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EXPENDABLE BATHYTHERMOGRAPH (XBT) ACCURACY STUDIES

Dr. E.R. Anderson

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Naval Sea Systems Command
Washington, DC 20350

Final Report for Period May 1971 - December 1979

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NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CALIFORNIA 92152

NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CA 92152

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ADMINISTRATIVE INFORMATION

Between May 1973 and October 1975, 460-meter and 1830-meter expendable bathythermograph (XBT) profiles were collected by personnel of the Experimental Acoustics Branch during six propagation-loss experiments. The XBT profiles were made with 11 different 460-m and two different 1830-m XBT systems from four ships and two research platforms. Additional independent temperature measurements were made by means of other systems, such as hydrocasts, STD/SV profiling systems, and a thermistor chain system. This collection of measurements provides a data base for several XBT accuracy studies.

A draft of the manuscript was sent to the Sippican Corporation for review and comment, which are included here following the Recommendations section.

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This report is an examination of the accuracy of expendable bathythermograph (XBT) system temperature profiles. It covers a suite of studies on 1961 460-m and 26 1830-m XBT profiles collected between 1971 and 1975. The samples show that many visually acceptable but actually erroneous measurements are being transmitted to the Fleet Numerical Weather Center (FNWC), which results in inaccuracies of acoustic predictions based on these measurements.

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PROBLEM

Develop techniques for predicting characteristics of underwater signals and reverberation fields from environmental inputs. These techniques are inputs to performance prediction models, fleet tactics, sonar design, and force level studies. Specifically, examine the accuracy of expendable bathythermograph (XBT) system temperature profiles. This report contains a suite of accuracy studies based on 1961 460-m XBT profiles and 26 1830-m XBT profiles collected between May 1971 and October 1975 during six Naval Undersea Center (now Naval Ocean Systems Center) propagation loss experiments. The measurements were made on 11 460-m systems and two 1830-m systems from four ships and two research platforms.

RESULTS

- Properly functioning XBT systems may develop malfunctions while making a series of profiles and produce visually acceptable, but erroneous, temperature profiles. Other information, such as independent temperature measurements, is required to detect and identify such malfunctioning 460-m XBT systems. In these studies, independent surface temperatures were measured concurrently with 736 visually acceptable XBT profiles made on seven different 460-m systems. Surface temperature comparisons showed that two of the systems, after making a series of accurate profiles, developed malfunctions. Comparison of 400-m temperatures showed that the malfunction did not result in a simple temperature displacement of the profile. Consequently, it produced profiles having systematic errors in the vertical temperature gradients. The profiles made after the system malfunctioned were visually acceptable profiles. Of 736 profiles, 36.5 percent were made by the malfunctioning systems.

- Of a total of 1961 attempted 460-m profiles, the following percentages apply:

Visually acceptable to the maximum depth	80.1%
Partially successful	10.8%
Catastrophic failures	6.4%
Miscellaneous failures	2.7%.

- Of a total of 518 460-m XBT profiles made when the XBT systems were not malfunctioning, only 37.8 percent of those reaching 400 m satisfied 200-, 300-, and 400-m accuracy criteria at all three depths and 19.9 percent failed to satisfy the accuracy criteria at all three depths. The accuracy criteria were based on average hydrocast and STD/SV temperatures.

- Comparison of XBT temperatures with average hydrocast and STD/SV temperatures, quasisimultaneous STD/SV temperatures, and thermistor chain temperatures taken underway at 3 knots showed that the 460-m XBT systems measure, on the average, temperatures that were higher and vertical temperature gradients that were larger than those measured by the other systems. Once the profiles associated with the large differences were identified and removed from the data set, the remaining profiles accurately measured the temperature. For this data set, the average differences were near zero with standard deviations of 0.07°C to 0.13°C.

• Of a total of 559 profiles made when the XBT systems were not malfunctioning and also were reaching a minimum depth of 200 m, the 200-, 300-, or 400-m temperatures for 54 (9.7 percent) of the profiles exceeded the average hydrocast and STD/SV temperatures by more than or equal to ±0.50°C at one or more of the three depths.

• The data set included 26 attempts to make 1830-m XBT profiles. Of the 26 attempts, 10 were successes, 7 were partial successes, 8 were catastrophic failures, and one exceeded the calibration correction. The catastrophic failures were so classified because of apparent temporary insulation failure in the upper 50 m. The measurements made at depths greater than the apparent insulation failures for some profiles appear accurate. However, use of these measurements without other confirming measurements for depths greater than the first insulation failure may result in some risk.

• "Runs" of consecutive XBT profiles were observed in which the temperature measurements are accurate within prescribed limits. However, the measurements do not vary randomly within these limits and form a statistical run of biased data.

• An examination of individual simultaneous pairs of visually acceptable 460-m profiles showed that many of the pairs differed by large amounts. Some of the pairs measured large differences starting in the near-surface layer with the differences being a variable function of depth while others agreed identically in the near-surface layer and began to differ at some depth below the thermocline with the difference being an increasing function of depth.

• During the SUDS I experiments, 28 XBT profiles were judged by the observer to be visually acceptable and were digitized and transmitted to the Fleet Numerical Weather Center where they were used as inputs to predictions of Fleet sonar performance. Of the 28 profiles, 15 were made in area C, where enough hydrocast and STD/SV measurements were taken to establish an average 200-, 300-, or 400-m temperature. Of the 15, 13 reached a depth of 400 m. Of those reaching 400 m, the percentages satisfying the 200-, 300-, and 400-m accuracy criteria at the various depths were as follows:

All three depths:	3, or 23.1%
Two depths:	2, or 15.4%
One depth:	3, or 23.1%
No depths:	5, or 38.5%.

If this sample of 13 XBT profiles is representative of the data being transmitted to FNWC on a routine basis, the inclusion of many visually acceptable but actually erroneous measurements must certainly have an adverse effect on the accuracy of the acoustic predictions based on these measurements as inputs to the predictions.

RECOMMENDATIONS

• As a result of its review of these studies, the Sippican Corp suggests that the following procedure be used for those applications requiring retention of full available system accuracy.

> ". . . calibrate with an A2A test canister whenever (1) a new roll of chart paper is installed, (2) at four-hour intervals during continuing drops, and (3) whenever the 2-second, midscale calibrate trace exceeds ±.1°C from 16.7°C. In addition, a once

> per day check using an A4 XBT test box provides a quick indication of incipient launcher leakage before it becomes severe enough to affect system accuracy."

The preceding should be standard operating procedure for all users of Sippican's XBT systems. If this is not possible, independent surface measurements should be made simultaneously with each XBT profile. These measurements may be used to check whether an XBT system is properly functioning.

- Enter the identification number of the XBT probe carton on the XBT log.

- When it is recognized that a system has malfunctioned while making measurements, keep the configuration of that system intact. The Sippican Corp should be contacted promptly after the vessel returns to port, so that the cause of the system malfunction can be investigated.

- Modify the XBT system to include a depth sensor that would measure a single depth independent of the drop time and provide an indication of this depth on the analog record. This measurement could be used to correct for depth bias.

- Develop a method or technique for identifying visually acceptable but gradient-biasing XBT profiles before they are used in any application and before they are archived.

- Investigate possible reasons why an XBT system can malfunction and still record visually acceptable but erroneous profiles. Once the reason, or reasons, are identified, modify the XBT system to eliminate the causes.

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INTRODUCTION

In the late 1930s, Spilhaus[1] developed the first successful instrument to measure temperature continuously as a function of depth in the upper 150 m of the ocean. This instrument was called a bathythermograph (BT), and the record it produced a bathythermogram. The instrument was widely used by the US Navy's antisubmarine forces during World War II. With increased civilian and naval interest in oceanography during the post-World War II years, the bathythermograph became a major instrument in acquiring information on the details of the distribution of temperature in the upper 275 m of the world's oceans. During this time, many hundreds of thousands of BT temperature records were acquired. These records were first archived by the Naval Oceanographic Office and later by the National Oceanographic Data Center. Over the years, many of these analog records were digitized and presently form a major source of historical oceanic temperature data.

In the late 1950s and early 1960s, a requirement by both the US Navy and the civilian oceanographic community for an instrument that was more accurate and had a greater depth capability developed. As a result of this need, the concept of a lightweight, cheap, easy to use, expendable bathythermograph (XBT) was generated. By the early 1960s, three companies – Francis Associates, Bissett-Berman, and Packard Electric – had developed expendable bathythermograph systems.

In 1965, the US Navy organized a series of experiments to evaluate the accuracy, precision, and reliability of XBTs produced in the latter half of calendar year 1964 by the above three companies. The experiments were designed so a statistical analysis to compare the performance of the three XBT systems could be performed. The results of these experiments were reported by Arthur D. Little, Inc.[2] As a result of these comparisons, the Navy selected the XBT system developed by Francis Associates and manufactured by the Sippican Corporation to replace the Spilhaus bathythermograph as the primary instrument to acquire temperature information in the upper few hundred meters of the ocean.

To the author's knowledge, the first operational use of the Sippican XBT system was during the first half of 1966 when the Scripps Institution of Oceanography used the system during the Boreas Expedition in the northern North Pacific and the Navy Electronics Laboratory used the system during the FASOR II acoustic experiments conducted in the northern and western North Pacific. Several hundred probes were provided to both Scripps and NEL. Although few useful temperature records were obtained during either cruise, several important shortcomings in the operational system were revealed. Subsequent correction of these weaknesses led to the system presently in use.

In 1966, Arthur D. Little, Inc., published a report summarizing the operational characteristics and capabilities of the Sippican XBT system.[3] They made a critical examination of the accuracy and precision required of environmental ocean measurements for improved sonar range prediction purposes and compared these requirements with the performance of the XBT system. Such items as cost effectiveness, temperature and

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1. Spilhaus, A.F., A Bathythermograph, *Journal of Marine Research,* v 1, p 95–100, 1938.
2. Arthur D. Little, Inc, *Experimental Evaluation of Expendable Bathythermographs,* Dept of the Navy, Bureau of Ships, NObsr-93055, Project Ser No SF-101-03-21, Task 11353, November 1965.
3. Arthur D. Little, Inc, *Expendable Bathythermograph (XBT) System Evaluation for Tactical Sonar Application,* Dept of the Navy, Naval Ship Systems Command, NObsr-93055, Project Ser No SF-101-03-21, Task 11353, August 1966.

temperature-gradient errors, sound-speed gradient errors, sink-rate and depth errors, and the adequacy of a temperature profile unaccompanied by a salinity profile for sonar range predictions were studied.

In 1977, the Naval Research Laboratory published a memorandum report discussing subtle malfunctions of the 460-m (T-4 probes) XBT systems.[4] The report stated:

> "Malfunctions such as that exhibited in this report have been observed, identified, and tallied in several multi-ship experiments. The results are rather startling, in that most of the T4 malfunctions actually are subtle and easily could slip by the uninformed operator."

Their analysis discusses possible causes of the malfunction. They also state that the malfunction was only positively identified in two batches of probes and that, "further extrapolation to it being a general Fleet problem is open to speculation."

On 22–23 October 1977, the Naval Underwater Systems Center conducted an accuracy study of the T-4 XBT probe. The primary purpose of the test was to identify which portions of Navy stock XBT probes were unsuitable for tactical Navy use. They used 1250 probes from Navy stock and 264 probes purchased from the manufacturer. They sorted the XBT profiles into five mutually exclusive categories. Two of the five categories were analogous to the XBT profiles that the Naval Research Laboratory study (ref 4) referred to as containing "subtle malfunctions." A considerable number of the profiles were in these two categories.[5]

Beginning with the Naval Undersea Center's Gulf of Alaska acoustic experiments in 1971, the author began accumulating XBT temperature profiles as well as supporting temperature measurements, with the objective of examining the accuracy of routinely acquired XBT temperature profiles. The purpose of this publication is to report the results of these studies.

This report includes discussions of the following studies of 460-m XBT system temperature measuring accuracy:

a. Determination of system errors for the various temperature measurement systems used.

b. Comparison of XBT surface temperature measurements with independent surface temperature measurements.

c. Two comparisons of XBT measured temperatures with average hydrocast and STD/SV measured temperatures.

d. Comparison of XBT measured temperatures with quasisimultaneous STD/SV measured temperatures.

e. Comparison of XBT measured temperatures with simultaneous thermistor chain-measured temperatures.

f. Discussion of selected individual XBT profiles.

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4. Naval Research Laboratory Memorandum Report 3612, *Subtle T4 XBT Malfunctions*, by J.P. Dugan and A.F. Schuetz, September 1977.
5. Naval Underwater System Center, letter report Ser 8431-17, 13 February 1978.

g. Comparison of simultaneous XBT measurements.

h. Analysis of the accuracy of a set of XBT profiles digitized and transmitted to the Fleet Numerical Weather Center for operational use.

This report also includes a discussion of the accuracy of a limited number of 1830-m XBT profiles.

For the reader who is not interested in the statistical details of the above studies, the summary near the end of the report provides a detailed and complete resumé of the main text of the report.

DATA BASE

Expendable bathythermograph (XBT) temperature profiles, together with supporting hydrocast, STD/SV or CTD/SV, SVTP, thermistor chain, towed thermistor, and/or bucket thermometer temperature measurements, were made during the following acoustic experiments:

a. Gulf of Alaska: 5 May–16 August 1971.

b. SUDS I: 8–24 February 1972.

c. ORB-3: 12–18 December 1972.

d. ORB-4: 15–21 February 1973.

e. CAPER: 18–31 August 1974.

f. RAPLOC/DEEPTOW: 17–28 October 1975.

The general locations of these sets of measurements are shown in figure 1.

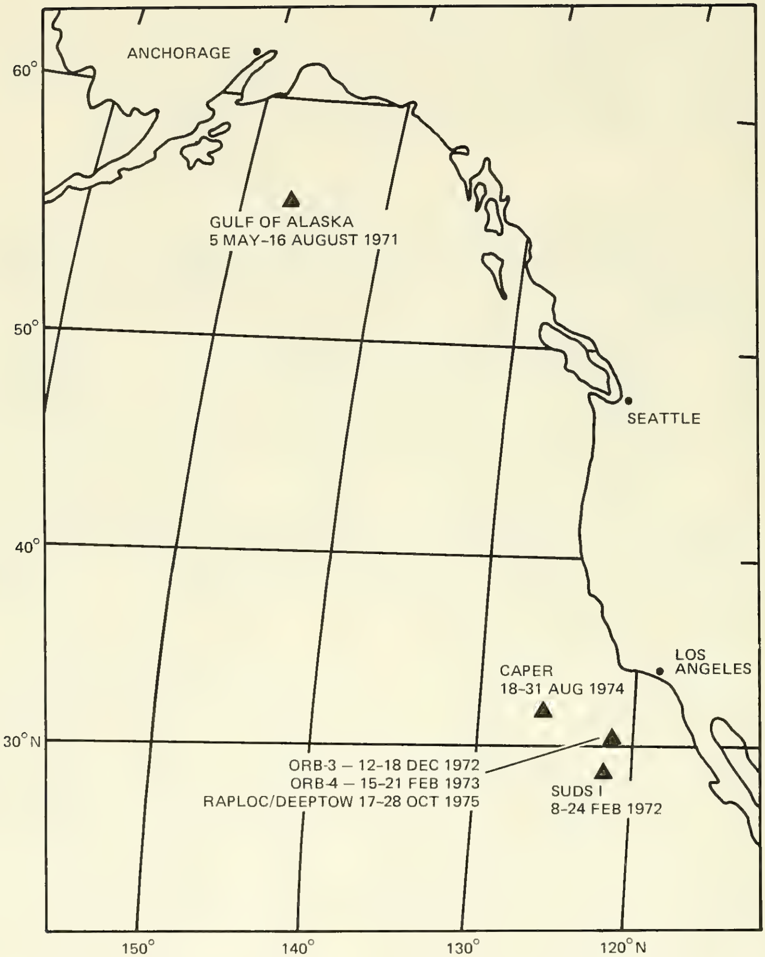

Figure 1. Location of XBT measurements.

GULF OF ALASKA

The Gulf of Alaska XBT measurements[6] were made from the USNS S.P. LEE in transit between San Diego, CA, and Kodiak, AK, and during eight acoustic experiments and two environmental surveys. The locations of these measurements are shown in figure 2. XBT measurements were made along the transit lines shown in figure 2a and at the locations labeled ABLE, CHARLIE, and PAPA, where acoustic experiments were conducted. The dashed lines in figure 2b, an enlargement of the area labeled INSET in figure 2a, show the tracks of the two environmental surveys with two of the eight acoustic experiments

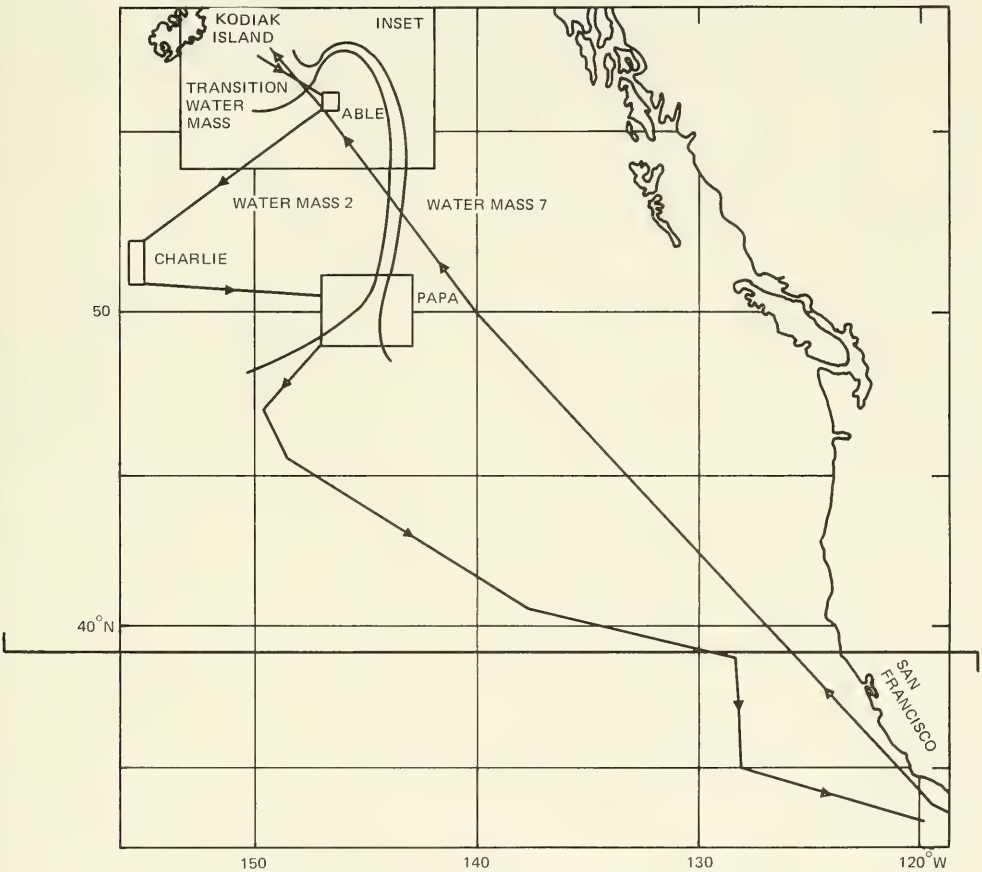

Figure 2a. Location of Gulf of Alaska XBT measurements.

6. Naval Undersea Center TP 301, v II, *Gulf of Alaska Sonar Tests April–August 1971: STD/SV, SVTP, and XBT Data Report,* by E.R. Anderson and J.R. Lovett, August 1972.

