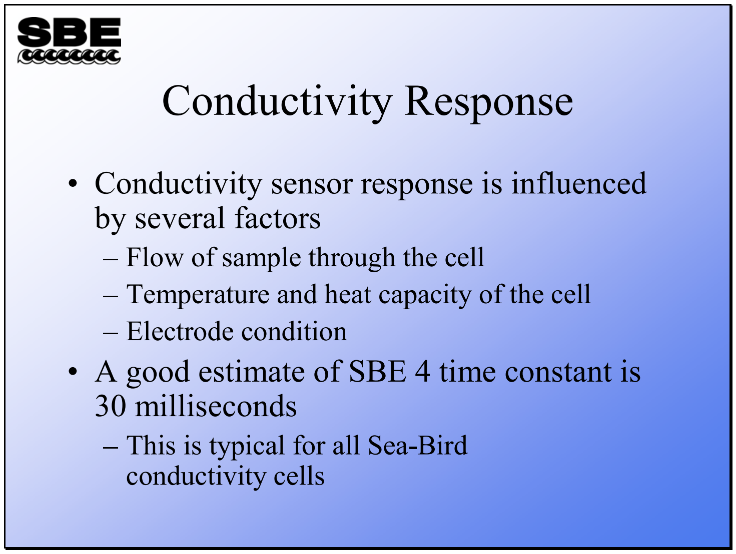


Thermometer Response Comparison



This plot compares the time response of the SBE 3F with the SBE 19*plus*. The SBE 3F has a smaller thermistor and a smaller needle, giving it a faster response time.

Conductivity Sensor Response

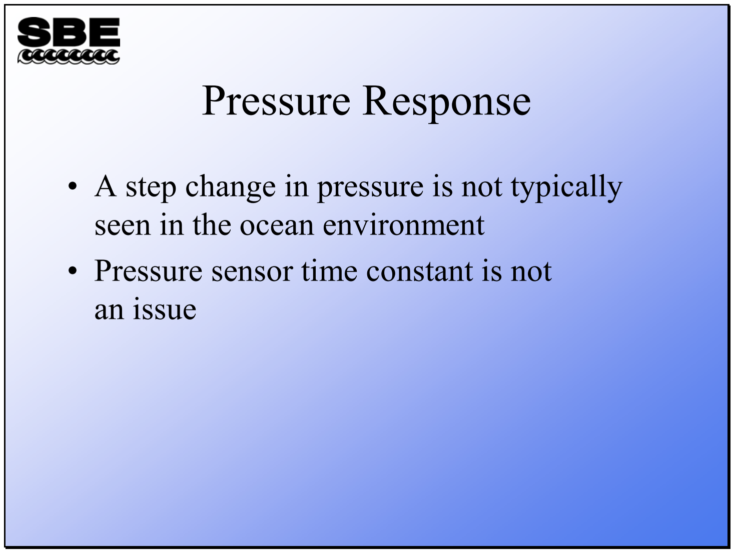


Sea-Bird conductivity cells have an effective volume (*i.e*., the region within the cell where the conductivity measurement is actually made) of about 2 cm^3. At 30 ml/s, this volume is flushed in 67 ms. The cell response to a step change in conductivity has a sin(x)/x character. Up to the first null (fn at 15 Hz), this response approximates the shape of the temperature sensor's exponential response. For the sin(x)/x function, the half-power point occurs at 0.443fn = 6.645 Hz and conductivity Tau is therefore 1/(2 * pi * 6.645) = 0.024 s. Because of viscous effects that tend to retain boundary layer water, the response measured in laboratory experiments is somewhat longer (0.030 s).

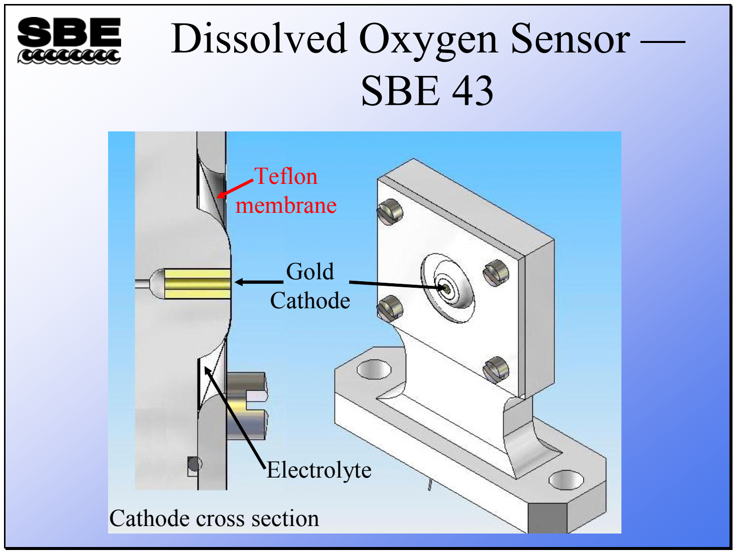
The measurement of a conductivity cell time constant is a difficult problem. Below are some references to papers that have addressed this problem.

- Gregg, M.C.,T. B. Meagher, E. E. Aagaard, and W. C. Hess (GMAH 1981) "A salt-stratified tank for measuring the dynamic response of conductivity probes", IEEE Journal of Oceanic Engineering, vol OE-6, 113-118.
- Gregg, M. C., and W. C. Hess (GH 1985) "Dynamic response calibration of Sea-Bird temperature and conductivity probes", Journal of Atmospheric and Oceanic Technology, vol 2(3), 304-313.

