Improving NBIS MK IIIB Measurements

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Abstract

In Neil Brown Instruments MK IIIB-CTDs (Conductivity Temperature Depth profilers), the system outputs for temperature, conductivity and pressure show some typical small amplitude deviations from smooth calibrations which should be corrected for to achieve the high accuracies required for the World Ocean Circulation Experiment (WOCE) Hydrographic Program (WHP).

1. Introduction

Since its invention more than 20 years ago, the MK IIIB-CTD (see Brown and Morrison, 1978) has proven to be an accurate and reliable tool in continuously measuring the three basic physical parameters of sea water necessary to determine its state: pressure, temperature and electrical conductivity. Although new technologies are available now, it is obvious that until these are as reliable as the MK IIIB, this instrument will for some years serve in international measuring campaigns like the ongoing WOCE Hydrographic Program (WHP).

Required accuracies in the WHP are extremely high (see WMO, 1988), namely 2 m°C, 0.05 %, and 0.002 PSU for temperature, pressure and salinity, respectively. It was only recently that careful laboratory calibrations and investigations of in-situ data, have revealed some typical features of MK IIIB measurements that display small deviations from low order smooth sensor calibrations and for which corrections are necessary to meet the WHP requirements. We demonstrate the existence of such small deviations typical for the MK IIIB and discuss how to treat them. However, we do not go further in data processing procedures, which is beyond the scope of this contribution.

We start with a discussion of the shape of the temperature sensor's calibration, which typically shows a strong nonlinearity, in some instruments even a discontinuity of several m°C in the calibration close to 0˚C. With present instrumentation, this feature can only be detected in careful laboratory calibration and only if calibration points at temperatures less 0°C are obtained. By a modification in the hardware, this discontinuity maybe shifted to –3°C outside the oceanic range.

The conductivity cell changes its geometry slightly, i.e. its cell constant and calibration, with temperature and pressure. This effect can lead to erroneous salinities in the deep sea of order 0.005 PSU. Compensation is demonstrated to remove these errors. Further, we describe a discontinuity of order 0.002 mS/cm in conductivity measurements which may occur around the mid-range of the sensor output at 32.768 mS/cm. It was first observed in the deep North

East Atlantic Ocean as a discontinuity in the relation of potential temperature and salinity, and then discovered on other instruments and in different water masses.

In the MK IIIB, a strain gauge sensor is used to measure pressure. It is well known that this type of sensor has a mechanical hysteresis and that it also changes calibration with temperature, both, statically and dynamically. Effects of hysteresis and static temperature response may lead to deviations from the basic loading calibration at fixed temperature by several dbar. The dynamic pressure response to sudden temperature changes may be of order 0.3 dbar/°C and higher, and thus may be relevant in strong temperature gradients as they occur, e.g., in the near surface thermoclines of the tropics. These features, too, can only be measured in laboratory experiments. We discuss methods how to compensate these responses.

2. Temperature Response Close to 0˚C

In the MK IIIB, the precision temperature is measured with a platinum resistance Pt100 at a resolution of 0.5 m°C in the oceanic range, i.e. roughly between –2°C and 29°C. To avoid mismatches in time constants of the (slow) platinum resistance and the (fast) conductivity cell, the original MK IIIB combines the signal of the Pt100 with the high pass filtered signal of a fast thermistor response, and it is this combined signal which is displayed on deck units and output to computer interfaces. We here deal only with slow temperature changes for which the combined output essentially is the same as for the Pt100 alone and which therefore can be used in the discussion below.

In 1990, a new International Temperature Scale, ITS_{90}, was established. It replaces the older International Practical Temperature Scale of 1968, $IPTS_{68}$, on which all MK IIIB CTD temperature sensors are calibrated by delivery from the manufacturer. A simple linear conversion from the $IPTS_{68}$ to the ITS_{90} for the oceanic range has been proposed by Saunders (1991) and is recommended for application by the Joint Panel on Oceanographic Tables and Standards JPOTS. The relation is

$$T_{90} = T_{68}/1.00024 \tag{1}$$

To consistently use the ITS_{90}, in the following all temperature corrections are referred to the ITS_{90}. Note that this conversion declines correction curves to lower values at high temperatures and that because it is linear, it does not affect the discussion below.

Usually, the platinum sensor is provided by the manufacturer together with an electronic card which carries the sensor's basic linear calibration on the $IPTS_{68}$. This internal calibration is such that the instrument has zero voltage output at 0°C, and it seems that at zero voltage output the analogue digital conversions gives rise to problems in all instruments tested.

In Figure 1 we display the corrections needed on three different instruments to be added to the temperature output TCTD to meet the ITS_{90}. The MK IIIB CTD 1069 (Figure 1a) is owned by the Alfred Wegener Institut, Bremerhaven, Germany, and was calibrated at the Scripps Institution of Oceanography (SIO) in April 1989 prior to use within the WHP in Antarctic waters. Therefore, many calibration points were taken especially close to and below 0°C. The shape of the calibration curve is striking: Although the calibration is almost linear, with a small quadratic term over most of the range, i.e., between 0°C and 25°C, we observe a strong discontinuity of 2 m°C at 0°C when proceeding to lower temperatures. The blow up in Figure 1d demonstrates this more clearly. No polynomial regression can properly approximate such a discontinuity. Not knowing about the SIO results, two MK IIIB CTDs, NB3 (Figure 1b) and NB2 (Figure 1c), owned by the Institut für Meereskunde in Kiel, IFMK, were

