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A customized elapsed fall time-to-depth conversion equation was found to be $z = 1,620t - 2.2384 \times 10^{-4}t^2 + 1.291 \times 10^{-7}t^3$, with z the depth in meters and t the elapsed fall time after probe release in seconds. The standard deviation of the depth error was about 5 m: a rule of thumb for estimating maximum bounds on the depth error below 100 m could be expressed as ±2% of depth or ±10 m, whichever is greater. This equation gave greater depth accuracy than either the manufacturer's supplied equation or the Navy standard equation.

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Evaluation of the Sparton Tight-Tolerance AXBT*

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30 November 1992 and 14 April 1993

ABSTRACT

Forty-six near-simultaneous pairs of conductivity–temperature–depth (CTD) and Sparton "tight tolerance" air expendable bathythermograph (AXBT) temperature profiles were obtained in summer 1991 from a location in the Sargasso Sea. The data were analyzed to assess the temperature and depth accuracies of the Sparton AXBTs. The tight-tolerance criterion was not achieved using the manufacturer's equations but may have been achieved using customized equations computed from the CTD data. The temperature data from the customized equations had a one standard deviation error of 0.13°C.

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1. Introduction

One of the most important instruments for oceanographic research is the expendable bathythermograph (XBT), a nonrecoverable device that produces at moderately low cost a set of temperature versus depth values through the water column down to some maximum depth determined by the device type. The air-deployed version is the AXBT ("A" for air deployed), and under the military designation AN/SSQ-36, it is widely used by operational and research components of the U.S. Navy to conduct surveys of the upper-ocean thermal structure from fixed-wing aircraft and helicopters, and from these surveys large numbers of AXBT profiles enter the international oceanographic data archives. Because XBT and, to a lesser extent, AXBT profiles often dominate the archival databases, it is important to have some idea of the error bounds on these data types. Hallock and Teague (1992) and Boyd and Linzell (1993) have recently analyzed errors in Sippican T-7 and T-5 XBTs, respectively; Wright and Szabados (1989) examined temperature and depth accuracies of Sippican T-4, T-5, T-6, T-7, and T-10 XBTs; and Boyd (1987) studied the errors in data from Sippican deep and shallow AXBTs. References to other, earlier studies may be found in the bibliographies of these articles. The overall conclusions are that the different types of expendables have different error characteristics, and that the accuracy of the data from the probes can be improved by properly modifying the nominal temperature and depth equations supplied by the manufacturers. This work examines the temperature and depth accuracies of a new type of AXBT that has recently come on the market.

Boyd (1987) gives more details on the design and operation of AXBTs. After deployment from an aircraft, the instrument package hits the water and the unit equilibrates at the surface for 30–60 s, at which point a probe carrying a thermistor is released. As the probe descends, the temperature signal is transmitted through a thin wire link to a surface VHF transmitter, which telemeters the data to the deploying aircraft as a frequency modulation of the carrier signal. Depth is not measured directly but is computed from the elapsed fall time.

The accuracy of the data obtained depends upon the accuracy of the conversion equations, which transform frequency into temperature and elapsed fall time into depth. The U.S. Navy specifies the equations that are to be used for making these conversions, and all AXBTs are manufactured such that the depth and temperature accuracies obtained using these equations fall within specified tolerances. For many research purposes (and

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for some recent operational applications) these tolerances are not satisfactory: within ±0.56°C for temperature and within ±5% for depth. Boyd (1987) showed it was possible to increase significantly the accuracy of the instrument by developing customized conversion equations. Subsequent work (Boyd and Linzell, unpublished manuscript), however, has shown that each time changes are made to the AXBT mechanical design, changes are likely to also occur in the conversion equations—particularly the fall-rate equation. These changes then impact the obtained data accuracy. The reader is referred to Green (1984) and Hallock and Teague (1992) for discussions of the various physical and mechanical factors influencing expendable probe fall rates.

A number of manufacturers have produced AXBTs over the years, including Hermes, Magnavox, and Sippican. Between 1981 and 1989, Sippican Ocean Systems of Marion, Massachusetts, was the primary supplier of AXBTs to the military and civilian research communities in the United States. However, in 1990, Sparton of Canada won the contract to produce 800-m-depth AXBTs for the U.S. Navy, resulting in their becoming—for a time, at least—the new de facto supplier of AXBTs to most of the U.S. research community as well. The Naval Oceanographic and Atmospheric Laboratory [NOARL, now the Naval Research Laboratory (NRL) Detachment at the Stennis Space Center] purchased over 1000 of these units for several large experiments conducted in summer 1991 in the North Atlantic. Because we anticipated that the accuracy of data obtained from these units would be improved by using conversion equations different from the Navy standard equations or from the previously developed Sippican equations (Boyd 1987), a calibration experiment was conducted in June of 1991 with the cooperation of researchers from the University of Washington Applied Physics Laboratory and the Scripps Institute of Oceanography who were engaged in the Acoustic Mid-Ocean Dynamics Experiment (AMODE) tomography experiment. On 25 June 1991, at a location several hundred miles northeast of Puerto Rico, 46 Sparton AXBTs were dropped by a Naval Oceanographic Office P-3B aircraft very close to the research vessel R/V *Endeavour* during the same time that personnel onboard the vessel were conducting multiple conductivity–temperature–depth (CTD) casts. This note reports on the results of the comparison of those two datasets.