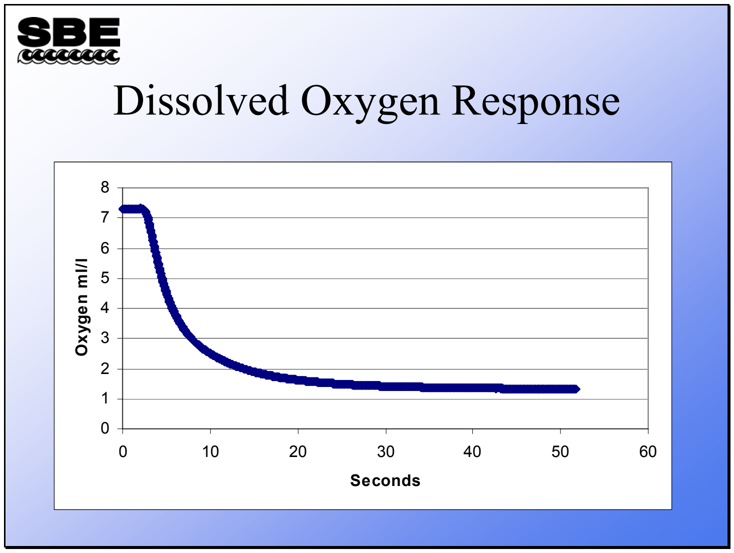
Pressure Sensor Response



Dissolved Oxygen Sensor

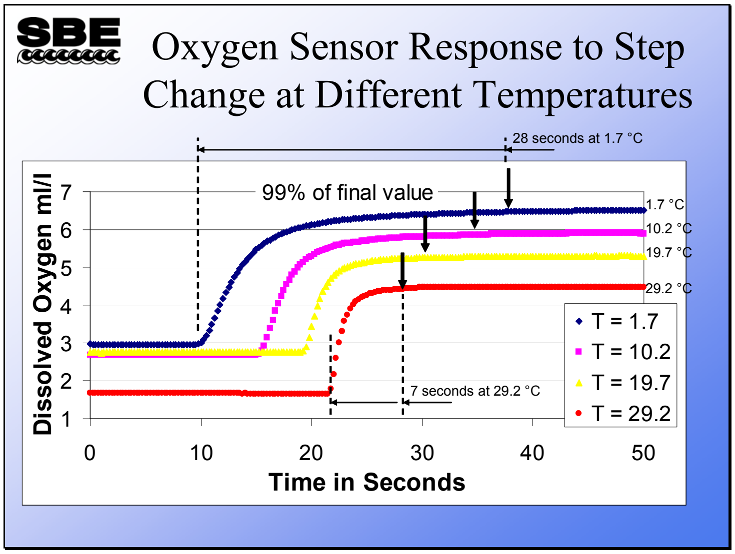


Dissolved Oxygen Sensor Response



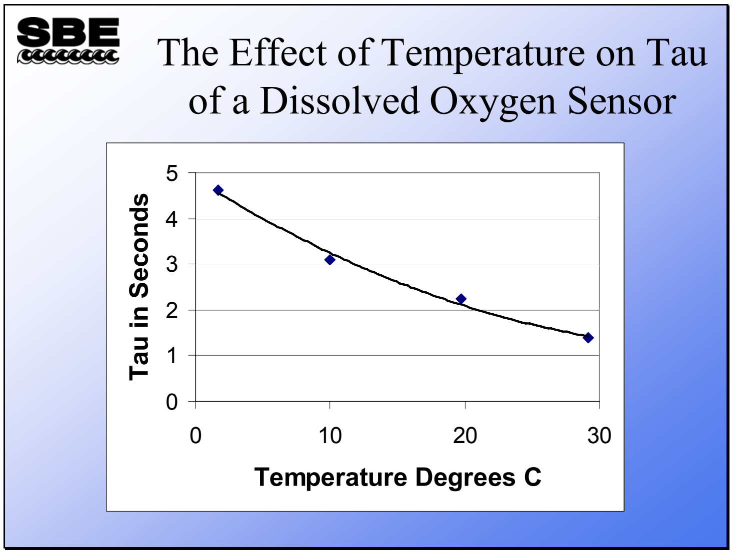
This graph (and the graphs on the following pages) is for an SBE 43 with a 0.5 mil membrane. The 0.5 mil membrane is recommended for profiling applications. Sea-Bird also offers a 1 mil membrane for moored applications.

Dissolved Oxygen Sensor Response (*continued*)



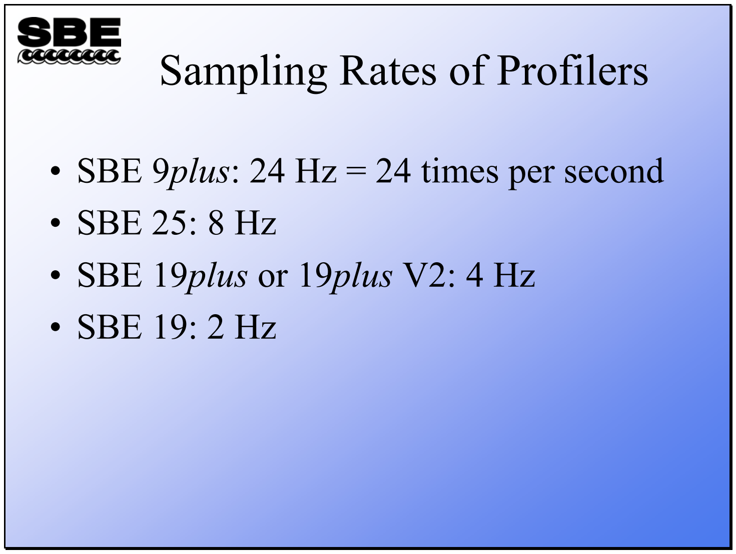
The plot above illustrates the effect that temperature has on a dissolved oxygen sensor. The colder the water that the sensor is working in, the longer it requires to come to a final value. This phenomenon is observable as upcast and downcast hysteresis. We will consider how to lessen this effect with the data processing *Align CTD* module in Module 9.

