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A CALIBRATION PROCEDURE FOR THE SBE 19 CONDUCTIVITY, TEMPERATURE, AND DEPTH (CTD) PROFILER

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This report describes a calibration procedure using linear and nonlinear parameter estimation techniques for a conductivity, temperature, and depth (CTD) profiler used in hydrographic survey applications. To ensure accurate sound velocity profiles, it is important that CTD sensors are properly calibrated. Techniques employed to calibrate these CTDs are described herein.

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I. ABSTRACT

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II. INTRODUCTION

The SBE 19 CTD is used for hydrographic survey applications to measure conductivity, temperature, and depth of seawater for computing the velocity of sound for bathymetry corrections. To ensure accurate measurements of these parameters, the individual sensors must be calibrated to accuracies of +/-0.001 Siemens/meter (conductivity), +/-0.005 degrees Celsius (temperature), and +/-0.5% full scale (pressure). A computed sound velocity accuracy of +/-0.01 meters/second can be obtained if individual sensors are calibrated to these accuracies. Since the CTD sensors are nonlinear devices, it is necessary to make a number of empirical measurements with each sensor over the entire measurement range and fit these measurements to mathematical models of the sensors.

At a given conductivity or temperature, the CTD profiler measures a Wien-Bridge oscillator frequency produced by its temperature and conductivity sensors and associated signal conditioning electronics. The CTD profiler's pressure sensor output voltage is amplified and digitized by a 12-bit analog-to-digital converter. The "true" value of each parameter is then measured by laboratory standards. The "true" and measured parameter values are then used to calculate a set of coefficients that can be used to convert frequency, temperature, and pressure to conductivity, frequency to temperature, or the digital number to pressure, according to the mathematical model of a given sensor, over the entire calibration range of the sensor (Seabird Electronics, Inc., 1989).

III. PRESSURE CALIBRATION

The mathematical model of the SBE 19 pressure sensor is linear and is given as

$$p=aN+b$$

where p is the absolute pressure (psia), N is a binary number related to the output voltage of the pressure sensor, and a and b are the coefficients to be determined. Since the equation for pressure is linear in the parameters a and b, a least-squares linear regression technique can be used to determine a and b for a given set of measurements of N and p.

A pressure transfer standard is used to induce a known pressure, p, on the SBE 19 pressure sensor for a period of 15 seconds. The number, N, measured by the instrument is averaged for the 15-second period. At least two (N, p) pairs are necessary to determine the coefficients a and b uniquely. The pressure transfer standard measures gauge pressure (psig), so atmospheric pressure must be added to its pressure readings in order to convert them to the absolute pressure units of the instrument. Additional measurements are determined at atmospheric pressure to complete the data set.

The coefficients determined from these data produce more accurate results when the hysteresis error of the pressure sensor is taken into account. It is necessary to take data throughout the full range of the sensor while increasing the pressure from atmospheric pressure to full scale and again while decreasing the pressure from full scale to atmospheric pressure to account for the hysteresis error. Data points are recorded at atmospheric pressure and at 60 psia increments while increasing pressure to 300 psia. Data points are then recorded at 60 psia increments while decreasing pressure to atmospheric pressure from 300 psia and again at atmospheric pressure. A total of 11 (N, p) pairs is obtained in this manner. These 11 (N, p) pairs are used to compute the coefficients a and b using a least-squares linear regression procedure. The Hxefficients can then be used to compute any pressure in the range of the instrument. A linear fit to the sensor is sufficient for a +/- 0.5% full-scale accuracy.

IV. TEMPERATURE CALIBRATION

The SBE 19 CTD profiler uses an aged thermistor for temperature measurement. The thermistor is aged to provide long-term measurement stability. The mathematical model of the temperature sensor of the SBE 19 CTD profiler is given by

$$T = \frac{1}{a + b\ln\left(\frac{f_0}{f}\right) + c\ln^2\left(\frac{f_0}{f}\right) + d\ln^3\left(\frac{f_0}{f}\right)} - 273.15$$