2. Sparton AXBTs

The 800-m Sparton AXBTs produced under the 1990 navy contract [identified by NALC (Navy Ammunition Logistics Code) 8W74] must meet the navy specifications for temperature-to-frequency and elapsed fall time–to-depth conversion equations. The navy standard AXBT temperature-to-frequency conversion equation is

$$F = 1440 + 36T, \tag{1}$$

where T is degrees Celsius, and F is frequency in hertz. The standard specifies an accuracy of ±20 Hz, or about ±0.56°C within the temperature range −2°–35°C. When inverted to yield the frequency-to-temperature conversion equation, it becomes

$$T = -40.0 + 0.02778F. \tag{2}$$

To meet this standard, Sparton tests each standard AXBT production unit at 0°, 25°, and 35°C. Probes that do not lie within the bounds at all three data points are discarded. NOARL requested a more accurate AXBT (a "TT" or "tight tolerance" AXBT) having a two standard deviation temperature accuracy of ±0.15°C over the temperature range of −2°–30°C. The procedure whereby this was to be achieved was left up to the manufacturer, although it was specified that the manufacturer had to supply a frequency-to-temperature conversion equation that would give the desired accuracy.

According to the manufacturer, to meet the NOARL TT criterion of ±0.15°C, they calculated four possible equations and then examined each production unit to see if it fit one of the four equations to within ±0.125°C at each of *four* temperatures: 0°, 12°, 25°, and 35°C. Units were first compared with equation A, then with B, etc. When a unit's test data was within the limits of one of the equations, it was assigned to that equation and so labeled. Units that did not fit closely enough to any of the four equations were removed from consideration.

The four equations are given in Table 1. According to Sparton, equation A was generated by initially testing 40 AXBTs from the first thermistor batch, calculating the mean frequency at each of the four test temperatures and fitting a straight line by hand to the results (i.e., yielding an equation that gave frequency as a function of temperature). When a second batch of thermistor units was introduced into the production, two additional equations (B and C) were created by computing the mean frequencies at the four standard temperatures over 80 sampled probes, fitting a straight line by hand to the data, and assigning equation B to be a line shifted 2 Hz above the line of best fit and equation C to be a line shifted 2 Hz below the line of best fit. These two equations were chosen, according

TABLE 1. Frequency-to-temperature conversion equations supplied by the AXBT manufacturer for the four separate thermistor groups (designated A, B, C, D).
Equation: $T = a + bF$.

Group	Coefficient a	Coefficient b
A	40.255	0.02791
B	40.428	0.02798
C	40.316	0.02798
D	40.022	0.02779

to the manufacturer, "to achieve a higher over-all yield." Equation D was introduced to be an equation very close to the navy standard equation. AXBTs arrived marked according to which equation the manufacturer felt applied best and this distinction was maintained during the data processing. Of the more than 1000 AXBTs that passed the screening process, about 73% were assigned to equation A, 13% to equation B, 12% to equation C, and 2% to equation D.

The navy-specified depth equation is

$$z = 1.52t, \tag{3}$$

where z is depth in meters and t is elapsed time in seconds after probe release. The standard requires the depth to be accurate to ±5% of depth over the full depth range, beginning 3 s after probe release and under conditions of zero relative current shear (a situation that rarely obtains in the ocean). Sparton supplied a modified depth equation in which they attempted to account for the deceleration of the probe due to loss of mass as the wire unspooled. This equation was

$$z = 1.575t - 9.602 \times 10^{-5}t^2, \tag{4}$$

with a suggested accuracy of ±2% of depth.