Dissolved Oxygen Sensor Response (*continued*)



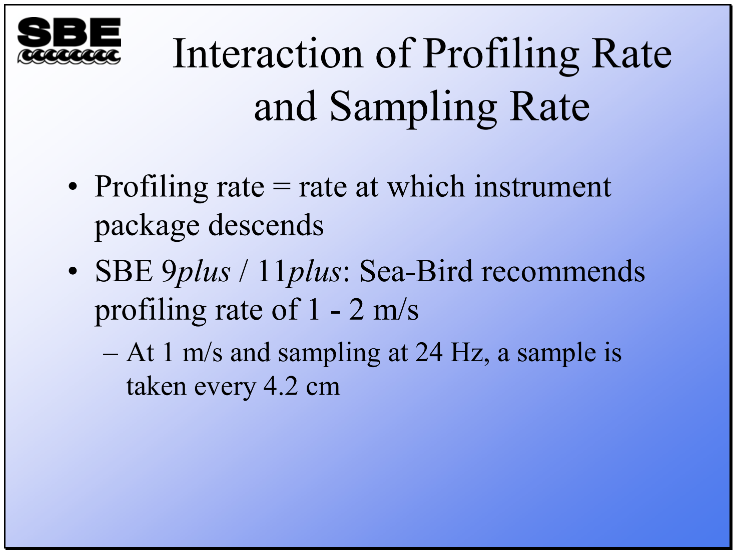
To induce a change in the oxygen sensor reading, oxygen in the environment must diffuse through a water boundary layer to the membrane surface. Next it must diffuse through the Teflon membrane that covers the electrode and into the electrolyte above the electrode. There a chemical reaction takes place at the electrode surface. The rates of these processes are temperature dependent. Thus the response of the sensor to a step change in its environment is temperature dependent. The plot above shows the changes in Tau for a typical sensor. Nominally, Tau at 20° C is 2 seconds, but varies with the age and condition of the sensor and membrane.

CTD Sampling Rates



Sea-Bird offers CTDs with sampling rates shown above. The SBE 9*plus*, with the fastest sampling rate, produces the most detailed data. The other instruments are less capable but offer lower price, less complex deployment equipment, and a more compact instrument package. Not all applications require or benefit from the sampling rates achievable with the SBE 9*plus*.

Sampling Rate and Profiling Rate



The CTD samples at a fixed rate and the instrument package is lowered through the ocean at a fixed rate. Consider the SBE 9*plus*, sampling at 24 Hz and falling through the ocean at 1 m/s. We would be taking a sample every 4.2 cm.

$$100 \text{ cm sec}^{-1} / 24 \text{ sec}^{-1} = 4.2 \text{ cm}$$

Now consider reality. The CTD samples at 24 Hz and the instrument package falls through the ocean at a nominal 1 m/s. However, the ship heaves, alternately slowing and lifting the instrument package or dropping and accelerating the instrument package. This situation is not well enough constrained to assign an exact length scale to our measurement. We will investigate this problem further in the advanced data processing portion of the course.

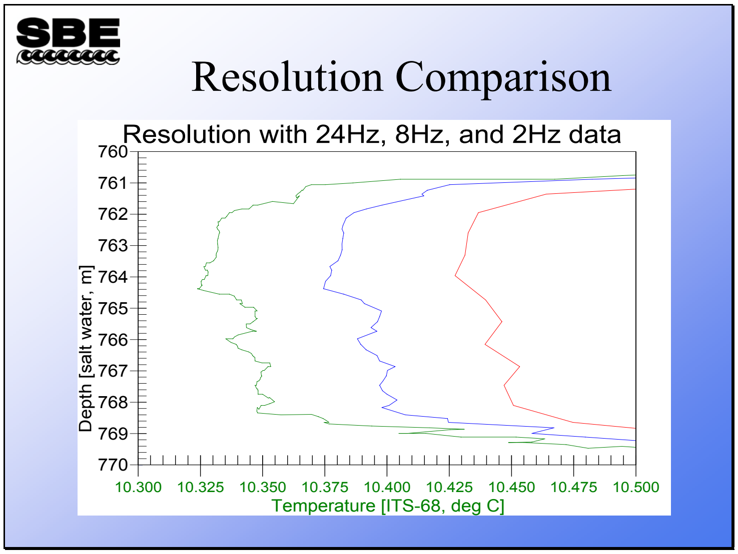
Sampling Rate and Profiling Rate (*continued*)

Interaction of Profiling Rate and Sampling Rate

- SBE 25: At 1 m/s and sampling at 8 Hz
  - A sample is taken every 12.5 cm
- SBE 19*plus* or 19*plus* V2: At 1 m/s and sampling at 4 Hz
  - A sample is taken every 25 cm
- SBE 19: At 1 m/s and sampling at 2 Hz
  - A sample is taken every 50 cm

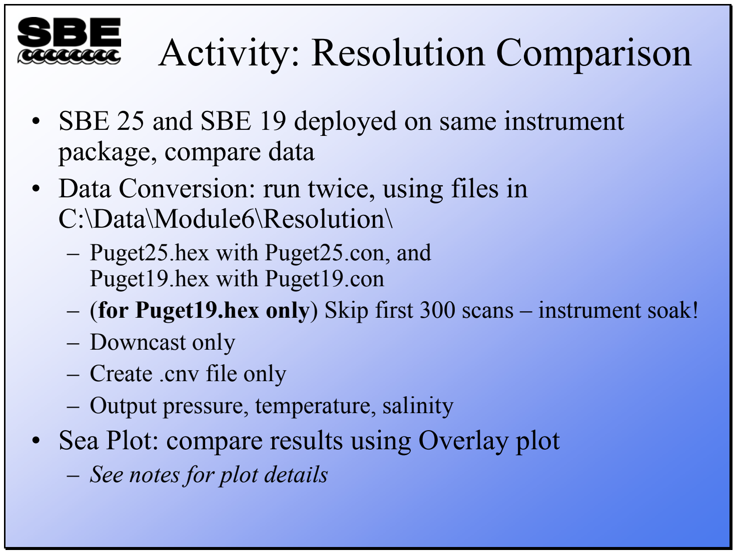
As discussed earlier, the lower sample rates of the SBE 19, 19*plus*, 19*plus* V2, and 25 translates into a coarser resolution than that calculated in the SBE 9*plus* example. The following page illustrates the impact that sample rate has on resolution.