where T is the temperature in degrees Celsius, f is the frequency in hertz measured by the SBE 19 profiler, f_0 is frequency measured by the SBE 19 profiler at the minimum temperature calibration point, and a, b, c, and d are the coefficients to be determined. At first glance, this equation does not appear to fit a third-order polynomial model in the parameters a, b, c, and d; therefore, the coefficients could not be found using least-squares curve fitting. However, if we let

$$x=\ln(\frac{f_0}{f})$$

and

$$y=\frac{1}{(T+273.15)}$$

and substitute these definitions in the above equation, and solve for y in terms of x, the equation is transformed to

$$y=a+bx+cx^2+dx^3.$$

In this form, the equation is now a third-order polynomial in the variable, x. Since the transformed polynomial is linear in the parameters a, b, c, and d, these parameters can be determined using least-squares curve fitting techniques by solution of the normal equations. Unlike the pressure sensor, to achieve the desired accuracy of temperature, it is necessary to model the temperature sensor with a third-order polynomial in $\ln(f_0/f)$ since temperature sensors are strongly nonlinear.

The SBE 19 CTD profiler is placed in a temperature-controlled saltwater bath with a stability of +/-0.002 degrees Celsius over a period of 30 seconds. Frequency measurements made by the instrument are averaged for a period of 15 seconds. The "true" temperature of the saltwater bath is simultaneously measured using a National Institute of Standards and Technology (NIST) traceable standard platinum resistance thermometer (SPRT), accurate to +/-0.002 degrees Celsius.

At least four frequency-temperature pairs are necessary to determine uniquely the coefficients a, b, c, and d of the thermistor model. Nine frequency-temperature pairs are measured throughout a temperature range of 0 to 30 degrees Celsius. Four of the nine points are determined in a saltwater bath at 15 parts per thousand at evenly spaced temperature intervals. The additional five measurements are made in a saltwater bath at 35 parts per thousand at evenly spaced temperature intervals in a range of 0 to 30 degrees Celsius. All temperature measurements are made at atmospheric pressure. The nine frequency-temperature pairs are used to determine the coefficients a, b, c, and d. Coefficients determined from experimental third-order curve fits of 3 sensors have resulted in temperature residuals on the order of +/-0.001 degrees Celsius.

V. CONDUCTIVITY CALIBRATION

The SBE 19 CTD profiler measures the conductivity of seawater using a platinized, inductive conductivity cell. The mathematical model of the cell is given as

$$C = \frac{af^{m}+bf^{2}+c+dt}{10(1-9.57\times10^{-8}p)}$$

where C is the conductivity in Siemens/meter, f is the frequency in kilohertz measured by the CTD profiler, t is the temperature in degrees Celsius measured by the CTD profiler, p is the pressure in decibars measured by the CTD profiler, and a, b, c, d, and m are parameters to be determined.

Since the equation for conductivity is nonlinear in the parameter m, linear least-squares curve fitting by solution of the normal equations cannot be used as in the case of temperature and pressure. A variety of methods for nonlinear curve fitting is available to determine the parameters a, b, c, d, and m. All of these methods use an iterative scheme to search for the best or optimal parameters by minimizing the measurement errors of the sensor model using either a first-order steepest descent method or second-order Newton method or some combination of the two.

Steepest descent and Newton methods attempt to minimize a chi-square objective function by computing a new set of parameters from an initial approximation of the set or from the set of parameters determined in the preceding iteration. In this case the chi-square objective function is the difference between the conductivity measured by the instrument using the mathematical model of the sensor and the "true" conductivity determined by laboratory standards. The chi-square objective function is approximated by a linear vector equation when steepest descent methods are used or by a quadratic form when Newton methods are used. The direction of search for the new set of parameters is in a direction that decreases the objective function or the measurement errors. This direction corresponds to the negative gradient of the objective function.

In general, second-order methods are preferred for their desirable characteristic of rapid convergence when sufficiently close to the parameter set that minimizes the objective function. However, use of the second-derivative curvature information in the quadratic form of the second-order objective function approximation can be destabilizing if the model fits poorly or is contaminated by outlier points that are unlikely to be offset by compensating points of opposite sign. Second-order methods also suffer from an additional problem: if the initial approximation to the parameters is not a good one, then the quadratic form used to approximate the chi-square objective for the purpose of determining the optimal parameters is not a good approximation. Therefore, all that can be done is to step down the gradient toward the optimal parameters as done in a steepest descent method. Using a steepest descent method has its own disadvantages. It is generally slower than second-order methods and can sometimes oscillate around the optimal solution if the linear form of the objective function approximation is not a well-behaved function (Press et al., 1988).