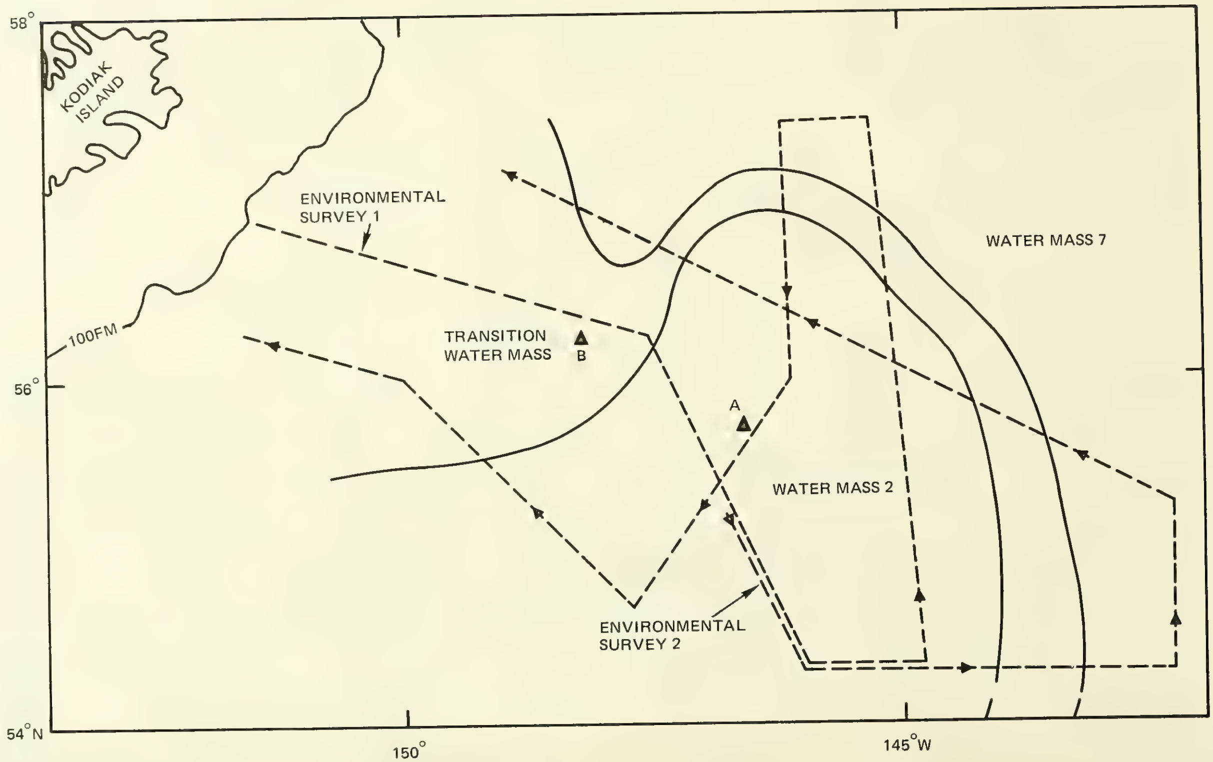

Figure 2b. Location of Gulf of Alaska XBT measurements.

conducted at location B and three at location A. The solid lines indicate the boundaries of a transitional water mass separating two distinct water masses designated as water mass 2 and water mass 7. These two water masses are homogeneous with respect to oceanic parameters such as temperature, salinity, or sound speed. The purpose of the environmental surveys was to delineate the location of the boundaries of the transitional water mass in the vicinity of the experiments made at locations A and B. Table 1 lists the experimental period, time interval, the number of XBT profiles attempted, and the number of hydrocast and STD/SV profiles. The XBT measurements were obtained when the same XBT system was used. The STD/SV profiles during environmental survey 2 and acoustic experiment A3 were made by means of a Ramsey Engineering Company SVTP MK-I system. The remainder of the STD/SV profiles were made with a Plessey Environmental Systems 9040-4C profiling system. Surface temperatures were recorded continuously at A1, A2, A3, and during both environmental surveys, when a towed thermistor was used.

Location	Time Interval	Number of Profiles		
		XBT	Hydrocast	STD/SV
In transit	5-14 May	31	–	–
B1	18-22 May	33	1	5
B2	26 May-6 June	31	–	5
ES1	10-16 June	159	–	29
A1	18-25 June	44	1	30
A2	1-7 July	44	1	21
ES2	7-9 July	93	–	10
A3	16-21 July	50	–	14
In transit	26-27 July	5	–	–
ABLE	27-29 July	11	1	–
In transit	29-31 July	11	–	–
CHARLIE	31 July-2 Aug	16	2	–
In transit	2-4 August	11	–	–
PAPA	4-7 August	31	2	–
In transit	7-16 August	56	–	–
	TOTALS	626	8	114

Table 1. Gulf of Alaska measurements.

SUDS I 1972

The SUDS* I 1972 XBT measurements were made at three locations off the coast of Southern California during 18 propagation loss runs (ref 7). The locations of these propagation loss runs are shown in figure 3 by the solid lines. The dashed lines show the

*SUrface Duct Sonar measurements

7. Naval Undersea Center TP 465, v I-V, *Surface-Duct Sonar Measurements (SUDS I-1972): Oceanographic Measurements,* by E.R. Anderson, February 1976.

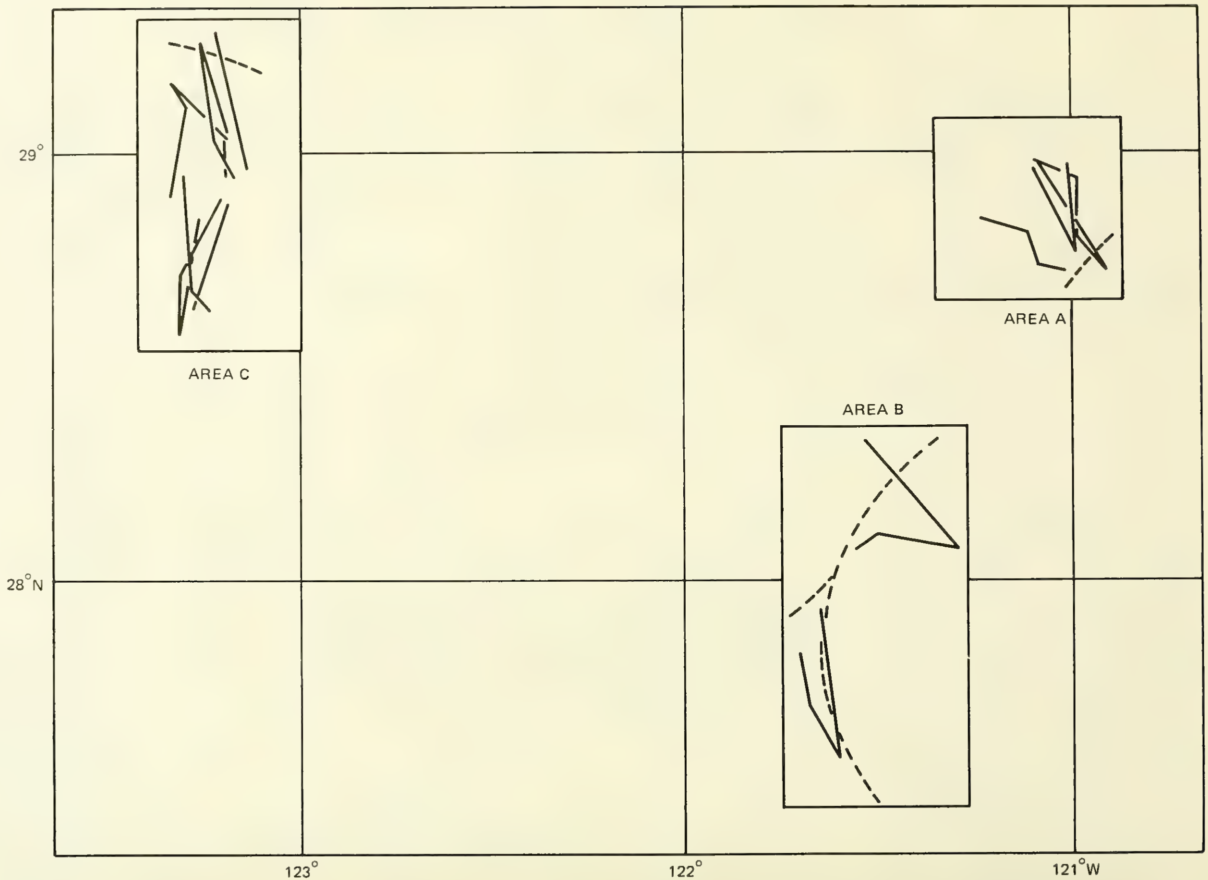

Figure 3. Location of SUDS I XBT measurements.

surface locations of near-surface water mass boundaries that were crossed during certain of the runs. The XBT measurements were made from the USNS S.P. LEE, USNS DE STEIGUER, and the RV CAPE, with three different XBT systems. The XBT profiles by the LEE were made along the tracks shown in figure 3, while the DE STEIGUER and CAPE measurements were made with the vessel hove to and drifting during the propagation loss runs. Additional measurements were made in transit between the experimental areas and San Diego, and between the experimental areas themselves. Table 2 lists the number of XBT profiles attempted, as well as the number of hydrocasts and STD/SV profiles made by the three participating ships. The LEE STD/SV profiles were made by means of a Plessey Environmental Systems 9040-4C STD/SV profiling system; the DE STEIGUER profiles were obtained with a Ramsey Engineering Company SVTP MK-I system.

Ship	Location	Time Interval	Number of Profiles		
			XBT	Hydrocast	STD/SV
LEE	Area A	8-12 February	89	3	5
	In transit	13-14 February	18	1	1
	Area B	14-16 February	63	–	–
	In transit	16-19 February	16	–	1
	Area C	19-23 February	111	2	5
	In transit	23-24 February	21	–	–
DE STEIGUER	In transit	7-8 February	3	–	–
	Area A	8-13 February	60	1	1
	In transit	13-14 February	15	1	–
	Area B	14-16 February	20	–	1
	In transit	16-18 February	5	–	–
	Area C	18-23 February	59	3	3
	In transit	23-24 February	23	–	–
CAPE	Area A	9-13 February	36	–	–
	In transit	13-14 February	10	–	–
	Area B	14-16 February	17	–	–
	In transit	16 February	2	–	–
	Area C	19-23 February	45	–	–
		TOTALS	163	11	17

Table 2. SUDS I-1972 measurements.

In addition to the hydrocast and the STD/SV measurements, the LEE also measured temperature during all propagation loss runs by means of a towed thermistor chain. This system measures temperature, from the surface to 242 m, at 44 depths spaced 5.6 m apart every 10 s, with a resolution of 0.03°C and an estimated accuracy of 0.1°C. Since the system measures a temperature profile every 10 s, simultaneous XBT and thermistor chain measurements were obtained. On 23 February 1972, with the thermistor chain vertical in the water (zero tow speed), five XBT profiles were obtained. In addition, during the propagation loss runs, the LEE, towing the thermistor chain at 3 knots, made 153 XBT temperature profiles. These two data sets provide measurements for special accuracy studies.

ORB-3 AND ORB-4

The ORB-3 and ORB-4 measurements were made off the coast of Southern California during December 1972 and February 1973 at the locations shown in figure 4 (references 8 and 9). The XBT measurements were all made from the Marine Physical Laboratory research platform, the ORB. Measurements were made under tow at 5 knots along the tracks shown in figure 4 and at anchor at the locations shown by the solid triangles. The dashed line shows the surface location of a boundary between two different near-surface water masses. All measurements during ORB-3 were simultaneous and were made on two independent XBT systems. These systems are designated A and B in the following discussion. The measurements provide data for a special relative accuracy study. Table 3 lists, for each experiment and each XBT system used, the time interval, the number of in-transit and at-anchor XBT profiles attempted, and the number of STD/SV profiles. The STD/SV profiles were all made with Plessey Environmental Systems STD/SV sensors.

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8. Reference available to qualified requesters.
9. Reference available to qualified requesters.

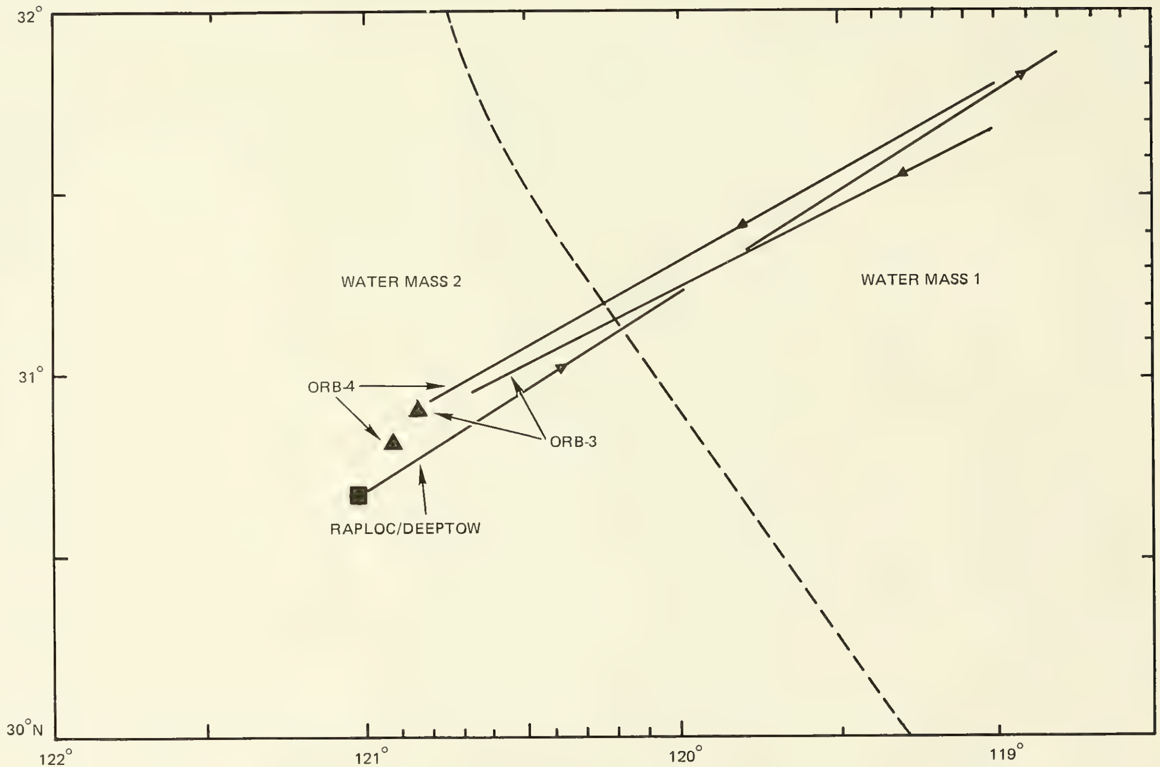

Figure 4. Location of ORB-3, ORB-4, and RAPLOC/DEEPTOW XBT measurements.

Experiments	XBT System	Time Interval	Number of Profiles		
			XBT		STD/SV
			In Transit	At Anchor	
ORB-3	A	12-18 December	23	33	12
	B		23	33	
ORB-4		15-21 February	27	98	16
		TOTALS	73	164	28

Table 3. ORB-3 and ORB-4 measurements.

CAPER*

The CAPER measurements were made off the west coast of Southern California during six propagation loss runs (reference 10). The locations of these runs are shown by the solid lines in figure 5. The dashed lines show the locations of near-surface water mass boundaries crossed by the indicated runs, and the solid square shows the location of the anchored FLIP, the receiving platform used during the propagation loss runs. XBT profiles were made along the propagation loss tracks, shown in figure 5, by the USNS DE STEIGUER, by the FLIP, and by the R/V MOANA WAVE in the vicinity of the propagation loss runs. Hydrocast and CTD/SV measurements were also made by the MOANA WAVE. The CTD/SV measurements were made with a Plessey Environmental Systems 9040-4C CTD/SV profiling system. Table 4 lists the number of XBT profiles attempted by the DE STEIGUER, MOANA WAVE, and FLIP, as well as the number of hydrocast and CTD/SV measurements made by the MOANA WAVE. The FLIP measurements were made with an 1830-m XBT system. In addition, when each XBT profile was made, an independent surface temperature was measured with a bucket thermometer.

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*Combined Acoustic Propagation in EASTPAC Region.

10. Naval Undersea Center TP 485, *Combined Acoustic Propagation in EASTPAC Region (Exercise CAPER): Sound-Speed Profiles*, by E.R. Anderson and P.G. Hansen, September 1975.

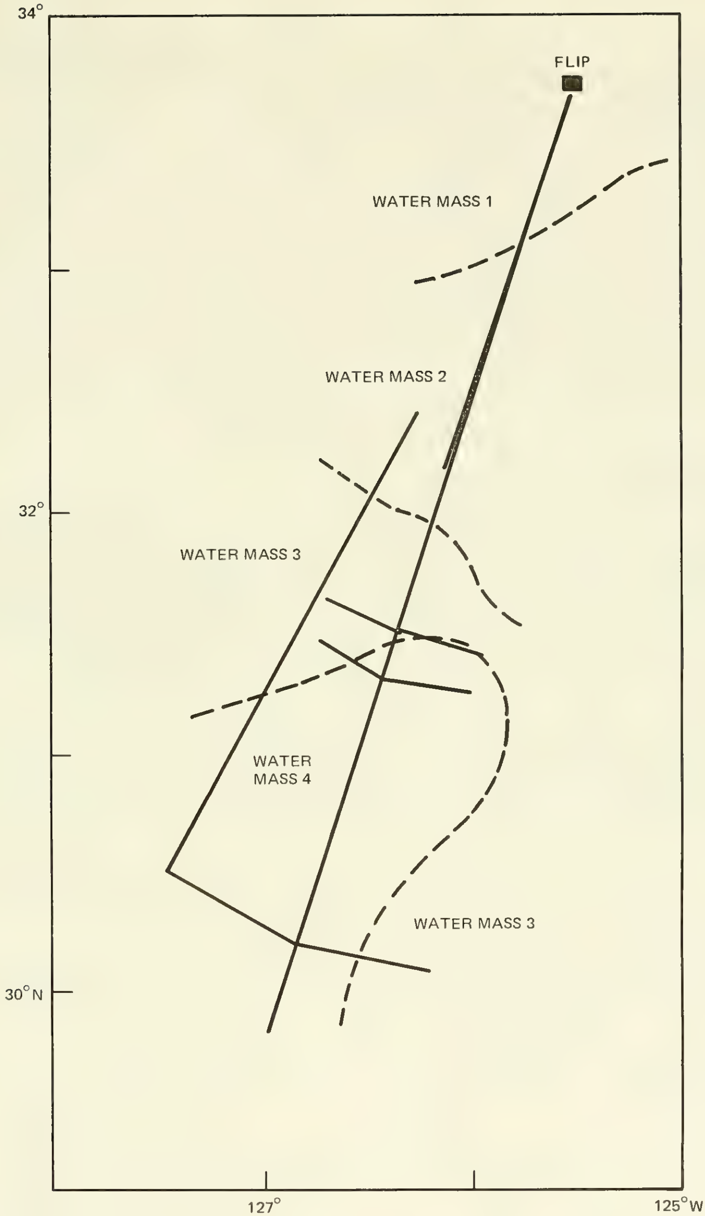

Figure 5. Location of CAPER XBT measurements.