CTD Resolution Comparison



The left-most plot is data collected at 24 Hz with a nominal 1 meter/second lowering speed. The middle plot is the same data set decimated to 8 Hz to represent the resolution of the SBE 25. The right-most plot is the 24 Hz data set decimated to 2 Hz, which is representative of the resolution that would be seen with an SBE 19. The obvious conclusion is that a faster sampling rate yields higher resolution of temperature structure in the ocean temperature profile.

Activity



After running SBE Data Processing's Data Conversion module, we should end up with the following files, which we will plot in Sea Plot to see the effect of sampling rate on the resolution:

- Puget19.cnv – SBE 19 converted data
- Puget25.cnv – SBE 25 converted data

Run Sea Plot:

- Plot Setup tab:

  Plot type -- Single Y – Multiple X, Overlay

  Overlay Setup button –

  X Axis1 (Temperature) offset = 0.03

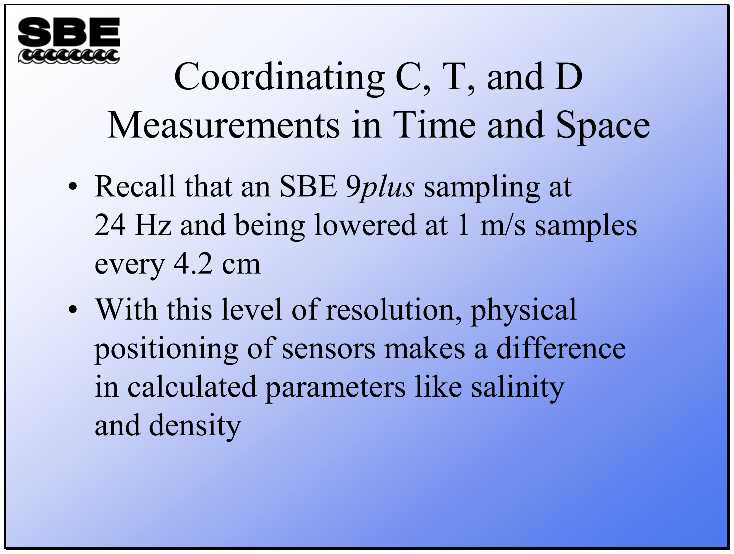
  X Axis2 (Salinity) offset = 0.04

  Pick Line Colors to differentiate between data sets and T and S plots

- Y-Axis tab: pressure, 0 – 40 db
- X-Axis 1 tab: temperature, 9.5 – 9.6 degrees C
- X-Axis 2 tab: salinity, 28.85 – 29.00 PSU

How do the SBE 19 and SBE 25 plots compare?

Coordinating Measurements



Salinity is a function of conductivity, temperature, and pressure. The mathematical relationship that defines salinity in these terms was established in 1978 by a group of scientists working with the international scientific organization UNESCO.

Salinity must be calculated from conductivity, temperature, and pressure measurements made on the same water parcel.

Coordinating Measurements (*continued*)

SBE

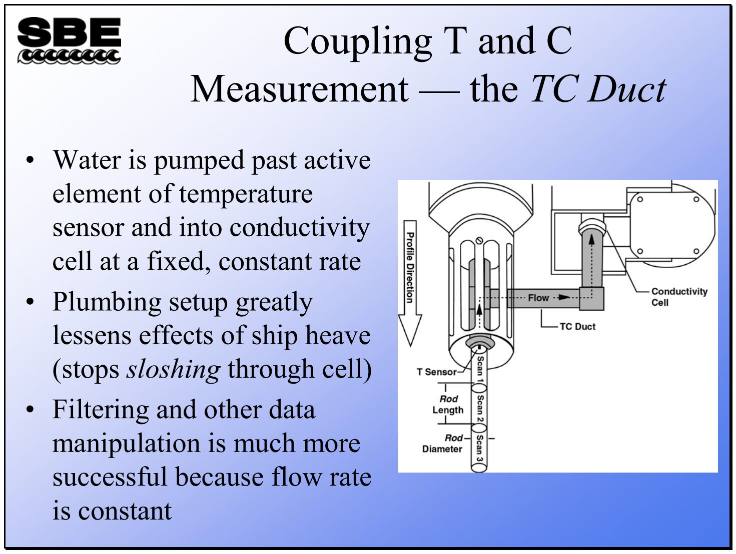
Conductivity and Temperature Measurement Revisited

- SBE 3 thermistor is contained in a 0.75 mm diameter needle that senses an approximate volume of 2 ml of seawater around it
- SBE 4 conductivity cell measures the conductivity of 2 ml of seawater
- These measurements are made in different places

The active part of the thermometer is found at the end of the slender needle. The volume of water measured by the end of the needle is approximately 2 ml.

Recall that the conductivity cell is a glass tube containing platinum electrodes; conductivity is measured on the volume of water that the cell contains, approximately 2 ml.

