Measurement of the Physical Properties of Seawater
Temperature, Salinity and Pressure
(Moored, Towed and Profiled) Feb 04

Introduction - A goal of the ocean scientist/engineer studying the physics of the ocean is to:

1) obtain a quantitative description of the characteristics and circulation patterns of oceanic waters as a function of space and time, and
2) understand the nature of the forces which cause the water movement and ultimately the distribution of the water properties.

In the study of the oceans, the most important dynamic property of seawater is its density (ρ), which is a function of the temperature (T), the salt content or salinity (S), and the pressure (P) of the water. In other words, the oceanographer wishes to know T, S, P and as continuous functions of x, y, z, t, where x and y are latitude and longitude on the earth, z is depth, and t is time. Since it is practically impossible to measure all places all the time, we generally try to hold all except one variable constant and sample the quantity as a function of the remaining variable.

For example:

1. A moored thermometer at a fixed position x, y, z measures temperature as a function of time, T(t). To get an approximation of the vertical distribution, several temperature sensors may be placed in a vertical array to get $T(t,z_i)$. The discrete z_i should be chosen so as not to alias the temperature signal variations in the vertical.

2. A vertical profiling instrument (the most used version we refer to as a “CTD” because it samples Conductivity, Temperature and Depth) measures vertical profiles of temperature, T(z), where x, y and t are held nearly constant. Again this is not exactly true because it takes time to make a vertical profile, so t is not exactly constant, and during that time the wind and currents will move the ship so that x and y are not constant. However, in the ocean T varies more strongly with depth and less so with horizontal position and the time it takes to make a profile because the ocean is vertically stratified, so the assumption holds in practical applications.

   However, in a CTD survey of Massachusetts Bay a few years back, a problem was encountered. A synoptic picture of the density field was desired, but with a single ship the survey took several days to complete. During this time the internal waves at the M2 frequency (the principal lunar tidal frequency of 12.42 hours) significantly distorted the density field with this period so that a synoptic picture was impossible to obtain. A survey of the area would have to be completed in a fraction of the 12.42-hour period, or an average of many profiles taken during the 12.42-hour period would need to be made at each location to average out the tidal variability to get a good survey.

3. An autonomous underwater vehicle such as the Self Propelled Underwater Research Vehicle (SPURV used by APL/UW), ABE (WHOI), ODESY (MIT) or REMUS (WHOI) makes horizontal profiles of temperature, e.g. T(x) or T(y), at constant depth, and nearly constant time. They can also do surveys of T(x,y) in a time relatively fast compared to changes in the water column properties if the area of survey is small enough.

Since the important water properties are characterized by its temperature, salinity and pressure, let us start our study there.

Measurement of seawater Temperature, Salinity and Pressure:

Temperature - The temperature of the seawater is the easiest of the three physical quantities to measure, and is a measure of the internal energy or thermal activity of the water. Oceanographers use units of degrees Centigrade - °C. Generally the measure of temperature is in degrees Kelvin, relative to absolute zero where all motion stops. However, in the ocean we see a relatively small temperature change (generally between 0° and 30° C) so we use the Celsius scale, where

$$°C = ° K - 273.15°$$

A. Temperature Measurement -

1. Mercury (or alcohol) glass tube thermometer (nearly outdated in oceanography). These sensors rely on a glass tube of constant cross sectional area, attached to a reservoir of a fluid such as mercury that has a linear coefficient of expansion with temperature. As the temperature rises, the fluid expands and rises in the tube. The tube is marked off in degrees, and the level of the fluid is read relative to the markings to determine the temperature. These sensors have an accuracy of about 0.02 °C when used properly.

   The oceanographic instrument is the reversing thermometer that is designed to hold the temperature of the thermometer when it is "reversed" or tipped upside down at the depth of the required measurement. The thermometer is designed so that when it reverses, the mercury column breaks at a "y" in the tube and the mercury remaining in the tube is read to get the temperature of the thermometer at the time it reversed. The thermometer does have a thermal expansion problem of the glass tube and separated mercury column as the temperature changes, so the reversing thermometer is also equipped with an auxiliary thermometer, which is used to determine the temperature of the reversing thermometer (glass tube and mercury column) at the time that it is read. When properly calibrated, this then allows the user to correct the temperature to the actual temperature at depth, or "*in situ*" temperature. The reversing thermometers also come in pressure protected or unprotected versions. In the pressure protected version, the thermometer is completely enclosed in a glass tube so that there are no pressure effects on the reading. In the unprotected version, the seawater is allowed to compress the glass tube and mercury reservoir and so change the reading depending on the pressure. Again with good calibratings, the difference in temperature observed between the pressure protected and unprotected thermometers can be used to estimate the pressure at the depth that the thermometers reversed. In standard hydgrographic casts where several bottles with thermometers are lowered on the wire at one time, the depth of each thermometer is estimated by measuring the amount of wire out and the angle that the wire has at the ship.

   The reversing thermometers (generally one or two pressure protected, and one unprotected) are mounted in racks on water sample bottles and lowered over the side of oceanographic research vessels to obtain temperature and water samples for later analysis in the laboratory or aboard ship. The bottles are tripped with messengers that slide down the cable and hit the mechanism on the top bottle that releases the thermometers to tip over and also releases another messenger to trip the next bottle, etc. These "hydrographic casts" are made with many bottles and thermometers on a single lowering. At best these measurements are long and difficult to make. In addition to taking the temperature, water samples are also collected then must be analyzed to get other properties such as salinity, O_2, nutrients, etc. Presently, nearly continuous vertical profiles are being made with electronic profiling instruments. The sensing elements used in these instruments are either platinum resistance thermometers or thermistors. Note that even with these modern electronic profilers, water samples still are collected for nutrients, seawater chemistry, and biological variables.

With the early CTDs, reversing thermometer temperatures were taken as a stability check on the electronic instruments. The stable reference was the mercury reversing thermometers, and the electronic temperature was used to interpolate the vertical temperature structure between thermometers. However, the temperature sensors on most CTDs and oceanographic instrumentation are so accurate and stable, that they are better than reversing thermometers. Therefore, reversing thermometers are rarely used today. On the Falmouth Scientific Instruments (FSI) CTD presently used by the WHOI CTD group, two platinum resistance thermometers (with different time constants) and one thermistor are used as a check on each other down to the millidegree level.

