Dynamic Response of CTD Pressure Sensors to Temperature

S. M. CHISWELL

Joint Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii

(Manuscript received 5 September 1990, in final form 27 February 1991)

ABSTRACT

Pressure sensors used in CTDs (conductivity temperature depth) respond to transients in temperature. It is often assumed that these transients have a negligible effect on pressure. However, in a Sea-Bird CTD used in Hawaiian waters, these transients lead to pressure errors as high as 8 db.

We describe how we correct these errors using linear system theory by computing the response function of the pressure sensor to temperature transients. The CTD housing insulates the pressure sensor from the water to some extent, so that the effective response function is a combination of the intrinsic response of the pressure transducer convolved with a response function due to transfer of heat through the housing. Using this method, pressure is corrected to within 1 db.

The impulse response functions for two similar pressure tranducers are quite different, probably due to small manufacturing variations. Thermal insulation of pressure sensors also varies from CTD to CTD. The net effect is that the response functions vary considerably from CTD to CTD.

1. Introduction

A Sea-Bird SBE-9 CTD has been used since October 1988 in the Hawaii Ocean Time Series (HOT) program. HOT is part of the World Ocean Circulation Experiment (WOCE) repeat hydrographic sampling program. Cruises are made at approximately monthly intervals to a site 100 km north of Oahu, Hawaii. Up to 20 CTD casts are made at the site during each cruise, mostly to 1000 db, although one cast each cruise is made to 4500 db.

Early on in the HOT program, it became apparent that the CTD-measured pressure suffered from some form of hysteresis. The pressure when the CTD was back on deck at the end of a cast was often as high as 6 db. We initially attributed these high end-of-cast pressures to a miscalibration of the pressure sensor. However, later work showed that the pressure errors were due to the response of the pressure transducer to transients in temperature. We now correct pressure using a standard linear response theory (e.g., Bendat and Piersol 1966), where the output of the pressure sensor can be regarded as a sum of linear responses to both pressure and temperature.

This article documents the pressure correction techniques used in the HOT program. Its aim is to demonstrate the procedures used to determine the response functions, to quantify the magnitude of the pressure corrections, and to describe the algorithms implemented to correct pressure.

Sea-Bird CTDs use Paroscientific Digiquartz pressure transducers (Paros 1976). The sensing element in these transducers is a quartz oscillator whose resonant frequency varies with applied stress. Digiquartz transducers have a calibration equation of the form (Busse 1986):

$$P_m = C\left[1 - \left(\frac{\nu}{\nu_0}\right)^2\right]\left\{1 - D\left[1 - \left(\frac{\nu}{\nu_0}\right)^2\right]\right\}, \quad (1)$$

where P_m is the measured pressure; ν is the sensor output frequency; and C, D, and ν_0 are calibration coefficients. Paroscientific have recognized that the output frequency is also temperature dependent, and in their standard temperature compensation, express the calibration coefficients as power series of the sensor temperature T_d, which is measured with a solid-state device attached to the transducer. With this compensation, the sensors are claimed to be accurate to 0.02% of full scale over the operating range (−54° to 107°C). However, as Busse (1986) states:

> [Eq. (1)] does not include terms for thermal rates or temperature gradients which can be presumed small for most applications,

thus, Eq. (1) is valid only when temperature changes are so slow that the system can be regarded as being in a steady state. As will be shown later, this is not the case for our CTD measurements.

Several different model sensors are available for Sea-Bird CTDs, depending on the pressure range of interest.

Corresponding author address: Dr. S. M. Chiswell, Joint Institute for Marine and Atmospheric Research, University of Hawaii at Manoa, 1000 Pope Road, Honolulu, HI 96822.

The sensor can be mounted either inside the CTD pressure casing or in an external module. The main Sea-Bird CTD used in the HOT program has a 6800 db (10 000 psi) transducer mounted internally. The second CTD used in the HOT program has a similar pressure sensor mounted in an external casing.

This paper has particular relevance to Sea-Bird CTDs using 10 000-psi sensors. However, the techniques we describe are quite general and can be applied to any CTD.

2. Linear system theory

For the purposes of defining our terminology, we give a brief review of the linear system theory (e.g., Bendat and Piersol 1966).

In a linear system, the output $y(t)$ is computed from the time varying input $x(t)$ as

$$y = f * x, \tag{2}$$

where $*$ signifies the convolution integral

$$f * x = \int_{-\infty}^{\infty} f(\tau)x(t-\tau)d\tau. \tag{3}$$

The impulse response function f is the response of y to a unit impulse in x. For real systems, the output is a response to the past history of x only, and $f(\tau) = 0$ for $\tau < 0$.

In principle, if both x and y are measured, f could be computed by deconvolving x from y. However, it is generally easier to impose the input as either a constant value (steady state) or a step function. These each put different constraints on f as shown in the next two sections.

a. Steady-state input

If the input is constant in time, $x(t) = x_0$, then, substituting into Eq. (3):

$$y = f * x = x_0 \int_{-\infty}^{\infty} f(\tau)d\tau$$

or,

$$\int_{-\infty}^{\infty} f(\tau)d\tau = \frac{y}{x_0}. \tag{4}$$

Thus, the area under the response function represents the response of y to a constant input, i.e., it is the slope of the calibration when y is plotted as a function of x.