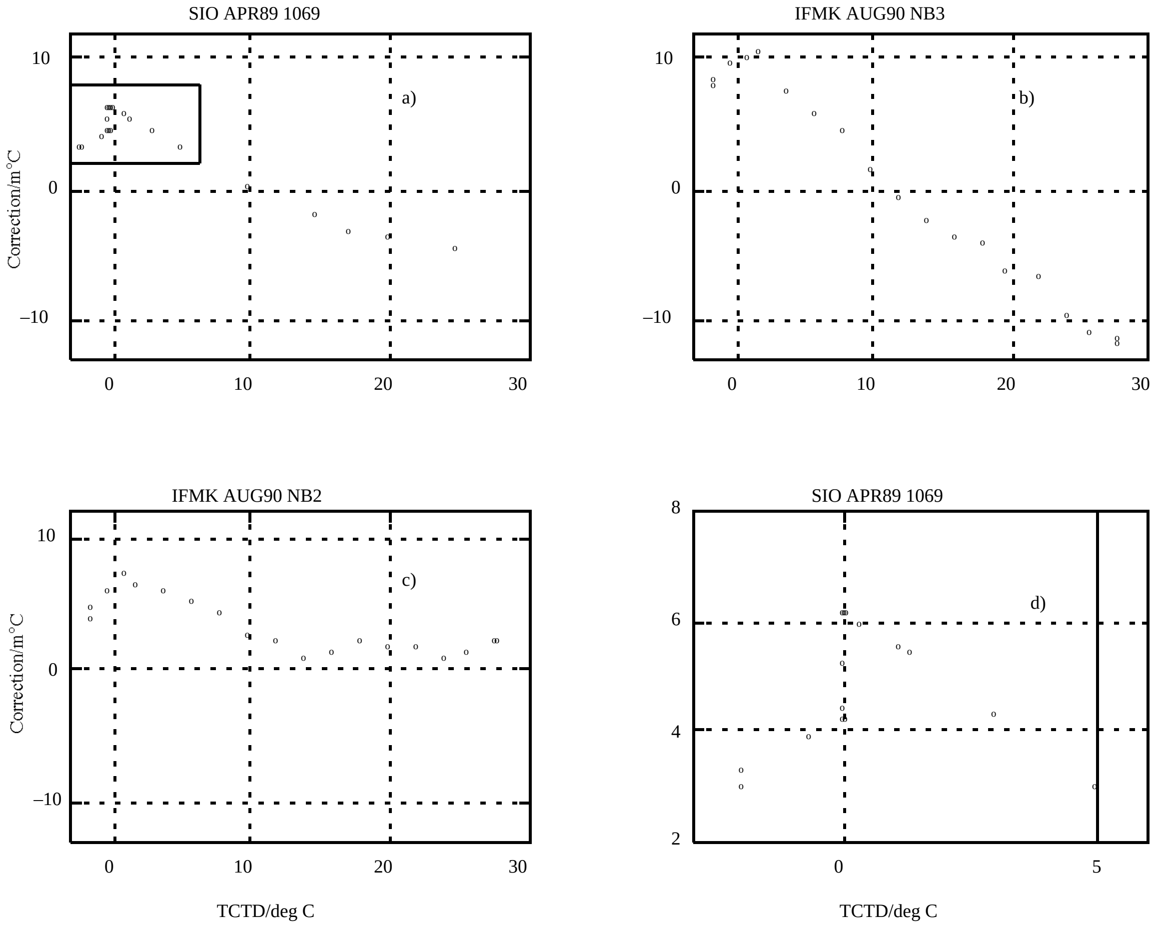

Figure 1: Corrections to be applied to basic temperature calibrations of MK IIIB CTDs to meet the ITS_{90} temperature scale: (a) S/N 1069 of the Alfred Wegener Institut, Bremerhaven, was calibrated at the Scripps Institution of Oceanography SIO in April 1989, (b) NB3 and (c) NB2 at the Institut für Meereskunde, Kiel. Note the strong nonlinear deviations of order 2 m°C from low order regressions close to 0˚C, which for S/N 1069 is blown up in (d).

calibrated in the institute's laboratory over the whole oceanic range in August 1990. Resolution of the IFMK calibration at 0°C and less was not required to be as good as in the SIO calibration because the instruments were to be used in the subtropics of the South Atlantic at temperatures above 0°C. Nevertheless, the discontinuity or at least strong nonlinearity of the calibration characteristics close to 0°C for both instruments are similar to that of the 1069 CTD calibrated at SIO.

Additional calibrations of several other MK IIIB temperature sensors (not shown here) were performed at SIO and at IFMK and at the Institute of Oceanographic Sciences in Wormley, UK (P.M. Saunders, personal communication, 1993) as well. All confirm these findings. Both, SIO and IFMK use Platinum reference thermometers Pt25, but bridges made by different manufacturers: that at SIO is made by Neil Brown Instruments NBIS, and a PTM bridge made by Sensoren Instrumente Systeme SIS is used at IFMK. Also, with a different type of CTD which resolves 1 m°C in temperature, IFMK could not determine a discontinuity at 0°C. From this we conclude that the discontinuity observed at 0˚C in temperature calibration of several MK IIIB CTDs at two calibration laboratories with different reference bridges, is inherent to MK IIIB CTDs and neither due to the calibration procedures nor the calibration instruments.

To meet the WHP requirements for precision in temperature, the observed deviations from smooth calibration curves at 0°C must be removed. For the MK IIIBs NB3 and the NB2 (Figure 1b and 1c), where deviations are strongly nonlinear but not really discontinuous, this was achieved by 5th order polynomial regressions with residuals less 1 m°C over the whole range and more than 10 degrees of freedom in the approximation. Such an approximation would not help in the case of the MK IIIB 1069 with its obvious discontinuity. In this CTD, the temperature range was shifted such that zero voltage now reads outside the oceanic range at –3°C. Note that by applying this procedure, the 0 °C display of the deck unit will be correspond to –3 °C in-situ temperature and that the high end reading will be shifted to lower values, too. Details of this hardware change are provided by SIO. It can also be performed at the manufacturer (now General Oceanics, Inc.).

3. Conductivity Corrections

In this paragraph the effects of temperature and pressure changes on the conductivity cell's response and a mid range discontinuity in conductivity measurements are discussed.

The MK IIIB conductivity cell is made of aluminum. It not only responds to changes in the electrical conductivity of sea water, but also to changes of temperature, T, as well as pressure, P, by mechanical deformations which change the cell's constant. If the basic response CCTD of the cell is converted to conductivity C by a polynomial POL(CCTD) valid at fixed temperature T0 and fixed pressure P0, the temperature and pressure compensated conversion maybe written as (Fofonoff et al., 1974)

$$C = W * POL(CCTD) \tag{2}$$

where the compensation factor W is given by

$$W = (1 + a*(T-T0) + b*(P-P0)) \tag{3}$$

The thermal and pressure linear expansion coefficients are a=–6.5E–6 and b=1.5E–8 (see Fofonoff et al., 1974) and the basically linear polynomial is calculated at T0 and P0. For laboratory calibrations it is convenient to have P0=0 and T0=20˚C. When the conductivity cell is calibrated while temperature and/or pressure are different from T0 and P0, respectively, the reference conductivity to be used for the calculation of the polynomial coefficients must be weighted with the compensation factor W. The effect of compensation is demonstrated in Figure 2. It shows the relation of potential temperature and salinity in the deep sea at 33˚N, 22˚W in the North East Atlantic Ocean. The cell was calibrated just before the cruise in the laboratory by changing the temperature in a bath of almost constant salinity close to atmospheric pressure. If one does not take into account the temperature compensation in determining the polynomial coefficients, the calculated salinity is off from the historic relation for this area (Saunders, 1986) by 0.005 PSU while compensation shifts conductivity such that salinity meets this classic relation.