2. Platinum Resistance Thermometer (PRT) - The PRT is the laboratory standard for accurate temperature measurement. In the laboratory environment with a good temperature controlled resistance bridge with mercury wetted contacts and a polarity reversing switch, the temperature can be measured to 0.000,1 °C repeatably. A PRT sensing element is often used in remote instruments, but, because the resistance per unit length of platinum wire is low and the change in resistance per unit length of wire small, a long wire is used in the PRT to give a good signal. This mass of wire has a thermal mass and hence a time constant. The longer the platinum wire sensing element, the greater the resistance change per unit temperature change (which is good because it gives greater accuracy and resolution), but the longer wire has longer the time constant (bad because it limits the vertical structure than can be resolved with the sensor). These older PRTs had a time constant near 1 second as discussed in the section on sensor response measurement with a discussion of the Plessey 9040 CTD’s temperature sensor. The FSI CTD uses a PRT in a stainless tube that has a response time of 400 ms depending on the lowering (and hence flushing) rate. Newer PRTs are being made in smaller stainless tubes with time constants as fast as 100 ms. However it is not yet clear that they will have the stability when cycled to full ocean depths. The stainless steel pressure case on the PRT is necessary to remove any pressure effects and assure accuracy and stability, but at the price of a longer time constant. A PRT is the stable sensor used in the Neil Brown Mark III and Mark V CTD systems, which are the standard for WOCE (the World Ocean Circulation Experiment) and generally in the oceanographic field. Pressure protected thermistor sensors are cheaper and nearly as

accurate, so are being used in more and more in oceanographic instruments and is the standard in the Sea Bird CTD systems.

3. Thermistors - Thermistors are probably the most widely used temperature sensing element today, e.g. automotive temperature sensors, oven temperature sensors, microprocessor controlled thermostats, and hospital and home thermometers. Like the PRT, the thermistor changes resistance with temperature. It is cheap ($20) and has a potential repeatability of better than 0.001 °C. Interchangeability of thermistors to 0.1 °C without calibration is standard i.e. in hospitals where required accuracy is better than 1 degree F and the disposability of the sensing element is desirable to prevent the spread of diseases. The cost of a temperature sensor can be significantly reduced if thermistors can be interchanged so that expensive calibration procedures need not be undertaken. The thermistor is often checked at a single point, then shipped. (See thermistor manual in readings).

In the Wien Bridge Oscillator temperature sensor made by Sea Bird Inc. (see Pederson, 1968 in readings), a thermistor is used as the temperature sensing element (a variable resistance element) in an AC bridge circuit. The sensor is powered by a DC voltage between 10 and 24 volts and draws about 7.5 ma, or a power of 75 mw. The sensor contains a regulator to provide the electronics with a constant voltage. An AC bridge circuit (Wien Bridge Oscillator) that excites the bridge containing the thermistor and oscillates at a frequency proportional to the resistance (temperature) of the thermistor. This frequency is then output by the sensor for separate recording. This sensor has the advantage of not requiring a regulated voltage supply. The FM output signal is not dependent on cable length, impedance or resistance, which may attenuate the amplitude of the signal, but not change its frequency (nominally 10 kHz at room temperature). The electronics and thermistor are permanently connected together and the geometry of leads and components fixed. The thermistor is housed in a stainless steel hypodermic needle to protect it from the ambient pressure changes. The leads from the thermistor to the bridge circuit are short to reduce thermal effects in the leads, and changes in capacitance caused by geometry changes. These factors are necessary to make the sensor more stable. Calibration histories show that the sensors start off with less than a 5 millidegree C per year drift rate. This rate decreases with time, so that after 10 years it is less than 3 millidegrees C per year and more typically 1 or 2 millidegrees. Thus, knowing the drift rate from calibration histories, the temperature can be measured to within 2 millidegees over periods as long as one year with these sensors. Newer techniques used by may instruments now use the short term stability of present A/D converters and stable reference resistors to achieve similar stability without the cost and time of component selection and adjustment required by the Wien bridge oscillator.

A thermistor is not a linear device; that is, the resistance of the thermistor is not linearly related to temperature. Thermistors behave in a logorithmic manner. Sea Bird has determined that the best fit to the calibration data for the their thermistor in the Wein bridge oscillator is of the form,

$$T(°C) = 1/\{a + b\ LN(fo/f) + c\ LN^2\ (fo/f) + d\ LN^3\ (fo/f)\} - 273.15$$

where f is the observed frequency of the sensor. For Sea Bird temperature sensor serial number 512, calibration coefficients from the 1985 calibration are:

a = 3.66e-3 °C b = 5.90e-4 °C
c = 1.89e-5 °C d = 7.77e-5 °C
fo = 5857.3 Hz

A linear least squares fit to the calibration constants will remove some of the random uncertainty associated with each calibration point, and the calibration history can show how a sensor is aging and if the latest calibration is consistent with the past calibrations. Any inconsistency could be an indication of sensor problems or failure.

A glass encapsulated thermistor can have a time constants of order 0.1 sec, and some thermistor flakes can have response times of 0.01 second. The pressure protected sensor which we are using on moorings now on Georges Bank have a time constant about 500 ms at a few cm/sec flushing rate. (Note that the time constant is not the best way to typify the frequency response function of a sensor.)

4. Quartz thermometers - (Not widely used because of the cost of the crystals.) This family of sensors takes advantage of the fact that quartz crystal oscillators can be made temperature sensitive. A low-power crystal oscillator is constructed with the crystals the temperature sensing element. Again the problem of cable attenuation is eliminated. The reference thermometer often used in the laboratory is a Hewlett-Packard Oceanographic temperature sensor. The quartz crystal is cut for maximum temperature linearity (AT cut). The sensor is capable of resolving microdegree C temperature fluctuations and its sensitivity is very constant with times. It is subject to shock damage that causes crystal dislocations and absolute temperature shifts. To obtain the best accuracy, a triple-point-of-water-cell is required for standardization to assure that no shift has occurred. Also the mass of the crystal in its pressure case makes for long time constant measurements. This sensor is nearly linear, and for most purposes can be fit by,

$$T(°C) = -4.864 + 9.9477\times10^{-4} * Freq(Hz)$$ for UNH sensor M8

To obtain the best fit, a quadratic in temperature is used and for M8,

$$T(°C) = -324.15260 + \sqrt{(1.0475847\times10^{7} + 6.4893 * Freq(Hz))}$$
which is of the form - sensor frequency = $AT^2 + BT + C$.

B. Calibration - All sensors are only as good as their calibration. A good sensor will produce poor results with poor calibration, but a poor sensor will only provide relatively poor data with the best calibration. Good measurements require both good sensors and good calibrations. A good sensor requires both good static and dynamic calibration to obtain optimum results. A major part of any calibration is a sensor's past calibration and performance history.

1. Temperature Standard - The International Practical Temperature Scale of 1968 (IPTS-68) defines the temperature of water of a given ionic state in triple phase (ice, water, gas) as 0.010,00 °C ±0.000,01 °C. This 1968 temperature standard is different from the older 1948 standard. Presently the International Temperature Scale of 1990 (ITS-90) is the standard for calibrating temperature sensors, but is not the standard for calculating

derived quantities (such as salinity, density, velocity of sound, etc.) Therefore, the user needs to make sure what reference is being used for the calibrations, and how the results are reported so that an error is not made.

There are programs to change back and forth between the standards. Simply,

$$T68 = T48 - 4.88x10^{-4}\ T48 + 5.80x10^{-6}\ T48^2$$

Thus, at -2 °C, the correction is 1 m°C, at 15 °C, the correction is -6 m °C, and at 35 °C, the correction is -10 m°C. This is a small correction, but significant in ocean dynamics studies. For our work we shall use the IPTS-68 standard for calculations with the 1980 equation of state of seawater.