If the system is properly calibrated for steady-state conditions, y is likely to be either insensitive to x ($\int f dt = 0$) or will be an estimate of x itself ($\int f dt = 1$).

b. Step function input

If the input is a step function, with amplitude X, $x(t) = \{x_0 + X$ for $t > 0$; x_0 for $t < 0$, we note that the derivative is

$$\frac{\partial x}{\partial t} = X\delta(t),$$

where $\delta(t)$ is the Dirac delta function. Then, since

$$\frac{\partial y}{\partial t} = \frac{\partial(f * x)}{\partial t}$$

and, from the properties of convolution, $[\partial(a * b)/\partial t = a * \partial b/\partial t]$, we get:

$$\begin{aligned}\frac{\partial y}{\partial t} &= f * \frac{\partial x}{\partial t} \\ &= f * [X\delta(t)] \\ &= Xf\end{aligned}$$

or

$$f = \frac{1}{X}\frac{\partial y}{\partial t}. \tag{5}$$

Thus, if one can impose x as a step function, the response function can be computed directly from the first derivative of the output.

3. Linear response model of a CTD

In order to correct the pressure for temperature transients, we take a purely empirical approach and neglect the details of how the pressure is actually measured. We treat the pressure sensor as a "black box" having the measured pressure P_m as its output. [It should be noted that this pressure has already been corrected according to Eq. (1) for steady-state temperature effects.]

We assume that the pressure sensor responds to two inputs: the true pressure P and the temperature of the sensor T_d. Equation (2) can be generalized for a system having two inputs where the output is a linear sum of the responses to the individual inputs:

$$P_m = P + f * T_d. \tag{6}$$

Here, we assume that apart from its transient response to temperature, the pressure sensor has been properly calibrated.

In Sea-Bird CTDs, the sensor is physically insulated from the water, and its temperature changes primarily by conduction of heat through the CTD casing. In practice, T_d cannot be controlled directly, making it difficult to impose it as step function. However, T_d can be regarded as a response to the external (water) temperature, and it can thus be written as

$$T_d = g * T. \tag{7}$$

Equation (7) thus models the diffusion of heat from the seawater into the pressure sensor (or vice versa). Substituting for T_d into Eq. (6), we get:

$$P_m = P + f*(g*T),$$

and, because convolution is associative, we can thus write the measured pressure in terms of a response to the external temperature:

$$P_m = P + h*T.$$

The true pressure P is thus calculated as

$$P = P_m - h*T. \quad (8)$$

The response function h is thus a combination of the intrinsic response of the pressure transducer and of the transfer of heat to the sensor.

Equation (8) is clearly limited to the degree to which the Digiquartz sensor acts as a linear system. The response functions g and h are relatively easy to determine—one only needs to lower the CTD quickly into a bath of cold water to impose a step function in T.

4. Experimental procedures

The experimental setup consists of a well-insulated thermostatically controlled water bath deep enough to hold the CTD. The volume of water is about 62 l, and a pump with a flow rate of about 20 l min^{-1} circulates the bath water to prevent it from stratifying. A pulley system allows the CTD to be lowered into the water fast enough to effectively impose a step function in external temperature. The CTD is connected through flexible piping to a dead-weight pressure tester, which enables us to impose pressures up to 5000 db. A second Paroscientific Digiquartz transducer kept at a constant temperature is also connected to the dead-weight tester and is used as a reference sensor to measure the imposed pressure. (This reference sensor was calibrated independently using a dead-weight tester.) Imposed pressure P, CTD pressure P_m, water temperature T, and internal CTD temperature T_d are logged with a computer.

Two sets of experiments were performed. The first was designed to determine if the steady-state calibrations were correct. The second set was designed to determine the response functions g and h.

a. Steady-state calibration

Steady-state calibrations of the temperature and pressure sensors showed that the calibrations provided by Sea-Bird and Paroscientific for both CTDs were within claimed specifications, except that the sensor temperature for the internal transducer had an offset