Coordinating Measurements (*continued*)

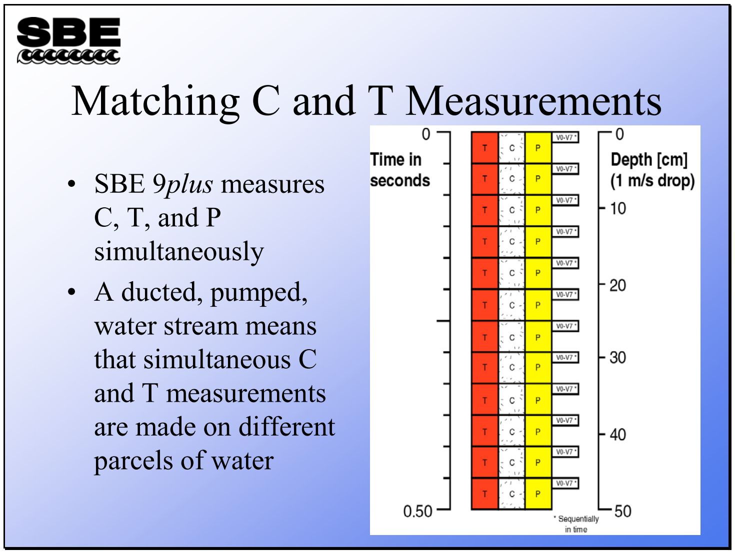


To ensure that the temperature and conductivity measurements are made on a constrained water sample, they are plumbed together and the *T-C pair* has water drawn through them with a pump that moves water at a consistent, known speed.

One way to visualize this is as a *rod* of water that moves into the duct and flows past the thermometer and into the conductivity cell. The diagram above shows the approximate size of the water parcel that constitutes a sample.

Because the water sample is pumped through the duct and conductivity cell, it is not subject to accelerations (sloshing) due to ship heave. This technique of constraining the sample as it is measured greatly improves the quality of the measurement and facilitates data manipulation.

Coordinating Measurements (*continued*)

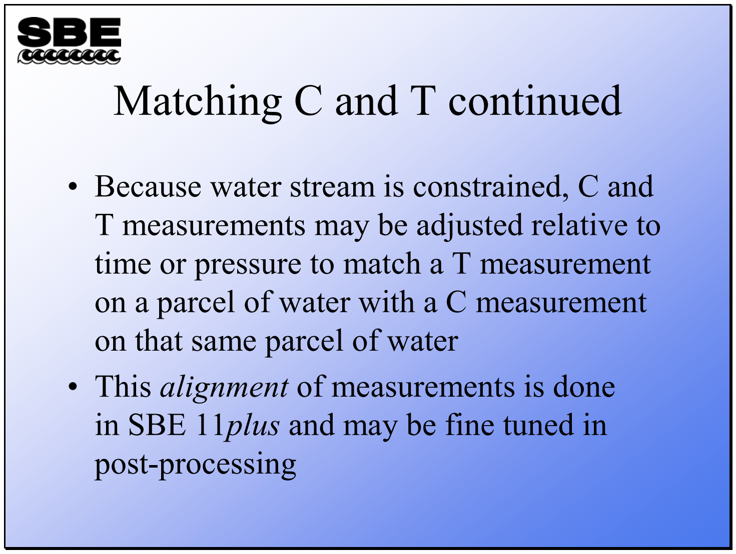


The SBE 9*plus* acquisition architecture measures temperature, conductivity, and pressure simultaneously. Careful examination of the plumbing of the TC duct shows that a water parcel first encounters the SBE 3 thermistor and then transits into the conductivity cell.

For the most accurate estimate of salinity and density, the data stream must be manipulated, moving temperature and conductivity relative to pressure to match the measurements on a parcel of water.

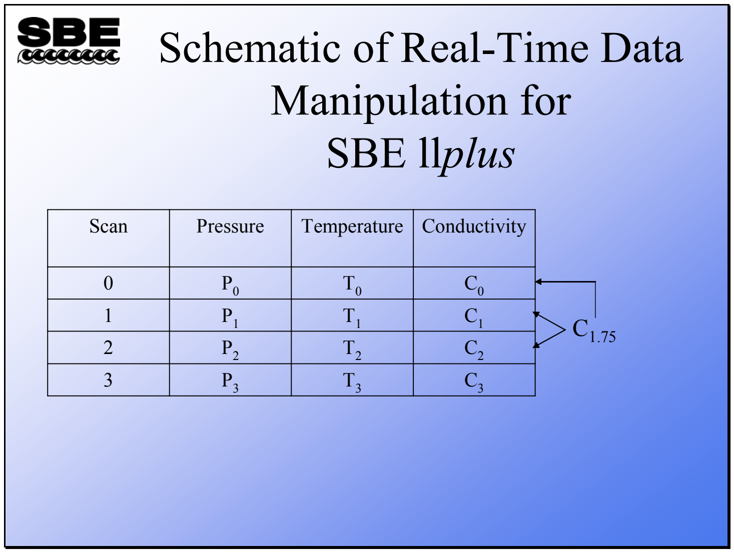
Because the 9*plus* measures T, C, and P simultaneously, and owing to the distance that the sample travels in the plumbing of the TC duct and the conductivity cell, the water that the T sample is taken from at time 0 is actually the same water that the C sample is taken from during time 2.

Coordinating Measurements (*continued*)



The adjustment of samples in the data stream is taken care of in the SBE 11*plus* deck unit and is termed *sample alignment*. Although we have been discussing the advancement in terms of an integer number of scans, careful calculation of flow rates, plumbing distances, and sample rates yields a nominal adjustment of 1.75 data scans. Because the conductivity cell is plumbed after the temperature, the conductivity channel must be advanced relative to the pressure and temperature measurements. The next slide illustrates this with an example.