The ITS-90 standard is based on a change in the definition of the temperature references. It does not change the triple-point-of-water temperature, but does change the melting point of Gallium (29.7646°C). This conversion is well fit by

$$T68 = T90 + 0.000,0 + 2.21666x10^{-4}\ T90 + 5.95238x10^{-7}\ T90^2$$

and results in a 6 millidegree change in temperature at 20° C. This is important estimating the stability of water in the deep ocean, and any data needs to be properly corrected depending on the intended use. WHOI has made the change to the ITS-90 standard, and uses this standard in the laboratory, and uses the above equation to get the temperatures back to the standards required by the accepted equation of state of seawater. Sea Bird uses the ITS-90 standard, and is currently reporting the calibration constants for both the ITS-90 and IPTS-68 standards.

The standards for oceanographic temperature calibrations rely on using a laboratory PRT as a transfer standard, which is routinely calibrated using standards traceable to the National Institute of Standards and Technology (the old National Bureau of Standards). This is then standardized in a triple-point-of-water cell (273.1600°K or 0.0100°C) and also in a melting point of Gallium cell (302.9146°K or 29.7546°C) before and after use. The triple-point-of-water is the temperature of pure water, ice and water vapor in thermal equilibrium. If the sample is warmer, some ice melts to take up the extra heat. A typical triple-point-of-water cell gives the temperature of 0.01000°C +0.000,00°C and -0.000,15°C. The lower than ideal temperature is due to the fact that the water is not ideally pure, and the impurities lower the triple point slightly. The cell must be first prepared by cooling and freezing the ice mantle, then it can be kept for weeks packed in ice in a refrigerator at near freezing temperatures.

C. Other important considerations in temperature measurements -

1. Pressure sensitivity. Thermistors and PRTs are also pressure sensitive, so to eliminate this effect the sensing elements are put into pressure protected tubes. However, this increases the mass of the sensor and reduces the frequency response. Therefore, if you need fast response, you may have to give up stability. The Neil Brown Mark III and FSI CTDs use a PRT for stability and accuracy and also use an unprotected thermistor for fast response. Based on the lowering rate (i.e. the flushing rate which controls the frequency response of the PRT and thermistor), the thermistor signal is high pass filtered with a cut-off that matches the response of the PRT, and added to the PRT

signal to get a measurement of true temperature with higher frequency response. In early Neil Brown CTDs, the high pass filtering cut-off was set by a switch in the instrument. Since the cut-off is dependent on the lowering rate of the instrument (which determines the time constant of the PRT), scientists have gotten into trouble by not setting the switch properly and therefore applying the wrong correction. Once the data from these two temperature sensors has been added together improperly, it can not be sorted out and corrected. Therefore, it is preferable (and most instruments with multiple sensors) record all the data and do the combination of response times later in a computer under proper control of the user, and where any addition of sensor outputs is not irreversible.

2. Self-heating. It takes energy to make a measurement. Thus the thermistor or PRT is heated by the current required to make the measurement, and the measurement may be contaminated. With the PRT and a bridge, a minimum of current flows through the sensor, so heating is minimized. With the thermistor controlled Wien bridge oscillator, about 75 milliwatts is used in the sensor, but a minimum of about 10^{-7} watts is dissipated in the thermistor itself, to reduce self heating error to less than 0.000,1 °C.

   In the early version of the HP quartz temperature thermometers used in the Scripps Deep Sea Tide Gauge, the self-heating was clearly evident. Below 3.5 km depth in the North Pacific, the temperature is adiabatic and increases with depth (controlled by the increase in pressure doing work on the water). The instrument on deployment fell through his water and showed the 1.5 microdegree per cm gradient typical in this region. However, as soon as the sensor reached the bottom and was not flushed by the 1 m/sec fall rate, the temperature jumped up several milli degrees C. When the instrument was released from the bottom, the temperature jumped back and followed the adiabatic gradient. This jump or offset in temperature was caused by excess heating in the sensor's electronics being conducted into the quartz sensing element through the electronics board and pressure case. This problem was fixed by placing the sensing crystal in a pressure case on the end of a thin stainless tube to isolate it from the electronics heating, and then by mounting the sensor on the bottom frame with the temperature sensing element below the electronics case. Then this observed forced/free convection change in temperature disappeared.

   Note that this effect really makes the temperature sensor a velocity sensor, since the temperature is now velocity dependent. We used this sensitivity successfully to made a heated element velocity sensor for use in the low velocity (< 10 cm/sec) regions of the deep Pacific. Again, one needs to make sure that the sensor he is using is not being contaminated by sensitivity to other variables.

3. External heating. In atmospheric temperature measurements, care must be taken to keep the direct heating from solar radiation to a minimum. A white radiation shield accomplishes this task. Radiation shields take the form of either a tube that orients itself with the wind and may be aspirated by the wind or by an electric fan, or a symmetric stack of plates such as the Gill radiation shield. .

4. Sensor Signal to Noise Ratio - drift, resolution, repeatability. The ability of a sensor to measure the environment is best shown by its signal to noise ratio. The full sensor noise spectrum is seldom given by scientists or manufacturers, but instead they refer to

such quantities as drift, resolution and repeatability. In reality the thing you want is to plot the signal being measured against the noise of the sensor. Normally geophysical signals have higher energy at low frequency and lower energy at higher frequency. The sensor noise level can be determined by several means we will discuss when we review data analysis. The low frequency part of the sensor noise, is often referred to as “drift” or long-term stability, and is also reflected in the parameter known as accuracy. The high frequency part of the sensor noise spectrum is related to “repeatability” and resolution or short-term stability. In general we use:

Accuracy - represents the ability of a sensor to measure a signal relative to some absolute standard. A temperature sensor might be specified as having a range of -5°C to +25°C with an accuracy of 0.01°C over one year. This means that in the this temperature range, the sensor has a low drift (generally due to aging of components), so that within a year’s time, the reading typically will change by less than 0.01°C. However, most manufacturers list the specs of a prototype or laboratory development sensor which may be quite different from the actual production model. The best method of determining accuracy is to do calibrations often, and establish a sensor calibration history.

Resolution - the ability of a sensor to see differences or changes in signal. We discussed the least count resolution of the digitizing electronics, but the limitation in the sensor itself determines how great a signal change that it can see. Generally the resolution is smaller than the accuracy. The sensor can change slowly with time, and have a poor accuracy, but still have a good resolution. The temperature sensor above with an accuracy of 0.01°C might easily have a resolution of better than 0.000,1°C. That is, you can determine that there is a temperature change of 0.000,1°C, but the absolute temperature of the water can only be determined to 0.01°C.