3. Data sources and processing

The AXBT and CTD profiles compared were nearly simultaneous in space and time: matching profiles were within 100 m and 45 min (usually much less) of each other. This was only possible with the enthusiastic cooperation of the VXN-8 aircraft crew members who skillfully dropped the AXBTs from an altitude of only a few hundred feet immediately next to the ship. Observers onboard the ship said they could often read the several-inch high markings on the side of the buoys as they entered the water. Sea state as observed from the aircraft appeared to be 1 or possibly 2. The CTD data were collected by researchers from the University of Washington Applied Physics Laboratory and processed using standard procedures to a 1-m resolution. Accuracy is estimated to be ±0.005°C in temperature and ±3 m in depth (B. Howe 1992, personal communication). AXBT data was collected using the NOARL (now NRL) Isis System, which determines the AXBT frequency to such an accuracy that the resulting temperature accuracy is 0.05°C or better. The automatic start procedure in the acquisition software introduces a delay in beginning data acquisition that is estimated to be on the order of 0.1 s or less, corresponding to a depth error of less than 15 cm Nominal AXBT temperatures and depths were initially calculated using the Sparton supplied equations.

Each AXBT was associated with its closest (in time) CTD, and corresponding features on the near-simultaneous AXBTs and CTDs were matched. Since many of the smaller-scale features in an ocean profile are masked by the large-scale structure of the main thermocline, we bandpass filtered the CTD and AXBT profiles with a boxcar filter, as suggested by Prater (1991). (Previously this technique was successfully applied in studies of the ship-deployed XBT by Boyd and Linzell 1993. The feature-matching approach decouples the temperature and depth errors, which the earlier technique of matching depths of isotherms from the CTDs and expendable probes does not do.) Half-power points were chosen at 5 and 100 m. An example of this matching of filtered profiles is shown in Fig. 1. Features were chosen between about 10- and 950-m depth and were distributed as evenly over the full depth range as possible. Approximately 13 points per profile were selected. The CTD and nominal AXBT depths at which the features were matched were recorded, along with the *unfiltered* temperature values at those depths. The result was 539 observations, with each observation consisting of CTD depth, CTD temperature, AXBT nominal depth, AXBT elapsed fall time, and AXBT nominal temperature. In addition, whether a particular AXBT had originally been assigned to depth equation A, B, C, or D was noted. Twenty units had been assigned to equation A, eleven each to equations B and C, and four to equation D.

To evaluate the expected limits to the accuracy of this technique, we compared eleven features on the four CTD profiles. Over the three hours of the measurements, the standard deviation of the feature temperatures was 0.10°C and of the feature depths, 5.7 m. No particular overall trend was observed in either feature temperatures or feature depths. The specification for the TT AXBTs was a two standard deviation temperature accuracy of 0.15°C; hence, a one standard deviation accuracy of 0.07°—just at the limits of what our technique should be able to determine. The technique would have a lower intrinsic error level in temperature, at least, in a more stable oceanic environment such as the persistent thermohaline steps off South America used by Boyd (1987), Wright and Szabados (1989), and Hallock and Teague (1992). In our particular test, as in many real-world experiments, such an optimum choice of location was not possible.

4. Results

a. Temperature accuracy

We first examined the data to see if the specified two standard deviation accuracy of 0.15°C was attained with the tested probes. The CTD–AXBT feature temperature differences are plotted versus CTD temperature in Fig. 2a. A linear or higher-order trend is apparent in the data. On average, the AXBT feature temperatures were 0.11°C warmer than the CTD temperatures, with a standard deviation of 0.13°C. Because of the offset we concluded that the temperature accuracy specification was not achieved using the equations supplied by the manufacturer.