Coordinating Measurements: Aligning Data



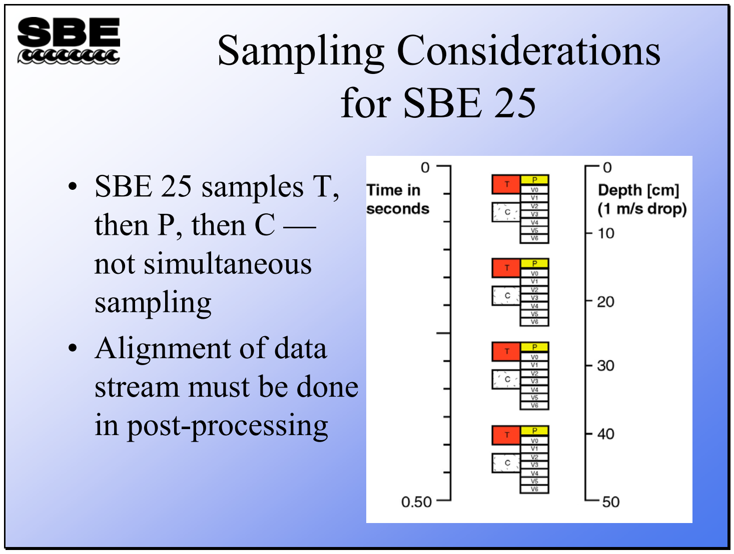
Scan	Pressure	Temperature	Conductivity
0	P_0	T_0	C_0
1	P_1	T_1	C_1
2	P_2	T_2	C_2
3	P_3	T_3	C_3

For example, a value for conductivity at 1.75 scans, $C_{1.75}$, is calculated by interpolating between the values for C_1 and C_2. C_0 is set to equal $C_{1.75}$. Then C_1 is set to equal the value obtained from interpolation between C_2 and C_3. This process continues to the end. The 11*plus* can perform this advancement on each of its data channels, with different advancements for each channel. The amount to advance a channel is entered in seconds. Recall that the 9*plus* collects scans at 24 Hz, which equals 0.042 seconds/scan; therefore, a 1.75-scan advancement equals 0.073 seconds.

You might want to enter advancement values for dissolved oxygen sensors or fluorometers as well as for conductivity.

The 1.75-scan advancement is a nominal value; changes in flow rate caused by plumbing changes will necessitate changes in advancement. Similarly, you should consider any advancement that the 11*plus* makes to your other sensors a nominal value and make your final decision based on observing the data.

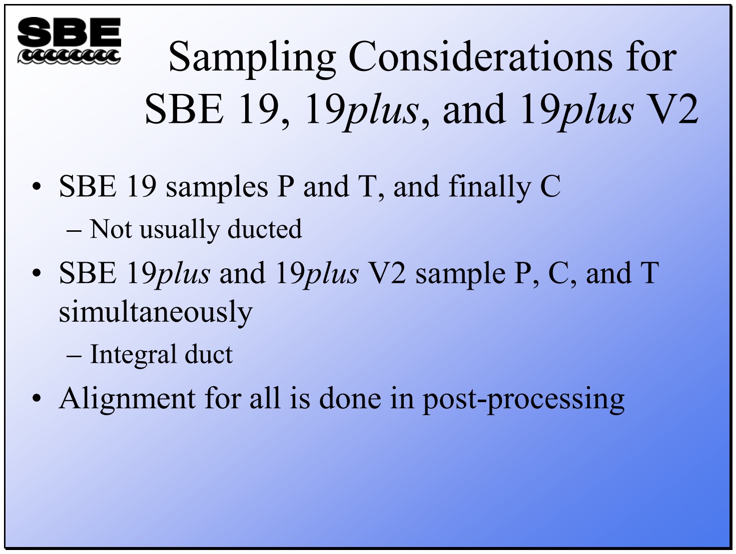
Coordinating Measurements: SBE 25



The SBE 25 has a different sampling order. The alignment of T and C must be done in post-processing, regardless of whether the SBE 25 is used for internally recording data or as a real-time instrument with a deck unit. As an internally recording instrument, the SBE 25 has the capability of averaging samples to increase the memory endurance. Averaging degrades the resolution of the instrument and makes the alignment of T and C less effective.

As the diagram shows, T and P are measured simultaneously, with C following. The SBE 25 has the same TC duct as the SBE 9*plus*, but pumps at a slower rate (~20 ml/s) than the SBE 9*plus* (~30 ml/s). This means it will take approximately a third longer for the same parcel of water to reach the conductivity cell. Therefore, the parcel transit advance for C would be closer to 0.0973 seconds for the SBE 25. But because C is measured ~ 0.03 seconds after T, the SBE 25 needs a larger advance for conductivity than just the parcel transit time between T and C. Based on the reduced flow and the sample sequence in this application, a reasonable nominal advance for conductivity for the SBE 25 is 0.1 seconds. Again, variations in flow between configurations may require fine adjustments to this alignment.

Coordinating Measurements:
SBE 19, 19*plus*, and 19*plus* V2

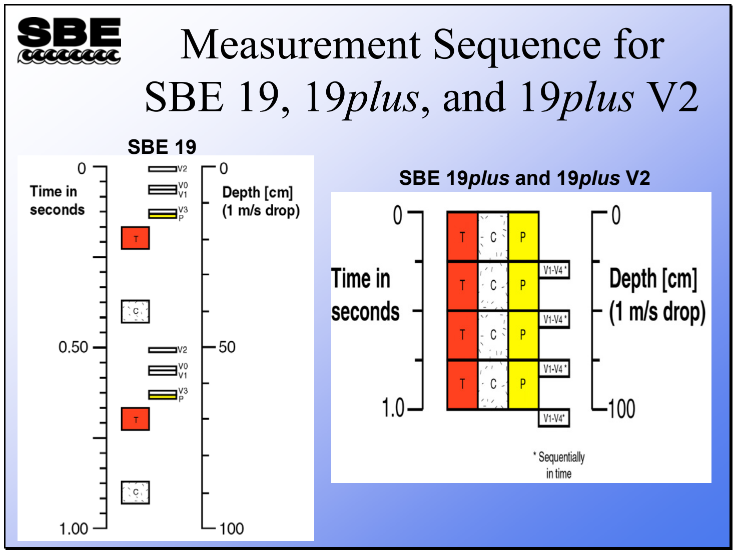


The SBE 19 has a different sampling protocol than the SBE 25 and the 9*plus*. The 19 uses the same signal condition circuit, an oscillator, to sample both T and C. A relay switches the oscillator between the thermistor and the conductivity cell. Further, to improve circuit stability, reference resistors are switched into the oscillator every 120 samples.