Ship/Platform	Water Mass	Time Interval	Number of Profiles		
			XBT	Hydrocast	CTD/SV
DE STEIGUER	1	25-31 August	28	–	–
	2		57	–	–
	3		47	–	–
	4		45	–	–
MOANA WAVE	1	18-31 August	22	1	2
	2		33	–	4
	3		98	1	14
	4		24	1	2
FLIP	1	21-31 August	8	–	–
		TOTALS	362	3	22

Table 4. CAPER measurements.

RAPLOC/DEEPTOW

The RAPLOC/DEEPTOW measurements were made off the coast of Southern California during October 1975 at the location shown in figure 4. The XBT measurements were all made from the Marine Physical Laboratory research platform ORB. Measurements were made at anchor at the location shown by the solid square and under tow at 5 knots along the track shown as a solid line. Three independent XBT systems, comprising two 460-m systems (designated as A and B) and one 1830-m system (designated as C), were used to make simultaneous measurements. These provide data for a special relative accuracy study. Table 5 lists, for each XBT system, the time interval, the number of at-anchor and in-transit XBT profiles attempted on each system, and the number of CTD/SV profiles. The CTD/SV profiles were made with a Plessey Environmental Systems 9040-4C profiling system. In addition, independent surface temperatures were measured with a bucket thermometer.

XBT System	Time Interval	Number of Profiles		
		XBT		
		In Transit	At Anchor	CTD/SV
A	17-30 October	15	67	11
B	17-28 October		49	
C	17-28 October		18	
	TOTALS	15	134	11

Table 5. RAPLOC/DEEPTOW measurements.

SUMMARY

During six acoustic experiments conducted between 1971 and 1975, a total of 1987 XBT temperature profiles were acquired. Of this total, 26 were made with 1830-m XBT systems and the balance, 1961 profiles, were made with 460-m XBT systems. Included were special sets of measurements to provide data for several absolute and relative temperature-accuracy studies. The measurements were made on 11 different 460-m and two different 1830-m systems from four ships – LEE, DE STEIGUER, MOANA WAVE, and CAPE – and two Scripps Institution of Oceanography research platforms – ORB and FLIP. Thermistor chain profiles were made during the SUDS I experiments and surface temperatures were measured during the Gulf of Alaska experiments by means of a towed thermistor, and during CAPER and RAPLOC/DEEPTOW by means of a bucket thermometer. In addition, 22 hydrocasts and 192 STD/SV, CTD/SV, or SVTP profiles were acquired. Many of these measurements were quasisimultaneous with XBT measurements. These measurements were made for the purpose of calibrating the XBT systems to a common temperature standard.

SIPPICAN XBT CHARACTERISTICS AND OPERATIONAL PROCEDURES

All XBT temperature profiles used in this accuracy study were obtained with Sippican Corporation XBT systems. The system consists of a temperature probe, launcher, and recorder. The Sippican System measures temperature with a thermistor bead sensor and depth by measuring time. Time is converted to depth by knowing the rate of fall of the temperature probe through the water. According to the Sippican Corporation, the range of measurement and the system accuracy for the XBT system are as follows:

Temperature:	–1.7 to 35.6°C ±0.2°C
Depth:	0 to 230 m ±4.6 m
	>230 m ±2.0%.

According to Mr R.P. Demeo, Manager, Quality Assurance and Reliability Engineering, Sippican Corporation, the ±0.2°C system temperature accuracy is considered to be an absolute accuracy and is not to be interpreted as equivalent to a standard deviation in the statistical sense (personal communication). The output of the XBT system is an analog record consisting of a continuous trace of temperature as a function of depth from the surface to 460 m or 1830 m. The length of the -2.0-to-35.0°C temperature scale is 17.42 cm, of the 0-to-460-m depth scale 12.26 cm, and of the 0-to-1830-m depth scale 49.17 cm.

The recorder is controlled by an automatic program which is initiated by inserting an XBT probe into the launcher. Closing the launcher breech completes a circuit between the probe and the recorder and triggers the recorder into a check/run mode. The chart drive operates for about 2 s and records a calibration temperature of 16.7°C ±0.1°C. The chart drive then stops in the launch mode, but starts again in the measure mode when the temperature probe is released and enters the water. During 88 s (460-m probe) or 358 s (1830-m probe), the temperature versus depth profile is recorded and the chart drive stops in the reload mode.

Before a series of XBT measurements, or at weekly intervals when measurements are being made over a period of time, a calibration check of the complete system is required. A test canister is loaded into the launcher, and the system is run through the operating cycle. At the start of the cycle, the chart drive will operate for about 2 s, marking a

16.7°C ±0.1°C temperature on the chart. The chart drive will then stop. On the test panel of the recorder is a switch with -1.1°C and 34.4°C positions. Pressing the switch to the -1.1°C position should record a temperature of -1.1°C ±0.1°C, and pressing the switch to the 34.4°C position should record a temperature of 34.4°C ±0.1°C on the chart. If these temperatures are not recorded, the entire system must be recalibrated according to procedures described in the operating manual.

XBT PERFORMANCE SUMMARY

Table 6 summarizes the performance of the XBT systems used to obtain each of the data sets. Shown for each XBT system are the number of attempted XBT profiles, catastrophic failures, miscellaneous failures, successes, partial successes, and visually acceptable XBT profiles.

Equipment	Platform	Attempts	CF	MF	S	PS	VA
GULF OF ALASKA	LEE	626	12	34	531	49	580
SUDS I	LEE	318	35	4	254	25	279
	DE STEIGUER	185	17	0	149	19	168
	CAPE	110	11	1	78	20	98
ORB-3	ORB-A	56	4	0	44	8	52
	ORB-B	56	5	0	45	6	51
ORB-4	ORB	125	3	0	103	19	122
CAPER	DE STEIGUER	177	15	7	115	40	155
	MOANA WAVE	177	19	6	131	21	152
	FLIP	8[a]	1	0	7	0	7
RAPLOC/DEEPTOW	ORB-A	82	4	0	76	2	78
	ORB-B	48	1	0	45	3	48
	ORB-C	18[a]	7	0	3	8	11
	TOTALS	1987	134	52	1581	220	1801
	PERCENT ATTEMPTED		6.7	2.6	79.6	11.1	90.6

Notes:

CF = Catastrophic Failure: No usable measurements for depths greater than 50 m.

MF = Miscellaneous Failure: Failed because of operator error, wire blowing against ship, etc.

S = Success: Visually acceptable to maximum depth.

PS = Partial Success: Visually acceptable to a depth greater than 50 m but less than the maximum depth.

VA = Visually Acceptable: The sum of the success and partial success. No basis for rejecting as incorrect, based on a visual inspection of the analog record.

[a]1830-m XBT profiles.

Table 6. XBT performance summary.

The Gulf of Alaska data list 34 miscellaneous failures. Some of these may be catastrophic failures since the records of all catastrophic failures were not preserved. The missing profiles are considered miscellaneous failures because their precise status cannot be determined.

Of a total of 1987 attempts, 134 (6.7%) were catastrophic failures, 220 (11.1%) were visually acceptable to depths between 50 m and the maximum depth, and 1581 (79.6%) were visually acceptable to the maximum depth.

Figures 6, 7, and 8 are examples of a catastrophic failure, a partial success and a success, respectively. Figure 6 is an example of a catastrophic failure, as indicated by the 3.5°C increase in temperature from 5 to 26 m. Figure 7 is an example of a partial success. This profile gives visually acceptable temperatures from the surface to 89 m. Temperatures for depths greater than 89 m are obviously incorrect. Figure 8 is an example of a success. This trace gives visually acceptable temperatures from the surface to the maximum depth of 460 m. In the absence of any other information, there is no valid reason to reject this profile as incorrect. Also shown in each figure is the 16.7°C calibration check.

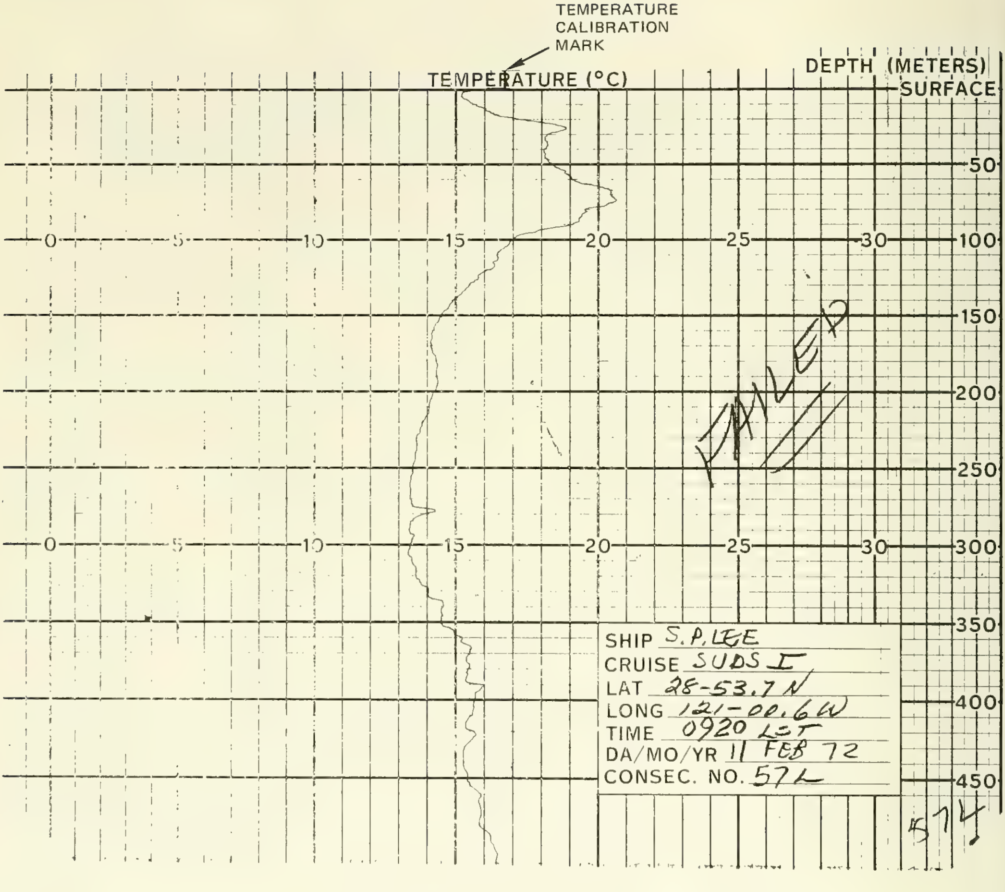

Figure 6. Example of a catastrophic failure.

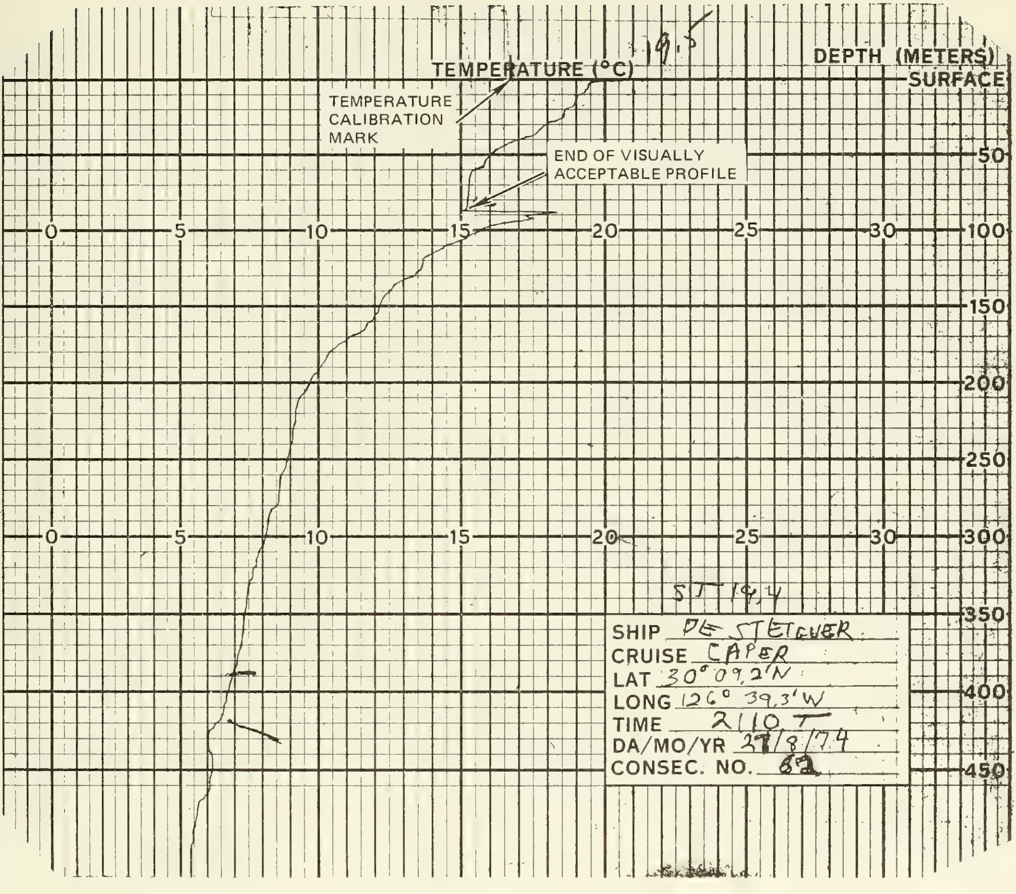

Figure 7. Example of a partial success.

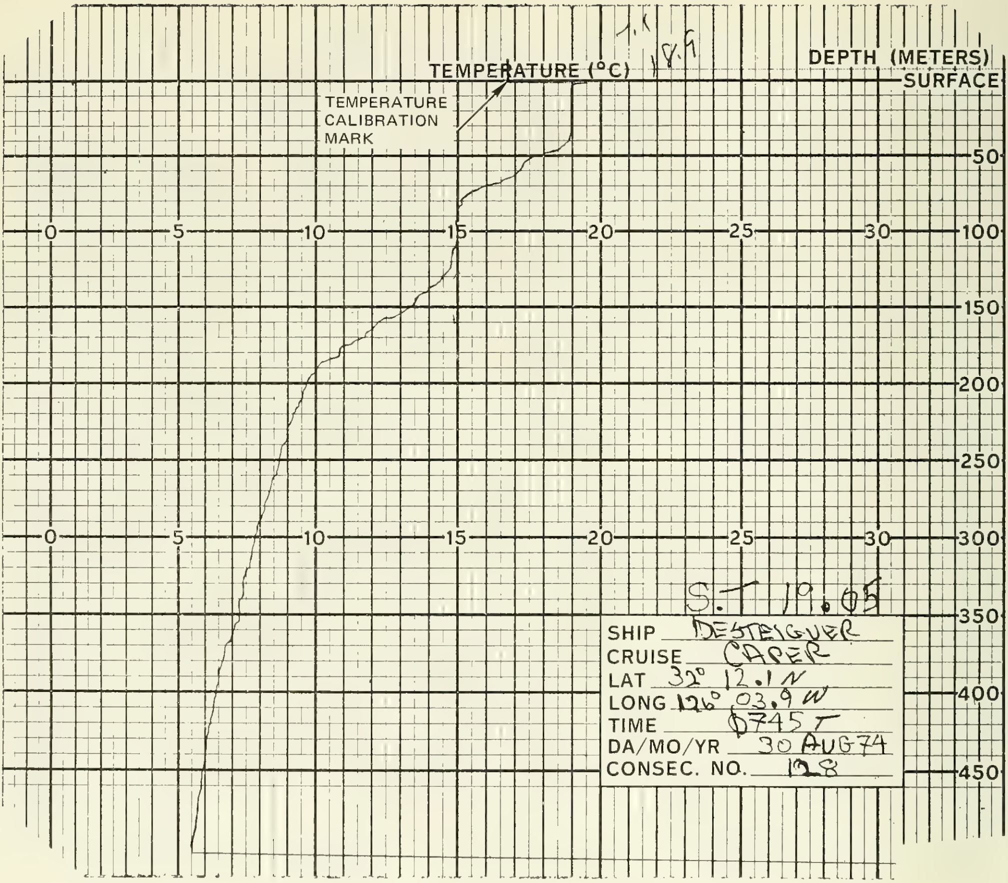

Figure 8. Example of a success.

SYSTEM MEASUREMENT ERRORS

The primary temperature standard for this study is comprised of the hydrocast temperature measurements. Several complete hydrocasts were made during the Gulf of Alaska, SUDS I, and CAPER experiments. During the RAPLOC/DEEPTOW experiments, no complete hydrocasts were obtained. However, on nine CTD/SV profiles, a hydrocast sampling bottle and thermometers were attached to the CTD/SV cable just above the CTD/SV sensor package. At the maximum depth of the CTD/SV profile, a hydrocast temperature and depth measurement were obtained. In addition, a water sample was taken to provide a salinity measurement. Simultaneous CTD/SV temperature, salinity, and depth measurements were made. Similar measurements also were made on some of the Gulf of Alaska and SUDS I STD/SV profiles and on some of the CAPER CTD/SV profiles. No hydrocast measurements were made during the ORB-3 and ORB-4 experiments. For these data sets, the STD/SV sensor measurements are used as the standard for determining the XBT system errors.

This section compares the STD/SV, CTD/SV, SVTP, XBT, thermistor chain, towed thermistor, and bucket thermometer temperatures with the hydrocast measurements, and determines the corrections required to bring these measurements into agreement with the hydrocast measurements. The corrections are referred to as system errors. *Once a system error is determined, it is used in all subsequent comparisons.* Thus all system errors determined in the following analyses are referenced to the hydrocast temperatures.

The generally accepted accuracy of the hydrocast temperature measurement is ±0.02°C.

STD/SV, CTD/SV, AND SVTP SYSTEM ERRORS

During the Gulf of Alaska experiments, temperature accuracy checks were obtained on three hydrocasts and, at maximum depth, on seven STD/SV profiles. Table 7 summarizes the differences between STD/SV temperatures and hydrocast temperatures for depths greater than or equal to 1000 m. To obtain the right-hand column of differences, the hydrocast sample bottles and thermometers were attached on the same cable as the STD/SV sensor package. Thus these differences are the result of essentially simultaneous sets of measurements. Table 8 summarizes the seven temperature comparisons obtained at the maximum profile depth. On STD/SV 40, two sample bottles were placed one above the other to obtain the two independent comparisons. An inspection of the differences tabulated in tables 7 and 8 shows that for depths greater than or equal to 1000 m, the differences vary randomly about 0.00°C. It is concluded that the Gulf of Alaska STD/SV system error is zero.

No hydrocast measurements were made at the time the Gulf of Alaska SVTP measurements were made, so no direct comparisons between hydrocast and SVTP measurements were possible. In water mass 2, the temporal and spatial variability in temperature for depths greater than 200 m was small. The maximum depth of the SVTP profiles was 600 m. At this depth, the average of 15 SVTP measurements was 3.32°C with a standard deviation of 0.04°C. The average of 41 STD/SV measurements was 3.29°C with a standard deviation of 0.03°C. On the average, at 600 m, the SVTP measured a water temperature 0.03°C higher than the STD/SV. It is concluded that the Gulf of Alaska SVTP system error is –0.03°C.

Depth, m	Differences, °C (STD/SV – Hydrocast)		
	-4^h30^{min}	$+8^h30^{min}$	0^h0^{min}
1000	-0.02	0.00	-0.01
1200	-0.03	-0.02	-0.02
1500	-0.03	–	0.01
2000	–	–	0.00
2500	–	–	0.01
3000	–	–	0.01
3500	–	–	0.01

Note: The heading for each column of differences is the time in hours (h) and minutes (min) that the STD/SV profile was taken with respect to the applicable hydrocast.