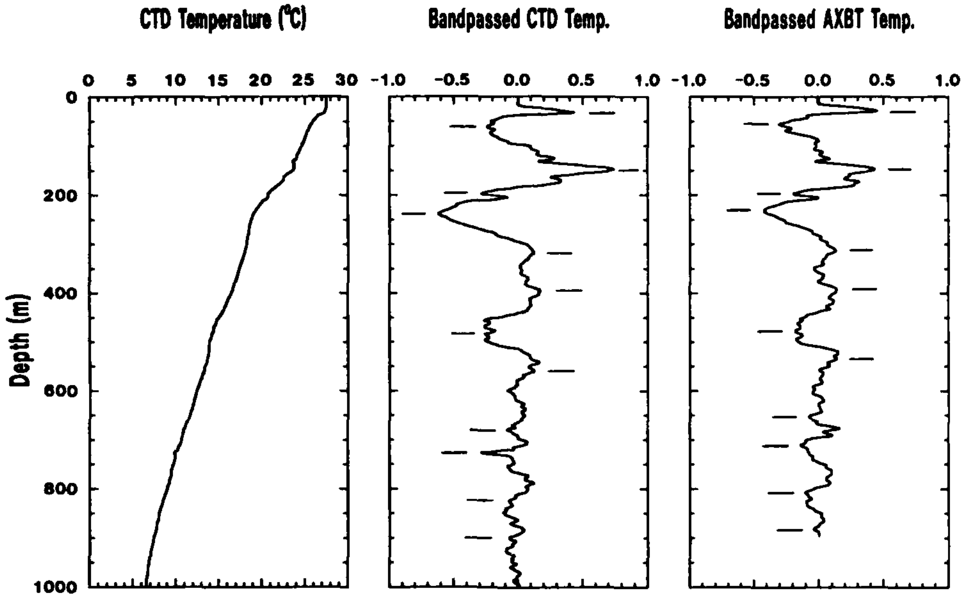

FIG. 1. Example of an unfiltered CTD temperature profile from this study, its bandpass-filtered version, and the bandpass-filtered version of an associated AXBT. Matched features are indicated on the filtered profiles.

To improve the temperature accuracy of the AXBT data, we developed new equations for each of the four groupings. Using standard linear regression techniques we fit linear, quadratic, and cubic models to each of the four thermistor groups and to the pooled dataset. In none of the cases was the coefficient of the cubic term significantly different from 0, so the cubic model was removed from consideration. These models are summarized in Table 2. We then used the procedures suggested in Kleinbaum et al. (1988) to evaluate whether the linear or the quadratic model was preferable in a statistical sense. The linear model is the commonly accepted form.

TABLE 2. Summary of the linear and quadratic equations found by this study for converting frequency to temperature. Here, T is temperature (°C); F is frequency (Hz).

Linear equation: $T = a + bF$.

Group	Coefficient a	Coefficient b
A	−40.508	0.027965
B	−40.736	0.028094
C	−40.603	0.028067
D	−40.415	0.027945
Pooled	−40.596	0.028028

Quadratic equation: $T = a + bF + cF^2$.

Group	Coefficient a	Coefficient b	Coefficient c
A	−37.533	0.025023	7.1667×10^{-7}
B	−37.634	0.025031	7.4503×10^{-7}
C	−37.945	0.025438	6.4102×10^{-7}
D	−38.464	0.026051	4.5448×10^{-7}
Pooled	−37.839	0.025304	6.6307×10^{-7}

Kleinbaum et al. (1988) suggest several criteria for choosing among regression models. The first criterion is to choose the model with the largest sample squared *multiple* correlation coefficient R^2, but in our case all linear and quadratic fits were highly significant with $R^2 \approx 1$. The second criterion is to compute a test statistic to compare the highest-order model ("maximum model" or "k-variable model") with lower-order models. If the statistic is not significant, then the lower-order model is adequate. The test statistic F_p is

$$F_p = \frac{[\mathrm{SSE}(p) - \mathrm{SSE}(k)]/(k - p)}{\mathrm{MSE}(k)},$$

where k is the number of variables in the highest-order model (2 for a quadratic), p is the number of variables in the other models under consideration, SSE(p) is the error sum of squares for the p-variable model and SSE(k) for the k-variable model, and MSE(k) is the mean-square error for the k-variable model. This statistic is compared to an F distribution with $k - p$ and $n - k - 1$ degrees of freedom. The results are summarized in Table 3. For criterion 2, the quadratic is a slightly better model than the linear except for lot D. The third criterion involves picking the model with the smallest error variance, MSE. From Table 3 we see that the quadratic is in all cases slightly better than the linear. In summary, then, the quadratic fits were in general somewhat better than the linear fits, although the difference between the two was nowhere greater than 0.06°C over temperature range of the data.

The CTD minus corrected AXBT feature temperature differences are plotted versus CTD temperature

TABLE 3. Evaluation of the candidate frequency-to-temperature conversion equations according to criteria 2 and 3 from Kleinbaum et al. (1988). Criterion 2 compares the quadratic model with the linear model using the test statistic F_p. The test statistic is compared with an F distribution whose critical values at a 95% significance level are given in the last column. Criterion 3 looks for the minimum MSE. In all cases except where indicated by the asterisk, the quadratic model is slightly better than the linear model.

Lot	Model	SSE	MSE	F_p	F_{crit} (95%)
A	Linear	4.476	0.019	13.55	3.88
	Quadratic	4.232	0.018		
B	Linear	1.747	0.013	12.33	3.92
	Quadratic	1.599	0.012		
C	Linear	1.751	0.014	9.46	3.92
	Quadratic	1.628	0.013		
D	Linear	0.259	0.007	3.83	4.10*
	Quadratic	0.236	0.006		
Pooled	Linear	9.253	0.017	29.63	3.86
	Quadratic	8.779	0.016		

in Fig. 2b. The mean temperature differences are 0 to 1 part in 10 000, but the standard deviations range between 0.08° and 0.14°C (Table 4). From this we conclude that perhaps using custom-fit equations the temperature accuracy specification was achieved. Certainly the revised equations do give considerably improved accuracy over both the manufacturer-supplied equations (Fig. 2a) and over the navy standard equation as applied to all four thermistor lots (Fig. 2c). If the navy standard equation had been used, the mean offset would have been −0.10°C (AXBT warmer) and the standard deviation 0.14°C.