Another problem with MK IIIB conductivity measurements becomes obvious from Figure 2. At potential temperature 2.1˚C, a sudden change in salinity occurs. It is not due to a change in water masses as careful inspection of many MK IIIB CTD profiles obtained with different CTDs in different ocean areas like the subtropical North East and South Atlantic,

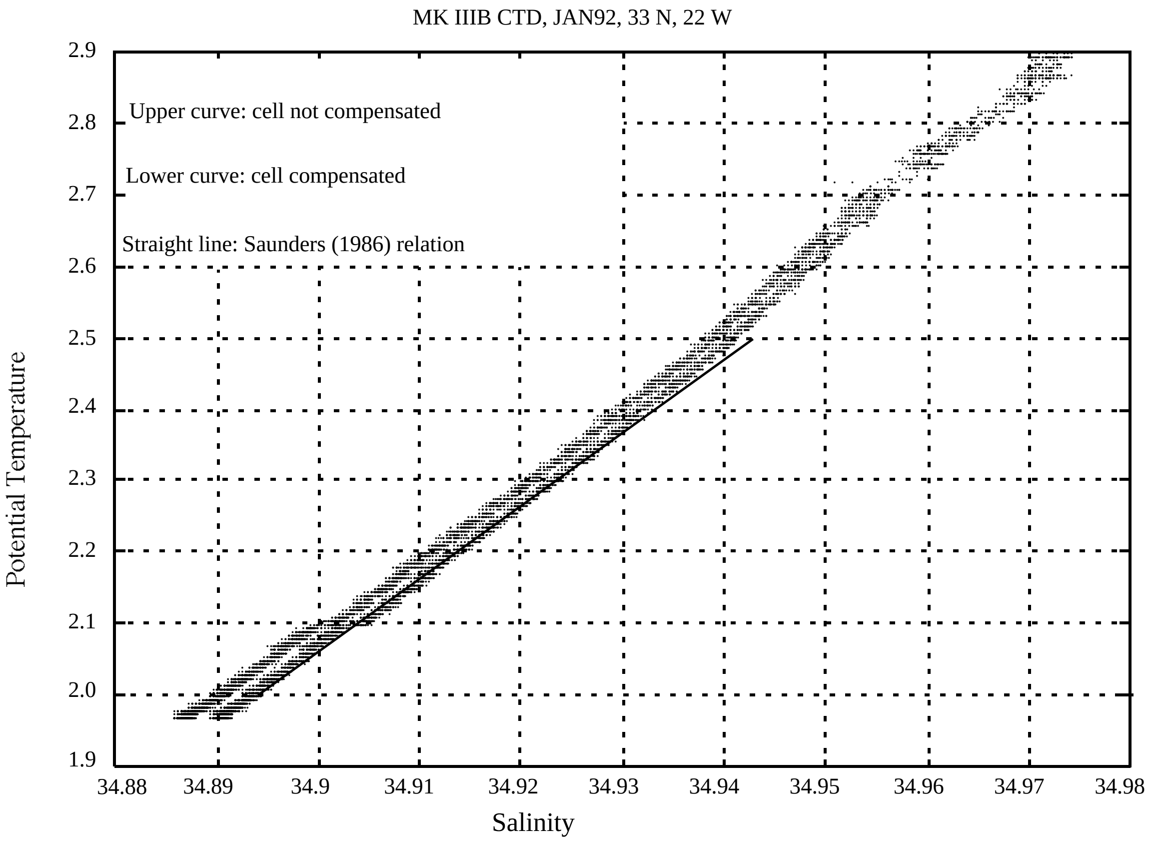

Figure 2: **Compensating for pressure and temperature responses of the conductivity cell improves the measured relation of potential temperature and salinity in the deep North East Atlantic, 33˚N 22˚W, to meet the classic linear relation proposed by Saunders (1986).**

have shown. Similar steps in salinity occur whenever the uncalibrated conductivity cell output passes through 2^{15}, i.e., the 32.768 mS/cm mid-range value.

The effect may best be demonstrated at a profile from the North East Atlantic where this value is passed twice on a CTD's way down to the bottom (Figure 3). The two jumps in the potential temperature salinity relation both show up at uncalibrated conductivity value CCTD=32.768 mS/cm. Coming from higher values while the CTD is lowered, the critical value is hold for a while before the output gets below. This causes the jump to higher salinities at 34.953 PSU. When the CTD is further lowered, a minimum in conductivity is passed. Under higher pressure conductivity increases, is hold again when the critical value is reached at 34.916 PSU, and this causes the jump back in salinity to lower values.

To remove these jumps is rather simple. Once the output is below the critical value of 32.768 mS/cm, an offset C32768 is added which is to be determined experimentally. For the CTDs under investigation, C32768 was between –0.002 mS/cm and –0.001 mS/cm. If this procedure is applied to measured data (Figure 4a), the jump in salinity is removed almost completely besides a small spike remaining at the lower end (Figure 4b). This spike is due to constantly held values of CCTD=32.768 mS/cm. It can be removed by vertical interpolation to achieve the final curve (Figure 4c).

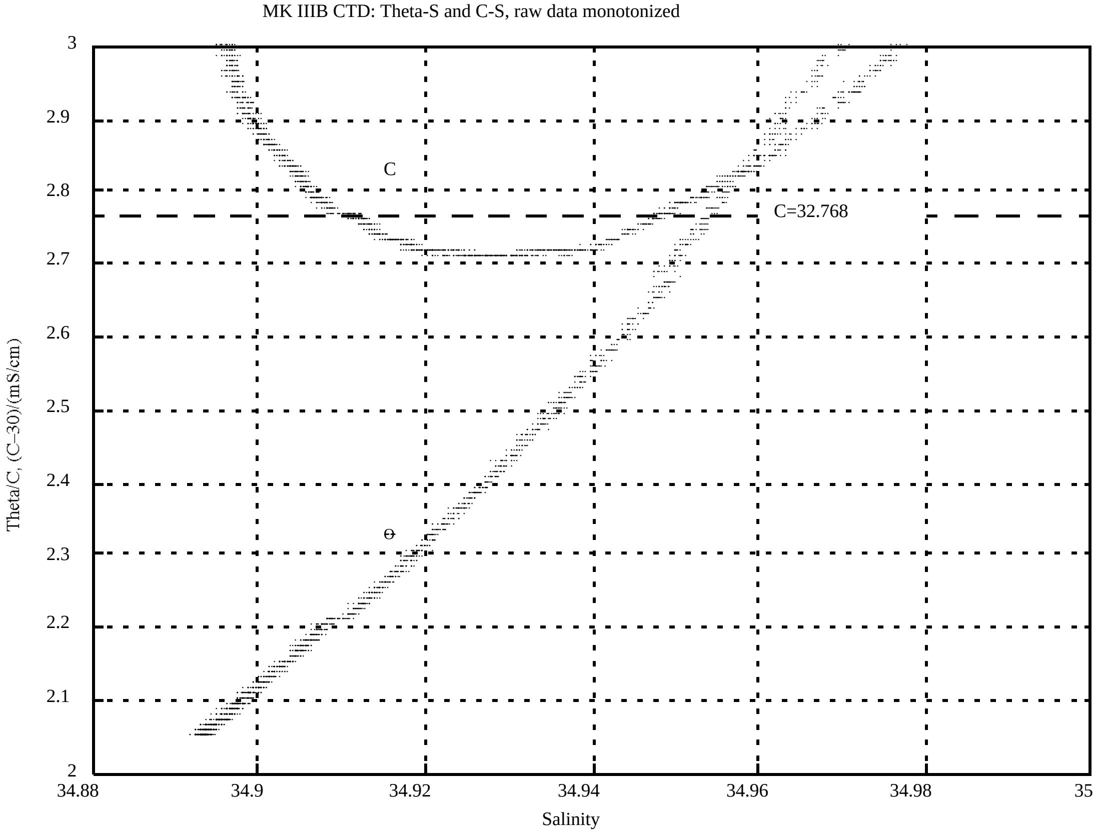

Figure 3: **Steps in the relation of potential temperature and salinity are caused by a discontinuity in the conductivity sensor's mid-range output at 32.768 mS/cm. Arrows denote the downward direction of the CTD. Note that conductivity output passes the critical value 32.768 mS/cm twice while the CTD is on the way down.**

