THE AIRBORNE EXPENDABLE BATHYTHERMOGRAPH FOR OCEANOGRAPHIC MEASUREMENTS

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Abstract

The Airborne Expendable Bathythermograph (AXBT) system is described as an oceanographic instrument. The results of recent calibrations and field tests characterizing the accuracy and performance of the latest models are reported. It is shown that instruments produced by different manufacturers can produce varying results even though they all meet the same Navy specifications.

Introduction

The Airborne Expendable Bathythermograph (AXBT) system has been in use for oceanographic surveys for more than eight years[1,2]. During this period an increasing number of instruments have been used for various scientific programs. AXBT's are manufactured to U.S. Navy design specifications and procured in large batches from a contractor successful in winning the bidding contest. Over the past eight years three manufacturers have supplied AXBT's to the U.S. Navy from which scientific programs have been supplied. While these units are similar in design and produce data outputs which satisfy the same Navy specifications, they all exhibit differences of significant importance to scientific users.

AXBT Description

The AXBT (AN/SSQ36 sonobuoy) is a cylindrical package approximately 12.4 cm in diameter and 91 cm in length weighing 6.4 Kg, shown in Figure 1. This package can be launched from standard sonobuoy launch tubes found in several models of U.S. Navy aircraft from altitudes of 50 meters to 3050 meters and up to speeds of 450 Km/hr. The package is parachuted to the water's surface where the parachute is jettisoned and an antenna deployed automatically. Figure 2 shows the AXBT in the deployed configuration. Shortly thereafter a radio frequency carrier begins to be transmitted. About one minute later a probe containing a thermistor sensor and oscillator circuit is released from the surface floating package. This probe descends at a rate of about 1.5 meters/sec sending an audio signal via an insulated wire to the radio transmitter in the surface buoy. At the moment of release this audio tone is connected by a switch to the modulator of a frequency modulation (FM) transmitter. This FM signal is received by the aircraft and recorded versus time to produce the familar bathythermograph trace.

The AXBT output is designed to produce a frequency proportional to the temperature described by the following equation:

$$f = a + bT \qquad (1)$$

where f = audio frequency in Hertz (Hz)

T = temperature in degrees Celsius, and

a and b are constants.

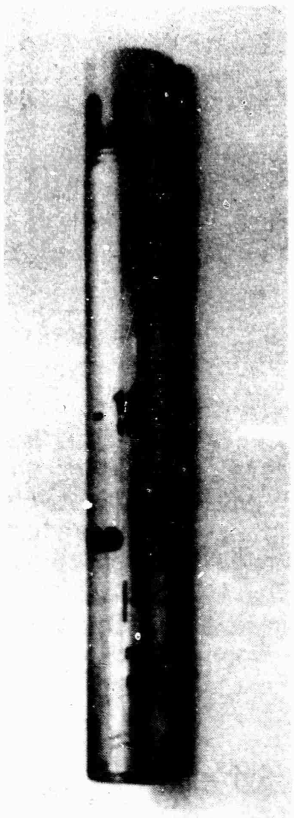

Figure 1 Hermes AXBT prior to launch

The standard Navy specifications call for a = 1440 Hz and b = 36, defining a straight line equation. The AXBT output must follow this function over the range of -2° to 35° C to within ±20 Hz, which is equivalent to ±0.56° C. More details for AXBT's can be found in handbooks on each type of instrument[3,4,5]. Errors of this order of magnitude have been reported by Brisco, Johannessen and Vincenzi[6] and led to the calibration work by the authors.

Calibrations

In 1974 a group of about 300 AXBT's manufactured by Motorola were calibrated for the NORPAX pole experiment[7]. The results of this showed that a linear relationship could be determined for the AXBT's that were somewhat different from the Navy standard to give accuracies of the order of ±0.17° C over a range of 7° to 17° C. Unfortunately, this required the calibration of each individual unit and the determination of a separate calibration coefficient for each unit.