b. Depth accuracy

The differences between the CTD and AXBT feature depths for the navy standard fall-rate equation (3) and the manufacturer's suggested equation (4) are plotted in Figs. 3a and 3b (thermistor group should have no effect on fall rate, so all probes were pooled into one dataset). The suggested equation (4) is a significant improvement over the navy standard equation, but the AXBT depths computed using (4) still appear to be somewhat too shallow below 200 m. Certainly the depth errors resulting from using equations (3) or (4) are outside the 5- or 6-m error inherent in our technique.

TABLE 4. Summary of the temperature standard deviations (°C) found after applying the equations in Table 2 to data separated by each of the four thermistor groups and to the pooled data. The temperature accuracy specification was a two standard deviation range of 0.15°C, which appears not to have been met in most cases.

Group	A	B	C	D	Pooled
Linear	0.14	0.11	0.12	0.08	0.13
Quadratic	0.13	0.11	0.11	0.07	0.13

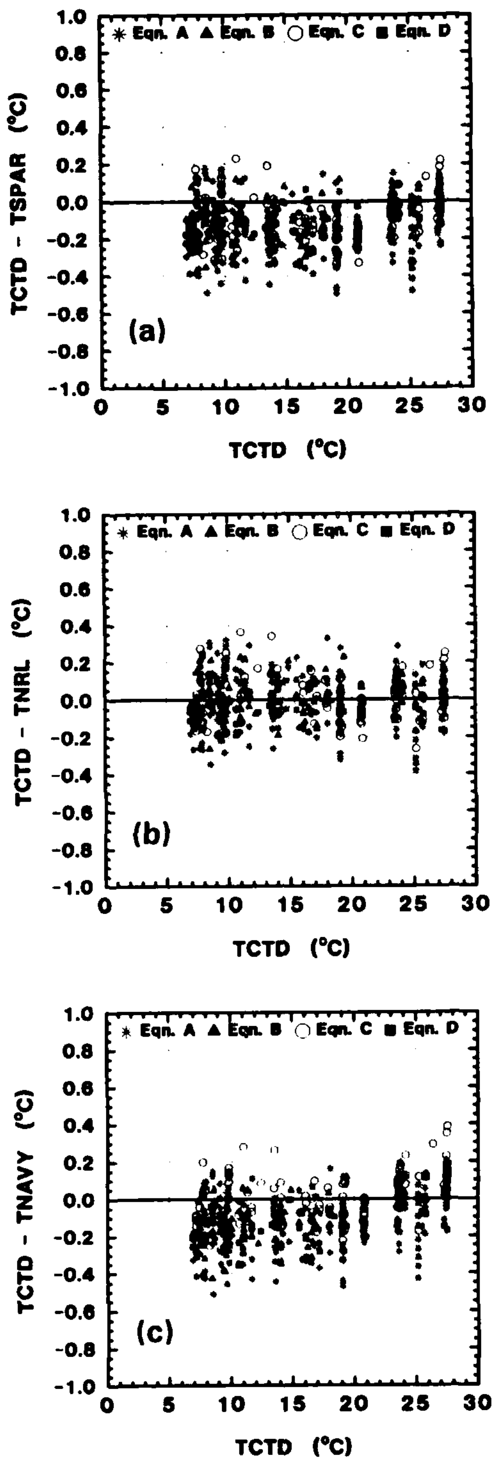

FIG. 2. The difference CTD temperature minus AXBT temperature plotted versus CTD temperature for all CTD–AXBT feature pairs: (a) using the manufacturer-supplied equations in Table 1 for AXBT temperature; (b) using the quadratic equations in Table 2; (c) using the navy standard equation (2) for all four thermistor groupings.