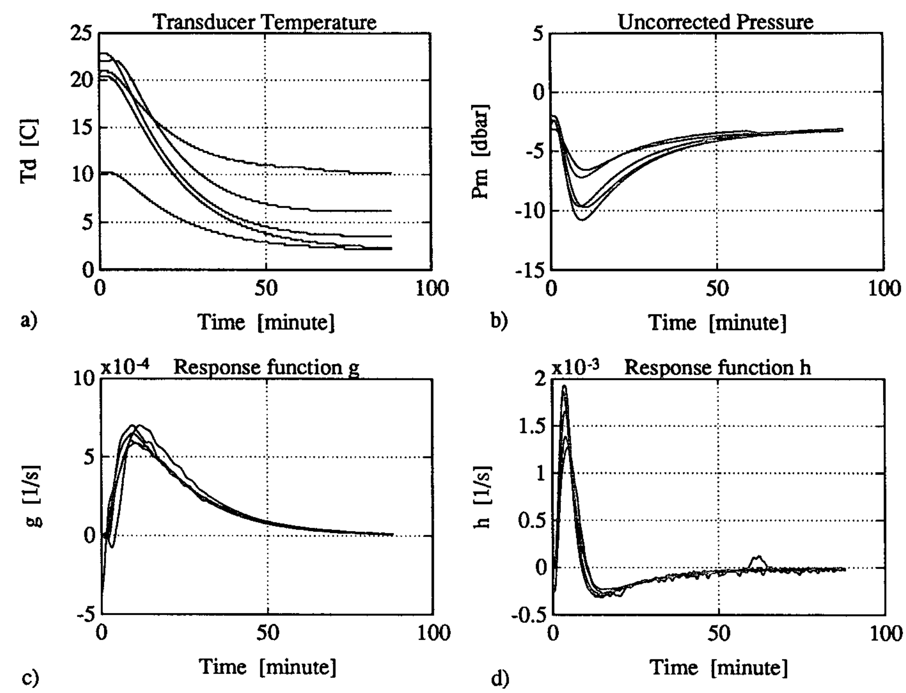

FIG. 1. Results from five tests where the CTD with an internal pressure sensor was "plunged" into a bath of cold water after it had been allowed to equilibrate to an initial temperature. In all tests the plunge occurred at time $t = 0$, the initial transducer temperature shows the initial temperature of the CTD, and the final transducer temperature shows the bath temperature. (a) Transducer temperature T_d; (b) CTD pressure P_m; (c) response functions g calculated from the first derivatives of curves shown in (a); and (d) response functions h calculated from the first derivatives of curves shown in (b).

of about 1.8°C. Over a range of 1°–20°C, the pressure showed a maximum error of 5 mb.

Thus, we use Eq. (4) to put conditions on g and h:

$$\int_{-\infty}^{\infty} g dt = 1, \quad \text{and} \quad \int_{-\infty}^{\infty} h dt = 0. \qquad (9)$$

b. CTD response functions

The response functions g and h were determined by imposing a step function in T keeping the pressure at one atmosphere (i.e., no applied pressure). The CTDs were allowed to equilibrate to laboratory temperature for several hours, and then lowered upside down into the water bath so that the pressure sensor was just at the water level. This insures that the imposed pressure was less than 5 mb (although if one measures it, minimizing the imposed pressure is not necessary).

Several runs were made with differing water bath temperatures (Figs. 1 and 2). The responses of the two CTDs are quite different. The temperature of the internal transducer takes about 13 min to drop by $1/e$ of its original value, compared with 5 min for the external sensor. For a temperature step of about 22°C, the internal sensor has a pressure response of about 8 db, with the largest pressure deviation occurring about 9 min after the temperature step. The external sensor has a response about twice as large in the opposite direction, and maximum pressure occurs about 7.5 min after the step.

Individual response functions, g and h, calculated using Eq. (5) show a reasonable degree of repeatability from run to run.

For each CTD, we computed the mean impulse response functions (Fig. 3) as the average of each run, making sure that the averaged response functions obeyed the constraints in Eq. (9).

It should be stressed that it is critical that the final response functions have exactly the integrals specified in Eq. (9). For example, the positive and negative lobes in h should be forced to have equal areas. Otherwise, the convolution in Eq. (8) will introduce a slow drift in the corrected pressure.

As formulated here, the response functions g and h are measured directly. Once g and h are determined, f might be computed by deconvolving them. Here, however, we noticed that h is very close (within experimental error) to being proportional to the first derivative of g ($h = a\partial g/\partial t$). This makes the determination of f simple, since in the digital domain, a convolution function with two elements,

$$f = \left[\frac{a}{(\Delta t)^2}, -\frac{a}{(\Delta t)^2}\right],$$

performs a backwards differentiation (scaled by a).

The short length of f reflects the fact that the response of the pressure sensor to temperature transients is much shorter than the time scale of diffusion of heat into the CTD housing.

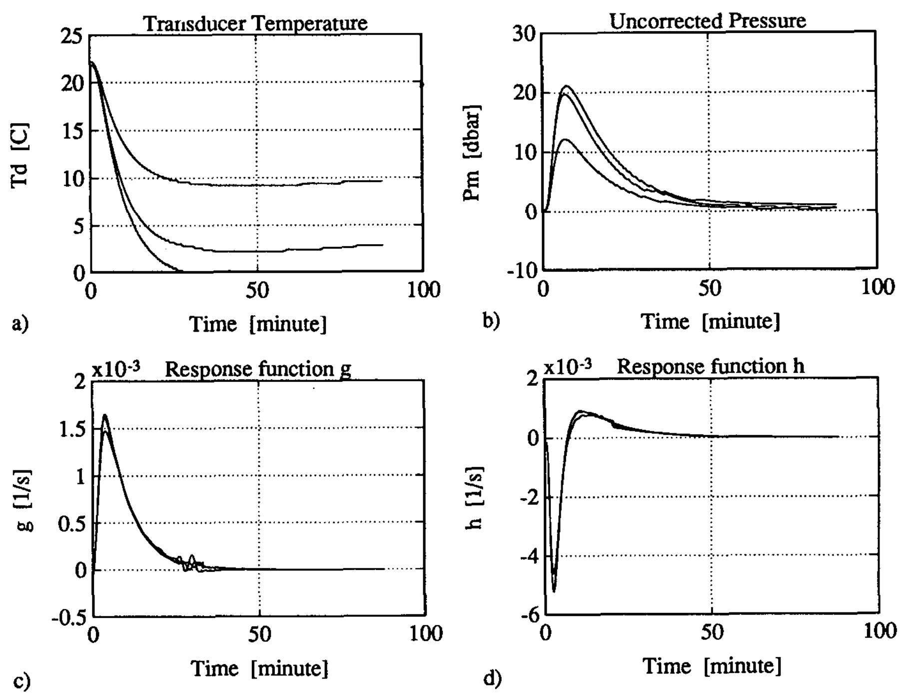

FIG. 2. As in Fig. 1, except for a CTD with an external pressure sensor.