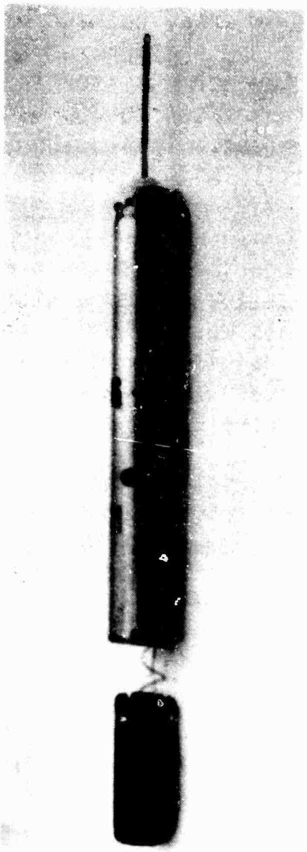

Figure 2 Hermes AXBT with temperature probe deployed

Beginning in 1974 a new design AXBT manufactured by Magnavox became available. This unit differed substantially from previous Motorola units in the area of thermistor, oscillator and probe design. Calibration of 57 units revealed that the entire population could be characterized by the following relationship:

$$T = a + bf + cf^2 \qquad (2)$$

where f = output frequency in Hertz (Hz)
T = temperature in degrees Celsius and
$a = -45.11$, $b = +0.03381$ and $c = -1.676 \times 10^{-6}$

The maximum rms error over a range of 0° to 25° C was 0.16° C. Additionally, the temperature and voltage sensitivity of the oscillator circuit was greatly improved over the previous units resulting in a much better instrument for oceanographic purposes.

A question which remained unanswered regarding the accuracy of the overall system was the verification of probe descent rates. Some question regarding this quantity remained from differences noted in actual ocean tests.[8] To resolve this question thirteen Magnavox AXBT's were disassembled and fitted with small pressure sensors. Suitable electronics replaced the original temperature oscillator board and units were reassembled. Each was carefully weighed so that it was within one gram of its original weight. The external package was unchanged save for a small (∿2mm) hole in the nose leading to the pressure sensor. These special AXBT's were deployed on 10 November 1976 off Southern California. Ten good records resulted yielding a mean descent rate of 1.59 m/sec to 300 meters depth. The standard deviation for these data was 0.043 m/sec. This value is 4.6% greater than the nominal value of 1.52 m/sec but still within the ±5% specification for descent rate.

During the above described experiment, seven previously calibrated AXBT's were deployed while simultaneous Salinity, Temperature and Depth (STD) profiles and Nansen Bottle casts taken. This was to verify previous laboratory tests and calibrations. Unfortunately, the results of this experiment show large deviations in AXBT temperature versus STD values which were supported at a number of points by Nansen Bottle reversing thermometer data as shown in Figure 3.

Research into this difference revealed that the manufacturer had changed thermistors, the newer types having thicker coatings which greatly modified the thermal time constant of the probe assembly. New time constant measurements yielded the results shown in Figure 4. Unfortunately, fairly large scatter in the data exists due to uneven coating of the individual thermistors. Since the probes contain pairs of thermistors in series there can be large differences in each thermistor in the pair.

The time response of the AXBT's to a unit step input (Figure 4), plus the physics of the problem (see below), suggests a relatively simple transfer function of the form:

$$h(t) = \sum_{n=1}^{N=3} A_n e^{-t/T_n} \qquad (3)$$

The parameters of this function were successively determined by the methods described by D'Azzo and Houpis [1966].[9] The appropriate numerical values were found to be:

n	A_n	T_n (sec)
1	0.851	3
2	0.038	43
3	0.111	184

The resulting empirically estimated transfer function is shown in Figure 4.

The representation of the transfer function as three exponentials was suggested physically from the causes of the thermal lag. Under the assumption that the thermistor coating and probe all touch at a common point, then one would expect the following situation:

1) The coupling between the plastic coating covering the thermistor and the thermistor itself has a time constant which corresponds to $T_1 \approx 3$ seconds.