To develop a better fall-rate equation we investigated six different fall-rate models: linear with and without a constant, quadratic with and without a constant, and

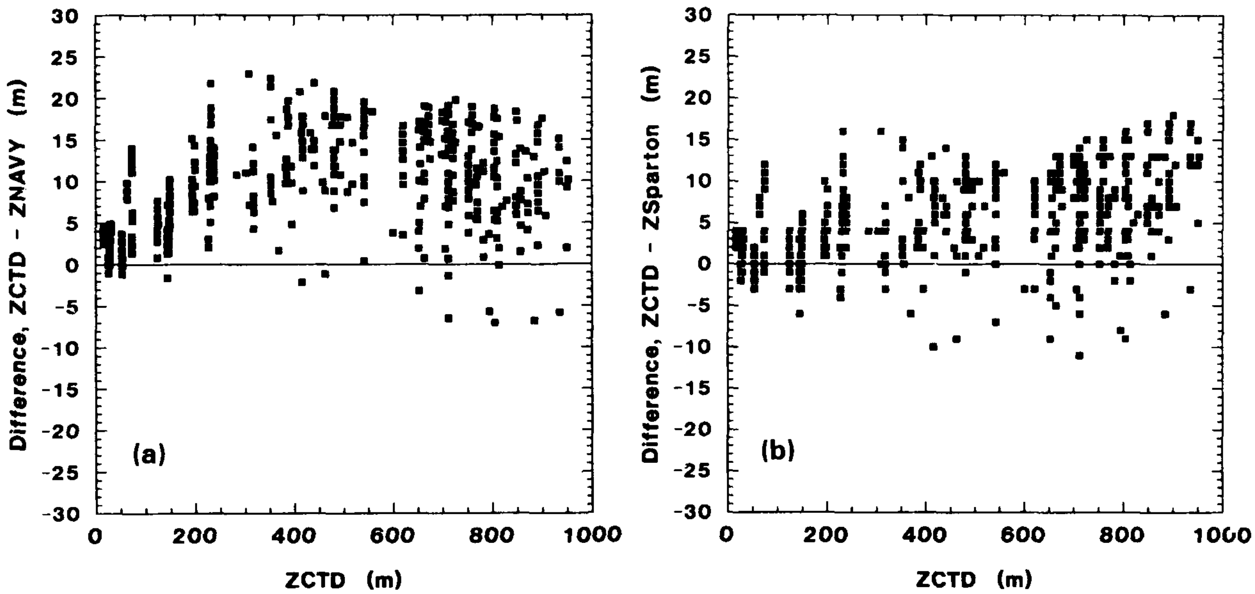

FIG. 3. The difference CTD depth minus AXBT depth plotted versus CTD depth for all CTD–AXBT feature pairs: (a) using the navy standard equation (3) for AXBT depth, (b) using the manufacturer supplied equation (4).

cubic with and without a constant. For all regressions, R^2 was greater than 0.999, so all regressions were highly significant, but the other criteria of Kleinbaum et al. (1988) indicated that the linear models were clearly worse than the quadratic and cubic models. The cubic models were slightly better in a statistical sense than the quadratics. Results for the Kleinbaum criteria 2 and 3 are given in Table 5 and a summary of the resulting quadratic and cubic equations in Table 6. The residuals are plotted versus CTD depth in Figs. 4a and 4b. Clearly there is very little difference between the depths computed using any of the four models; the maximum difference being less than 2 m. We ourselves use the cubic model forced through 0:

$$z = 1.620t - 2.238 \times 10^{-4}t^2 + 1.291 \times 10^{-7}t^3. \quad (5)$$

Whichever model is selected, the standard deviation of the depth error is about 5 m. Below 100 m, a rule of thumb for estimating the maximum depth error expected for the majority of AXBTs can be expressed as ±2% of depth or ±10 m, whichever is greater.

c. Overall accuracy

The overall final accuracy of the AXBTs and the new conversion equations as compared with the navy standard equations is shown in Figs. 5a–d. The first two panels are the CTD and AXBT profile temperature differences for the navy standard equations (2) and (3) (Fig. 5a), and the quadratic temperature equations (Table 2), and cubic fall-rate equation (5) (Fig. 5b), plotted every 2 m in depth. The last two panels are the means over all profiles of panels (a) and (b). The customized equations can be seen to be a significant improvement.

5. Concluding remarks

In 1991 the Naval Oceanographic and Atmospheric Research Laboratory (now part of the Naval Research Laboratory) purchased over 1000 new model 800-m-

TABLE 5. Evaluation of the candidate fall-rate equations according to criteria 2 and 3 from Kleinbaum et al. (1988), as in Table 3. Both linear equations are a statistically poorer fit than higher-order equations. The cubic forced through 0 is a slightly better model in a statistical sense, but as indicated in the text, the differences between the four second- and third-order equations are very small.

Model	SSE ($\times 10^4$)	MSE ($\times 10^1$)	F_p	F_{crit} (95%)
Forced through 0:				
$z = bt$	2.446	4.547	248.52	3.01
$z = bt + ct^2$	1.300	2.421	13.09	3.86
$z = bt + ct^2 + dt^3$	1.269	2.368		
Not forced through 0:				
$z = a + bt$	1.709	3.182	93.33	3.01
$z = a + bt + ct^2$	1.278	2.385	4.65	3.86
$z = a + bt + ct^2 + dt^3$	1.267	2.368		

TABLE 6. Summary of the cubic and quadratic fall-rate equations found in this study. The first cubic equation is marginally better in a statistical sense than the second, but Figs. 4a and 4b show the differences are minimal. Depth z is in meters and elapsed fall time t is in seconds.