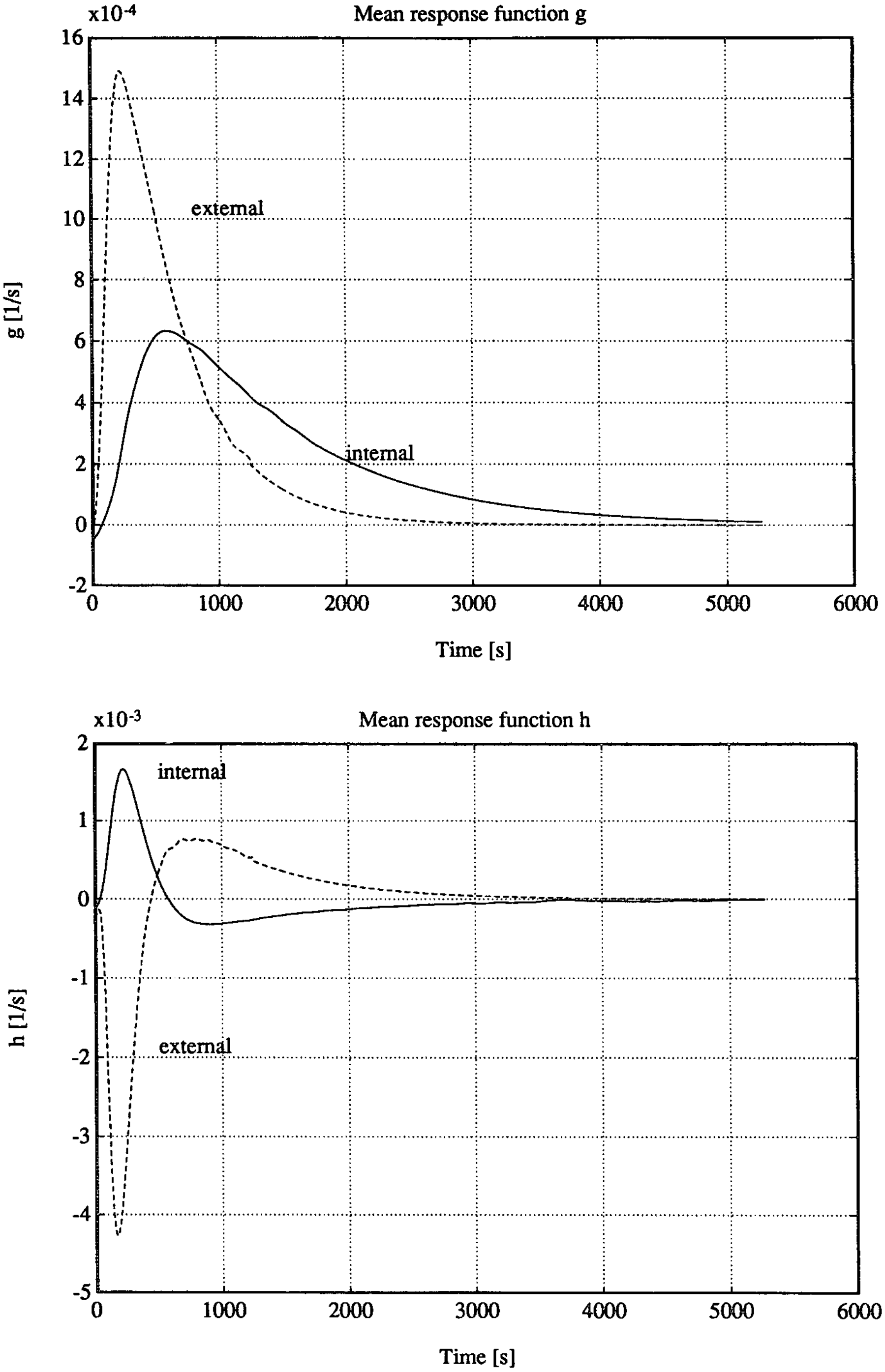

FIG. 3. Average impulse response functions g and h for both CTDs.

5. Implementation of the algorithms

Equations (6) and (8) suggest two methods for correcting the pressure. In principle, since T_d is measured in the Sea-Bird CTD, one could correct pressure using Eq. (6). Since f is so much shorter than h, this involves far fewer calculations than does using Eq. (8). In practice, however, T_d in the Sea-Bird CTD is measured with low precision (as can be seen by the steps in T_d visible in Fig. 1), so that the term $f * T_d$ consists of a series of delta functions. Either this term or T_d has to be low-pass filtered, and some of the advantages of having a short response function are lost.

In the processing employed as part of the HOT program, we correct pressure using Eq. (8). Practical implementation of this convolution technique is hindered by the length of the filter h in two respects. The first is that, in principle, one should record the CTD temperature for at least as long as the length of the convolution filter before making a CTD cast. It is usually difficult to measure on-deck pressure and temperature for very long prior to a cast.

Consequently, we have devised an algorithm that makes an estimate of the on-deck history of T from the value of T_d at the beginning of the cast. We assume that T was constant prior to the cast ($T = T_{\rm air}$ for $t < 0$) and that the CTD had reached equilibrium with air temperature. (This may not be true if the CTD is allowed to sit in the sun, but it is usual to keep the CTD in the shade between casts.)

We use as a initial estimate of $T_{\rm air}$ the first available value of T. We then compute an estimate of T_d using Eq. (7). Since Eq. (7) is linear, a new value of $T_{\rm air}$ can be calculated so that the mean difference between T_d and $g*T$ over the length of g is zero:

$$T_{\rm air} \rightarrow T_{\rm air} + \frac{1}{\alpha}\int (g*T) - T_d dt,$$

where α scales the response of T_d to a unit step function in T. In other words, an estimate of the history of T is made from the observed difference between T_d and $h*T$.