Repeatability - the ability of a sensor to duplicate a previous output with the same input. This is related to accuracy, but now a sensor can be very repeatable, but not accurate. It depends on the time frame. People talk about short-term and long-term stability. They are just using expressions to let you know how long a time the instrument is repeatable, or how stable it is.

For the Sea Bird type of temperature sensor used on the UNH and WHOI moorings, we can look at the low frequency part of the sensor noise from differences from calibration to calibration relative to the same standard. Therefore, in a years time, we can make reliable measurements to ±0.001°C. This is better than we could do with a mercury reversing thermometer which has often been used for *in situ* calibration and comparison.

Again NOTE: Calibration history and knowledge of past performance proves information for higher quality measurements.

Pressure - Pressure is a measure of the external force on a parcel of water. Oceanographers generally use units of dbars where 1 dbar ≈ 1 m depth. This is for simplicity since the dbar is a standard unit of pressure, and it is also very near the unit that we use for depth. Also, the equation of state of sea water expects the pressure in dbars, so it is easiest to keep it in that form. On the other hand, the Pascal is the MKS unit of pressure and is 1 NEWTON/M². Since 1 dbar = 10^4 Newton/m² or 10^4 Pascals, depths such as 200 meters become pressures of 2 megaPascals or 2,000 kiloPascals, which are not as easy to interpret physically. Engineers usually calibrate sensors in pounds per square inch (PSI), and 1 PSI = 0.6895 dbars or 1 dbar = 1.4503 PSI. To be most accurate one should calculate depth from pressure using the hydrostatic approximation (assuming no fluid motion) so

$$P(\text{dbars}) = \int_0^h \rho(z)\, g\, dz(\text{meters}).$$

For typical ocean densities of 1027 kg/m^3 and acceleration due to gravity of 9.80 m/s², the constant of proportionality is 1.0065 dbars/m or only 2/3% error using dbars as meters. Thus, for convenience, oceanographers use dbars although it is not a standard MKS unit of pressure. Note for many publications, you may have to change back to the MKS unit of Pascals.

A. Measurement - We will use absolute pressure rather than differential pressure. Differential pressure is relative to some reference or most often atmospheric pressure. Differential pressure referenced to atmospheric pressure is often referred to as gauge pressure. However, note that this changes as atmospheric pressure changes; therefore we want to use absolute pressure relative to a vacuum. Because atmospheric pressure changes, any sensor with reference to atmospheric pressure has a built in error. One standard atmosphere = 14.695 PSI = 10.1325 dbars. We measure pressure in the ocean by:

1. Protected and unprotected mercury reversing thermometers. The difference in temperature between a pressure protected and unprotected thermometer can be used to determine the depth. This was often used on hydrographic stations with large wire angles due to working in poor oceanographic conditions. To help correct for the wire angle, it was measured at the ship and simple corrections applied and checked with the reversing thermometers. This was generally a poor measurement by today’s standards.

2. Strain gauges. Probably the most often used pressure sensors are strain gauges that can be found in your car, as well as many oceanographic instruments. They can be relatively low cost and low accuracy to high cost and high accuracy. They generally use a diaphragm with strain gauges on the diaphragm. The pressure is applied to one side of the diaphragm with a vacuum on the other as the reference. The deflection of the diaphragm is measured relative to the absolute pressure applied.

3. Potentiometers. These generally use a bourdon tube to move a potentiometer to produce a variable resistance for the measurement. They are generally of poor quality, but have a large, easy to process signal and require little electronics.

4. Bourdon tubes. These are the basic pressure sensor with pointing needle that you see everywhere. The bourdon tube is used to convert pressure into movement that can be used to drive (1) a quartz crystal sensing element, (2) a potentiometer, (3) an optical angle readout, and (4) a mechanical pointer readout. They are generally not as accurate for oceanographic work as a good quality strain gauge, but are often used as the accurate readout for laboratory pressure calibrations and observations. To make the readout more accurate, the needle can be many feet long, and the dial may have a reflective strip to aid in aligning the needle with the markings.

5. Capacitance. Here the diaphragm is much weaker and is used as one plate in a capacitor in an RC oscillator. As the diaphragm is deflected, the frequency changes. These are often used for atmospheric pressure measurements. However, they are also very sensitive to accelerations, so bad for use on a moving buoy.

6. Vibrating wire. The Vibrotron (see readings) was the most accurate oceanographic pressure sensor until the mid-70's. It used a vibrating wire stretched between a diaphragm and a rigid end. The wire was placed in a magnetic field, and attached to an oscillator that oscillated at the natural frequency of the wire. As the diaphragm was exposed to pressure, it deflected, reducing the tension in the wire and reducing its natural frequency. Its major defects were drift and temperature sensitivity. It came in a version with the sensing element in a constant temperature oven to reduce the temperature effects (at the expense of the added power to run the oven). However, the temperature effect was regular and could be removed (to the first degree) by careful calibration of pressure versus temperature. That left drift as the main disadvantage, and this sensor was replaced by quartz sensors that had lower drift and lower temperature sensitivities.

7. Quartz oscillators. Hewelett Packard and Paroscientific (see readings for several papers) both developed quartz crystal pressure sensors in the 1970's. The HP unit was optimized for well logging at high temperatures, so had a larger temperature sensitivity at oceanographic temperatures. The Paroscientific Digiquartz pressure sensors were developed more specifically for oceanographic applications and are the best and most expensive pressure sensors for sea floor or profiling pressure observations.

B. Sea Floor Pressure Observations

In the case where the ocean is in approximate static equilibrium, the vertical equation of motion becomes the hydrostatic equation, and this can be integrated from the top of the atmosphere (∞) to the bottom of the ocean (-h) to obtain the pressure observed by our instrument there.

$$P(-h) = \int_{\infty}^{-h} \rho(z)\ g\ dz$$

We can break this up into several pieces as follows:

1. The integral from the top of the atmosphere ($z=\infty$) to the sea surface ($z=\eta$) is just the atmospheric pressure, P_a.

2. The sea surface is generally not smooth, but consists of waves whose elevation we describe by η as a function of time. Then the next term is the integral from the sea surface (z=h) to the mean sea level (z=0). This then is a pressure due to the surface waves that we approximate as the surface density, ρ_0, times the elevation η.
3. The next term involves the integral from the mean sea level (z=0) to the sea floor (z=-h). We shall break this further up into terms depending on the density. The first is the average density, ρ_{avg}, times the mean depth (-h) and is just the mean hydrostatic pressure seen by the bottom pressure sensor.
4. The final term is the deviation from the mean density where

   $$\rho(z) = \rho_{avg} + \rho'(z)$$

   where the perturbation density ρ' contains the effects of internal density changes on the bottom pressure.

Then we can write the pressure our bottom instrument sees as the contribution of these terms:

$$P(-h) = P_a + \rho_0 g\eta + \rho_{avg} gh + \int_0^{-h} \rho'(z)\ g\ dz$$

So we see the signal we see at the bottom is due to (1) the atmospheric pressure, the contribution due to the waves and other deviations of the sea level from its mean position, (3) the average hydrostatic pressure due to the depth of the water, and (4) the contribution due to internal density changes.