Table 7. Comparison of Gulf of Alaska STD/SV and hydrocast temperature measurements.

Number	Depth, m	Temperature °C		
		STD/SV	Reversing Thermometer	Difference
9	1430	2.20	2.20	0.00
10	3512	1.44	1.45	-0.01
40	5042	1.52	1.53	-0.01
		1.52	1.57	-0.05
59	4182	1.46	1.46	0.00
88	3925	1.44	1.45	-0.01
90	1005	2.69	2.69	0.00

Table 8. Comparison of Gulf of Alaska STD/SV and reversing thermometer temperatures at maximum profile depth.

During the SUDS I experiments, temperature accuracy checks were obtained on six hydrocasts and at maximum depth on two STD/SV profiles. Tables 9 and 10 summarize the results of a comparison between temperatures measured at depths greater than or equal to 2000 m by the STD/SV system and the hydrocast. An inspection of these data shows that for depths greater than or equal to 2000 m, the STD/SV gives temperatures that are consistently lower than the hydrocast temperature measurements. The average difference for the differences tabulated in tables 9 and 10 is -0.02°C. It is concluded that the SUDS I STD/SV system error is 0.02°C.

Depth, m	Differences, °C (STD/SV – Hydrocast)	
	$+0^h50^{min}$	$+6^h50^{min}$
2000	-0.05	-0.05
2500	-0.01	0.00
3000	+0.01	-0.02
3500	-0.01	-0.02

Table 9. Comparison of SUDS I STD/SV and hydrocast temperature measurements.

STD/SV		Temperature, °C		
Number	Depth, m	STD/SV	Reversing Thermometer	Difference
8a	2045	2.04	2.05	-0.01
			2.06	-0.02
			2.05	-0.01
11	3789	1.50	1.52	-0.02
			1.54	-0.04
			1.53	-0.03

Table 10. Comparison of SUDS I STD/SV and reversing thermometer temperatures at maximum depth.

The original CAPER plan included several quasisimultaneous CTD/SV profiles and hydrocast measurements. Because of the failure of the CTD/SV depth sensor, only one set was obtained – hydrocast 1 and CTD/SV 25, taken 5 h 55 min apart in time (see reference 10 for a detailed analysis of the CAPER CTD/SV measurements).

Table 11 compares, for depths greater than 1200 m, these two sets of measurements. At all depths, the CTD/SV temperature measurement was less than the hydrocast measurement. For three of the depths greater than 1200 m, where time and space variations were small, the CTD/SV temperature was 0.02°C lower than the hydrocast temperature, while for one depth it was 0.06°C less. During the SUDS I experiments (reference 7), the same CTD/SV temperature sensor was used. As noted above, the SUDS I STD/SV temperatures were also 0.02°C lower than the hydrocast temperatures. It is concluded that the CAPER CTD/SV system error is 0.02°C.

Depth, m	Temperature °C CTD/SV 25 27 August 0030LST	Hydrocast 1 26 August 1838LST	Difference
1312	2.97	2.99	-0.02
1752	2.23	2.29	-0.06
2200	1.87	1.89	-0.02
2659	1.65	1.67	-0.02

Table 11. Comparison of CAPER CTD/SV 25 and hydrocast 1 temperature measurements.

During RAPLOC/DEEPTOW, 18 hydrocast temperature measurements were obtained simultaneously with nine CTD/SV temperature measurements by attaching two sets of reversing thermometers on the CTD/SV cable just above the CTD/SV sensor package. These comparisons are summarized in table 12. An inspection of these data shows that the CTD/SV temperatures are consistently higher than the hydrocast temperatures. The average of the 18 comparisons was 0.01°C with a standard deviation of 0.01°C. It is concluded that the RAPLOC/DEEPTOW CTD/SV system error is -0.01°C.

Number	Depth, m	Temperature °C CTD/SV	Reversing Thermometer	Difference
7	518	5.52	5.50	0.02
			5.49	0.03
8	1016	3.86	3.86	0.00
			3.86	0.00
4	1511	2.71	2.71	0.00
			2.70	0.01
10	1514	2.74	2.74	0.00
			2.73	0.01
6	1526	2.69	2.68	0.01
			2.66	0.03
3	2014	2.09	2.07	0.02
			2.06	0.03
9	2523	1.78	1.79	-0.01
			1.78	0.00
2	3017	1.64	1.64	0.00
			1.63	0.01
5	3521	1.58	1.57	0.01
			1.55	0.03

Table 12. Comparison of RAPLOC/DEEPTOW CTD/SV and reversing thermometer temperatures at maximum depth.

XBT SYSTEM ERRORS

It is common practice to read temperatures visually from the XBT analog recording. With practice, it is possible to read the profiles to a temperature accuracy of ±0.2°C and a depth accuracy of ±2 m. However, for this analysis, the profiles were all read by means of a Hewlett-Packard digitizing system that consisted of an HP9830A calculator, an HP9864A digitizer, and an HP9866A printer. The HP9864A digitizer measures to the nearest 0.01 inch in x and y. Over a temperature range of –2.0°C to 35.0°C, this translates to a temperature digitizing accuracy of 0.055°C; and over a depth range of 0 to 460 m or 1830 m, to a depth digitizing accuracy of 0.95 m. All temperatures were recorded to the nearest 0.01°C and the depth to the nearest 1.0 m. The digitizing programs are listed in appendix A.

According to Sippican Corporation (personal communication): "No trace should be used if the calibration line deviates from 62.0°F (or 16.7°C) by more than 0.5°F (or 0.3°C). If the deviation falls between 0.2°F and 0.5°F (or 0.1°C and 0.3°C), the calibration line *must* be used as reference to avoid significant errors in temperature computation." The digitizing programs listed in appendix A use the calibration line as a reference. In the data set used in this study only seven Gulf of Alaska, four SUDS I, and four RAPLOC/DEEPTOW profiles had calibration line deviations that exceeded ±0.34°C (±0.3°C to the nearest 0.1°C). These profiles will be noted at appropriate places in the analysis to follow.

The manufacturer states that the absolute value of the accuracy of the XBT system, to the nearest 0.1°C, is ±0.2°C. In any statistical analysis that requires an estimate of the accuracy of a measurement, it is more useful to have the accuracy specified as a standard deviation. The following rationale is used to obtain an estimate of the standard deviation of the XBT system. Since, in this study, all XBT temperatures are read and recorded to the nearest 0.01°C, the absolute accuracy may be interpreted to be ±0.24°C (±0.2°C to the nearest 0.1°C). For a sample drawn from a normal population, plus or minus two standard deviations includes 95% of the sample. If it is assumed that ±0.24°C is equal to two standard deviations, then an estimate of the standard deviation for XBT measured temperatures is ±0.12°C. In the discussion to follow, the standard deviation of the XBT system is assumed to be ±0.12°C.

Procedure for Determining XBT System Error

Perhaps the most accurate way to determine the XBT system error in the field is to make several simultaneous XBT and STD/SV profiles. Since the temperature measurements used in these studies were made in support of acoustic propagation loss experiments, the making of several simultaneous profiles was not generally possible. As a result, it was necessary to devise an alternative method. All the visually acceptable XBT profiles made in water masses where hydrocast and/or STD/SV measurements were made are used to establish the XBT system errors. These profiles were processed as follows:

1. Compute the average 200-, 300-, and 400-m hydrocast and/or STD/SV temperatures for all hydrocast and STD/SV temperature measurements made in the same near-surface water mass.

2. Read XBT profile temperature at 200, 300, and 400 m, applying any indicated temperature and/or depth corrections.

3. Establish a *preliminary* XBT system error by comparing XBT 200-, 300-, and 400-m temperatures with the hydrocast and/or STD/SV* temperature for quasisimultaneous measurements.** In making this comparison, the appropriate STD/SV system errors are applied. If no comparisons were available, the preliminary system error was assumed to be zero.

4. Establish the following 200-, 300-, and 400-m *temperature accuracy criterion interval* for each XBT system: $\bar{T} - e \pm \sqrt{s_1^2 + s_2^2}$, where $\bar{T}$ is the average hydrocast and/or STD/SV temperature for a given water mass, e is the preliminary XBT system error, s_1 is the standard deviation of the average hydrocast and/or STD/SV temperature, and $s_2 = 0.12°C$, the standard deviation of the XBT system measurement accuracy.

5. Compare each 200-, 300-, and 400-m XBT temperature with the accuracy criterion interval to determine whether the criterion is satisfied.

6. For each XBT system, compute the average 200-, 300-, and 400-m temperature for all XBT profiles that satisfy the accuracy criterion at *all three depths.****

7. Compare the average 200-, 300-, and 400-m XBT profile temperature with the average hydrocast and/or STD/SV temperature to establish a *final* XBT system error.

Average Hydrocast and/or STD/SV Temperatures

The primary standards for comparison are the average temperatures measured by the hydrocast and the STD/SV. Execution of step 1 establishes these temperatures.

Since the temperature profile in the upper few hundred meters is different in different water masses, it was necessary to first determine whether more than one water mass was present in the area where the XBT profiles were obtained. In the Gulf of Alaska area, three water masses were present. These were designated water mass 2, water mass 7, and transition water mass (figure 2 and reference 11). The SUDS I data set includes measurements made in areas A and C in different water masses (figure 3 and reference 7). Since no hydrocasts or STD/SV measurements were made in area B, the area B XBT profiles are not included in this study. The CAPER measurements were made in four water masses designated water masses 1, 2, 3, and 4 (figure 5 and reference 10). Since only one STD/SV measurement was made in water mass 4, no average temperatures could be established for this water mass. The ORB-3, ORB-4, and RAPLOC/DEEPTOW measurements were made in two water masses designated 1 and 2 (figure 4 and reference 8 and 9). However, most of the measurements were made at anchor in water mass 2. The average temperature ($\bar{T}$), the number of observations (n), and the standard deviation (s) of the hydrocast and STD/SV 200-, 300-, and 400-m measurements are summarized in table 13.

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*In the discussion to follow, the designation STD/SV will be used collectively to refer to the STD/SV, CTD/SV, and SVTP measurements.

**The independent surface temperature measurements are not used in this analysis because of the difficulty of measuring precisely the surface temperature (see p 30-31 for detailed discussion).

***The most accurate XBT profiles are the subset of the complete set of profiles that satisfies the accuracy criterion at all three comparison depths. This subset is used to establish the *final* XBT accuracy criteria.

11. Reference available to qualified requesters.

	200 m			300 m			400 m		
	n	$\overline{T}$	s	n	$\overline{T}$	s	n	$\overline{T}$	s
GULF OF ALASKA									
Water mass 2	65	3.83	0.04	65	3.73	0.04	65	3.60	0.04
Transition water mass	20	4.10	0.21	20	3.88	0.09	20	3.74	0.07
Water mass 7	8	4.62	0.67	8	4.09	0.32	8	3.87	0.20
SUDS I 1972									
Area A	9	10.26	0.12	8	9.45	0.19	7	8.31	0.30
Area C	10	9.76	0.19	10	7.87	0.10	10	6.62	0.09
ORB-3	4	8.65	0.08	4	7.40	0.12	4	6.34	0.04
ORB-4	8	9.26	0.19	7	7.64	0.14	6	6.44	0.09
CAPER									
Water mass 1	2	9.38	0.08	2	7.56	0.06	2	6.09	0.06
Water mass 2	15	9.10	0.16	15	7.47	0.17	15	6.20	0.12
Water mass 3	3	9.91	0.29	3	7.62	0.18	3	6.22	0.13
RAPLOC/DEEPTOW	11	8.70	0.12	11	7.22	0.12	11	6.25	0.04

Table 13. Summary of average hydrocast and STD/SV 200-, 300-, and 400-m temperatures.

Preliminary XBT System Errors

Execution of steps 2 and 3 establishes the preliminary system errors. Table 14 lists, for each XBT system, the number of comparisons and the minimum and maximum time in minutes between the XBT and hydrocast or STD/SV measurements. The preliminary XBT system error is the average of the indicated number of differences. For those systems where there were no comparisons, the preliminary system error was assumed to be zero. Table 15 summarizes the average preliminary system errors and the standard deviations from the average. The temperature difference is the average 200-, 300-, and 400-m difference between the hydrocast or STD/SV temperature and the XBT profile temperatures.

Final XBT System Errors

Execution of step 4 establishes a 200-, 300-, and 400-m accuracy criterion for each XBT system. Step 5 compares the 200-, 300-, and 400-m temperature for individual XBT profiles with the appropriate accuracy criterion to determine whether the XBT temperature satisfied the accuracy criterion.

In step 6, the average 200-, 300-, and 400-m temperature for all XBT profiles that satisfied the accuracy criterion at all three depths is computed for each XBT system. Finally, in step 7, the average XBT temperatures are compared with the average hydrocast and/or STD/SV temperatures listed in table 13 to establish a final average XBT system error. These final system errors are listed in table 16. The system error is added algebraically to all XBT profile temperatures to bring the XBT temperature into agreement with the hydrocast and STD/SV temperatures. Note that some of the system errors are substantial, varying

	Number of Comparisons	Time Interval, min	
		Minimum	Maximum
GULF OF ALASKA	91	0	30
SUDS I 1972			
LEE	40	0	47
DE STEIGUER	9	1	50
CAPE	0		
ORB-3			
System A	6	0	15
System B	9	0	28
ORB-4	16	1	45
CAPER			
DE STEIGUER	0		
MOANA WAVE	15	0	83
FLIP	0		
RAPLOC/DEEPTOW			
System A	24	0	10
System B	23	0	10
System C	9	0	6

Table 14. Summary of time intervals between quasisimultaneous XBT and hydrocast or STD/SV temperature measurements.

	Temperature Difference, °C	Standard Deviation, °C
GULF OF ALASKA	-0.21	0.15
SUDS I 1972		
LEE	-0.04	0.19
DE STEIGUER	0.21	0.21
CAPE	0.00	
ORB-3		
System A	0.14	0.21
System B	0.13	0.09
ORB-4	0.02	0.24
CAPER		
DE STEIGUER	0.00	
MOANA WAVE	0.05	0.09
FLIP	0.00	
RAPLOC/DEEPTOW		
System A	-0.10	0.18
System B	-0.15	0.16
System C	-0.19	0.13

Table 15. Preliminary XBT system errors.

	Temperature Difference, °C		Temperature Difference, °C
GULF OF ALASKA	-0.17	ORB-4	0.02
SUDS I 1972		CAPER*	
LEE	-0.05	DE STEIGUER	0.03
DE STEIGUER	0.23	MOANA WAVE	0.12
CAPE	0.05	FLIP	–
ORB-3		RAPLOC/DEEPTOW	
System A	0.11	System A	-0.11
System B	0.09	System B	-0.16
		System C	-0.19

*Not enough measurements to establish a final system error for FLIP.

Table 16. Final XBT system errors.

from –0.19°C to 0.23°C. These errors are fixed and not random. The random errors are the errors associated with repeated measurements made with the same system. To be certain that the absolute value of the temperatures recorded by a given XBT system is accurate, it appears necessary to determine the XBT system error. To do this, independent and simultaneous temperature measurements are required. In the absence of these latter measurements, the absolute value of the XBT recorded temperature is questionable if accuracies in the average temperatures of better than about ±0.2°C are required.

THERMISTOR CHAIN SYSTEM ERROR

The thermistor chain is a towed device used for measuring temperatures from the surface to a maximum depth of 242 m. It consists of 44 thermistors spaced 5.6 m apart, plus associated shipboard equipment consisting of a winch and the necessary electronics for recording the temperature as measured by the 44 thermistors. The instrument is designed to measure a vertical temperature profile every 10 s with a resolution of ±0.03°C and an estimated accuracy of about ±0.1°C.

During SUDS I, temperatures were measured simultaneously by the thermistor chain hanging vertically in the water (zero tow speed) and the STD/SV system (reference 7). STD/SV 3 was made to a depth of 312 m in 10 min, starting at 0415 LST on 12 February 1972. STD/SV 3 reached a depth of 242 m, the maximum depth of the thermistor chain measurements, in 8 min at 0423 LST. During the period 0418–0422 LST, the chain made 27 scans of its sensors. Figure 9 summarizes the results of a comparison between these two sets of measurements. The left-hand figure is a plot of STD/SV 3 at the thermistor chain sensor depths.* The right-hand figure shows the differences between the average thermistor chain measurements and the STD/SV 3 measurements at the same depths. Two features are of interest. One is the relatively large differences from 96 to 124 m. These differences are

*The STD/SV system measures temperature every 0.2 s and records the measurements on magnetic tape. On the original tape the temperatures were missing at the depths where no temperatures are plotted in figure 9.

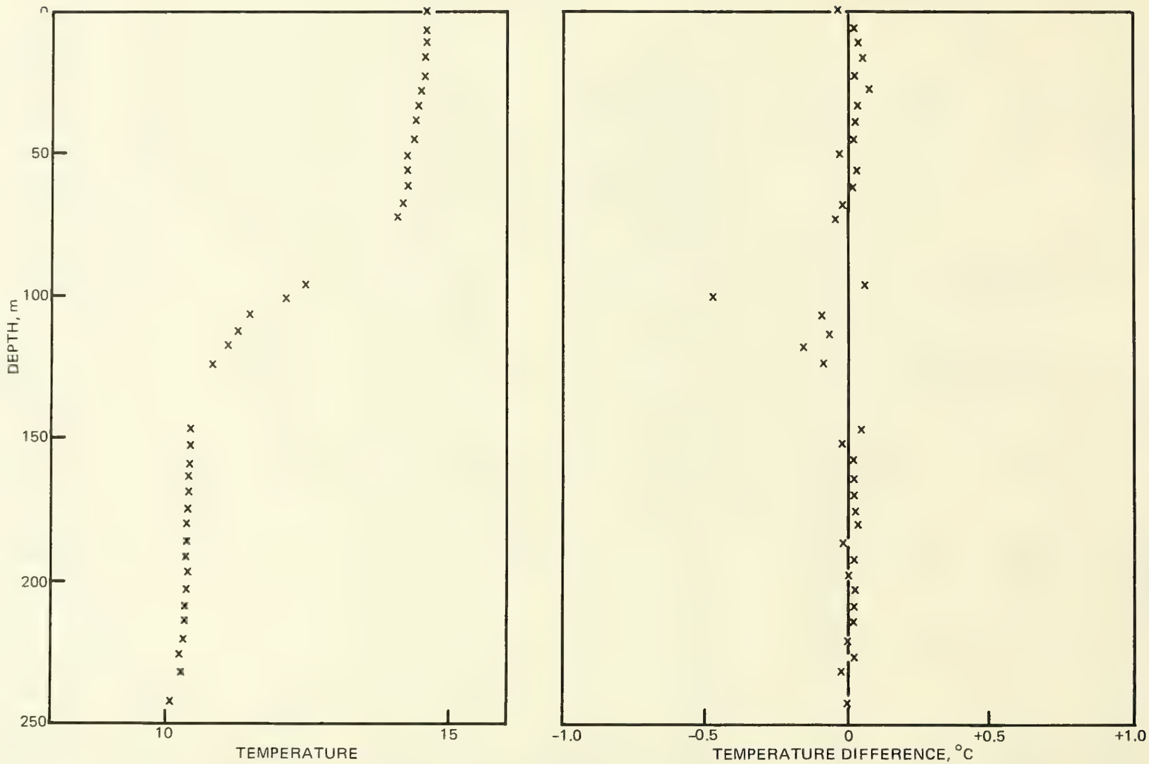

Figure 9. Comparison of SUDS I temperatures measured simultaneously by the thermistor chain and the STD/SV system. A positive difference indicates the thermistor chain is measuring temperatures higher than the STD/SV system.

related to the strong negative temperature gradients observed between 73 and 135 m. A small change in depth changes the temperatures considerably. For example, the temperature difference of -0.47°C at 101 m can be accounted for by a depth change of about 3 m. The second feature is that from the surface to 73 m and from 147 to 242 m, where the temperature gradients are small, eight of the differences are negative and 23 are positive or zero. The average difference for these two layers is 0.01°C. It is concluded that the SUDS I thermistor chain system error is -0.01°C.