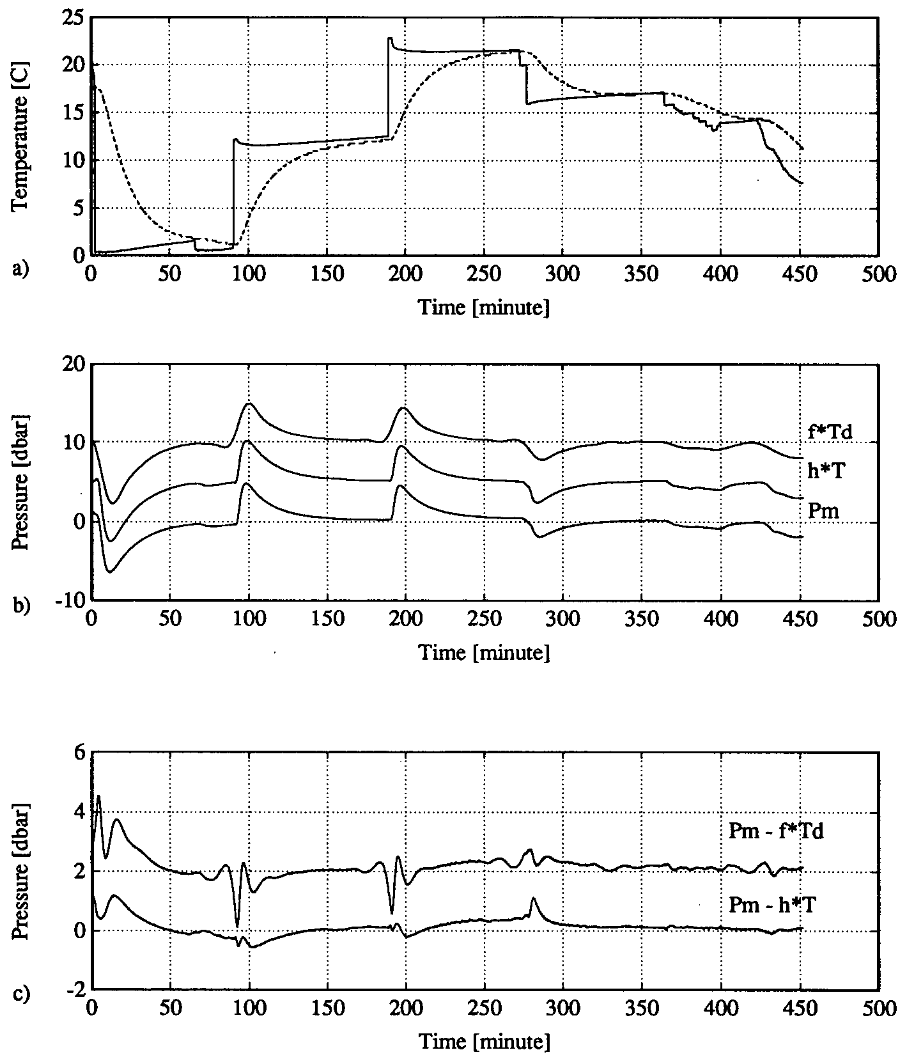

FIG. 4. Test of pressure corrections at atmospheric pressure for the CTD with an internal sensor. The pressure was kept constant while the temperature was varied. (a) Shows T (solid) and T_d (dashed) as a function of time. (b) Shows the measured pressure P_m and the two calculated responses $h*T$ and $f*T_d$ offset by 5 and 10 db, respectively. The term $f*T_d$ has been low-pass filtered with a cutoff frequency of 1/1000 s^{-1}. (c) Shows the corrected pressure using the two forms of the correction, $P_m - h*T$ and $P_m - f*T_d$ (offset by 2 db).

The second consequence of the long length of h is that the convolution becomes computationally prohibitive when applied at full temporal resolution. Typically, in the HOT program, data are collected at 24 samples per second so that a 5000-s convolution requires a 120 000-point filter. Fortunately, the convolution is smooth enough that it can be calculated at much lower temporal resolution from a decimated time series. In our data processing, the convolution is applied at 5-s resolution, reducing the calculations in the convolution by a factor of 14 400 compared with using full resolution.

6. Tests of the algorithms

Two sets of experiments are described here that were designed to test how well a linear response models sensor behavior. The first test was conducted at zero imposed pressure. Nonlinear effects are most likely to be exhibited at high imposed pressures, and the second set of experiments was designed to test how well Eq. (8) performs under high pressure.

a. Test of linearity at zero pressure

Tests of how well the sensor performs as a linear system were made by leaving the internal-sensor CTD in the bath and changing T by adding ice and hot water alternately. An example is shown in Fig. 4, where T changed over a range of 23°C as a series of steps and more gradual functions.