4. Pressure Sensor Output Corrections

In the MK IIIB CTD a stainless steel strain gauge pressure transducer is used to measure pressure. The early models were produced by Standard Controls; later versions are by Paine Instruments, with no significant differences in their characteristics. The specifications quoted by the manufacturer are given in Table 1, and have been found to be generally conservative. These sensors have proven to be dependable and of adequate sensitivity. With an understanding of the function, and adequate corrections applied in processing, an accuracy of 2 dbar, or better, can be obtained under most conditions. The errors associated with the uncorrected pressure signal may not appear to be significant as far as pressure is concerned. However, the impact on calculated parameters should not be forgotten; an uncorrected error of 2 dbar in pressure produces an error in calculated salinity of approximately 0.001.

4.1 Static and Dynamic responses

There are several characteristics of strain gauge transducers which contribute to measurement errors of significant magnitude in oceanographic applications. We may distinguish between errors which appear more or less as static and errors which occur as dynamic response to changing environmental conditions. Within the first category,

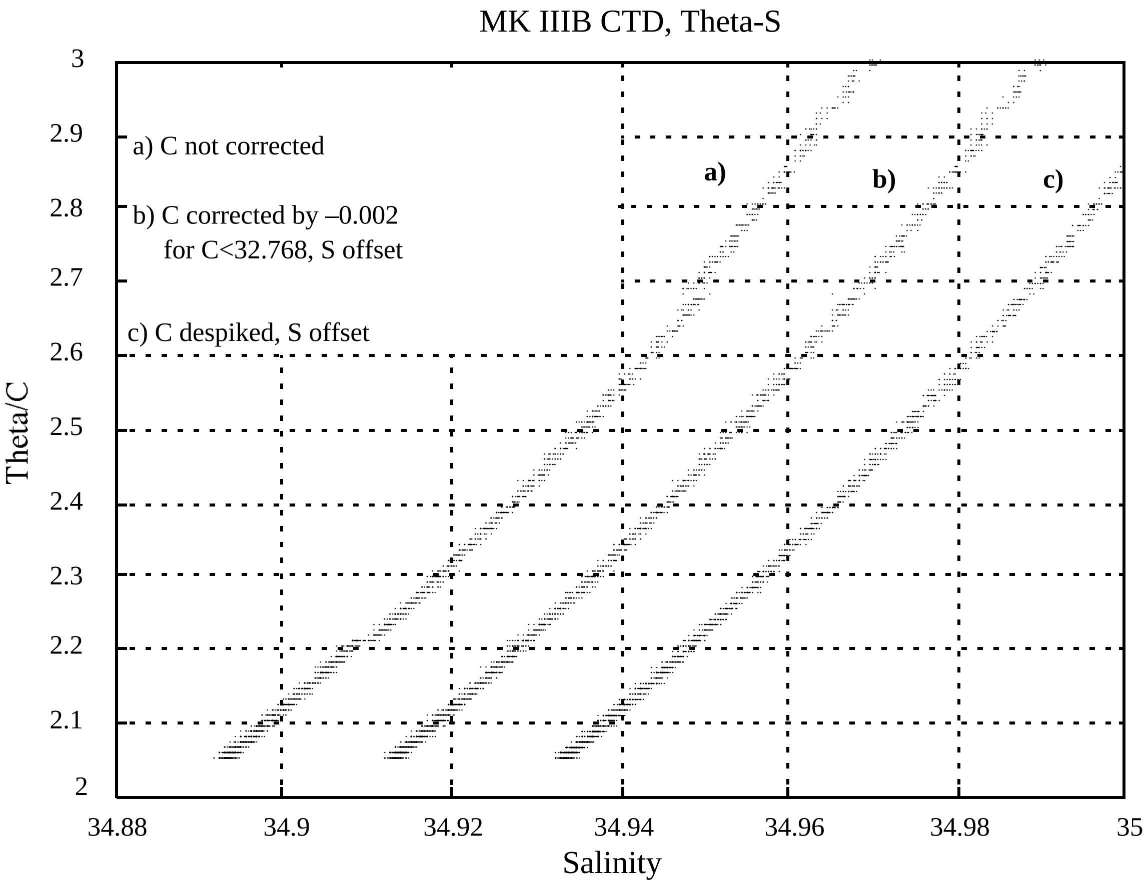

Figure 4: **Steps in the relation of potential temperature salinity relation (a) are removed (b) by adding C3278=0.002 mS/cm when the sensor output is less 32.768 mS/cm and (c) finally smoothed by interpolation where cycles have CCTD=32.768 mS/cm.**

Table 1: Specifications of Paine Instruments Model 211-35-090-05 Stainless Steel Strain Gauge Pressure Sensor

Range	0–6100 dbar
Compensated for temperature range	32˚C to 151˚C
Thermal zero shift	1.1 dbar/°C 0.01% F.S./F
Thermal sensitivity shift	0.55 dbar/°C 0.005% F.S./F
Nonlinearity and hysteresis	0.25% F.S. (15.25 dbar)
Shock, vibration, acceleration	0.01% F.S./G (0.61 dbar/g)
Repeatability	0.05% F.S. (3.05 dbar)

nonlinearities in pressure response of the transducer can well be removed by careful calibration on a dead weight tester. The same holds for thermal zero and sensitivity shifts. These can be observed when transducers are calibrated in baths of different temperatures over the oceanic range although these effects are almost compensated by measuring temperature on a thermistor attached to the outside of the pressure sensor (but see below for dynamic effects). Mechanical hysteresis occurs when, after a transducer has been brought to high pressure, it is unloaded to lower pressure. Although it takes some time for the sensor output to reset to the initial value after having brought back, we consider this type response also as static and treat it together with the others above.

Figure 5 displays the results of a static pressure sensor calibration. Corrections to be applied to loading curves depend nonlinearly on pressure readings PCTD and although the shapes of the correction curves do not change much for various constant temperatures (Figure 5a), a simple polynomial approach obviously cannot account for the temperature dependencies. Mechanical hysteresis makes up to 5 dbar corrections (Figure 5b), a quantity which cannot be neglected when conductivity cells are calibrated in situ with salinities derived from bottles closed on the way up. Here, too, the response is highly nonlinear and in many cases cannot be easily modelled by polynomials.