TOWED THERMISTOR SYSTEM ERROR

During the Gulf of Alaska experiments conducted at A1, A2, A3, and during both environmental surveys, a towed thermistor sensor recorded surface temperatures. During environmental survey 1, A1, and A2, 61 STD/SV profiles were made. During environmental survey 2 and A3, 22 SVTP profiles were made. In both series, simultaneous towed thermistor measurements were recorded. These measurements provide the data needed to determine the towed thermistor system error.

Figure 10 is a histogram that compares the towed thermistor measurements with the STD/SV (diagonal lines) and SVTP (dotted) surface temperature measurements. Shown, for 0.05°C temperature intervals, is the number of differences in the indicated interval. The average difference for the STD/SV comparison was 0.08°C with a standard deviation of 0.05°C; for the SVTP comparison, the average difference was -0.11°C with a standard deviation of 0.08°C. Thus the towed thermistor system error shifted by 0.19°C between the A2 and environmental survey 2 measurements. This could possibly be related to a recalibration of the towed thermistor system between the A2 and the environmental survey 2 measurements. At any rate, it is concluded that the towed thermistor system error was -0.08°C during environmental survey 1, A1, and A2, and 0.11°C during environmental survey 2 and A3.

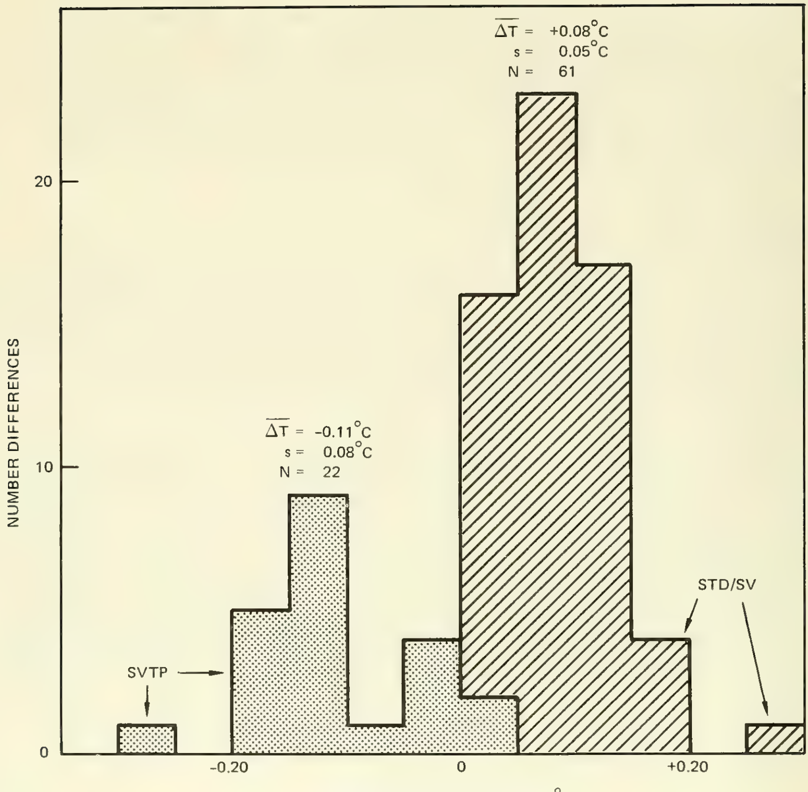

Figure 10. Comparison of Gulf of Alaska towed thermistor surface temperatures with STD/SV and SVTP surface temperatures.

MERCURY-IN-GLASS THERMOMETER ERRORS

During the CAPER and RAPLOC/DEEPTOW experiments, independent surface temperatures were measured with a mercury-in-glass thermometer. Temperatures were measured on deck immediately after a seawater sample was drawn with a bucket. Temperatures determined in this manner are referred to as "bucket temperatures" and the thermometer is referred to as a "bucket thermometer."

During CAPER, bucket temperatures were measured by both the DE STEIGUER and the MOANA WAVE. Eighteen comparisons of bucket and CTD/SV surface temperatures were made from the MOANA WAVE. For these comparisons, the bucket temperatures were consistently higher than the CTD/SV temperatures. The average difference was 0.04°C, with a standard deviation of 0.09°C. No CTD/SV measurements were made concurrent with the DE STEIGUER bucket temperatures. However, XBT profiles were made concurrently with 151 bucket temperatures. XBT surface temperatures, corrected for the XBT system error, were compared with the bucket temperatures. The results of these comparisons are summarized in figure 11. On the average, the bucket temperatures were 0.04°C, with a standard deviation of 0.10°C, which was higher than the corrected XBT surface temperatures. The differences varied from -0.22°C to 0.24°C.

During RAPLOC/DEEPTOW CTD/SV, surface temperatures were measured concurrently with 11 bucket temperatures. These comparisons showed that the bucket temperatures were higher than the CTD/SV measured temperatures. The average of the 11 comparisons was 0.07°C, with a standard deviation of 0.05°C.

It is concluded that the CAPER bucket thermometer errors were -0.04°C for both the MOANA WAVE and DE STEIGUER thermometers, and that the RAPLOC/DEEPTOW bucket thermometer error was -0.07°C.

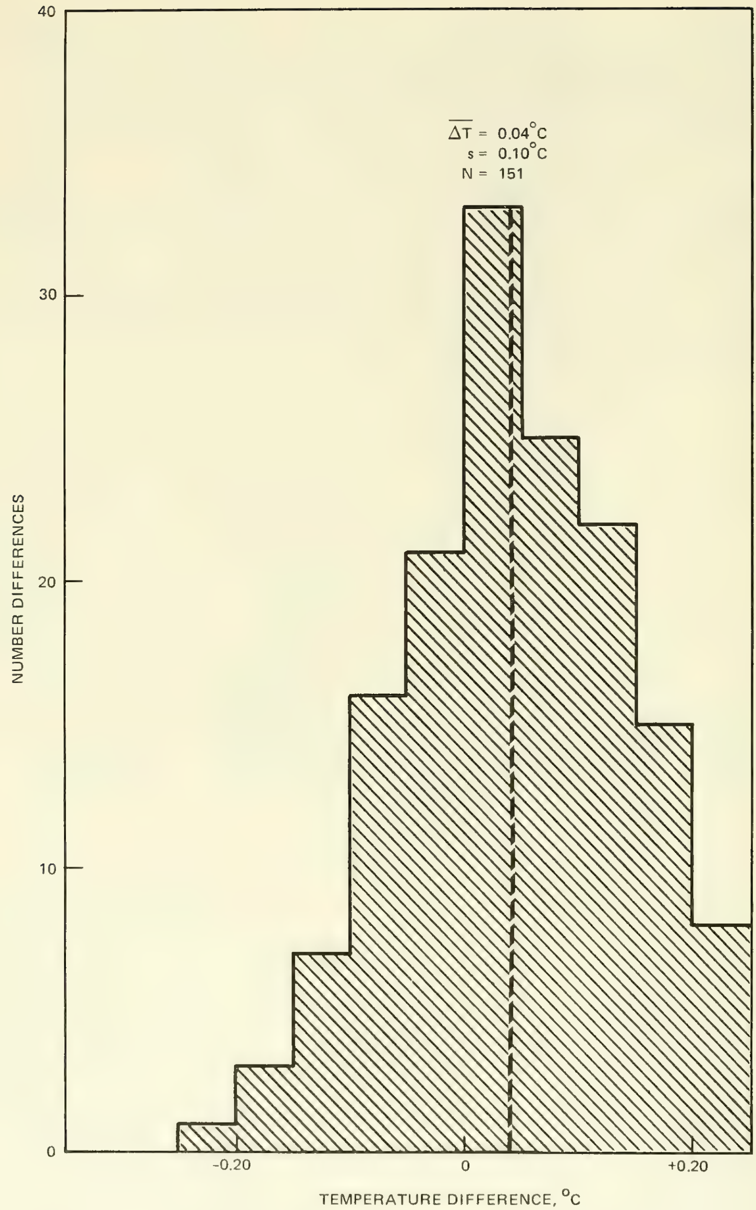

Figure 11. Comparison of CAPER's DE STEIGUER mercury-in-glass thermometer surface temperatures with XBT surface temperatures.

SUMMARY

In this study, the primary temperature standard is the hydrocast temperature measurements and the secondary standard is the STD/SV temperature measurements. During ORB-3 and ORB-4 experiments, no hydrocast measurements were made. The STD/SV measurements are used to determine the XBT system errors for the XBT systems used during these experiments. Table 17 tabulates the errors for the various measurement systems used to measure seawater temperature. These errors are added algebraically to the measured values to bring them into agreement with the hydrocast and STD/SV measurements.

	System	Errors, °C
GULF OF ALASKA	STD/SV	0.00
	SVTP	-0.03
	XBT	-0.17
	Towed Thermistor 1	0.08
	Towed Thermistor 2	-0.11
SUDS I	STD/SV	0.02
	XBT: LEE	-0.05
	DE STEIGUER	0.23
	CAPE	0.05
	Thermistor Chain	-0.01
ORB-3	XBT: System A	0.11
	System B	0.09
ORB-4	XBT	0.02
CAPER	CTD/SV	0.02
	XBT: DE STEIGUER	0.03
	MOANA WAVE	0.12
	FLIP	–
	Bucket Thermometer:	
	DE STEIGUER	-0.04
	MOANA WAVE	-0.04
RAPLOC/DEEPTOW	CTD/SV	-0.01
	XBT: System A	-0.11
	System B	-0.16
	System C	-0.19
	Bucket Thermometer	-0.07

Table 17. System measurement errors.

The system errors for the STD/SV, CTD/SV, SVTP, and thermistor chain systems were all small – varying from -0.03°C to 0.02°C. The errors for the towed thermistor and the bucket thermometers were slightly larger – varying from -0.11°C to 0.08°C. The system error for the towed thermistor changed from 0.08°C to -0.11°C between the measurements made during the A2 experiments and those made during environmental survey 2. This may have resulted from a recalibration of the system between the two sets of measurements. Some of the XBT system errors were substantial, varying from -0.19°C to 0.23°C. The system error for the XBT system used by the FLIP during the CAPER experiments was not determined, since adequate concurrent hydrocast or CTD/SV measurements were not made.

SURFACE TEMPERATURE ACCURACY OF 460-m SYSTEMS

One or more independent surface temperatures were measured simultaneously with XBT measurements during the Gulf of Alaska, SUDS I, CAPER, and RAPLOC/DEEPTOW experiments. During the Gulf of Alaska experiments, surface temperatures were measured with the hydrocast, STD/SV, and SVTP systems. In addition, surface temperatures were measured continuously during environmental surveys 1 and 2 and during propagation loss experiments A1, A2, and A3, by means of a towed thermistor system. During SUDS I, surface temperatures were measured with the hydrocast, STD/SV, and thermistor chain systems. During CAPER and RAPLOC/DEEPTOW, measurements were obtained with the CTD/SV system and a bucket thermometer. Also during CAPER, three measurements were obtained by the hydrocast system. In this section, these measurements will be compared with the XBT surface temperature measurements.

COMPARISON WITH HYDROCAST

During the SUDS I experiments, six hydrocast surface temperature measurements were made concurrently with XBT measurements. Three each were made by the LEE and the DE STEIGUER. The average of these six comparisons was –0.03°C, with the differences varying from –0.14°C to 0.07°C.*

During the CAPER experiments, three hydrocast surface temperature measurements were made by the MOANA WAVE concurrently with XBT measurements. These differences were –1.41, –0.57, and –0.39°C. These three large differences suggest a major problem with the MOANA WAVE's XBT system. More information on this problem will be developed when the CTD/SV and bucket temperature comparisons are discussed.

COMPARISON WITH STD/SV

STD/SV surface temperature measurements concurrent with XBT measurements were made during the Gulf of Alaska, SUDS I, CAPER, and RAPLOC/DEEPTOW experiments. The results of these comparisons are summarized in table 18. Shown are the number of comparisons, the average difference, and the standard deviation of the average difference. The large average difference and the very large standard deviation of the 22 CAPER comparisons provide additional confirmation that the MOANA WAVE XBT system was experiencing a major problem and therefore was not measuring the surface temperature accurately. Inspection of the individual CAPER differences showed them to range from –2.36°C to 2.19°C. Of the 12 negative differences, nine were greater than 1.00°C, and of the 10 positive differences, four were greater than 1.00°C. An inspection of the individual Gulf of Alaska differences showed that all of the last 12 differences were negative, varying from –0.06°C to –0.46°C. The average of these 12 differences was –0.24°C, and the average of the first 32 differences was 0.02°C. These data suggest that the XBT system was not operating properly during the latter part of the measurement program. This feature will be substantiated presently by comparison of the XBT surface temperatures with the towed thermistor temperatures.

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*A minus difference indicates that the XBT measurement was lower than the comparison measurement, and a positive difference indicates that the XBT measurement was higher.

	Number Comparisons	Average Difference, °C	Standard Deviation, °C
GULF OF ALASKA	44	-0.05	0.21
SUDS I	7	0.06	0.19
CAPER	22	-0.33	1.33
RAPLOC/DEEPTOW	17	0.06	0.13

Table 18. Comparison of surface temperatures measured by the XBT and STD/SV.

COMPARISON WITH THERMISTOR CHAIN

During the SUDS I experiments, with the thermistor chain vertical in the water (zero tow speed), six XBT profiles were obtained between 0650 and 0726 LST, 23 February 1972. On 12 February 1972 at 0428 LST, one XBT profile was made under similar circumstances. Comparisons of these measurements are contained in table 19. Recall that the thermistor chain measures temperature at 44 depths spaced 5.6 m apart from the surface to 242 m every 10 s, and that the 460-m XBT profiles take 88 s to complete. For the measurements made on 23 February, the thermistor chain profile is the scan that started at the same time the XBT probe was released. Thus the surface temperatures are measured simultaneously. The thermistor chain measurements used to compare with XBT 81L are the average of the nine 10-s scans made while the XBT probe was recording its 88-s profile. The standard deviation of the nine thermistor chain measurements made on 12 February was 0.01°C. All of these differences lie within the XBT system accuracy of ±0.24°C.

XBT Number	Time		Temperature, °C		
	Day/Mo	Hour	XBT	Chain	Difference
273L	23 Feb	0650	15.33	15.42	-0.09
274L		0700	15.33	15.42	-0.09
275L		0708	15.44	15.42	0.02
276L		0714	15.49	15.37	0.12
277L		0720	15.33	15.40	-0.07
278L		0726	15.23	15.40	-0.17
81L	12 Feb	0428	14.67	14.57	0.10

Table 19. Comparison of surface temperatures measured by the XBT and thermistor chain systems.

In addition to the above measurements the LEE, towing the thermistor chain at 3 knots, made continuous thermistor chain measurements during the SUDS I propagation loss runs. During these runs, 153 XBT profiles also were obtained. These measurements provide a set of comparative simultaneous surface temperature measurements that were made underway at 3 knots. Figure 12 contains ogives of the positive and negative differences between the XBT and thermistor chain measurements. The average difference was 0.04°C, with a standard deviation of 0.13°C. Of the total number of differences, 63.4%

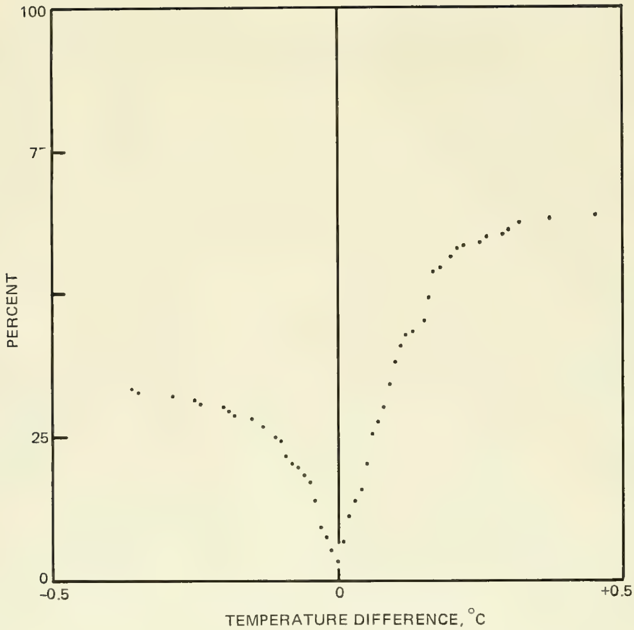

Figure 12. Ogives of positive and negative differences between 153 XBT profile surface temperatures and simultaneous thermistor chain temperatures made during SUDS I.

were positive, 33.3% were negative, and 3.3% were zero. This suggests that, on the average, the XBT measures a surface temperature slightly higher than the thermistor chain. The differences varied from -0.36°C to 0.45°C.

An examination of the raw data suggests that the larger differences were observed in the afternoon. Figure 13 was prepared to examine whether this was true. Figure 13 is a plot of the differences versus time of day. Figure 13 shows that the 12 largest absolute differences (7.8% of the 153 comparisons) were observed between 1100 LST and 1705 LST. Of these 12 differences, eight were positive and four were negative. Figure 14 contains copies of the XBT profiles associated with the largest positive (XBT 253L) and the largest negative (XBT 190L) differences. It is interesting that both these profiles have a large negative temperature gradient from the surface to about 3 m. Such a large negative gradient may be the result of solar heating of the near-surface waters under conditions of clear skies and calm to near-calm winds. When such near-surface gradients are present, it is difficult to obtain accurate simultaneous measurements of surface temperature since a small difference in the depth of a sensor results in a relatively large change in temperature, and hence a large difference in temperatures. It is concluded that the larger absolute differences are the result of not being able to measure the surface temperature accurately. Omitting the 12 largest absolute differences, more of the differences are still positive than negative, with the average difference being 0.03°C and the standard deviation 0.09°C.

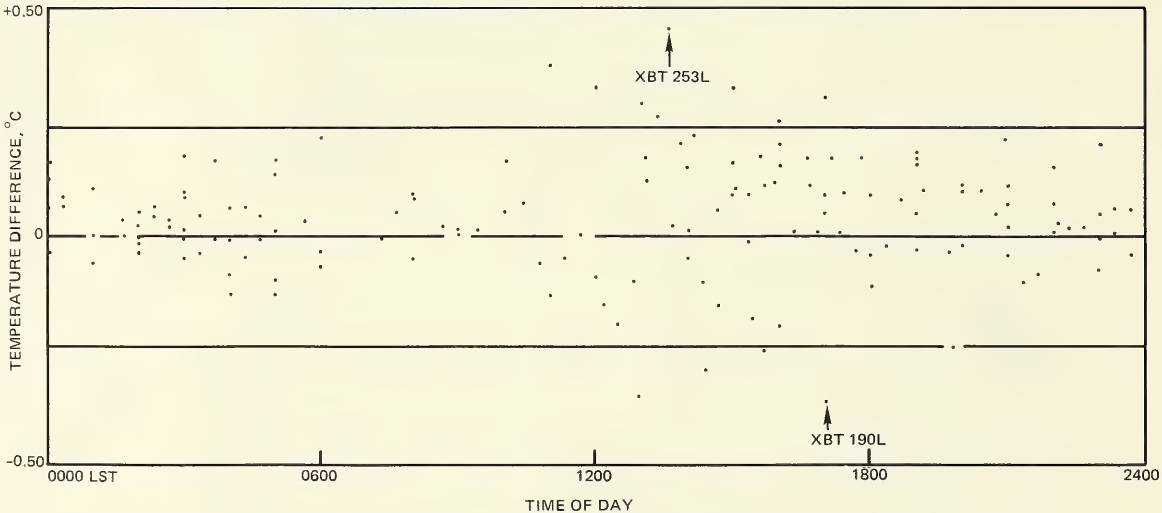

Figure 13. Difference between surface temperature measured by the XBT system and the thermistor chain during SUDS I plotted as a function of time of day.