C. Calibration -

1. Absolute Pressure Reference. For pressure calibrations a dead weight tester is used. This places a weight of known mass on a piston of known area, so we have a known mass in a gravitational field (a force) acting over a known area, which equals a force per unit area or pressure. We will use PSI for calibration because that is engineering unit used by most of the dead weight testers including the units in the WHOI calibration laboratory. In order to reduce the frictional effects of the piston on the walls of the pressure cylinder, the weights are rotated. On simple calibration units this is done by hand, and on more expensive units, there is a motor to spin the weights at a regular velocity.

2. Static - We apply the pressure to the sensor and wait until we have an equilibrium condition before we take the measurement. In calibrating several sensors which will be used in one experiment in different locations for measuring pressure differences (they are the driving forces of ocean currents such as high and low pressures in the atmosphere drive the winds), we put the sensors on the same pressure manifold so they all see the same pressure. Thus, a constant error or offset error will be removed to the first order when the differences are taken.

3. Dynamic. Since pressure waves moves with the speed of sound in seawater, we generally do not have a problem with slow sensor response so it is usually not

considered, and probably not a problem with the sensors we are considering. However, if the sensor has a hydraulic filter such as a tide stilling well, there may exist significant effects. In the study of tides, the problem of filtering out waves to leave tidal fluctuations which were recorded on a chart was “solved” by a tide well which is an 8” diameter pipe with small orifice in the bottom. To the first order, the higher frequency surface waves were removed, but the lower frequency tides were admitted. An hydraulic filter is a non- linear filter which can have rectifying effects at certain wave frequencies which can “pump up” the well to a higher mean sea level than really exists. Also any plugging up of the orifice can effect the results e.g. barnacles or octopus.

The non-linear response of a sensor to pressure can be a problem if averages are taken over a large part of the non- linear range. Then people have found that to get good results they need to make a reading of the sensor, convert it over to pressure using the calibration equations, and then average the resulting pressure. Therefore, one has to be aware of potential problems with sensors that are not linear (such as most of the oceanographic sensors you will encounter).

Finally, a dynamic term of concern is the Bernoulli effect, i.e. the velocity effect on pressure. If we measure along a fluid streamline, that path that the fluid flows along, then the following is conserved;

$$P/\rho + gh + 1/2\,|v^2| = \text{constant.}$$

Therefore, the pressure is not only a function of the depth h, but also of the fluid velocity v. This can cause measurable effects in high flow regimes such as in estuaries. To reduce this effect, oceanographers are now borrowing the atmospheric scientist’s solution by using two parallel plates and taping off the static pressure from a port in the middle of one plate.

D. Other considerations

1. Drift - generally caused by stress on the material making up the pressure sensor that creeps with time. This is dependent on the amount of pressure applied and the time since it was applied. Generally the drift decreases exponentially with time. This is the limiting factor in the high quality pressure sensors in the ocean. Again, instead of considering drift, we should consider the signal to noise ratio as a function of frequency as we did with temperature. Remember the large drifts of the Vibrotron pressure sensor discussed above which is the limiting factor in using these sensors and is due to the creep of the metal used in the sensor’s construction.
2. Temperature and voltage sensitivity - Most pressure sensors have some sensitivity to temperature and voltage as well as pressure. Thus, the voltage should be regulated so these effects are minimized. To remove the voltage effects in the Paroscientific pressure sensor, we found that if the voltage is greater than 10 volts, the sensor is no longer voltage sensitive. Temperature sensitivity is a more difficult problem. It is usually measured in a static manner, and then applied to dynamic data. For sea floor conditions where temperature changes slowly, this is probably good. To account for this in the Paroscientific pressure sensor, we calibrate the

sensor as a function of pressure and temperature, fit the calibration at each temperature to the form for the pressure sensor, and then fit the coefficients to a linear function of temperature. Then this gives us a normalization relationship as a function of pressure and temperature, and we have reduced the voltage effects to where they are negligible. For the best of pressure sensors, the temperature sensitivity is about 1 mm of seawater per deg C. The signal we are attempting to measure in our pressure difference records is around 10 cm of seawater, so the temperature effects will not dominate, but could easily be 10% of the expected signal. The latest version of the Paroscientific pressure sensors have a thermistor inside the pressure case on the pressure sensing element itself. This then allows the best temperature correction to be applied to the data. Another factor to include is the temperature sensitivity of the instrument's clock. In making a measurement with the Paroscientific pressure sensor we are counting the ratio of its frequency against the instruments clock. If this clock has a temperature sensitivity, it will effect the pressure observations. With the Sea Data pressure instruments used at UNH we calibrated the clock and used this sensitivity in the normalization of pressure.

In the CTD profiling instruments, the temperature can easily change 20°C in 10 minutes during a profile. Since it takes only a relatively short time to make a profile (e.g. 10 minutes for a 100 m profile with water sample), the best thing to do is to insulate the pressure sensor so that it has a large thermal lag and does not change appreciably during a profile.

3. Hysteresis - This again varies with the sensor. For a sea floor bottom pressure instrument, the pressure range does not vary much and hysteresis effects can be neglected. In a CTD where the pressure can vary over the range of the sensor, this can be a problem. The best sensors have reduced this effect to where it is negligible, but a combination of temperature and hysteresis effects are easily seen in a CTD profile where the on deck pressure before and after a deep cast can vary by up to a meter!

Salinity - Salinity is a measure of the total dissolved solids in the water. It is measured in grams of solid minerals in 1 kilogram of seawater, or parts per thousand, which we write as o/oo. (Remember that % is parts per hundred, so to get ppt we add a o.) The reference for salinity currently in use is the Practical Salinity Scale of 1978 (PSS-78) and the units are the Practical Salinity Unit or PSU. This is essentially the same as parts per thousand, but is defined for the modern measurement of salinity. (See readings of UNESCO technical papers Number 36 and 37 on the Practical Salinity Scale 1978).

A. Measurement - We cannot directly measure salinity. In the ocean a typical value is 34.7 PSU. About 85% of the total dissolved solids in seawater are NaCl. (Hence the name salt water.) Historically we have measured the amount of chloride ion (the largest percentage of the dissolved solids - 55%) by chemical titration and then calculated salinity from chlorinity by

$$S = 0.03 + 1.804 * \text{chlorinity}.$$

Therefore, for a chlorinity of 19.000 we get a salinity of 34.306 and for a chlorinity of 19.3760 we would calculate a salinity of 34.9843 PSU. This assumes that the amount of chloride ion is a good measure of the total dissolved solids, which is generally good over most of the world's oceans. Much of data on water properties (salinity), which are in the oceanographic data archives, were obtained by taking water samples with Nansen bottles and doing chemical titrations. The best of these data are nearly as good as the data obtained today, and are the only data available in many parts of the ocean.