While the response to changing pressure may be considered to be instantaneous, the transducer's response to changing temperature is not. As the transducer is typically threaded into a port drilled through the CTD pressure case endcap which is located on the inside face of the CTD endcap and surrounded by a substantial thermal mass of stainless steel of relatively low thermal conductivity, the sensing element of the transducer is not in immediate contact with flowing sea water, but is insulated by, both, the water filling the port, and the material in which the sensing element is enclosed. Thus, in a changing temperature field, the pressure sensing element in the transducer may be at a temperature ten or more degrees different from that of the surrounding water including temperature gradients on the element itself. Continuous although slow adjustment of the sensing element's temperature to the outer temperature rises changes pressure output which is complicated of course by non zero profiling velocity and temperature gradients.

To reduce the response of the sensor under transient changes of temperature, the manufacturer uses a resistive temperature compensating element in the internal circuitry of the transducer. Ideally, this element would exhibit the same response time and yield a response to temperature changes equal in magnitude but opposite in sign to that of the strain gauge, so that temperature effects were exactly canceled. In practice, this compensation is not exact, one reason being the time required for both the strain gauge and the compensating element to reach full temperature equilibrium (or full response to temperature changes) may not be the same. A second one is that the thermistor which is adapted outside the pressure sensor for static compensation has much larger time constants (up to 1 to 2 hours) than the pressure sensing element because of its thermal insulation. This time constant may mismatch with that of the compensation circuit.

The final response with all compensations mentioned above applied, can be demonstrated by plunging a CTD's pressure sensor from a stirred warm water bath into a stirred cold water bath and back again (Dunk test, Figure 6). Typically for many MK IIIB CTDs, a roughly 20°C sudden temperature step causes a pressure sensor output response amplitude of about 4 dbar and a half response time of order 1800 s. The effect of all compensations is adequate to bring the overall transducer response to within the established specifications of the manufacturer. Nevertheless, in order to achieve the high accuracy as required for the WHP, further corrections are needed.

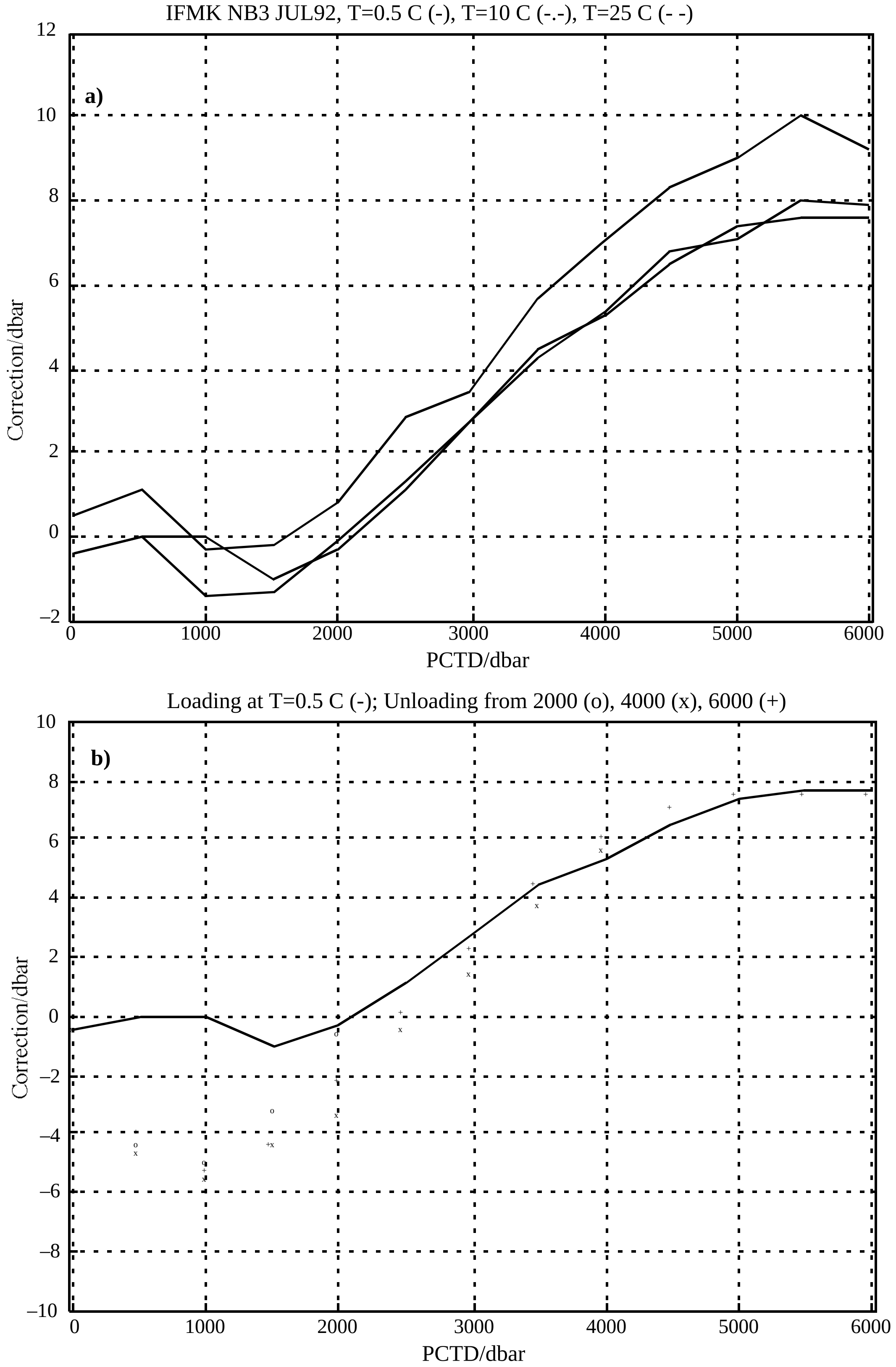

Figure 5: **Static corrections for a MK IIIB pressure sensor: (a) increasing pressure at three different temperatures; (b) mechanical hysteresis for three different maximum loads (o 2000 dbar, x 4000 dbar, + 6000 dbar) compared to the loading curve (straight line) all at temperature 0.5˚C.**

One concept to start dynamic correction is, to at least avoid the possible mismatch of time constants from the compensation circuit and the outer thermistor. Consequently, one would disconnect the thermistor static temperature compensation and thus treat the pure pressure sensor response only. Such a procedure will lead to larger response amplitudes, shorter response times, avoid mismatches in time constants and result in well behaved pressure sensor response curves. This concept is favored by the two contributing authors from the ODF at SCRIPPS. In many MK IIIBs, however, analogue compensation as provided by the manufacturer still makes sense since a smooth response curve of small amplitude results like that in Figure 6. Therefore, at IFMK the analogue compensation is kept in such cases. In both concepts the correction schemes which maybe applied do not differ principally from each other. We therefore without loosing generality may restrict the discussion of such schemes to sensors where the hardware has not been altered.