The uncorrected pressure had a range of 10 db. Figure 4 shows that either Eq. (6) or (8) can be used to

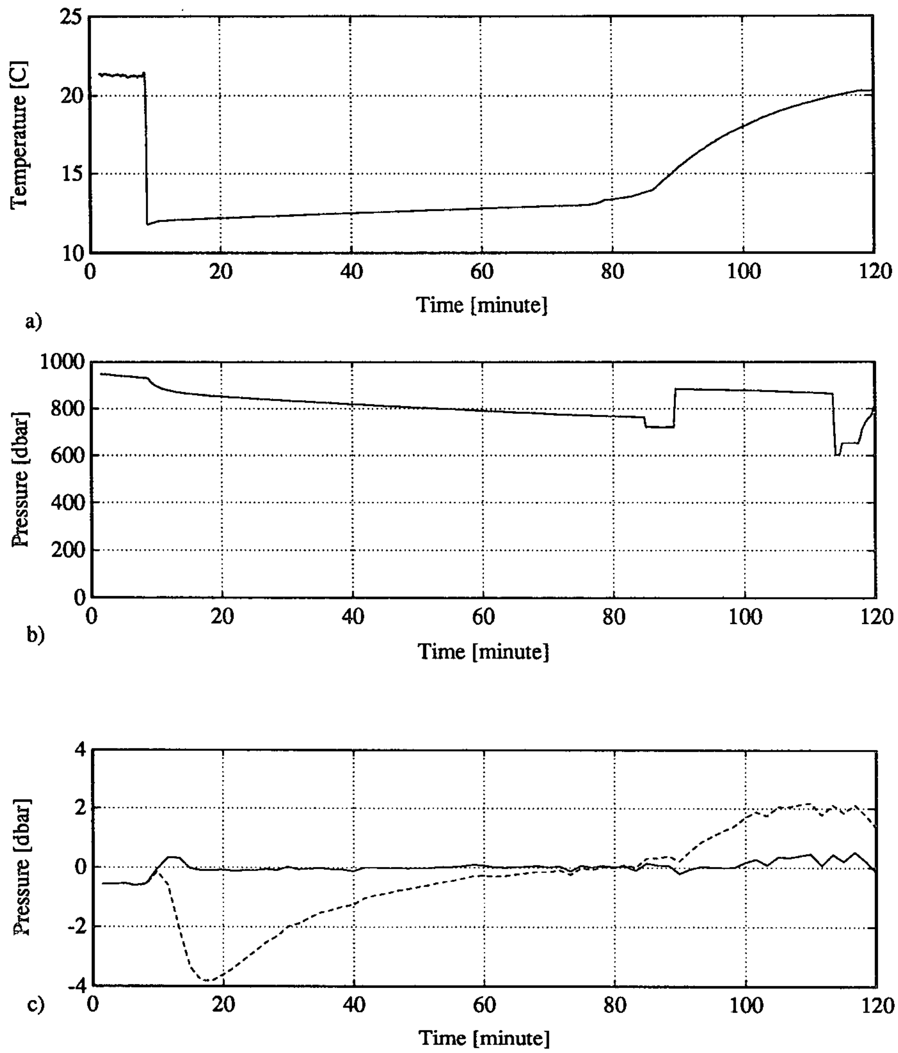

FIG. 5. Test of linearity at high pressure. The pressure was kept between 800 and 1000 db while the temperature was varied. (a) T as a function of time, (b) imposed pressure, and (c) difference between imposed pressure and uncorrected pressure ($P - P_m$, dashed line) and the difference between imposed and corrected pressure [$P - (P_m - h*T)$, solid line].

correct the pressure reasonably well, although Eq. (8) appears to perform better.

b. Test of linearity under high pressures

Tests of the linearity of the system were repeated with the CTD under pressure. Figure 5 shows the results of one such run, where the pressure was kept near 900 db as the CTD was lowered into the bath. With a step in T of 10°C, the difference between the pressure standard and uncorrected CTD pressure showed a range of 5 db, while the corrected pressure differed from the standard by less than 1 db.