Modern technology allows us to measure the electrical conductivity of seawater and calculate salinity from conductivity assuming standard ionic composition of seawater and hence the conductivity of seawater does not change significantly. (Note this is the assumption in all measurements of salinity, i.e. that the ionic composition of the dissolved solids does not change.) This will probably be violated in estuaries where the salinity results from the mixing of fresh water with seawater at the mouth of the estuary, and the dissolved solids brought down the river. There are two ways that are currently used to measure the conductivity of seawater:

1. Inductive - Here two coils (transformers) are coupled by a tube containing sea water. An AC signal is applied to one coil, and the amount of signal transferred to the other depends on the electrical properties of the fluid connecting the two coils. The dimensions of this tube must be critically controlled, and must not change. There also must be no bubbles or other materials in the cell, which do not have the conductivity of seawater. This method is often used in the less accurate sensors today i.e. about 0.05 ppt accuracy. The newest CTD on the market, the Falmouth Scientific Instruments unit has returned to the inductive cell to get around problems with the electrode cells in the Neil Brown Mark III and V CTDs. (Also note that this new development is directly related to Neil Brown. He started in the laboratory with electrode sensors, switched to inductive sensors, back to electrode, and now to inductive.)

2. Direct electrode measurement. The method used in laboratory salinometers and in the Neil Brown Mark III and V and the Sea Bird CTDs. It is based on the simple and then in the cross terms, to fit the observed laboratory data, i.e.

$$
\begin{aligned}
S = a &+ bT + cT^2 + d\,T^3 + \ldots \\
&+ eC + f\,C^2 + G\,C^3 + \ldots \\
&+ h\,P + i\,P^2 + j\,P^3 + \ldots \\
&+ k\,TC + l\,TC^2 + \ldots \\
&+ m\,T^2C + \\
&+ \ldots
\end{aligned}
$$

The standard scale is the Practical Salinity Standard and called PSS-78, which was adopted by the oceanographic community in 1978. The UNESCO reports give background papers, descriptions, FORTRAN program listings and test tables for the PSS-78.

For a very rough approximation over typical values found in the open ocean, we can reduce the complicated power expansion of the accurate equation to

$$S = 3.55 + 10.2*C - 0.73*T$$

which is not a function of pressure to the first order. So for T=10.0°C, P=0.0 dbars and C=3.808 S/M, the full equation gives S=35.00 ppt. The above approximation yields S=35.092 ppt. Inverting the above approximation, it is observed that conductivity is a stronger function of temperature than salinity.

$$C = 0.098*S + 0.0716*T - 0.348$$

In the ocean, the temperature (range 0 to 30°C) fluctuates more than salinity (range 30 to 40 PSU and typically between 33 and 35 PSU), so a conductivity record tends to look very much like a temperature record. With computers so prevalent, it is easy to do the calculation correct with the full equation of state. There are conversions to get from conductivity to salinity and back. (We used to do this by hand from conversion table. With bottle data from hydrographic stations, this was not too bad, but it became impossible with profiling CTDs. A computer was necessary for this instrument to be usable.) It should be noted that one of the first seagoing CTD systems by Neil Brown was available in an STD version, where an electronic circuit approximated the equation of state to get salinity from the temperature, conductivity and pressure. This instrument was quickly replaced by the CTD as computers were then being used to log and process data on board ship.

As an example, the Sea Bird conductivity sensor (used on moorings and in CTDs) uses a Beckman three-electrode conductivity cell as the variable resistance element in an AC Wien Bridge Oscillator. The two outside cells are at ground and the middle cell the is the varying electrode, so the cell is symmetrical. The AC signal prevents electrode polarization. The measurement is contained entirely within the cell. Neil Brown uses a smaller 4-electrode cell, which has the potential for greater frequency response because of the smaller size. There are two voltage electrodes and two current electrodes, which make the measurement. The dimensions of both cells are critical to the measurement, so contamination is critical. The Neil Brown cell has had drift problem related to Calcium Carbonate (limestone) forming in the cell and changing the dimensions to the extent that the readings (cell constant) changes. This is taken care of by regularly flushing the cell with dilute acid to dissolve the accumulated calcium carbonate. A larger cell, as in the Falmouth Scientific CTD, reduces the problems of very critical size. The Neil Brown Mark V CTD uses a 6-electrode design and more complicated electronics to reduce the electrode effects. However, these instruments are more complicated and harder to keep working properly.

All electrodes suffer from fouling, such biological growth, oils, etc. In moored applications, this is the limiting factor in observations. With longer monitoring programs being required, it is important to make time series observations of salinity (so we can calculate density, etc.), and we can not do long term conductivity observations as easily as temperature or pressure measurements.

B. Calibration -

1. Reference - As stated above standard for salinity measurement is the PSS-78. (UNESCO publication numbers 36 and 37) This is based on an assumed ionic

composition of seawater. Instead of an absolute reference, we use the ratio of conductivity of our water sample to a standard seawater (formerly produced in Wormly England called Wormly water) now produced by Ocean Scientific International (Hampshire, UK).

> Preparation : Surface seawater is collected from the North Atlantic and then pumped through filters (0.2mm) into a PVC lined tank and thoroughly mixed. Once purified by filtration and UV irradiation, distilled water is added to adjust the salinity, and the water is sealed in pre-washed glass bottles (capacity ca.200cm3).
>
> Calibration : The electrical conductivity ratio of each batch is compared to that of a defined standard potassium chloride (KCl) solution using a modified high precision salinometer.
>
> In accordance with the recommendations of the UNESCO, ICES, SCOR, and IAPSO Joint Panel on Oceanographic Tables and Standards (UNESCO Technical Papers in Marine Science, No. 36, 1981) the Standard Seawater label displays a conductivity ratio (K15) value where:
>
> K15 = (Conductivity of Std. Seawater at 15^{o}C and 1atm.) /(Conductivity of KCl soln. (32.4356g/kg) at 15^{o}C and 1 atm.)
>
> Each Standard Seawater batch is directly traceable to the standard defined KCl solution.
>
> Calculation : Conductivity ratios should be converted to Practical Salinities using the current International Oceanographic Tables, Volume 3, and the equations contained therein (UNESCO Technical Papers in Marine Science, No.39).

This water is available in the WHOI stockroom. It is sent with a stated conductivity ratio and salinity and is used in titrations, or in laboratory salinometers as a calibration transfer standard. In the salinometer, it is used to measure the conductivity ratio between the sample and the standard. From this ratio and the known conductivity ratio of the sample, the salinity is estimated using the Practical Salinity Scale of 1978 (PSS-78). In order to make accurate measurements this process requires time and effort.

2. Static - Again we use the temperature-controlled tank with salt water. By varying the temperature at constant salinity, one can calibrate a conductivity sensor at different conductivities. Generally two salinity baths are used to give the full oceanographic conductivity range and overlap the conductivities in both ranges. Water samples are collected during the calibration, and analyzed for salinity on a lab salinometer. Then the equation of state is used to calculate the conductivity of the bath. The sensor output is then plotted versus conductivity and fitted to the calibration curve in the least squares sense.