The SBE 19*plus* and 19*plus* V2 sample T, C, and P simultaneously. This is an improved protocol over the 19.

Like for the SBE 25, the alignment of T and C must be done in post-processing, regardless of whether the SBE 19, 19*plus*, or 19*plus* V2 is used for internally recording data or as a real-time instrument with a deck unit.

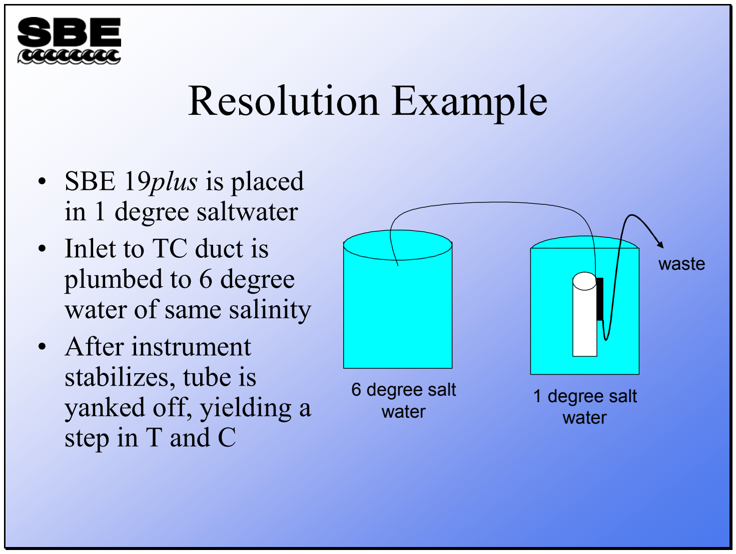
Coordinating Measurements: SBE 19, 19*plus*, and 19*plus* V2 (*continued*)



As was mentioned on the previous page, the SBE 19 samples P, then T, and finally C, at a sampling rate of 2 Hz. Because T and C use the same oscillator, there is separation in the measurements to allow time for the oscillator to settle into the new frequency after it has been switched. Alignment of T and C is done in post-processing and, as mentioned earlier, averaging of scans to improve memory endurance tends to degrade the instrument's resolution and make alignment less effective.

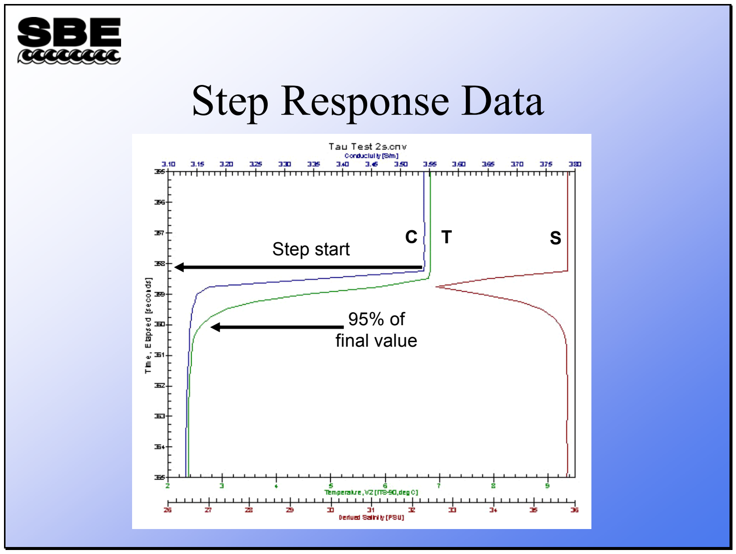
The SBE 19*plus* and 19*plus* V2 offer simultaneous sampling of P, T, and C, similar to the SBE 9*plus*. They have a sampling rate of 4 Hz. This sampling schedule is an improvement over the SBE 19 and SBE 25.

Estimating Conductivity and Temperature Resolution



We can conduct an experiment to demonstrate the spatial resolution that is possible with a given set of temperature and conductivity sensors at a specified sampling rate. In our experiment we have a large tank of saltwater at approximately 1 °C. We remove some of the water and allow it to warm to approximately 6 °C. The instrument of interest is placed in the 1 °C water and allowed to equilibrate. The inlet of the temperature and conductivity sensors is plumbed to the warm water tank and water is pumped past the sensors at the normal profiling rate. The warm water is pumped into a waste container so as not to warm the 1°C tank during the test. Data is collected at the highest rate available, and when the system is stable the tubing is yanked off the inlet to the sensors, producing a step change. Our interest is in how well we can resolve rapid changes in the water column in the field. The instrument's step response is an excellent indication of this.

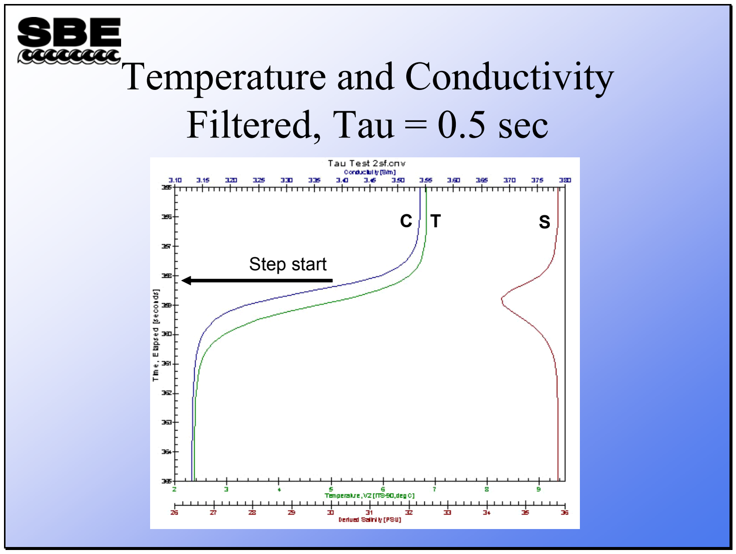
Estimating Conductivity and Temperature Resolution (*continued*)



The above plot shows the results of the experiment. The Y axis is time in seconds; this corresponds to decibars at a lowering rate of 1 meter per second. Note that the temperature trace lags the conductivity trace, because the SBE 19*plus* temperature sensor time constant is approximately 0.5 seconds while the conductivity cell has a time constant of about 0.030 seconds.