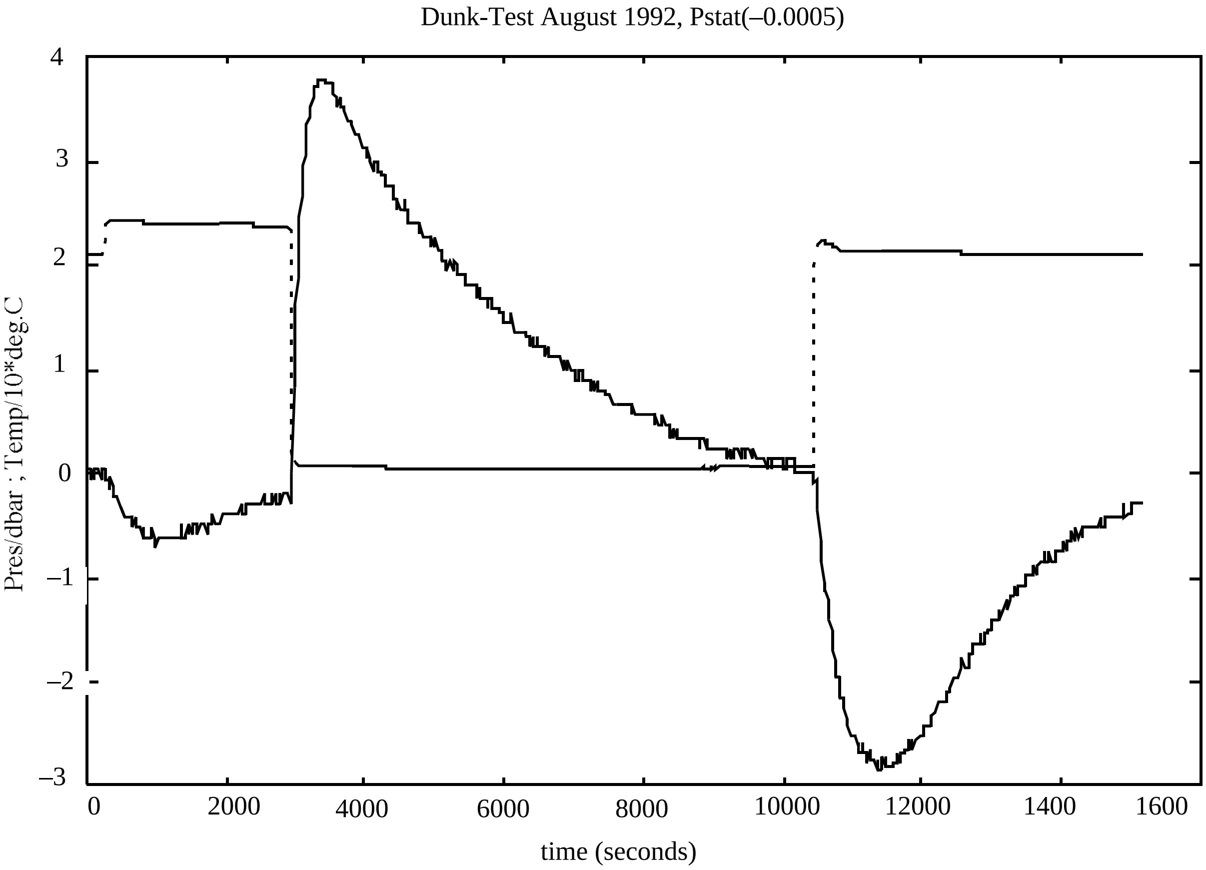

Figure 6: **Dynamic response of a MK IIIB compensated stainless steel strain gauge sensor (thick line) to temperature steps (broken line). Units are time t/s, pressure response Pres/dbar and temperature Temp/(10°C). The CTD's sensor was deployed from air pressure to a stirred warm water bath, then to cold and back to warm water again, in situ pressure in baths being 0.2 dbar.**

From the above discussions, an adequate correction scheme must include, both static corrections for nonlinearity, thermal shifts and mechanical hysteresis, and a dynamic correction when temperature varies with time. Assuming that these corrections can be superposed linearly, we write

(4) $$P = POL(PCTD, T0) + PSC + PDC$$

Here POL(PCTD, T0) is the basic polynomial calibration of the pressure sensor's output PCTD over the full range in loading mode at a fixed, preferably low, temperature T0, PSC is the static and PDC the dynamic correction, and P is the corrected best estimate of in situ pressure.

4.2 Static Correction

Since the static correction PSC often cannot be modelled by simple polynomials, PSC should generally be estimated by interpolation from a table of calibration data. It may be organized such (Table 2a in the Appendix) that the first column contains the reference pressure, followed by columns with the first loading curve as measured at the lowest temperature, followed by successively deeper unloading curve at that same temperature, and continuing with loading and unloading curves for the next higher temperature until the warmest loading and unloading curves. The number of temperatures represented, and/or the number of unloading curves retained for each loading curve, are not limited. Alternatively, the table may refer all calibration data to an already performed basic calibration which is valid for one loading curve, preferably one at low temperatures (Table 2b).

Since the pressure sensor under transient temperature changes does not feel the surrounding temperature as measured by the CTDs temperature sensor, a “lagged” temperature representing that on the sensing part of the pressure sensor should be taken for interpolation. It can be calculated recursively from the CTD's measured temperature and without making a substantial error be the same as that used for the dynamic correction discussed further below.

The interpolation of PSC is initialized when in situ conductivity exceeds a previously established “in-water” value. It is based either on the sensor's output (see Table 2a) or on a basic polynomial correction valid for loading at a fixed temperature (see Table 2b). The corrected pressure is interpolated in two dimensions from those four calibration points which were measured in loading mode at temperatures less and higher the current lagged temperature and which values bracket the sensor's output. A final offset, i.e., the correction required to bring the pressure to 0 dbar at the profile's start at the surface, is added throughout the cast.

When pressure reverses on the way up, the interpolation of PSC enters the unloading mode. First, those unloading curves are selected that were obtained at temperatures that bracket the current lagged temperature and that have the least maximum pressure higher than the maximum cast pressure. Valid for both these temperatures, two hysteresis corrections for the sensor output are determined by interpolation on the chosen unloading curves and weighting the results with the maximum cast pressure divided by the maximum calibration pressure. Finally, the hysteresis correction to be applied to the pressure reading is interpolated between these values using the current lagged temperature. If the CTD is again lowered before hysteresis has been reset, interpolation follows the unloading scheme until the previous maximum cast pressure is reached. From then on, the mode reverses to loading again.

If a lagged temperature is encountered which is outside the range of calibration, or if the CTD's pressure reading slightly exceeds the maximum calibration values, an extrapolation with constants is performed. This may infer some risk with certain types of sensors of nonlinear temperature response, but it is not generally a problem with the MK IIIB pressure transducers.