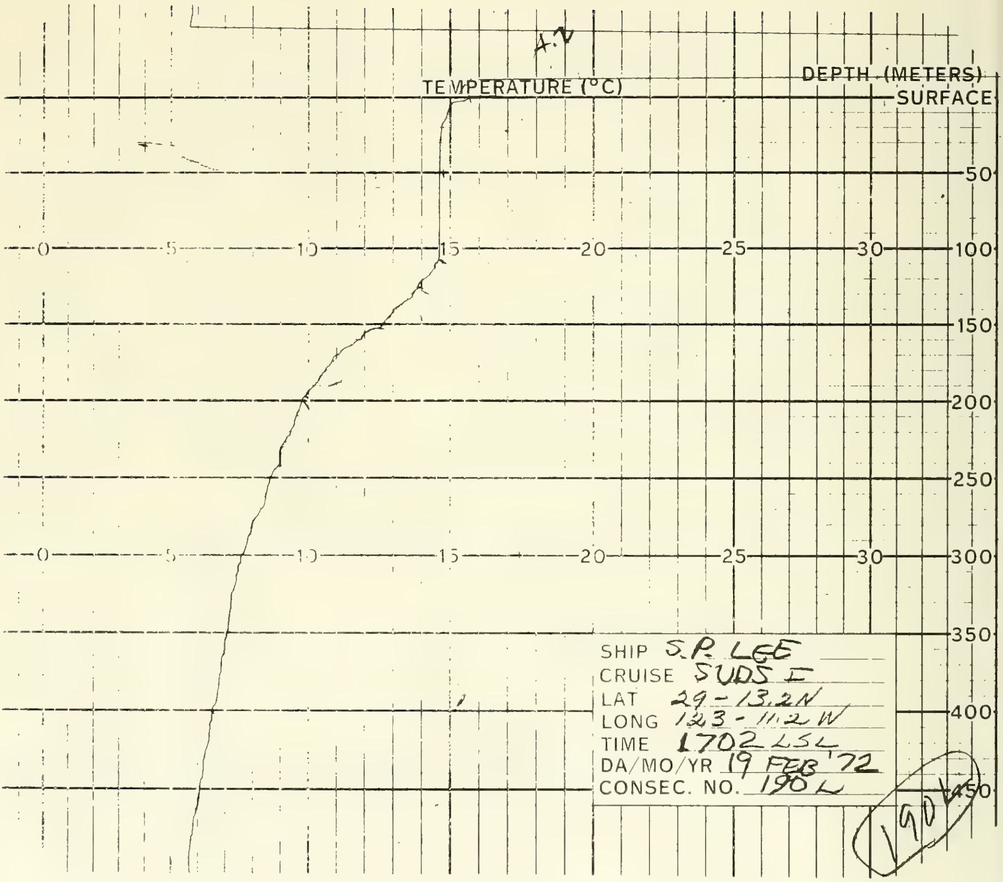

Figure 14a. SUDS I XBT 190L.

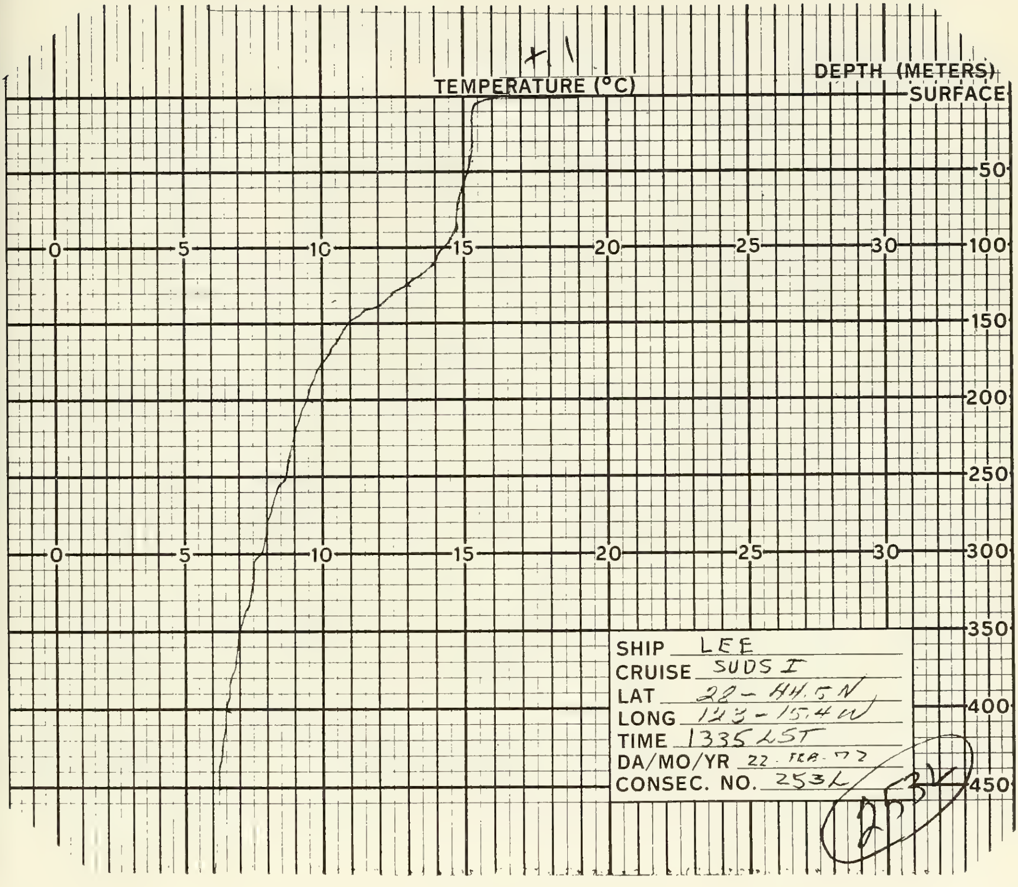

Figure 14b. SUDS I XBT 253L.

COMPARISON WITH TOWED THERMISTOR

During the Gulf of Alaska experiments, surface temperatures were continuously measured during environmental surveys 1 and 2 and during propagation loss experiments A1, A2, and A3 by using a single towed thermistor bead. During the time these measurements were made, 334 XBT profiles were obtained. The seven XBT profiles whose calibration lines deviated for 16.7°C by more than ±0.34°C are not used in the following analysis. In addition, 82 STD/SV profiles were made at the same time the towed thermistor measurements were made.

The differences between the towed thermistor measurements and the XBT (•), STD/SV (x), and SVTP (x) temperatures are plotted versus the XBT consecutive number in figure 15.* Also indicated are the dates of the acoustic events. A visual inspection of figure 15 shows that from XBT 1 to 165 the differences vary randomly about zero. However, for all XBT profiles after 165, all differences except for 14 are negative and there is a larger variation from difference to difference. In contrast, the STD/SV and SVTP differences vary randomly about zero during the entire time period that XBT 1 to 334 were taken.

Pertinent statistics for the comparisons presented in figure 15 are summarized in table 20, and figure 16 contains ogives of the differences for XBT 1 to 165 and XBT 166 to 334. The differences for XBT 1 to 165 are normally distributed with a near-zero mean and a standard deviation of 0.15°C. In contrast, the distribution of the differences for XBT 166 to 334 is skewed. The mean value is -0.31°C, with 148 (91.4%) of the differences negative and 12 (7.4%) positive. STD/SV profiles 1 to 41 were made during the same time interval that XBT profiles 1 to 165 were made, and STD/SV profiles 42 to 93 and SVTP profiles 94 to 117 were made during the same time interval that XBT profiles 166 to 334 were made. The average differences between the 80 STD/SV and SVTP surface temperatures and the towed thermistor surface temperatures were near zero (actually 0.007°C) with a standard deviation of 0.05°C. For these comparisons, it is concluded that the XBT system was not operating properly when XBT profiles 166 to 334 were made.**

The largest negative difference between the XBT and towed thermistor measurements was -1.15°C.*** This difference was measured by XBT 288, which is shown in figure 17. The towed thermistor surface temperature was 9.06°C, which, correcting for system errors, would be 8.89°C on the XBT 288 grid. An inspection of figure 17 reveals that the profile has a poorly defined surface depth. The XBT surface temperature was read at 8.07°C on the grid. Thus this large difference may be an artifact of the poorly defined surface depth. The next largest negative difference of -0.69°C was associated with XBT 302. This profile is shown in figure 18. In this case, the surface depth is well defined. On the grid, the towed thermistor temperature was 10.65°C. Thus this surface temperature

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*The consecutive numbers for which differences are missing are those associated with XBT profiles calibration lines differed from 16.7°C by more than ±0.34°C.

**The improper operation of the XBT system was not detected until the XBT surface temperatures were compared with the towed thermistor surface temperatures. This comparison was not made until the preparation of this report, some six years after the publication of reference 6. In the preparation of reference 6, the XBT profiles made when the XBT system was not operating properly were accepted as being correct profiles and published. In appendix B of reference 6, all XBT profiles listed after XBT 224 (19 June 1971, 0400 LST) were made with the improperly operating system.

***This difference is not plotted on figure 15 due to the scale but is plotted on figure 16.

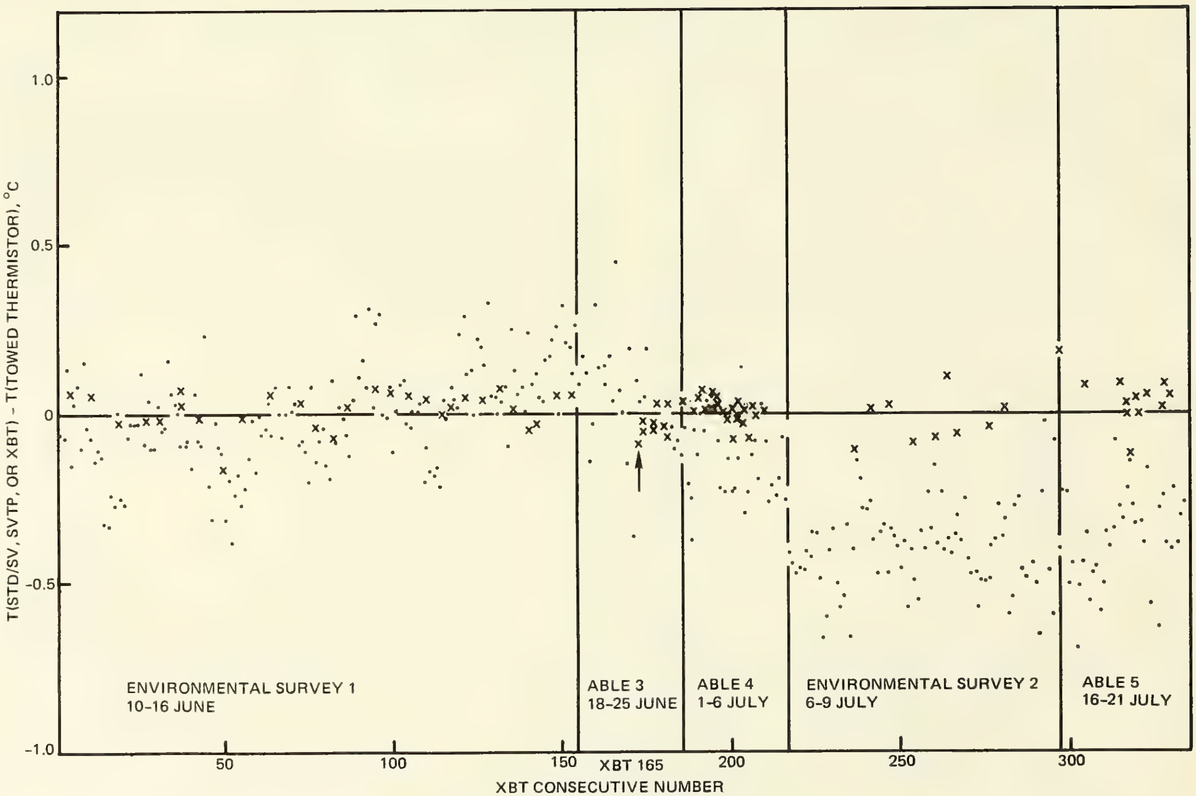

Figure 15. Difference between Gulf of Alaska PLESSEY STD/SV (x), RAMSAY SVTP (x), or XBT (·) temperature and towed thermistor surface temperature.

	Number	Temperature, °C	
		Average Difference	Standard Deviation
XBT 1-165	165	-0.002	0.15
XBT 166-334	162	-0.309	0.21
STD/SV 1-41*	29	0.011	0.05
STD/SV 42-93	30	-0.001	0.04
SVTP 94-117	21	0.012	0.08
All STD/SV and SVTP	80	0.007	0.05

*The towed thermistor was inoperative when some of the STD/SV profiles were made.

Table 20. Statistical summary for Gulf of Alaska surface temperature differences.

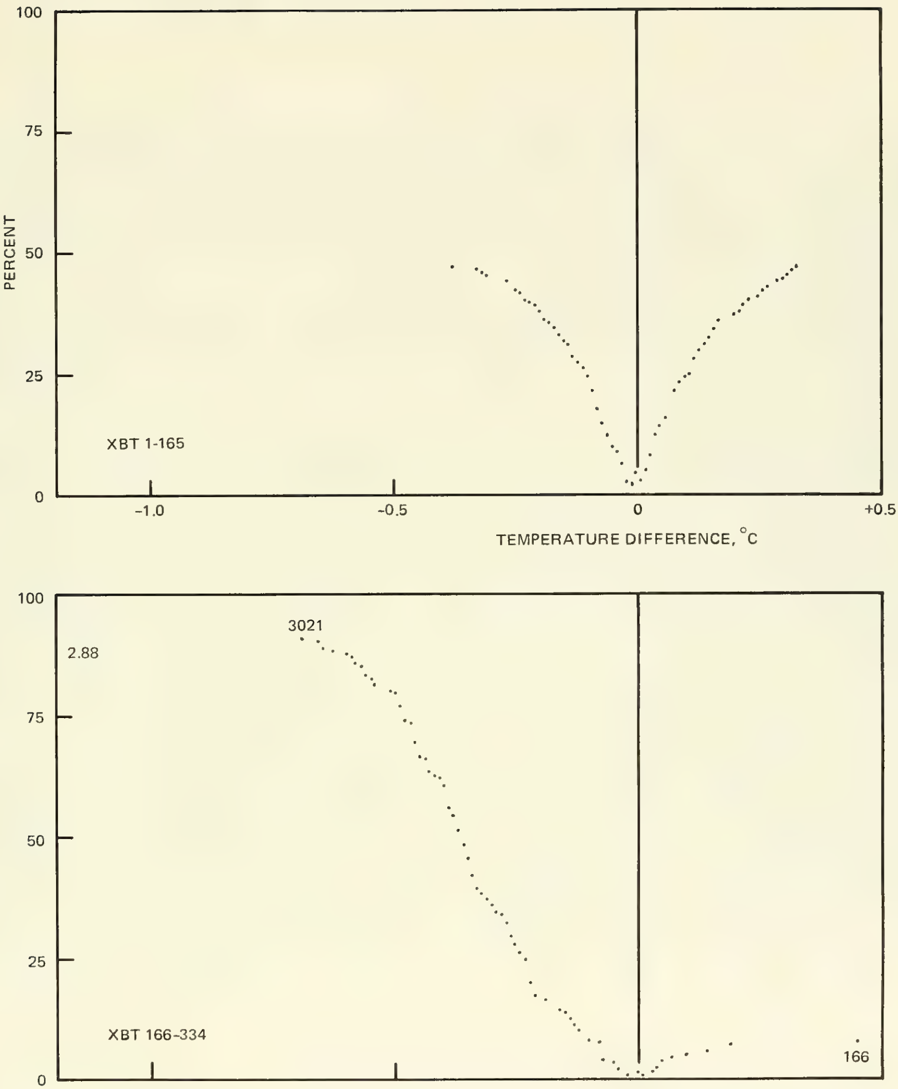

Figure 16. Ogives of positive and negative differences between Gulf of Alaska XBT surface temperatures and towed thermistor temperatures.

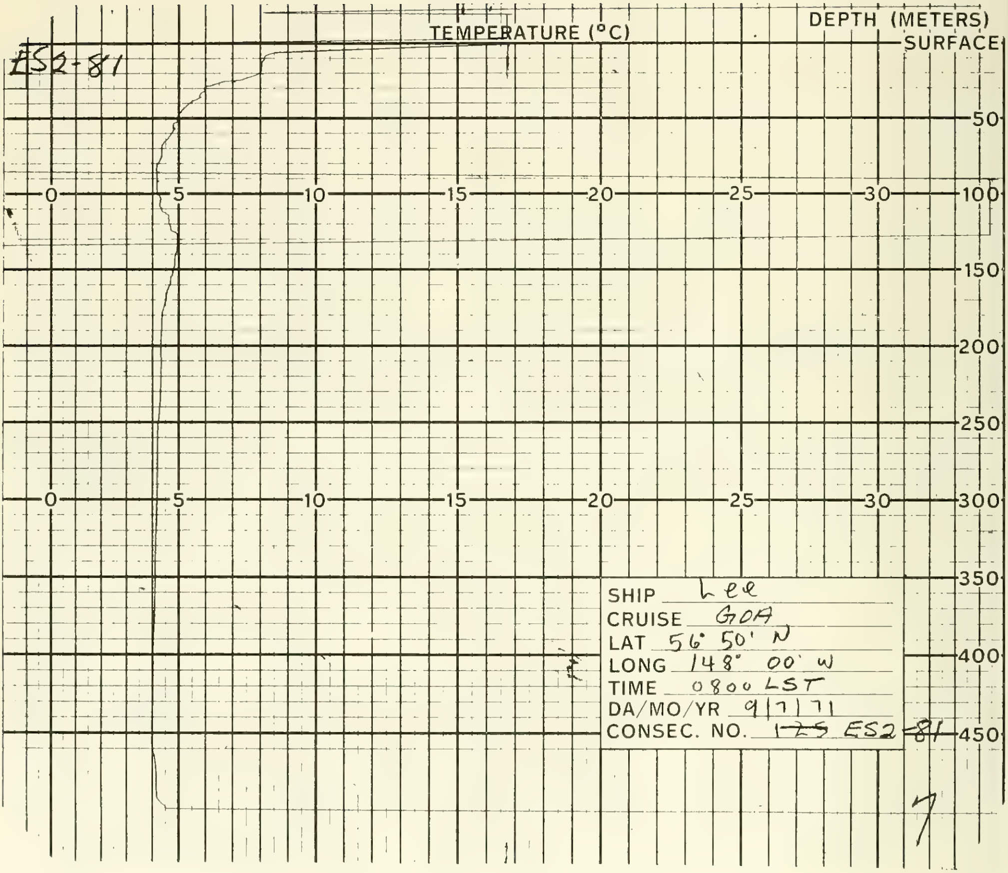

Figure 17. Gulf of Alaska XBT 288.