Model	a	b	c	d
$bt + ct^2$		1.602	1.210×10^{-4}	
$a + bt + bt^2$	1.586	1.590	1.046×10^{-4}	
$bt + ct^2 + dt^3$		1.620	2.238×10^{-4}	1.291×10^{-7}
$a + bt + ct^2 + dt^3$	0.670	1.611	1.943×10^{-4}	1.008×10^{-7}

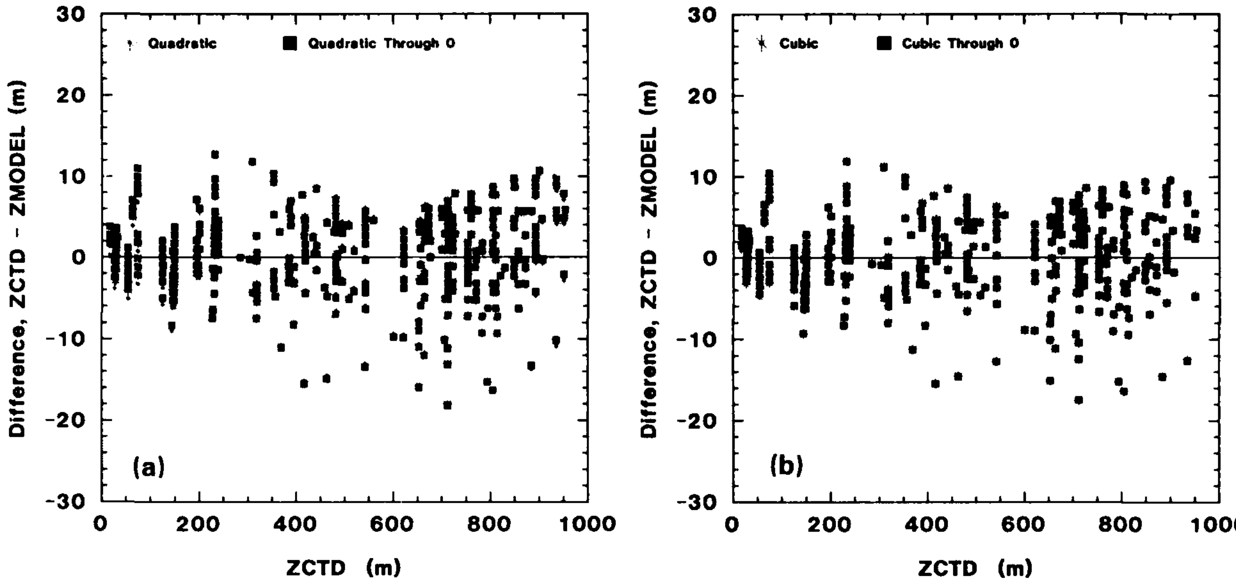

FIG. 4. The difference CTD depth minus AXBT depth plotted versus CTD depth for all CTD–AXBT pairs: (a) quadratic models from Table 6 for AXBT depth; (b) cubic models. A square indicates the model forced through 0; an asterisk indicates the model containing a constant. For all practical purposes, in both instances the depths calculated from the model forced through 0 and the model with a constant are the same.

depth AXBTs from Sparton of Canada. The AXBTs purchased were specified to be tight-tolerance units, which were to be a particularly accurate version of the standard unit having a two standard deviation temperature accuracy of 0.15°C. A calibration experiment with 46 CTD–AXBT pairs was conducted to check this accuracy, and, if necessary, to develop improved frequency-to-temperature and elapsed fall time–to-depth conversion equations, as previous work by the authors had shown that the accuracy of AXBTs can be significantly enhanced using customized equations.

The manufacturer supplied four different frequency-to-temperature conversion equations—depending upon thermistor group. On the average, however, the AXBT temperatures were found to be 0.11°C warmer than the CTD temperatures, with a standard deviation of 0.13°C. New equations were developed that removed the bias, and the one standard deviation accuracy ranged from 0.08° to 0.14°C. Hence the desired accuracy was not achieved with the manufacturer's equations but may have been achieved with the customized equations. The inherent accuracy of our technique was around 0.10°C. Nevertheless, the temperature accuracies were greater than would have been achieved using the navy standard equation alone.