4.3 Dynamic Correction

In the literature, two models have recently been published which attempt to correct for the dynamic effects of pressure sensors to temperature steps. Chiswell (1991) uses linear system theory to determine the dynamic correction of a Paroscientific Digiquartz pressure sensor implemented in a SeaBird 911 CTD as

$$\mathrm{PDC} = -h*T = P - \mathrm{PS} \tag{5}$$

Here PS denotes the statically corrected pressure PS = POL(PCTD, T0) + PSC, P is in situ pressure, T is the outer temperature as measured by the CTD, h is the transfer function describing the heat transfer from the surrounding water to the pressure sensor, and * denotes convolution. The transfer function h can be determined experimentally from a plunge test as the time rate of change of the pressure response PS divided by the amplitude of the temperature step (provided the static calibration is properly done and certain constraints on h are observed). Application to dunk tests yielded response amplitudes of 6 dbar on 18°C steps and residuals of up to 1 dbar.

Chiswell's method of course is also applicable to MK IIIB strain gauge sensors. As noted in the paper however, using the convolution integral in (5), needs knowledge of a long “history” of temperature ahead of a cast, and little is known about the stability of the transfer function h. Also, even small errors in h, e.g. from nonlinear parts of the response, may lead to big errors in PDC by the convolution involved.

In an attempt to replace the stainless steel strain gauge of a MK IIIB CTD by titanium strain gauge sensor, also marketed by Paine Instruments, Millard et al. (1993) investigated the response characteristics of this sensor. While linearity and hysteresis of the new sensor prove far better compared to the stainless steel sensor, the noise level is higher by a factor of two. Not applying any internal temperature compensation, the dynamic temperature response can be reduced to the order of a MK IIIB stainless steel sensor provided thermal insulation is performed carefully as described in the paper and offered as upgrade by the supporting company (now General Oceanics Inc.). Shape and amplitude of the resulting dynamic response are then similar to that of a MK IIIB with stainless steel sensor and internal compensation, and thus correction methods developed for the upgraded MK IIIB may also hold for the original instrument. Using the internal temperature TP as measured at the pressure sensing element and the water temperature T as measured by the CTD's main temperature sensor, the authors suggest a dynamic correction based on the time rate of changes in both temperatures and their difference:

$$\mathrm{PDC} = c(dT/dt) + b(d\mathrm{TP}/dt)\,\mathrm{abs}(\mathrm{TP} - T) \tag{6}$$

A plunge test with a 20°C step resulted to a roughly 3 dbar amplitude response and order 0.5 dbar residuals after correction. Note that when this method is applied to a MK IIIB with stainless steel strain gauge sensor, the temperature TP is not measured but must be modelled recursively as lagged temperature from T.

We have performed several alternative models to determine the dynamic correction PDC for the dunk test shown in Figure 6, all using recursively lagged temperatures. The best results were obtained with the following model

$$\mathrm{PDC} = a*\mathrm{To} - b*\mathrm{Ti} \tag{7}$$

where To and Ti are modelled outer and inner temperatures at the pressure sensor, respectively, calculated recursively for at ∫ second intervals i as lagged water temperature:

(8) To(i) = T(i) – (T(i) – To(i))*exp(ro*(t(i)–t(i–1))

Ti(i) = To(i) – (To(i) – Ti(i))*exp(ri*(t(i)–t(i–1))

The four coefficients a, b, ro and ri were determined using nonlinear least square methods:

(9) ro = –4.04E–3/s ri = –4.14E–4/s

a = –0.19 dbar/°C b = –0.21 dbar/°C

The residual of the dynamic correction with maximum amplitude of 0.8 dbar is shown in Figure 7. The coefficients a and b are close together, and indeed a three parameter model with a = b gives almost as good results.

The three models maybe compared in terms of residuals normalized by the associated temperature step. The values are up to 0.1 dbar/°C for the linear response model (Chiswell, 1991, his Figure 4c), 0.03 dbar/°C for the model of Millard et al. (1993, their Figure 6b) which uses internally measured temperatures, and 0.04 dbar/°C for the lagged temperature difference model (eq. 7). The relatively high residual of the linear response model may reflect not adequately modelled nonlinear responses as well as lack of knowledge of temperature history.

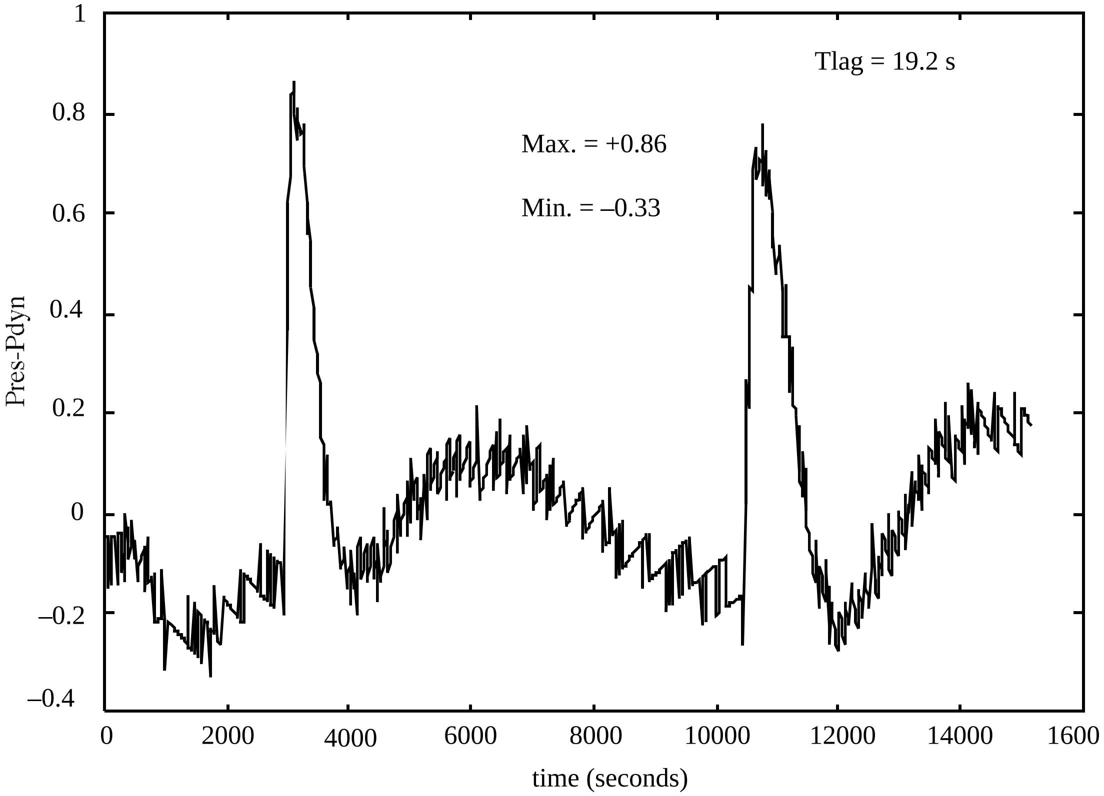

Figure 7: **Residual of dynamic correction for the response in Figure 6 using the model in equations (7) and (8).**

5. Conclusions

Several deviations from smooth calibrations of MK IIIB CTD sensors have been discussed. The temperature sensor may have a strong nonlinearity, in some instruments even a discontinuity close to 0˚C which needs to be removed especially for measurements in cold waters to meet WHP requirements. Shifting the zero voltage output to –3˚C output is strongly recommended for these instruments.