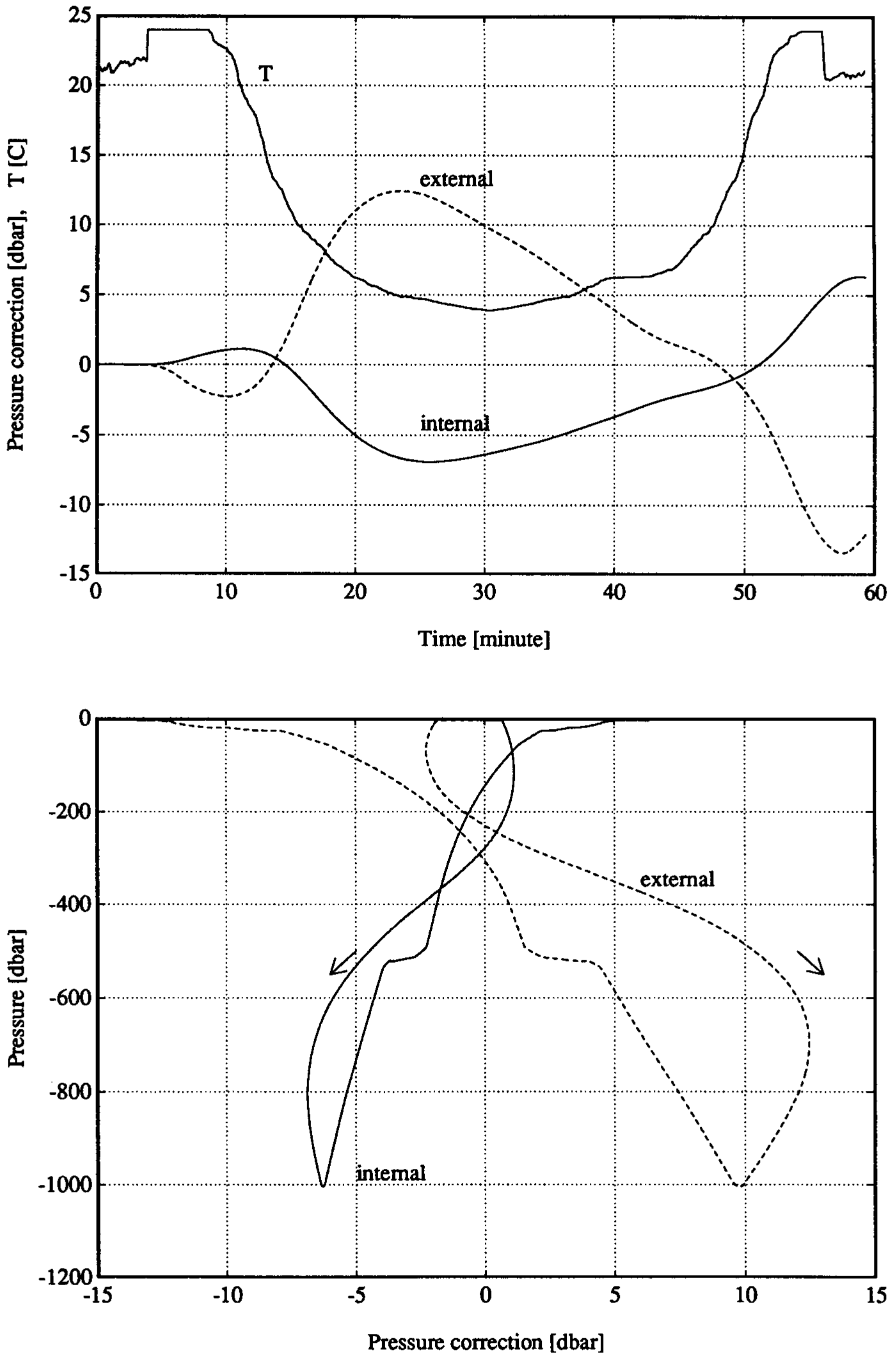

FIG. 6. (a) Temperature from a representative 1000-db cast plotted as function of time. For this cast, some on-deck information is available (temperatures about 21°C). Also plotted are the pressure corrections, $h * T$, that would be applied to the internal sensor (solid line) and external sensor (dashed line). (b) Pressure corrections plotted as function of pressure for the same cast.

7. Typical CTD casts

To illustrate the magnitude of pressure errors in typical CTD casts, we have computed the pressure correction term $h*T$ for each sensor for representative 1000-db and 4500-db CTD casts from the HOT deep-water station (Figs. 6 and 7).

The upper panels in these figures show the corrections as a function of time, the lower panels show the corrections as a function of pressure. For these casts, some on-deck information is available; on-deck temperatures are about 2°C lower than sea surface temperature. As the CTD enters the water, the resulting step in T produces an initial error, which, for the in-