2) The connection between the plastic coating and the water will affect the

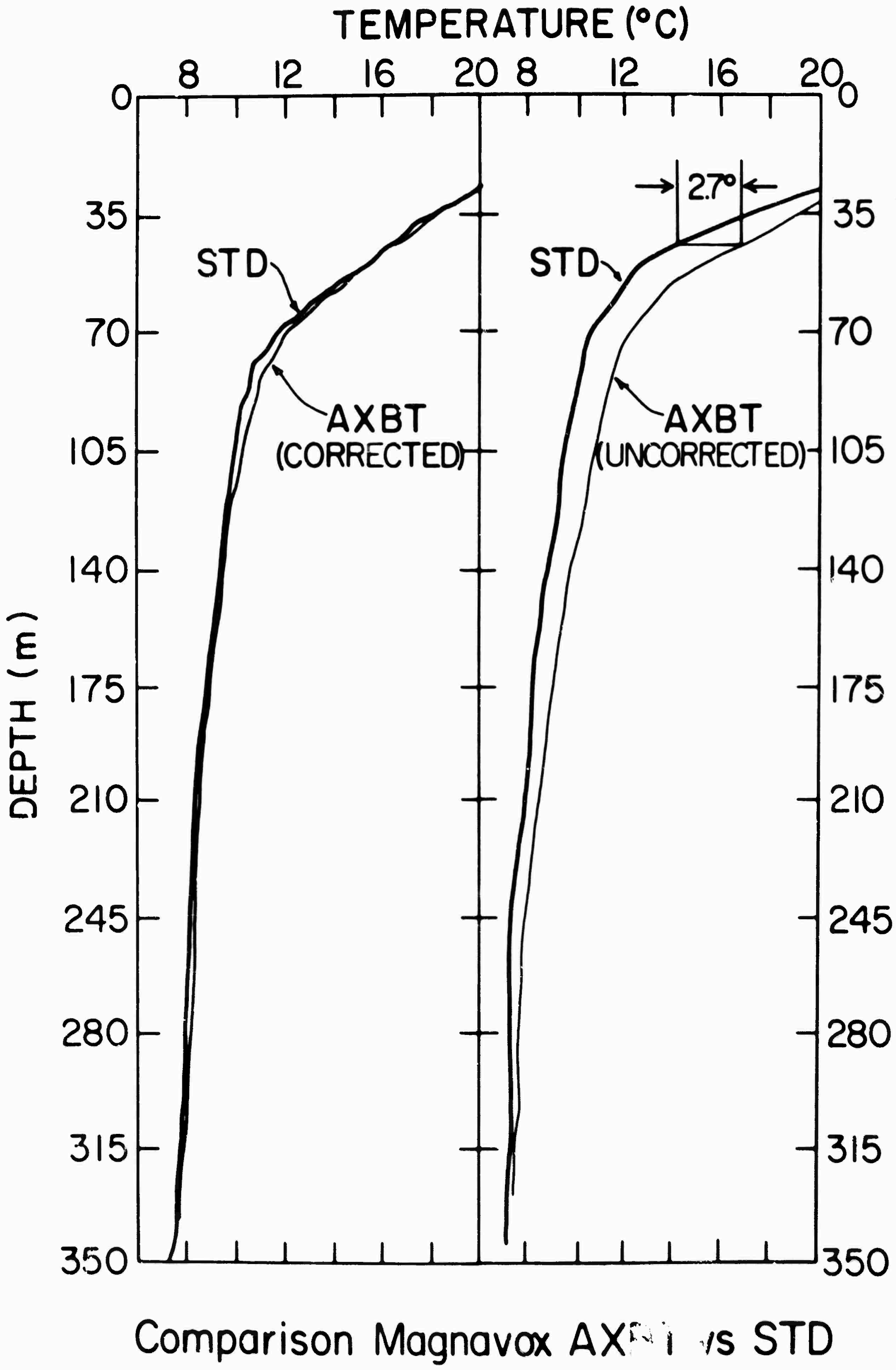

Figure 3 AXBT traces versus simultaneous STD casts

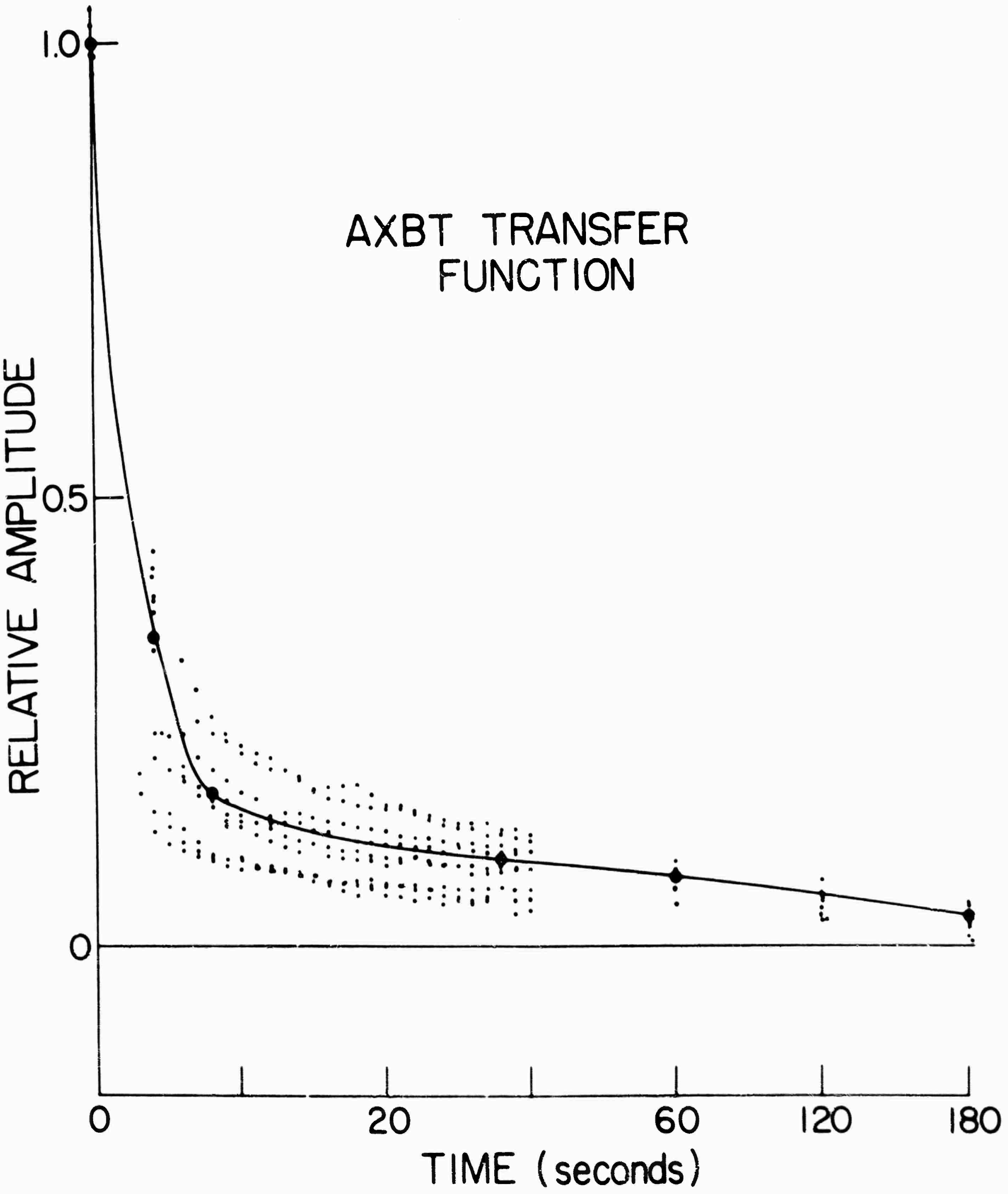

Figure 4 Experimental estimates of response of AXBT's to a step function temperature input. Data are for ten instruments from five different production lots. The heavy curve is the fitted transfer functions, equation (3).

AXBT as it falls through an ever-cooling water column. The thermal inertia of this coating is T_2 = 43 seconds.

3) The plastic coating that covers the thermistor and links it thermally to the metal mass of the probe that governs the AXBT fall rate is T_3 = 184 seconds. The approximate mathematical description of the above system is:

$$\frac{d\theta_T}{dt} = -\alpha(\theta_T-\theta_C)$$

$$\frac{d\theta_C}{dt} = -\alpha(\theta_C-\theta_T) -\beta(\theta_C-\theta_P) +\gamma(\theta_W-\theta_C) \tag{4}$$

$$\frac{d\theta_P}{dt} = -\beta(\theta_C-\theta_P)$$

where θ_T, θ_C and θ_P represent the temperature of the thermistor, coating and probe, respectively, and the constants α, β and γ are the time constants appropriate to each. The "forcing term," $\theta_W(t)$, is the water temperature encountered by the falling probe. It is assumed that the outer layers of the probe, except those covered by the coating, respond instantaneously to changes in $\theta_W(t)$.