   The oceanographer will often use *in situ* comparisons to calibrate his conductivity sensor by collecting water with Nansen or Niskin Bottle on the wire above the CTD on with a rosette sampler with the CTD and analyzing it back at the laboratory. In the case of moored conductivity sensors, the CTD is used to gather profiles next to the mooring to check for calibration changes and drift in the moored sensor. It is more difficult to take a good in situ calibration point because the ship is not right at the buoy, and the water properties may vary in space (both vertically and horizontally) and the temporal sampling may be different. To check the CTD I generally take one water sample per profile to standardize the conductivity sensor and check for drift.

3. Dynamic - The response time of a conductivity cell is basically the flushing time of the cell. For a 20 cm long Sea Bird cell moving through the water at 30 m per minute

(0.5m/s is a good lowering rate for a CTD) we get about a 1/2 second time constant. In addition to the time to just flush the cell, we also have the problem that the cell has a thermal mass, so the heat in the cell's walls will heat or cool the water in the cell slightly, affecting the measurement. Therefore, one should really measure the temperature inside the cell to get the proper temperature with which to estimate salinity. If the temperature sensor has a much slower time constant than the conductivity cell, then the salinity estimated with the mismatched readings has the wrong temperature, and results in what is called salinity spiking. That is sharp spikes in salinity which are not real, but due to an artifact of the measurements (i.e. a mismatch of time constants). To reduce these effects, the Sea Bird CTD pumps the water past the temperature sensor to speed up its response over free flow, and through the conductivity cell to increase its response and match the sampling of the two sensors. They often put an orifice to reduce the flow. but I use the pump at its fastest flow rate to reduce the response effects as far as possible. The Neil Brown sensor has a faster response time because the dimensions are smaller. A detailed discussion of the dynamic response of the Neil Brown conductivity cell is given in the readings in Gregg, et al, 1982.

C. Other considerations

1. Drift - The drift of a conductivity sensor is generally due to, (1) electronic component aging, (2) electrode fouling, (3) dimensional changes in the cell geometry, and (4) non-conducting material in the cell. Generally the electronic drift is smooth and smaller than other factors. The fouling problem is the limiting factor in making conductivity measurements (especially moored observations) in the ocean environment.

   a. Warm equatorial waters are conducive to calcium carbonate formation inside the cells. A mild solution of HCl will dissolve this and bring the cell back into calibration.

   b. Electrodes are platenized to increase the area of the electrode in contact with seawater. If the area is large, then this drops out of the equation, leaving only the basic seawater conductivity. The platinum black used is a very spongy material, which allows a large surface area of platinum to be in good electrical contact with the seawater. However, any mechanical damage (such as cleaning the cell with a brush) will change the cell constant, and the readings.

   c. Biology, especially in warm surface waters, is looking for a place to grow, and will contaminate the sensor in two ways. By growing around the cell openings, it will block the water flow and hence affect the reading. By growing in the cell, the dimension will be changed and material in the cell with conductivity other than that of seawater will affect the reading. These effects are reduced in moored sensors by the addition of TriButyl Tin poison tubes on each end of the cells. Occasionally a CTD sensor will be temporarily fouled with a jellyfish or other small piece of biological material, and may even require mechanical cleaning.

   d. If a wet electrode cell is allowed to dry out with salt water in it, salt crystals will be formed in the platenizing and reduce the area that is in contact with the seawater. When the cell is wet again, the area of the electrodes are changed, and these salt crystals affect the readings until they have dissolved, which can take a surprising amount of time (order of weeks). Therefore, Sea Bird recommends that the user keep a Tygon tube on the conductivity cell, keeping it moist. Note that in freezing weather care should be exercised to prevent freezing of the water in the cell and cracking it. Sea Bird flushed the cell thoroughly and ships it dry, so this method will also work if freezing is a problem.

e. Sediment in the conductivity cell. Sediment is generally small pieces of minerals such as quartz, and as such non-conductive. The conductivity cell measures the flow of current per square unit of cell cross-section, and when this area is blocked by a non-conducting material, the conductivity drops. a typical bottom moored record will show negative going spikes due to the effects of suspended sediments.

Equation of State of Sea Water and Derived Quantities

Once the temperature, salinity and pressure of a water parcel is known, then one has the equation of state of seawater to calculate the other derived quantities. The equation of State of Sea water of 1980 (see the UNESCO reports 38 and 44) is the current standard and uses the PSS-78 and IPTS-68 (not ITS-90) as inputs. Some of the more important quantities calculated are:

Potential Temperature. The potential temperature, θ, is the temperature of the seawater considering the compressibility effects. The internal energy (temperature) of a parcel of water is controlled by the amount of heat added and the work done on it.

Change in internal energy (temperature) = Heat added + Work done

If the process is adiabatic (i.e. no heated added or lost) then the change in temperature is directly related to the work done in compressing the water parcel. For example if water with temperature of 0.57 °C at the surface (0 PSI) were brought adiabatically to 5,000 m depth (8,000 PSI), the temperature would rise to 1.00 °C. Therefore, the potential temperature represents the temperature water had at the surface (which is where it acquired its temperature. To really compare the temperature of two water parcels, we need to know the potential temperature (the temperature of the water with compressibility effects removed). This is the temperature the water parcel would have if it were brought adiabatically to the surface where the pressure is zero. The rate of rise in temperature with pressure is called the adiabatic gradient or adiabatic lapse rate and is about 1.5 micro degrees C per cm or 0.16 °C/km depth change. (Note that the water depth in the triple-point-of -water cell can have a depth of some 30 cm, which would cause a 45-microdegree change in temperature due to adiabatic effects. This is measurable and a correction should be made by subtracting a small amount from the 0.01°C of the triple point cell, but practically this is negligible.)

Density. Probably the most important dynamic property of seawater is its density, ρ. The density of seawater is a function of the temperature, T, the salinity, S, and the pressure, P. Although the surface density changes are relatively small, 1024 to 1030 kg/m^3, these differences in density produce the horizontal pressure forces which in turn drive the major ocean circulation patterns such as the Gulf Stream. We shall express this complicated relationship by

$$\rho = \rho(S,T,P) \text{ or } \rho_{STP}$$

which implies that the *in situ* density is dependent on the *in situ* temperature, *in situ* salinity and pressure. The term *in situ* refers to the values that these parameters have at the location of interest, or as we would measure them with our instrumentation.