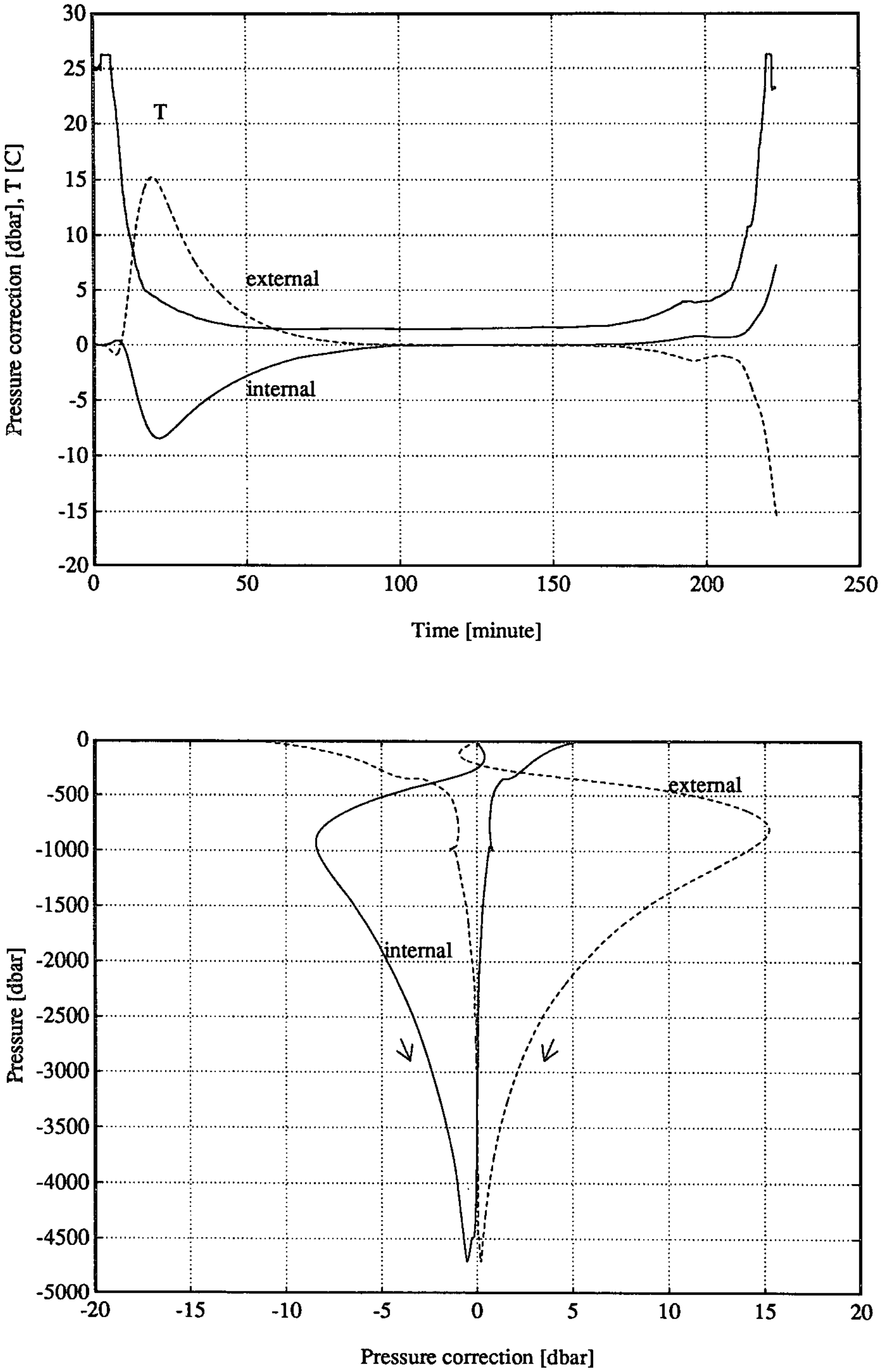

FIG. 7. As in Fig. 6, except for a 4500-db cast.

ternal sensor, is about 1.5 db and persists until the CTD reaches about 200 db.

The largest effect of $h * T$ occurs after the CTD passes through the thermocline. For typical lowering rates, the transition through the thermocline is short relative to the length of h, and the associated pressure responses are about half the size of those caused by a step function having the same amplitude as the cross-thermocline temperature difference.

For the internal sensor, maximum errors in pressure are about 8 db. For the external sensor, the errors are about twice as large and have the opposite sign.

8. Discussion

It is clear from Figs. 6 and 7 that for our CTDs, the maximum errors are about twice the pressure accuracy requirements of WOCE (±3 db; U.S. WOCE 1989) and warrant correction. A linear response correction reduces the pressure errors to within the WOCE requirements.

The response function g models the transfer of heat between the ocean and the transducer. This heat transfer is primarily through conduction, and thus g is very much dependent on the physical configuration of the pressure sensors. The response for our external sensor is much faster than that for our internal sensor because the external housing is physically much smaller than the CTD. Our CTD with internal sensor was manufactured in 1987; the pressure sensor is set back from the CTD endplate, but is otherwise uninsulated. In October 1988, Sea-Bird began to add insulation to minimize the thermal responses (Nordeen Larson, personal communication 1990). Our instrument is thus probably typical of the older uninsulated CTDs (about half of the 150 Sea-Bird CTDs in use are uninsulated). Insulated internal sensors have much longer and lower g response functions.

The response functions h shown here have opposite signs because the intrinsic responses of the sensors (f) have different signs, even though they have the same design. Thus, it appears that variations in the internal construction of the transducers, for example, the thickness of the brazing (which may lead to bimetallic strip-like effects; Nordeen Larson, personal communication 1991), could have a large effect on f.

An alternative mechanism (Nordeen Larson, personal communication 1991) may be that f is dependent on the temperature sensitivity of the transducer crystal. These crystals are designed to have minimum sensitivity at the operating temperature. However, the temperature at which the minimum sensitivity actually occurs can vary by up to 30°C for different production crystals. Consequently, the slope of the temperature sensitivity at oceanic temperatures could have either sign.

We do not know yet how stable these functions are in time. The g functions are likely to be stable unless the physical configuration of the CTD is changed, but it is possible that f changes as the sensors age.

Response functions for other CTDs or other sensors are likely to be different from those presented here. Digiquartz sensors are used in most Sea-Bird SBE-9 CTDs, but high-quality strain gauges, like the Paine titanium sensors, are supplied by Sea-Bird for less-demanding work; these sensors typically exhibit transient responses that are a factor of 2 or more larger than Digiquartz sensors (Nordeen Larson, personal communication 1990). Neil Brown CTDs use analog circuitry to compensate for temperature effects. At least in some instances, Neil Brown CTDs have responses larger than those discussed here (Pierre Flament, personal communication 1990).

While this work was done with Sea-Bird CTDs using Digiquartz sensors, the techniques are quite general and can be applied to other makes of sensor or CTD. Thus, we strongly recommend that users compute response functions for their own CTDs. Fortunately, the experimental procedures to do so are very simple and are easily performed. Several "plunge" tests into different bath temperatures should serve to define the response functions adequately.

Acknowledgments. I would like to thank Jefrey Snyder for performing the laboratory tests, Eric Loucks for programing the algorithms discussed here, and Roger Lukas and Mark Wimbush for helpful discussions during this work. I would also like to thank Nordeen Larson at Sea-Bird for his assistance. This work has been supported under NSF Grant OCE-8717195; School of Ocean Earth Science and Technology contribution 2608; Joint Institute for Marine and Atmospheric Research contribution 91-240.

REFERENCES

Bendat, J. S., and A. G. Piersol, 1966: *Measurement and Analysis of Random Data.* John Wiley and Sons, 390 pp.

Busse, D. W., 1986: A temperature model for Digiquartz pressure transducers. Document No. 8110, Paroscientific Inc., Redmond, WA, 4 pp.

Paros, J. M., 1976: Digital pressure transducers. *Measure. Data,* **10,** 16–22.

United States WOCE, 1989: Implementation plan. United States WOCE Implementation Report No. 1, United States WOCE Office, College Station, TX, 176 pp.