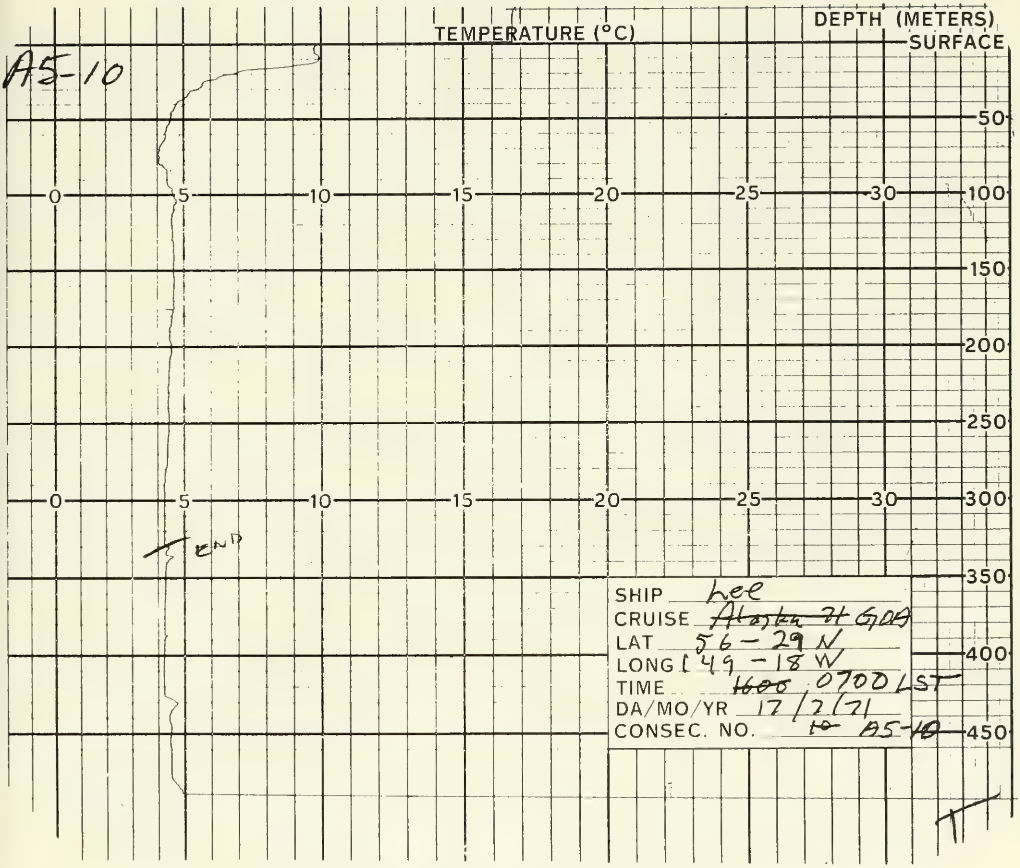

Figure 18. Gulf of Alaska XBT 302.

difference is not the result of a recognizable artifact of the XBT profile. The largest positive difference was 0.45°C associated with XBT 166. This profile is shown in figure 19. On the XBT grid, the towed thermistor temperature was 6.11°C. Again, this large positive difference is not the result of an obvious artifact.

As previously indicated, the calibration lines for seven of the XBT profiles exceeded 16.7°C by more than ±0.34°C. All seven profiles were made after XBT 166. Six of the seven were consecutive XBT profiles. An inspection of this series of six profiles, made during propagation loss experiment A3, showed that the calibration mark shifted abruptly between XBT 175 and 176. The calibration line for XBT 175 was at 16.54°C, 0.16°C lower than the 16.7°C standard and well within the permissible interval of ±0.34°C. The calibration line for XBT 176 shifted to 16.15°C, a variation of 0.55°C from the 16.7°C standard. The line varied from 16.11°C to 16.21°C for the next six XBT profiles when it again abruptly shifted to 16.76°C. The temperature differences between the XBT surface temperatures and the towed thermistor for these six XBT profiles were as follows:

XBT 176	0.60°C	XBT 179	0.69°C
XBT 177	0.17°C	XBT 180	1.06°C
XBT 178	0.76°C	XBT 181	0.23°C.

The reason for this abrupt shift in the calibration line is not known.

Finally, since all seven profiles that had an erroneous calibration line were made after XBT 165, it appears that the presence of erroneous calibration lines is related to a system malfunction.

To check whether the differences for XBT 165 to 334 are linear shifts in temperature, the 400-m temperatures for all XBT profiles obtained in water mass 2 were plotted. The data set was limited to the water mass 2 differences since the variation of the 400-m temperature in this water mass is small. Figure 20, similar in format to figure 15, is a plot of these temperatures. Pertinent statistics are tabulated in table 21. An inspection of figure 20 suggests that the 400-m temperatures exhibit characteristics similar to, but not the same as, those exhibited by the surface temperature differences. As shown in table 21, the average 400-m temperature as measured by 54 STD/SV and SVTP profiles taken during the same time interval as the XBT profiles were taken is 3.59°C, with a standard deviation of 0.03°C. The standard deviation of 0.03°C confirms the stability of the 400-m temperature in water mass 2. The average temperature for XBT 1 to 165 was 3.65°C, with a standard deviation of 0.12°C; for XBT 166 to 334 it was 3.77°C, 0.12% higher than for XBT 1 to 165, and had a standard deviation of 0.31°C, which is almost three times greater than the standard deviation for XBT 1 to 165. A comparison of figure 15 with figure 20 shows little correlation of the surface temperature differences with the 400-m temperatures for individual XBT profiles. For example, XBT 197, shown in figure 21, measured a surface temperature 0.22°C less than the towed thermistor and a 400-m temperature 0.91°C higher than the average STD/SV and SVTP 400-m temperature. Such errors would grossly distort an application requiring temperature as an input. A visual examination of the XBT 197 profile does not suggest any reason to suspect the validity of the measurement.

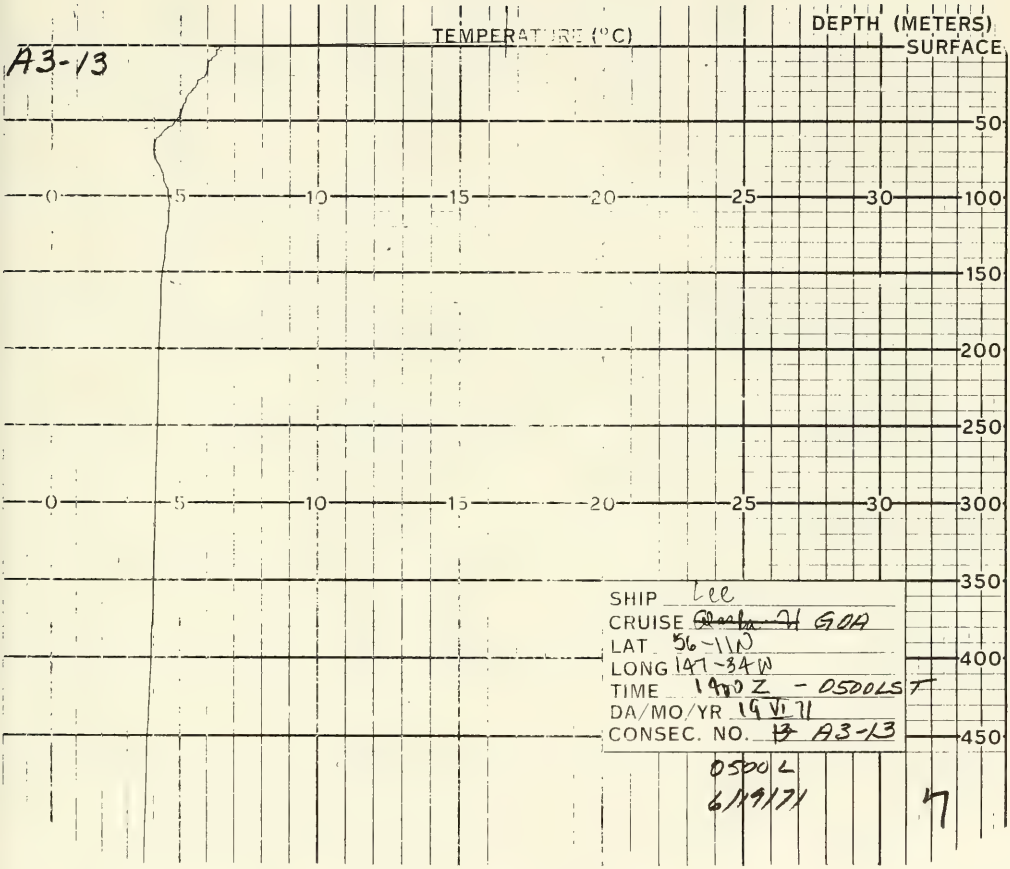

Figure 19. Gulf of Alaska XBT 166.

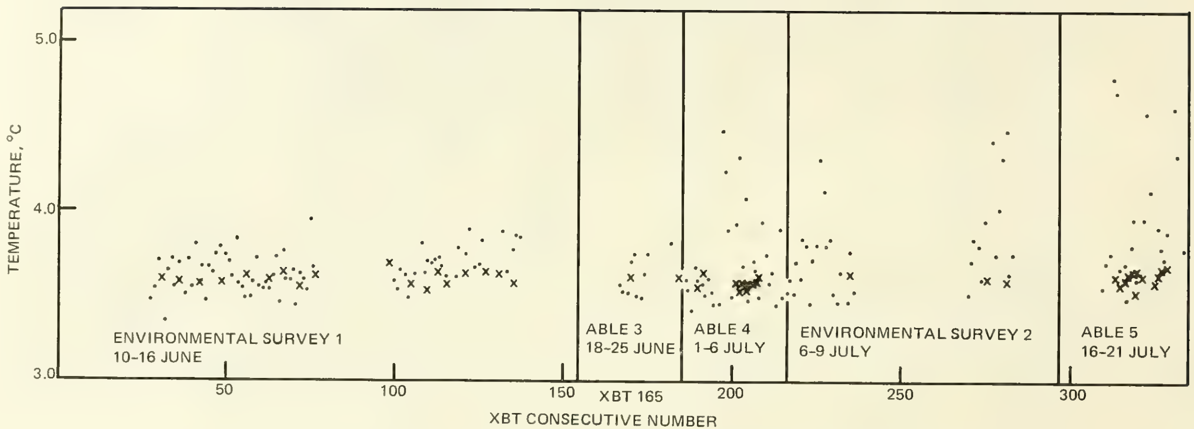

Figure 20. PLESSEY STD/SV, RAMSAY SVTP (x), and XBT (·) 400-meter temperature in water mass 2.

	Number	Temperature, °C	
		Average Temperature	Standard Deviation
XBT 1-165	75	3.65	0.12
XBT 166-334	96	3.77	0.31
STD/SV 1-41*	18	3.59	0.03
STD/SV 42-93	21	3.59	0.03
SVTP 94-117	15	3.61	0.04
All STD/SV and SVTP	54	3.59	0.03

*The number of XBT, STD/SV, and SVTP profiles differs from the numbers shown in table 20, since not all of the table 20 profiles were taken in water mass 2.

Table 21. Statistical summary for Gulf of Alaska 400-m water mass 2 temperatures.

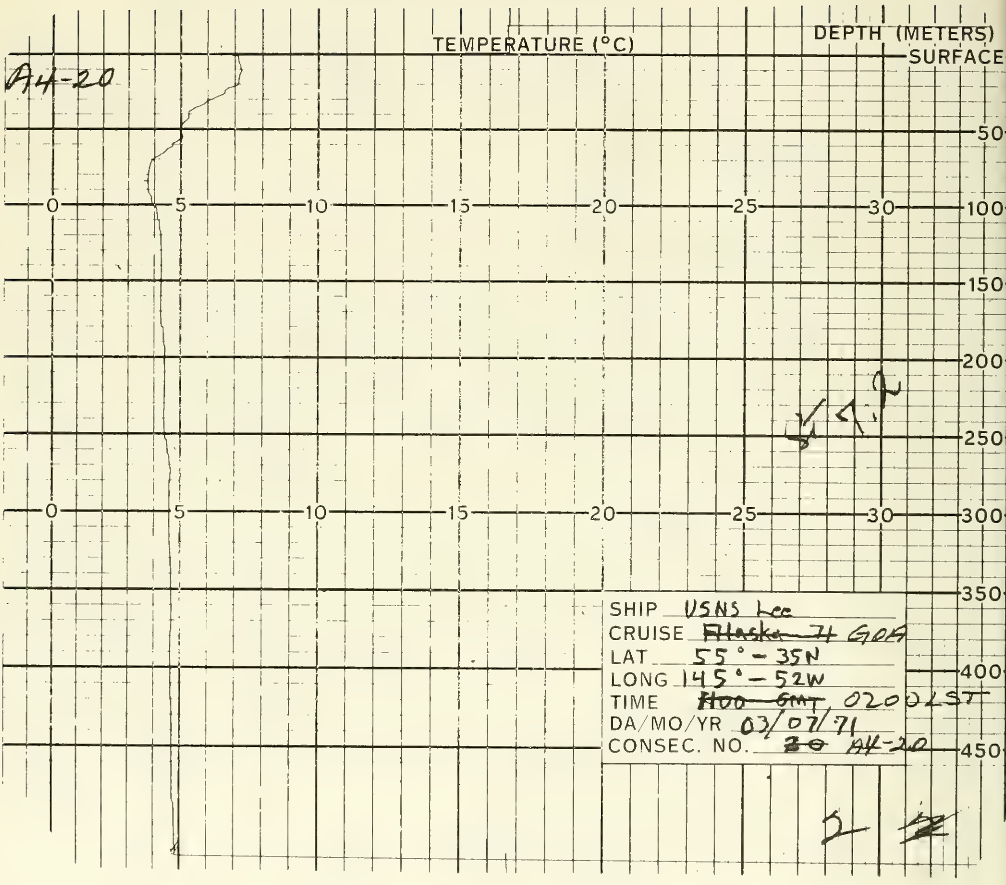

Figure 21. Gulf of Alaska XBT 197.

COMPARISON WITH BUCKET THERMOMETER

During the CAPER and RAPLOC/DEEPTOW experiments, bucket thermometer surface temperatures were obtained at the same time many of the XBT profiles were made. During the CAPER experiment, 151 bucket temperatures were obtained by the DE STEIGUER and 138 bucket temperatures were obtained by the MOANA WAVE. Since the DE STEIGUER XBT surface temperatures, corrected for system error, were used to establish the bucket thermometer system error (see above), the bucket temperatures are not independent of the XBT temperatures and cannot be used to determine the surface temperature measurement accuracy of the XBT system. However, the system error for the MOANA WAVE bucket thermometer was established from the CTD/SV measurements and is independent of the XBT temperatures.

Figure 22 is a plot of the MOANA WAVE differences in temperature between the XBT and bucket temperature versus the consecutive XBT number. Differences shown by the symbol (x) are the difference between the CTD/SV and bucket temperatures. The XBT differences for the first 45 profiles were comparable. However, for the XBT profiles made subsequent to XBT 45, large and erratic differences between the XBT and bucket temperatures were observed. From XBT 46 to 80, all but three of the XBT surface temperatures were less than the bucket temperatures, and XBT 56 measured a surface temperature 2.84°C lower than the bucket thermometer. For XBT 81 to 96, the XBT measured surface temperatures higher than the bucket thermometer. The surface temperature for XBT 82 was 2.22°C higher than the bucket temperature. From XBT 97 to 177, the last to be made by the MOANA WAVE, the XBT again measured surface temperatures lower than the bucket thermometer. Also shown in figure 22 are the differences between the CTD/SV surface temperature measurements and the bucket temperatures. The average difference for 20 comparisons was -0.02°C, with a standard deviation of 0.09°C.* From these comparisons, it is concluded that the MOANA WAVE XBT system began to malfunction starting with XBT 48. Pertinent statistics are summarized in table 22.

The observer aboard the MOANA WAVE, by comparing bucket temperatures with the XBT surface temperatures, recognized that the XBT system was malfunctioning, and after the completion of XBT 72 attempted to correct the malfunction by recalibrating the system. XBT 77 was the first visually acceptable XBT profile made after recalibration. Although recalibration brought about an improvement, the XBT 77 surface temperature was still 0.92°C lower than the bucket temperature. After completing XBT 164, the observer again recalibrated the system. The next XBT profile made after recalibration measured a surface temperature 0.40°C higher than the bucket thermometer, and the one following that measured a surface temperature 0.81°C lower than the bucket thermometer. Thus the malfunction was not corrected by a recalibration of the system.

To check whether the large surface temperature differences observed for the MOANA WAVE's XBT profiles were linear shifts in the temperature scale, the 400-m temperatures were plotted for the MOANA WAVE XBT profiles. These data are plotted in

*Since the bucket thermometer system error was determined by using the CTD/SV surface temperatures, the two measurements are forced to agree. However, the XBT system error is only 0.12°C (see above), which is small compared to the differences between XBT and bucket temperatures. Some readers may note that 18 CTD/SV surface temperatures were used to establish the XBT system error (see above), and that 20 comparisons are shown in figure 22. In establishing the XBT system error, two of the CTD/SV measurements were not considered quasisimultaneous with the XBT measurements and were not used.

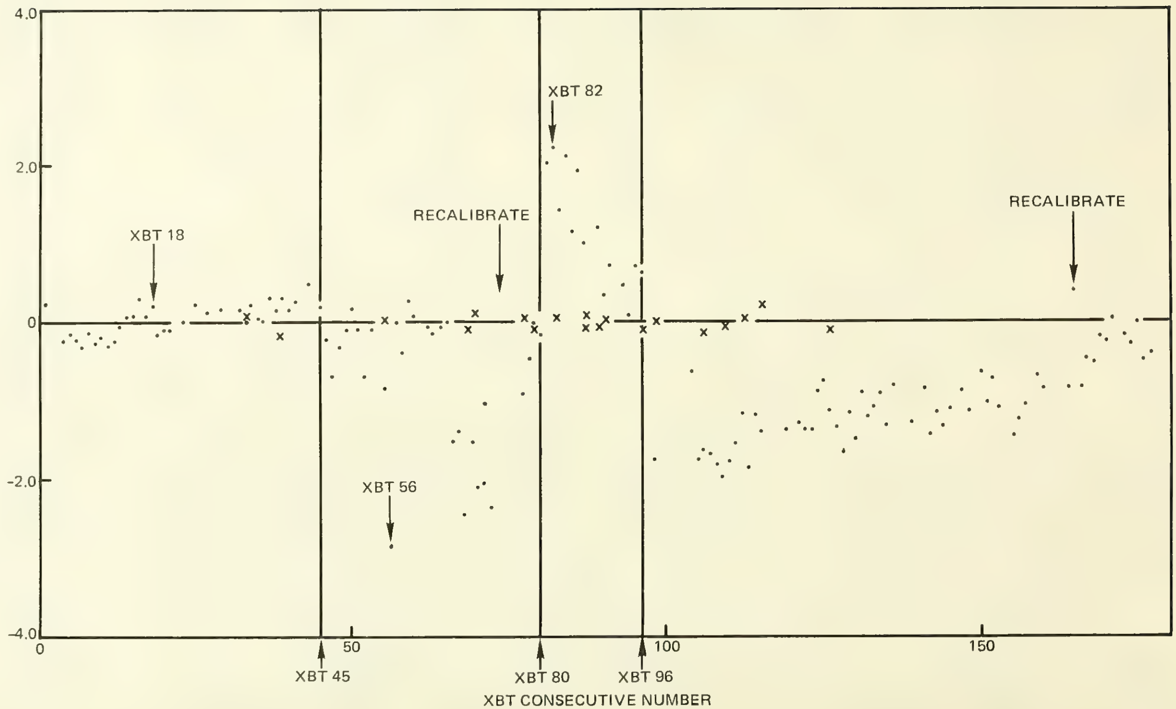

Figure 22. Difference between CAPER's MOANA WAVE CTD/SV (x) or XBT (•) and bucket surface temperatures.