Solving equation (4) by Laplace transforms gave (3) with the constants A_n being algebraic combinations of α, β and γ. Repeating the exercise with different physical assumptions (i.e., n=2 terms) in (3) gave a poor fit to the observed transfer function. Using more than three terms in (3) gave small corrections at time scales not justified by the experimental data. We thus have both numerical and physical rationale for taking N=3.

In practice the thermal lag is accounted for using the relation:

$$\theta(t) = \int_{t-\Delta t}^{t} h(t-t')\ \theta(t')dt' \tag{5}$$

Tests show the AXBT probes we used do not start to fall through the water column until approximately 120 - 240 seconds after they have "landed" on the sea-surface, hence the selection of Δt=120 seconds. We have no choice but to assume that the external parts probe system reach equilibrium with the surrounding water in that time period. The cruise results suggest this to be a reasonable assumption, but then the correction due to changes in the thermal inertia of the probe, which has not stabilized, would be small in this case anyway. Thus we initialize (5) by assuming equilibrium for $\theta(t)$ during the period t=120 to 0 seconds, the time at which the probe commences to fall.

The resulting corrections to $\theta(t)$ are straightforward except for the effect of thermal irregularities at vertical length scales of 1 - 4 meters. These tend to be amplified slightly in the inversion process (5). However, application of a five-point running mean filter to the solution of (5) for t $\geq$ 3 seconds solved the problem.

Examples of a corrected and uncorrected AXBT trace versus a simultaneous STD trace are shown in Figure 3. The error has been reduced by a factor of 10 so that the uncertainty between AXBT/STD is now comparable with:

1) the uncertainty in the temperature/frequency calibration between different instruments, or

2) the inter- and intra-lot scatter amongst the units used in the time constant determination (Figure 4), or

3) the scatter in the observed times between probe release and the start of modulation (= transmission of temperature data), or

4) some combination of 1) to 3).

All items considered, the Magnavox AXBT accuracy is of order 0.3 - 0.4° C with the largest errors occurring in the regions of highest vertical temperature gradient.

A third manufacturer, Hermes Electronics, produced the most recent group of AXBT's for the U.S. Navy. Again the design is outwardly similar but contains several differences. The thermistors and oscillator are different from previous designs and in this case utilizing glass head coated thermistors with a time constant of 300 to 500 milliseconds. Our tests have verified these figures which remove the serious time constant problem noted in the later Magnavox units. It was necessary to calibrate a quantity of these units to verify the predicted frequency to temperature relationship. A sample of 100 AXBT's from lots 18 and 20 were calibrated at 8° and 25° C. Several AXBT's from this sample were also calibrated six points over the range of 0° to 32° C. Analysis of these results showed that a good linear relationship over the range of 7° to 26° C could be expressed by the following equation:

$$f = a + bT \tag{6}$$

where f = frequency in Hertz
T = temperature in degrees Celsius
and a = 1425, and b = 37.18

The mean, standard deviation, and range for the calibration points of 8.0° C and 25° C, respectively, are:

	8° C	25°C
MEAN FREQUENCY	1722.5 Hz	2354.7 Hz
STANDARD DEVIATION	1.68 Hz	1.44 Hz
RANGE	+5.4, -4.4 Hz	+5.3, -3.2 Hz

These calibrations results are summarized in Figure 5 along with a plot of the theoretical probe error curve from the Navy straight line equation for all Hermes AXBT's.

A second group of 36 Hermes AXBT's were calibrated at 8° and 25° C during October of 1979. These units were from lots 13 and 31. The results of these calibrations are:

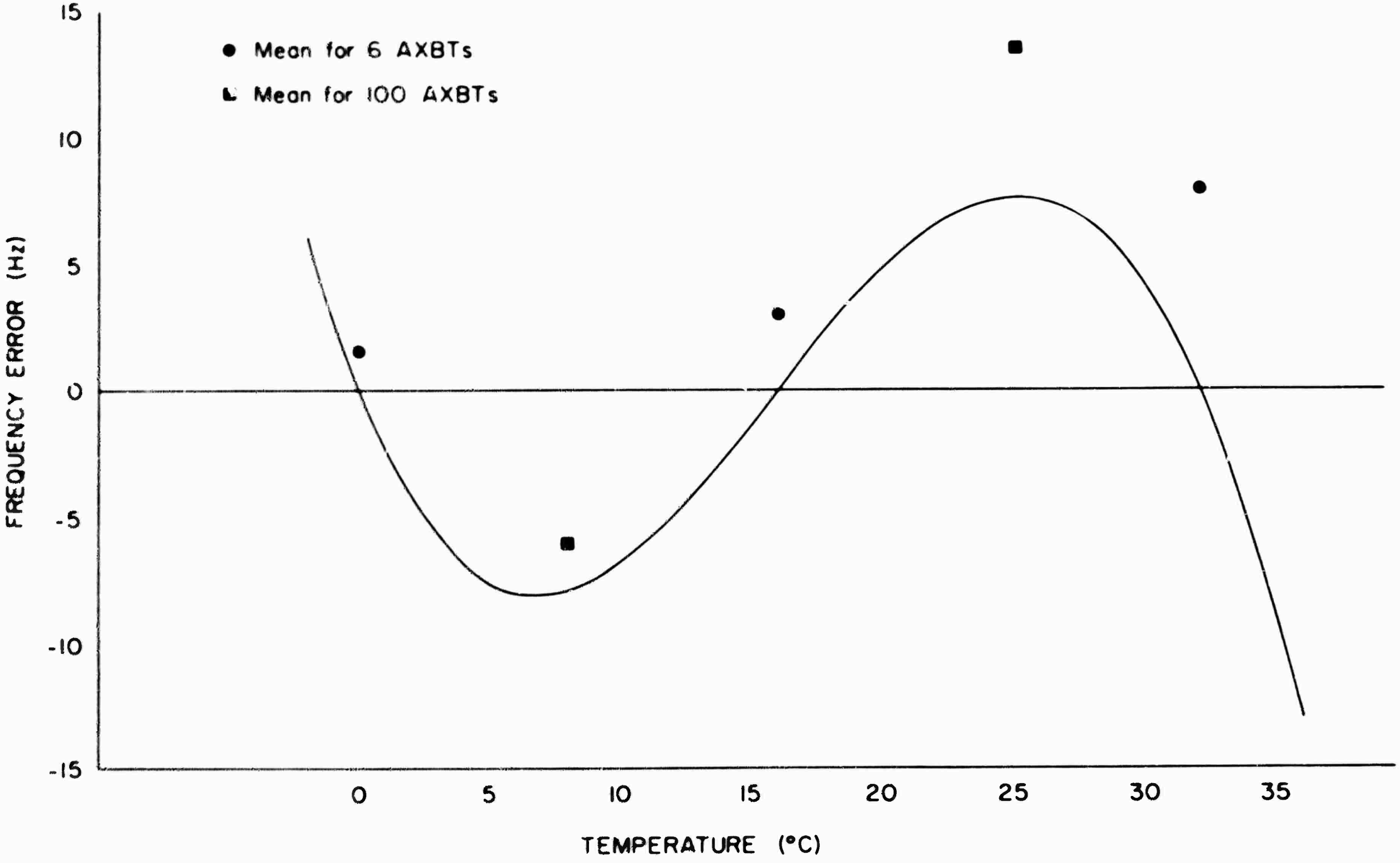

Figure 5 Calibration Data of Hermes AXBTs

	8°C	25°C
MEAN FREQUENCY	1723.9 Hz	2357.05 Hz
STANDARD DEVIATION	2.30 Hz	2.21 Hz
RANGE	+4.7, -3.6 Hz	+5.2, -3.2 Hz

The above data are for 35 instruments. One of the AXBT's showed frequencies below the mean values equivalent to about 2° C at 8° C and 2.6° C and 25° C. Discussions with the manufacturer indicated that this is most likely a failure of a trim potentiometer in the probe assembly. Several incidents of this type failure have been noted during drop tests. The AXBT in question has been returned to the manufacturer for analysis and positive identification of the fault.

Data Recording

Data recording methods used aboard U.S. Navy fleet aircraft vary with the type aircraft and generally do not provide adequate accuracy and resolution for oceanographic applications. In order to overcome these shortcomings and to provide versatile real time outputs for analysis during flight, a portable recording package was designed and constructed. This package is a compact, light-weight package (about 54 Kg) configured to be a stand alone work station requiring only 115 VAC, 50-400 Hz and the signal output from the sonobuoy receiver. Typically, this package is mounted on its self-contained legs and secured to the floor of the aircraft with cargo tie down straps.