It is not clear if the 46 AXBTs analyzed for this study can be considered representative of the general population of Sparton AXBTs or not. If they are, then the equation developed from pooling the data should be an improvement over the navy standard equation. The suggested pooled equation is the quadratic

$$T = -37.839 + 0.025304F + 6.6307 \times 10^{-7}F^2,$$

where T is temperature (°C) and F is frequency (Hz). The standard deviation is about 0.13°C.

While the general applicability of the above temperature conversion equation to other Sparton 800-m AXBTs has not been confirmed, the elapsed fall time–to-depth equation should be widely applicable to any of these units so long as no mechanical modifications have been made. At the time the units for the scientific experiments were manufactured, the company had not yet received final acceptance on the design; however, Sparton maintains that the additional changes were not of the type that should change the fall-rate characteristics of the probe. We thus suggest that an improved fall-rate equation is

$$z = 1.620t - 2.238 \times 10^{-4}t^2 + 1.291 \times 10^{-7}t^3, \quad (5)$$

where z is depth (m), and t is elapsed fall time (s). The standard deviation of the depth error is about 5 m, and a general estimate of the maximum depth error is that it is bounded by ±2% in depth or 10 m, whichever is greater.

One caveat exists for this fall-rate equation. Fall-rate equations for all expendable probes may be site dependent, or more properly, temperature profile dependent. Theoretical work by Green (1984) and by Sparton of Canada (G. Friesen 1992, personal communication) has indicated that the drag coefficient depends sufficiently upon temperature to impact significantly the elapsed fall time–to-depth equation. Hence (5) should be considered appropriate only for the North Atlantic and other waters that have a temperature profile fairly close to that in Fig. 1a until it is verified elsewhere.

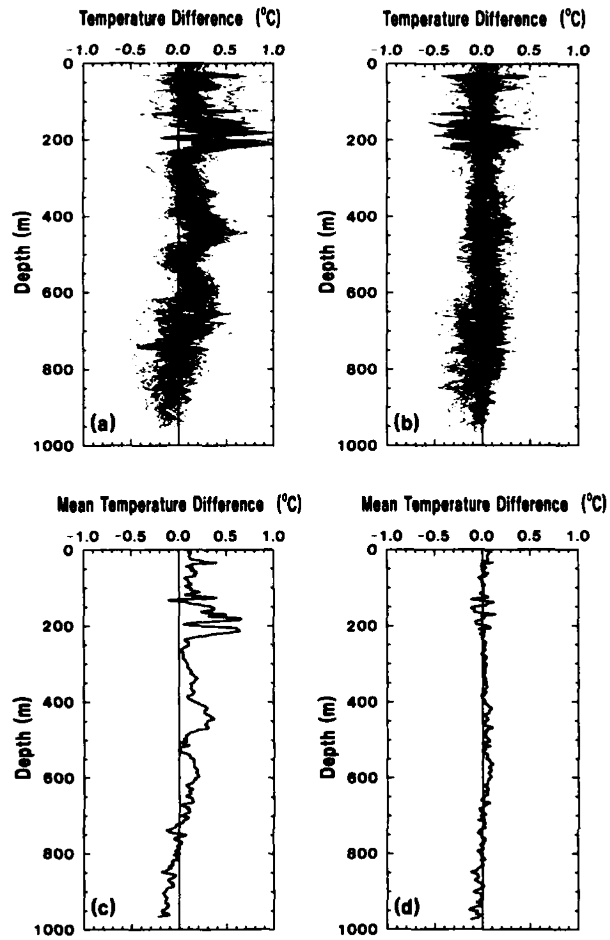

FIG. 5. Temperature differences versus depth at 2-m intervals for the CTD and AXBT profile pairs in this study: (a) using navy standard equations (2) and (3) for AXBT temperature and depth; (b) using the quadratic temperature corrections in Table 2 and the cubic fall-rate equation (5); (c) mean over all profiles in (a); (d) mean over all profiles in (b).

A final comment is in order regarding the approach used to attempt to create a tight-tolerance AXBT. Future researchers might also desire AXBTs with improved temperature accuracy, and we hope they may profit from our experience. We do not recommend the multiple equation approach used by the manufacturer. For future TT AXBTs, we recommend a sufficiently (in a statistical sense) large sample of the production lot be taken, one characteristic frequency-to-temperature conversion equation be computed from that sample, and then all units be screened in comparison with that single equation. An effort should be made to ensure no temperature bias in the screening baths, as appears to have been the case here. If this technique had been used, the processing of the data would have been much easier and fewer questions would exist regarding the general applicability of the resulting frequency-to-temperature conversion equation.

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The mention of commercial products or the use of company names does not in any way imply endorsement by the U.S. Navy or NRL.

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