Errors occurring at conductivity cell outputs less and equal to 32.768 mS/cm can be removed by software. The same holds for the compensation of the pressure and temperature responses of the cell.

For the stainless steel strain gauge sensor, both, a static and a dynamic correction must be applied. It is not clear which of the dynamic models discussed here or eventual future models prove best for individual sensors. At present, final maximal errors after dynamic corrections of 0.5 to 1 dbar at a 20˚C temperature step remain in each model. This would fulfill the WHP standards.

Replacing the stainless steel sensor of the MK IIIB by a titanium strain gauge sensor would reduce nonlinearity and hysteresis in pressure measurements, but increase noise (which can be filtered in later processing). The dynamic response to temperature steps is of the same order or less, provided the sensor is adequately thermally insulated. Thus, the replacement may be recommended, and indeed in some institutions has already been done.

Acknowledgments

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Appendix 1:

The 1st row of Table 2a contains temperatures of the bath with the pressure sensor. From the 2nd row on, the columns contain:

1: reference pressure (not yet corrected for gravity and temperature at the piston);
2: loading curve, lowest temperature (0.5˚C);
3-5: unloading at same temperature, starting with shallowest;
6-9: loading and unloading, next higher temperature (10˚C);
10-13: loading and unloading curves, highest temperature (25˚C).

Table 2a: Example of a static calibration for a MK IIIB stainless steel pressure sensor.

PRESS (dbar)	Temperature °C											
	0.5	**0.4**	**0.4**	**0.6**	**10.2**	**9.7**	**10.0**	**10.4**	**25.7**	**25.3**	**25.6**	**25.9**
0.0	0.4	0.6	0.6	0.1	0.4	0.5	0.4	0.4	–0.5	–0.5	–0.5	–0.5
500.0	500.0	504.5	504.7	504.0	500.0	504.3	504.5	504.1	498.9	503.1	503.4	503.3
1000.0	1000.0	1005.1	1005.6	1005.3	1001.4	1004.6	1005.4	1005.0	1000.3	1003.3	1004.3	1003.8
1500.0	1501.0	1503.3	1504.4	1504.5	1501.3	1503.4	1504.8	1503.9	1500.2	1501.8	1503.0	1502.5
2000.0	2000.3	2000.7	2003.4	2002.3	2000.1	2000.3	2002.7	2002.0	1999.2	1998.9	2001.0	2000.9
2500.0	2498.9	–9999.0	2500.5	2500.0	2498.7	–9999.0	2500.1	2499.6	2497.2	–9999.0	2499.0	2498.4
3000.0	2997.3	–9999.0	2998.6	2997.8	2997.3	–9999.0	2998.2	2997.9	2996.5	–9999.0	2996.7	2996.3
3500.0	3495.5	–9999.0	3496.4	3495.6	3495.7	–9999.0	3495.9	3495.6	3494.3	–9999.0	3494.3	3494.0
4000.0	3994.7	–9999.0	3994.5	3994.0	3994.6	–9999.0	3993.5	3994.0	3993.0	–9999.0	3992.8	3992.7
4500.0	4493.5	–9999.0	–9999.0	4493.0	4493.2	–9999.0	–9999.0	4492.9	4491.7	–9999.0	–9999.0	4491.6
5000.0	4992.6	–9999.0	–9999.0	4992.5	4992.9	–9999.0	–9999.0	4992.4	4991.0	–9999.0	–9999.0	4990.8
5500.0	5492.4	–9999.0	–9999.0	5492.5	5492.0	–9999.0	–9999.0	5491.6	5490.0	–9999.0	–9999.0	5490.2
6000.0	5992.4	–9999.0	–9999.0	5992.5	5992.1	–9999.0	–9999.0	5992.1	5990.8	–9999.0	–9999.0	5990.8

Table 2b: As Table 2a, but pressure output corrected with respect to a calibration of 3rd order polynomial for loading at T_0= 0.5.

PRES. (dbar)	Temperature °C											
	0.5	**0.4**	**0.4**	**0.6**	**10.2**	**9.7**	**10.0**	**10.4**	**25.7**	**25.3**	**25.6**	**25.9**
0.0	0.6	0.8	0.8	0.3	0.6	0.7	0.6	0.6	–0.3	–0.3	–0.3	–0.3
500.0	499.3	503.8	504.0	503.3	499.3	503.6	503.8	503.4	498.2	502.4	502.7	502.6
1000.0	999.1	1004.2	1004.7	1004.4	1000.5	1003.7	1004.5	1004.1	999.4	1002.4	1003.4	1002.9
1500.0	1500.5	1502.8	1503.9	1504.0	1500.8	1502.9	1504.3	1503.4	1499.7	1501.3	1502.5	1502.0
2000.0	2000.6	2001.0	2003.7	2002.6	2000.4	2000.6	2003.0	2002.3	1999.5	1999.2	2001.3	2001.2
2500.0	2500.3	–9999.0	2501.9	2501.4	2500.1	–9999.0	2501.5	2501.0	2498.6	–9999.0	2500.4	2499.8
3000.0	3000.0	–9999.0	3001.3	3000.5	3000.0	–9999.0	3000.9	3000.6	2999.2	–9999.0	2999.4	2999.0
3500.0	3499.5	–9999.0	3500.4	3499.6	3499.7	–9999.0	3499.9	3499.6	3498.3	–9999.0	3498.3	3498.0
4000.0	4000.0	–9999.0	3999.8	3999.3	3999.9	–9999.0	3998.8	3999.3	3998.3	–9999.0	3998.1	3998.0
4500.0	4500.0	–9999.0	–9999.0	4499.5	4499.7	–9999.0	–9999.0	4499.4	4498.2	–9999.0	–9999.0	4498.1
5000.0	4999.9	–9999.0	–9999.0	4999.8	5000.2	–9999.0	–9999.0	4999.7	4998.3	–9999.0	–9999.0	4998.1
5500.0	5500.1	–9999.0	–9999.0	5500.2	5499.7	–9999.0	–9999.0	5499.3	5497.7	–9999.0	–9999.0	5497.9
6000.0	6000.0	–9999.0	–9999.0	6000.1	5999.7	–9999.0	–9999.0	5999.7	5998.4	–9999.0	–9999.0	5998.4