AXBT data from sonobuoy radio receivers aboard P-3 type aircraft are in the form of an audio frequency between 1000 and 3000 Hz with an amplitude of about either 6 or 36 volts depending on the output selected (both are available simultaneously). A block diagram of the recording system is shown in Figure 6. Operation of the system is as follows. The operator initiates the data recording by pressing a launch switch at the time the AXBT exits the aircraft. A serial number previously entered into the system via a panel mounted thumbwheel switch is recorded on the digital cassette recorder. Simultaneously this serial number and time from the system digital clock are printed on the digital printer, and the auto-start circuits are enabled. Several minutes later (time depending on altitude of launch) the AXBT impacts the water's surface and begins transmitting a carrier to the aircraft. This event is detected by the operator on the oscilloscope monitor by noting the receiver noise going to zero signal level. About one minute after carrier detect, the AXBT releases the temperature probe which switches the audio signal from the probe to the transmitter modulator. A sudden appearance of an audio tone within the limits of amplitude and frequency of the phase lock loop filters in the auto-start circuit initiates the recording cycle. The signal is applied to the input of a frequency counter which counts the frequency for a one-second period. The digital output from the frequency counter is recorded in serial form on digital magnetic cassette and also recorded on the digital printer along with time. The frequency signal is also sent to a frequency to voltage converter. This analog output voltage is recorded on a strip chart recorder giving the usual temperature versus depth (actual time) trace. This cycle is continued for some preset time interval, typically between 220 and 280 seconds (equivalent to 335 to 425 meters depth at the nominal 1.52 m/sec descent rate). At the end of this time interval all systems are reset and ready for the next AXBT launch.