The method chosen to solve for the parameters a, b, c, d, and m is a compromise method that employs the best of both the second-order and first-order methods. It is one of a family of quasi-Newton parameter estimation techniques known as the Levenberg-Marquardt method. The Levenberg-Marquardt method varies smoothly between a second-order method and a steepest descent method. It uses steepest descent when the parameter set is far from the optimum and switches continuously to a second-order method for rapid convergence as the optimal parameters are approached (Dennis et al., 1981).

For the SBE 19 profiler, the chi-square objective function is given as

$$\chi^2(a,b,c,d,m) = C - \frac{af^{m}+bf^{2}+c+dt}{10(1-9.75\times10^{-8}p)}$$

and the gradient of the objective function is given by

$$\nabla\chi^2 = \begin{pmatrix} \frac{\partial\chi^2}{\partial a} \\ \frac{\partial\chi^2}{\partial b} \\ \frac{\partial\chi^2}{\partial c} \\ \frac{\partial\chi^2}{\partial d} \\ \frac{\partial\chi^2}{\partial m} \end{pmatrix}$$

where

$$\frac{\partial\chi^2}{\partial a} = -\frac{f^{m}}{10(1-9.57\times10^{-8}p)}$$

$$\frac{\partial\chi^2}{\partial b} = -\frac{f^{2}}{10(1-9.57\times10^{-8}p)}$$

$$\frac{\partial\chi^2}{\partial c} = -\frac{1}{10(1-9.57\times10^{-8}p)}$$

$$\frac{\partial\chi^2}{\partial d} = -\frac{t}{10(1-9.57\times10^{-8}p)}$$

$$\frac{\partial\chi^2}{\partial m} = -\frac{af^{m}\ln(f)}{10(1-9.57\times10^{-8}p)} .$$

The initial approximation to the conductivity parameter set is the set of parameters determined the last time the instrument was calibrated. Since the conductivity cell calibration is relatively stable over time, using this initial approximation will start the algorithm at a point very near the new optimal parameter set. As a result, the algorithm will spend the majority of its time using the second-order method, so convergence will be very rapid. Experience with the algorithm has demonstrated that convergence to a new set of conductivity parameters is achieved in 200 or less iterations when the initial approximation to the parameter set is the set determined from the previous calibration. Conductivity residuals from these computed parameter sets have residuals less than +/-0.0005 Siemens/meter.

The procedure for calibrating the conductivity sensor is to place the sensor in a temperature-controlled saltwater bath. The conductivity dependent frequency measured by the instrument is averaged for a period of 15 seconds. The temperature of the water is measured simultaneously using an NIST traceable SPRT, and samples of the water are captured during the measurement. The conductivity of the captured samples is determined using a laboratory salinometer having an accuracy of +/-0.00002 conductivity ratio (+/-0.0002 Siemens/meter). Nine conductivity-frequency-temperature-pressure quadruples are measured throughout a temperature range of 0 to 30 degrees Celsius. Four of the nine points are determined in a saltwater bath at 15 parts per thousand at evenly spaced intervals. The additional five measurements are made in a saltwater bath at 35 parts per thousand at evenly spaced intervals in a range of 0 to 30 degrees Celsius. A final measurement is made in air to provide for a zero conductivity measurement (infinite resistance between the conductivity cell electrodes). All conductivity measurements are made at atmospheric pressure. These ten quadruples are used to determine the coefficients a, b, c, and d.

VI. CONCLUSION

The procedure developed for calibrating SBE 19 CTDs provides for conductivity measurement accuracy of +/-0.001 Siemens/meter, temperature measurement accuracy of +/-0.005 degrees Celsius, and pressure measurement accuracies of +/-0.5% full scale. A computed sound velocity accuracy of better than +/-0.01 meters/second can be obtained from CTD measurements made with an SBE 19 CTD calibrated using the procedures described.

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