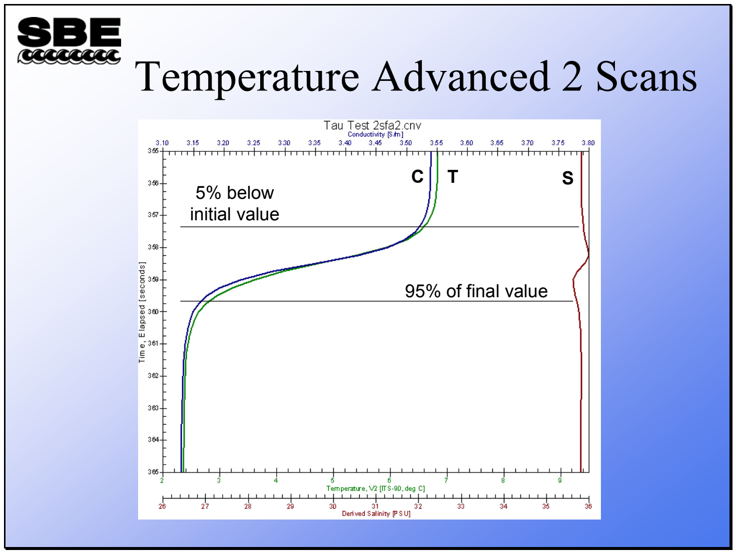
You can observe a large salinity spike produced by the mismatch in the time constants of the temperature and conductivity sensors.

Estimating Conductivity and Temperature Resolution (*continued*)



We can achieve the best salinity response by filtering the temperature and conductivity signals to give them the same time constants. It is accepted practice to filter a data channel forwards and backwards to avoid introducing a phase shift in the data. Because of this, both the leading and the trailing edge of the step response are smoothed. If only conductivity were filtered the smoothed leading edge would not match the temperature channel and a larger salinity spike would result.

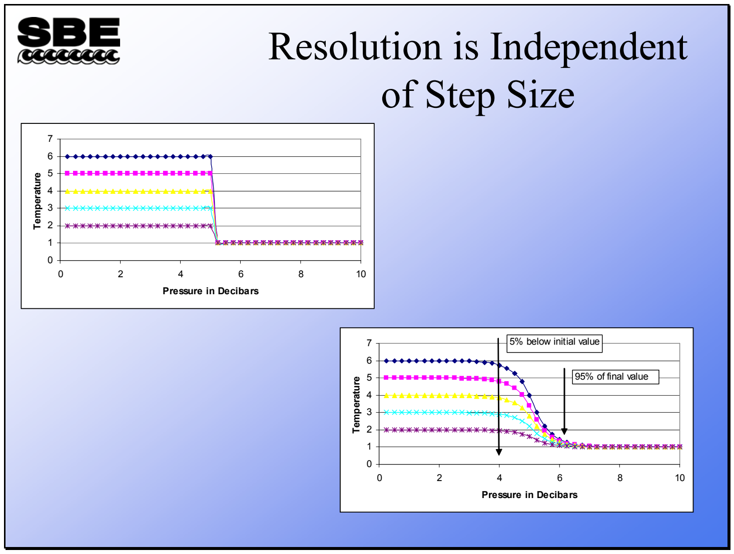
Estimating Conductivity and Temperature Resolution (*continued*)



The next step in the process is to advance temperature relative to time to align the temperature and conductivity channels. Note that the salinity spike is much reduced; if the data were bin averaged on 2 decibar bins, the salinity spike would average out of the data.

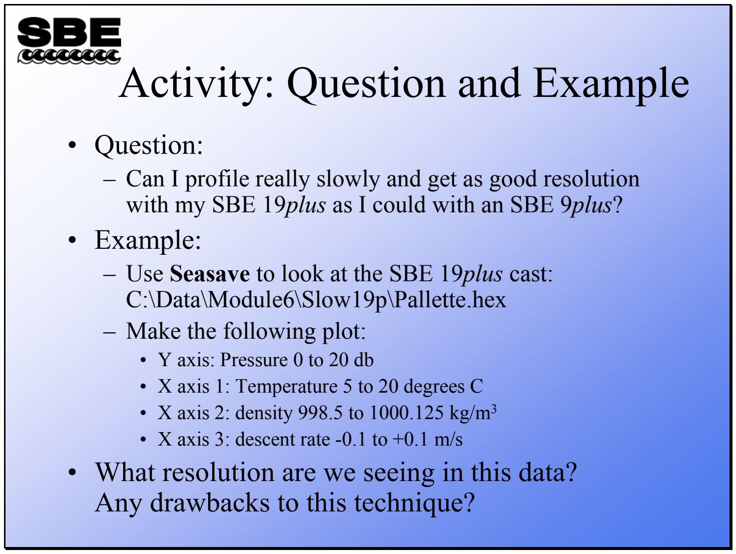
Assuming that a 5% below initial value and 95% of final value criteria are acceptable for the resolution of a step change in temperature and conductivity, the SBE 19*plus* can resolve a step change over approximately a 2.25 second interval (corresponds to a 2.25 decibar interval at 1m/s lowering rate). A slower lowering rate will result in a smaller resolution distance.

Estimating Conductivity and Temperature Resolution (*continued*)



You might think that the resolution of a step change depends on the magnitude of the change. Above are plots of the step response of a filter that closely resembles the temperature response of the SBE 19*plus*. It is obvious that the size of the step does not influence the distance (or time) required to resolve it.

Activity



This example is from data obtained by lowering an SBE 19*plus* by hand, at approximately 2 cm/second.