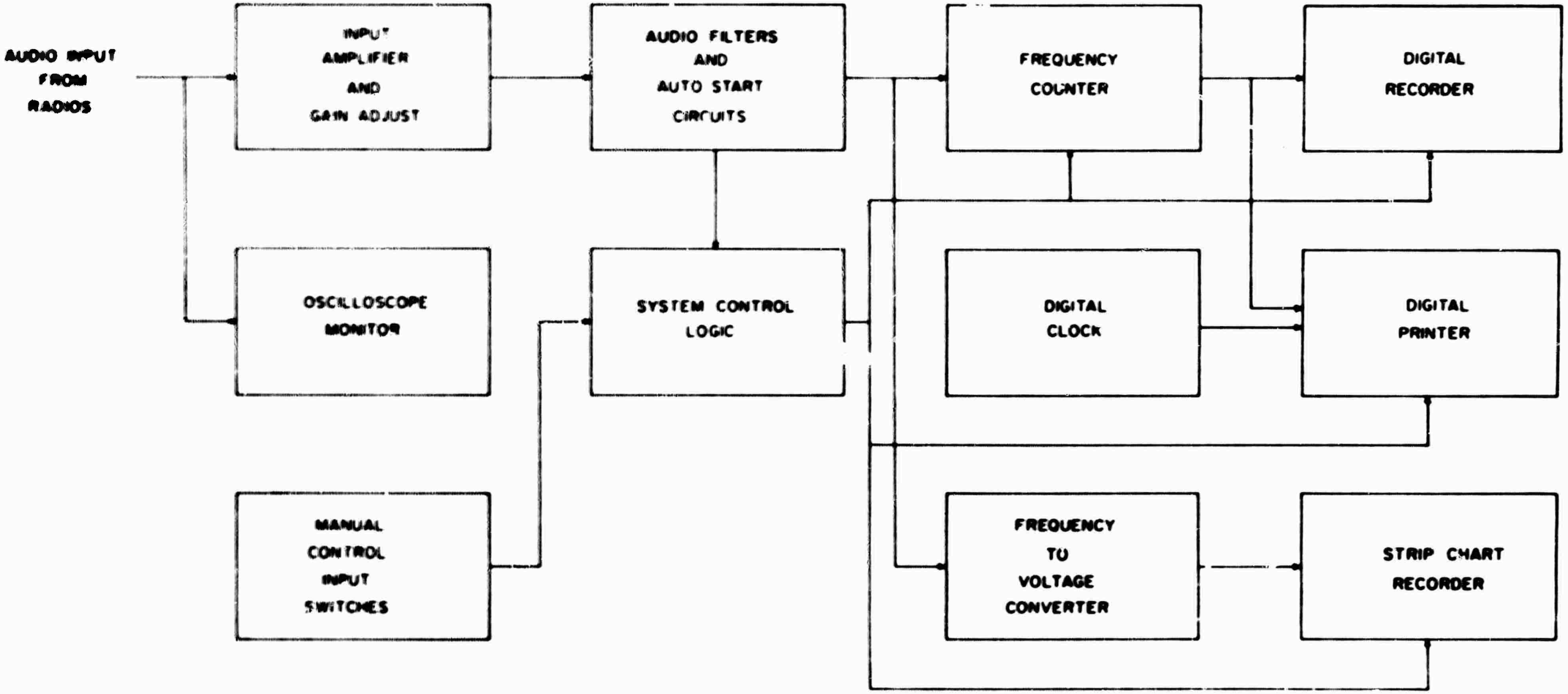

Figure 6 Block Diagram of Scripps AXBT Recording System

Considerable effort was expended in providing some redundancy in the system so that failures in the data recording package would not result in total failure. Toward that end dual frequency counters and cassette recorders were installed. Also, front panel switch selectable dual auto-start front end circuits were included. Ability to switch either frequency counter output to the digital printer was also provided. Dual power supplies are carried with a quick plug changeover capability.

By measuring the frequency directly over a one-second period least count error is ±1 Hz or about 0.027° C, substantially less than typical AXBT calibration errors. Depth resolution is the order of 1.5 meters, suitable for most oceanographic applications.

Field Results

Since 1974 we have used AXBT's from the three manufacturers previously noted. A group of 290 AXBT's manufactured by Motorola were used during January and February of 1974 in the North Pacific Ocean. A failure rate of 11% was sustained. The units exhibited a tendancy to fail to transmit audio signals as the probe descended to some significant depth. It was suspected that probe leakage was the cause of this. If a probe got well past the mixed layer depth at about 100 meters, it was not considered a failure.

During a second long term monitoring experiment in the North Pacific Ocean, Magnavox AXBT's were deployed on monthly flights between November 1974 and April 1977.[10] Approximately 1300 AXBT's were deployed during this experiment. A failure rate of 10% was sustained by these units. All of these AXBT's were of the rotorchute type, the earlier portions of the total number built on this contract. Later units replaced the rotorchutes with parachutes.

The third group of AXBT's were manufactured by Hermes, Ltd. and were used in a transequatorial experiment between November 1977 and February 1978.[11,12] A total number of 1620 AXBT's were deployed during this experiment with a failure rate of 4.7%. Clearly the latest design AXBT achieved better reliability than past AXBT's. It was noted that many of the failures were of a type not observed in previous experiments. This was evidenced by the start of the audio signal being delayed until the probe was at some significant depth where the temperature profile would appear to be offset in time (or depth). We call this problem a "late start" and depending on its magnitude can be difficult to detect. After some experience of flying at a constant altitude it is possible to notice an increase in time between when the carrier signal is detected and the audio is detected. If this late start is only a few seconds in time, it is quite difficult to detect and can therefore result in very misleading data. This problem is due to the mechanism which detects release of the probe, and switches the audio signal to the modulator. An improvement in this area is clearly called for and would further reduce the field failures observed during our experiment approximately by 50%.

The recording system has functioned very well in the field. No data have ever been lost to catastrophic failure of this system. The additional redundancy provided, spare parts kits and technically skilled personnel who have always operated the equipment have yielded these results.

Conclusions

The standard U.S. Navy AXBT can be used for oceanographic purposes if appropriate calibrations are performed and applied to field results. Even though all units are produced to meet the same specifications, subtle differences between different designs affect performance in the ranges of accuracy expected for oceanographic purposes. Care should be exercised when using even the same manufacturer's units from lots produced at different times as running production changes can have serious effects on performance. Significant use of the AXBT by the oceanographic community has focused attention on the need for better instrument performance and manufacturers have attempted to upgrade performance within the limits of maintaining the Navy standards and remaining cost competitive. Future improvements can be attained at a small cost increment by instituting some production calibration. Post-production calibration is more expensive because it is necessary to partially disassemble the instrument in order to perform the calibration. There is always some doubt about non-factory reassembly affecting the reliability, although we have had no problems in this area. Performance and reliability have substantially improved in recent designs. This together with the versatility of the U.S. Navy P-3 aircraft provides a powerful and effective tool for performing large scale synoptic oceanographic surveys.

Acknowledgments

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