Oceanographers tend to get tired of writing the 1000 every time they write density, so have invented the term *in situ* density anomaly, σ_{STP} which is defined as

$$\sigma = \sigma_{STP} = (\rho_{STP} - 1000).$$

Thus, the surface density anomalies vary from 24 to 30 kg/m^3. Changes in the value of the *in situ* density can be explored by considering its total differential to study the compressibility effects on density as follows

A. The most important or first order effect of pressure on density is to decrease the volume of a water parcel by squeezing the same molecules closer together, thus increasing the density. As an example, consider a water parcel at the sea surface with a salinity of 35 PSU, temperature of 0.0 °C and pressure of 0 dbars. The density anomaly is then 28.14 kg/m^3. If this parcel were moved adiabatically (that is without loss or gain of heat) to a depth of 4000 m where the pressure is about 6000 psi or 400 atmospheres, the density anomaly increases to 48.49 kg/m^3. In general pressure effects are very large and often obscure the effects due to the natural variability of temperature and salinity that we are interested in observing. Therefore, oceanographers define yet another term called sigma-t or σ_t, which is

$$\sigma_t = \sigma_{S(\textit{in situ}),\, T(\textit{in situ}),\, P=0}.$$

Here P is gauge pressure, which is zero at the surface rather than atmospheric pressure (14.7 PSI). This removes the very large pressure effect on density by evaluating the density at the *in situ* values of S and T but at the sea surface pressure. Sigma-t is a complicated function of S and T and is expressed as a power series of S and T. (See equation of state of seawater routines in UNESCO report 44.)

B. There is still a compressibility effect left in Sigma-t, mainly that due to the compressibility effects on temperature. In order to compare the density of two parcels of water, we need to remove all compressibility effects. Thus oceanographers define another density, the potential density anomaly or sigma-θ, where

$$\sigma_\theta = \sigma_{S(\text{in situ}),\theta,P=0}.$$

Thus, we have defined a density related term, σ_θ, whose value depends on the intrinsic properties of a water parcel, its potential temperature, θ, and the salinity, S. the external influence of pressure on volume and temperature have been eliminated. These values are determined by the air-sea interaction process at the sea surface, where a parcel of water gets these properties. We make the assumption that the water does acquire its properties at the sea surface. This seems reasonable since all solar heating occurs at the sea surface, all rainfall occurs here, and the rivers dump their fresh water out in surface waters. It is only sources such as salty water from the Mediterranean, and the heat and salt from hydrothermal vents and submarine volcanoes which contribute sources of heat and salt which are not at the sea surface or zero gauge pressure. Thus if we can correct for further effects and get back to original properties, we may have the opportunity to discover the source region where the water acquired its inherent properties, i.e. T and S. The use of Sigma-θ is a convenient way of relating the stability of the water column.

C. The final term or the pressure effect on salinity is negligible and not important to the order that computations are done, so is not considered here.

Specific Volume. Oceanographers are interested in a class of motion referred to as geostrophic where there is a balance between the pressure gradient forces and the Coriolis force on the rotating earth.

$$fv = 1/\rho \text{-} \partial P/\partial x$$

where is $f = 2\ \Omega\ \text{Sin}\phi$ = coriolis parameter representing the effects of the earth's rotation. Ω is the rotation rate of the earth = $7.29\ 10^{-5}$ rad/sec and ϕ is the latitude (note that the latitude is negative south of the equator. v is the velocity of the water in the y direction. (Note that the velocity in the y direction is related to the pressure gradient in the x direction.) This is one of the non-intuitive effects of working on an accelerating (i.e. rotating) reference system. In calculations of the pressure gradient forces we add up the effects due to density to get an artificial height. For this it is convenient to use a quantity related to the inverse density. The specific volume, α, is the inverse of density,

$$\alpha_{STP} = 1/\rho_{STP}.$$

The quantity know as the specific volume anomaly, δ, is the deviation of the specific volume from a standard,

$$\delta = \alpha_{STP} - \alpha_{(35\ \text{PSU},\ 0°\text{C},\ \text{P}).}$$

where $\alpha_{(35,0,p)}$ is the specific volume of a "standard ocean" defined so that δ is normally positive. Oceanographic texts generally divides α into various component terms which are due to the deviation of T and S from standard values so that it is easy to look up the values in standard oceanographic tables. However with the advent of the digital computer, and more recently the desktop PC, this is no longer done, and the quantity is calculated directly. The units of δ are generally expressed as cl/ton (10 ml/10^3 kg) and values are typically 50 to 100.

It should be noted that the velocity transport can be estimated by integrating the above equation between two points. Our bottom pressure observations are just this integral minus a mean term. That is bottom pressure observations do a good job of measuring geostrophic flow variations, but may miss the mean value.

A listing of the quantities calculated by the 1980 Equation of State of Sea Water are:

Inputs:
  temperature - degrees Centigrade referenced to IPTS-68
  salinity - practical salinity units (PSU) referenced to PSS-78
  pressure - dbars relative to atmospheric pressure
Calculations by the EOS-80 are:
  Density - kg/m^3
  Sigma-t- kg/m^3
  Sigma-θ - kg/m^3
  Density Anomaly- kg/m^3

Freezing Point - °C
Specific Heat - J/kg-°C
Adiabatic Lapse Rate - °C/m
Potential Temperature - °C
Sound Velocity - m/s

Instrumentation and Platforms

1. CTD. As an example of an earlier class project, consider the CTD system has was developed at UNH 15 years ago in support of the research effort of the Ocean Process Analysis Laboratory. It used the Sea Bird temperature and conductivity sensors that we have seen as well as the Vibrotron and Paroscientific pressure sensors. Since these sensors output FM signals, the electronics is just a frequency counter. In order to build a universal system and test out the concept of internally recording instrumentation which can be used on ships of opportunity, a microprocessor with RAM for data storage was used. The recording electronics was based on a 8085 microprocessor board made by Sea Data of Newton MA. The processor to shuffles the bits from the counters for each sensor and stores the results in RAM. When plugged into a PC, the data is dumped in binary from and stored in HEX format for processing. The PC then normalizes the data to pressure, temperature and conductivity, and calculates salinity, density, etc.

Sampling Considerations:

- a lowering rate of about 30 meters/min or 1/2 m/s was selected. We want a resolution matched to the resolution of the sensors or about 30 samples per meter vertical. So at 1/2 m/s this works to about 15 Hz sample rate. Given 15 Hz sample rate, this determines the time we have to count each sensor, so we need a period counting technique to get the required accuracy of the measurement.

-Least count resolution:

  Paroscientific Pressure - 0.03 dbars
  Sea Bird Temperature - 0.0003 milli degree
  Sea Bird Conductivity - 0.0004 s/m

Also, we can determine number of bits required for no ambiguity in typical applications

  Pressure - 19 bits => 15728 dbars overflow
  Temperature - 18 bits => 78°C overflow
  Conductivity - 19 bits => 209 S/m overflow

2. Uneven Lowering rate effects on CTD data
   - Unpumped and pumped UNH CTD profiles
   - Neil Brown CTD pressure sensor limitations in GOM
   - Roll filter, and elimination of effects

3. Bottom Pressure Observations
   a. Munk/Snodgrass tide gauge
   b. UNH bottom pressure
   c. Cape Cod Bay tidal analysis

3. Moored Temperature/Conductivity
   a. CODE from the bottom up
   b. Gulf of Maine moored temperatures and conductivities
   c. Gulf of Maine geostrophic circulation