Difference	Profile Number	Number	Temperature, °C Average Difference	Standard Deviation
Random	XBT 1-45	35	0.04	0.21
Most negative	XBT 46-80	29	-0.72	0.90
All positive	XBT 81-96	14	1.14	0.50
All negative	XBT 97-177	60	-1.03	0.52

Table 22. Statistical summary of CAPER's MOANA WAVE surface temperature differences.

figure 23 and summarized in table 23. For the first 45 profiles, the 400-m temperatures varied randomly about 6.42°C, with a standard deviation of 0.21°C. For the rest of the profiles, the 400-m temperatures exhibited a behavior similar to that observed at the surface, except that the 400-m variations were not the same as the surface variation. Thus the surface temperature differences are not the result of a simple shift in the temperature scale.

Also shown in figure 23 are the CTD/SV 400-m temperatures. The average 400-m temperature for 22 measurements was 6.23°C, with a standard deviation of 0.19°C. These measurements do not exhibit an erratic behavior such as that exhibited by the 400-m XBT measurements. Note that among the first 45 profiles, there is a group of three that measures temperature about 7.0°C and is about 0.5°C higher than the remainder of the 400-m measurements. CTD/SV 6 confirms these "anomalous" measurements as correct measurements.

Note also that all the MOANA WAVE XBT temperatures included in figure 23 were obtained from visually acceptable XBT profiles; that is, there was no basis after a visual inspection to reject the profiles as being incorrect. Figure 24 illustrates this point. For comparison, three XBT profiles are superimposed on a common chart: XBT 18, 56 and 82. (These profiles are from figure 23.) In the absence of any other information, such as a bucket temperature, all these profiles would be accepted as correct. In other words, there is no valid reason for rejecting any one of or all three profiles as erroneous. The XBT 18 surface temperature agreed within 0.19°C of the bucket temperature, and the 400-m temperature agreed within 0.17°C of the average CTD/SV 400-m temperature. The XBT 56 surface temperature was 2.84°C less than the bucket temperature, and the XBT 82 surface temperature was 2.22° greater. At 400 m, the differences from the average CTD/SV 400-m temperatures were -1.10°C and 2.66°C, respectively.

Shown in figure 25 are a pair of interesting MOANA WAVE XBT profiles: XBT 96 and XBT 98. These were taken 1 h 50 min apart in time and 5.5 nmi from each other. At the same time XBT 96 was made CTD/SV 19 was made, and at the same time XBT 98 was made CTD/SV 20 was made. Table 24 compares the surface and 400-m temperatures measured by XBT 96 and XBT 98 with CTD/SV 19 and CTD/SV 20. The CTD/SV measurements indicate a real change in the surface and 400-m temperatures. However, the change was much less than the change indicated by the XBT measurements. Again, in the absence of any other information both XBT profiles would be accepted as correct. However, as indicated by the CTD/SV measurements, neither is correct.

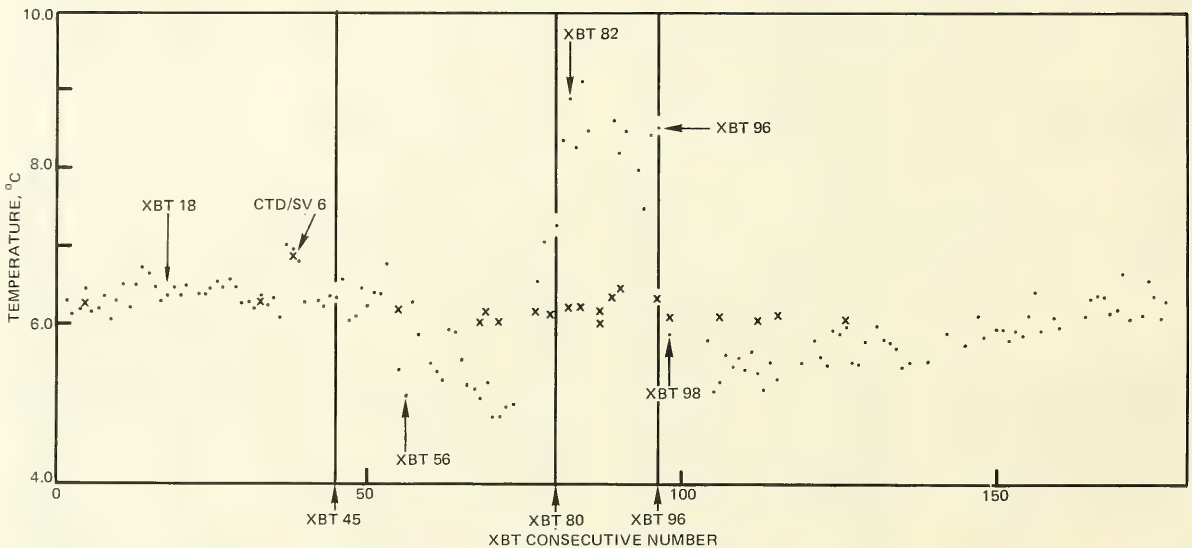

Figure 23. Difference between CAPER's MOANA WAVE CTD/SV (x) and XBT (·) 400-meter temperatures.

Temperatures	Profile Number	Number	Temperature, °C	
			Average Temperature	Standard Deviation
Random	XBT 1-45	42	6.42	0.21
Low	XBT 46-80	29	5.83	0.69
High	XBT 81-96	12	8.41	0.41
Low	XBT 97-177	57	5.88	0.35
	CTD/SV 4a-25	22	6.23	0.19

Table 23. Statistical summary of CAPER's MOANA WAVE 400-m temperatures.

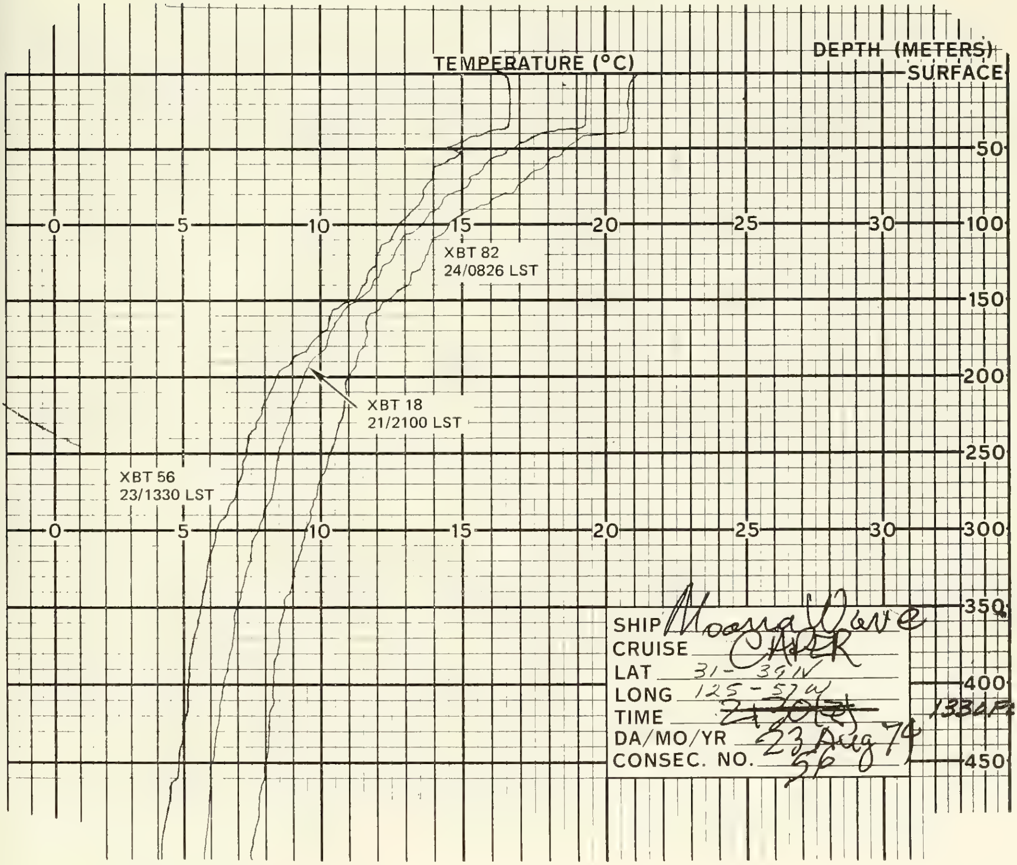

Figure 24. Examples of MOANA WAVE visually acceptable XBTs. Only XBT 18 is correct. XBT 56 and XBT 82 are incorrect.

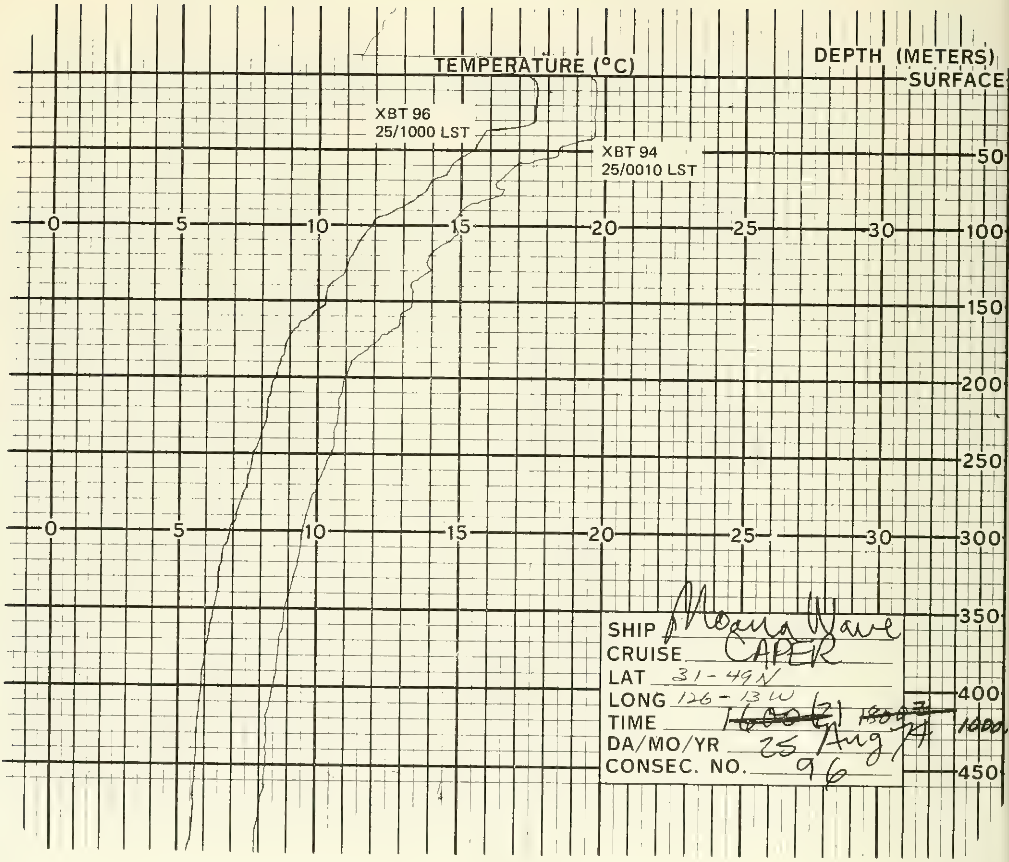

Figure 25. CAPER's MOANA WAVE XBT 94 and 96 taken 1 h 50 min apart in time and 5.5 nmi from each other.

	Temperature, °C	
	Surface	400 m
XBT 96	19.65	8.53
XBT 98	17.63	5.90
Difference	-2.02	-2.63
CTD/SV 19	18.93	6.35
CTD/SV 20	19.34	6.11
Difference	+0.41	-0.24

Table 24. Comparison of the surface and 400-m temperatures for XBT 96 and 98 and CTD/SV 19 and 20.

During RAPLOC/DEEPTOW, two 460-m systems – system A and system B – were used. Bucket temperatures were obtained simultaneously with 40 system A XBT profiles and with 31 system B XBT profiles. Pertinent statistics are summarized in table 25. On the average, the surface temperatures measured by system A and system B were slightly higher than those measured by the bucket thermometer.

	System A	System B
Number of comparisons	40	31
Average difference, °C	0.08	0.01
Standard deviation, °C	0.14	0.16
Largest difference, °C	0.37	0.42
Smallest difference, °C	-0.30	-0.35

Table 25. Statistical summary for RAPLOC/DEEPTOW surface temperature differences.

SUMMARY

Independent surface temperature measurements were made at the same time that XBT profiles were made during the Gulf of Alaska, SUDS I, CAPER, and RAPLOC/DEEPTOW experiments. A few measurements were made with the hydrocast and STD/SV systems. Most of the measurements used a towed thermistor (Gulf of Alaska), thermistor chain (SUDS I), or bucket thermometers (CAPER and RAPLOC/DEEPTOW). The data base is summarized in table 26. A total of 736 XBT profiles were made, together with one or more independent and simultaneous surface temperature measurements.

The purpose of these measurements was to check the surface temperature measurement accuracy of visually acceptable XBT profiles. As the analysis proceeded, a secondary purpose was realized. This was to use the independent measurements as detectors of malfunctional XBT systems.

Sensor	GULF OF ALASKA	SUDS I	CAPER	RAPLOC/DEEPTOW
Hydrocast	–	6	3	–
STD/SV	44	7	22	17
Towed thermistor	327	–	–	–
Thermistor chain	–	160	–	–
Bucket thermometer	–	–	138	71
TOTALS	371	173	163	88

Table 26. Summary of XBT surface temperature measurement accuracy data base.

During the Gulf of Alaska experiments, 334 visually acceptable XBT profiles were obtained while the towed thermistor measurements were being made. For seven of the 334 profiles, the calibration line exceeded ±0.34°C, leaving 327 visually acceptable profiles. Comparison of the XBT surface temperatures with the towed thermistor temperatures showed that the XBT system began to malfunction when making XBT profile 166. Of a total of 327 profiles, the accuracy of the XBT surface temperature was questionable for 162 profiles (49.5%).

The second system, used by the MOANA WAVE during the CAPER experiments, made 138 visually acceptable XBT profiles. At the time these measurements were made, independent surface temperature measurements were also made with a bucket thermometer. As in the case of the Gulf of Alaska measurements, the comparisons showed that the MOANA WAVE XBT system began to malfunction after XBT 45. The 103 surface temperatures recorded by the profiles made after profile 45 were all in error (74.6%).

The cause, or causes, of the malfunctions are not known. The malfunction of the two systems would not have been discovered if independent surface measurements had not been made.

Table 27 and figure 26 summarize pertinent statistics of the surface temperature comparisons for the profiles made when the systems were not malfunctioning (designated as profile set I)*; for the profiles made when the LEE (Gulf of Alaska) and the MOANA WAVE (CAPER) systems were malfunctioning (designated as profile set II)*; for all visually acceptable Gulf of Alaska and CAPER profiles; and for all 736 visually acceptable profiles.

*Profile Set I and Profile Set II are subsets of the set of all visually acceptable XBT profiles. These sets are defined as follows.

Profile Set I: All visually acceptable XBT profiles made when an XBT system was not malfunctioning, as determined from a comparison of XBT surface temperatures with independent measurements of surface temperature.

Profile Set II: All visually acceptable XBT profiles made when an XBT system was malfunctioning, as determined from a comparison of XBT surface temperatures with independent measurements of surface temperature.

	Number	Temperature, °C Average Difference	Standard Deviation
PROFILE SET I			
GULF OF ALASKA	172	0.00	0.15
SUDS I	171	0.04	0.13
CAPER	36	0.04	0.21
RAPLOC/DEEPTOW	88	0.05	0.15
TOTAL	467	0.02	0.15
PROFILE SET II			
GULF OF ALASKA	163	-0.31	0.21
CAPER	106	-0.65	0.97
TOTAL	269	-0.44	0.65
PROFILE SET I PLUS PROFILE SET II			
GULF OF ALASKA	335	-0.15	0.24
CAPER	142	-0.47	0.90
ALL DIFFERENCES			
	736	-0.15	0.47

Table 27. Statistical summary of differences among 736 visually acceptable XBT and an independent measurement of surface temperatures.

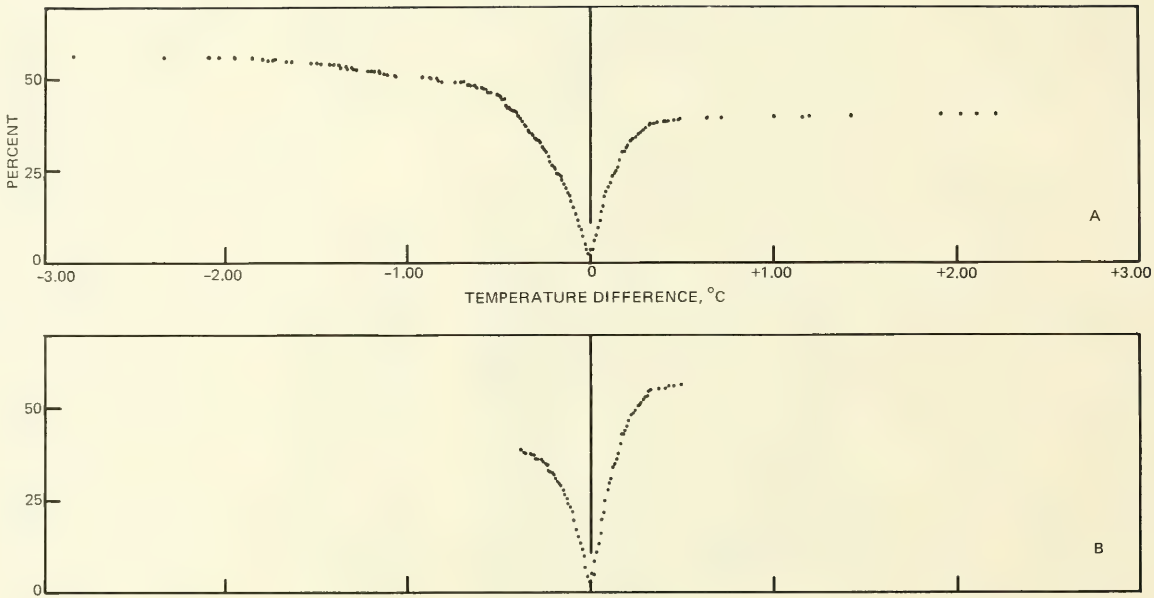

Figure 26. Positive and negative ogives of surface temperature differences: A. All visually acceptable profiles; B. Profile set I.

Two comments on the data presented in table 27 and figure 26 are indicated:

a. Once the profiles made when the XBT systems were malfunctioning were detected and removed from the data set, the XBT and independently measured surface temperatures were in agreement. The average of 467 comparisons was 0.02°C, with a standard deviation of 0.15°C. The distribution of the differences was slightly biased, with 56.5% being positive, 38.6% negative, and 4.9% zero.

b. All the XBT profiles used in this analysis were originally classified as visually acceptable profiles. In the absence of the independently measured surface temperatures, all of the 736 XBT surface temperatures would have been considered valid. In that event, the statistics are markedly altered, and the average difference is –0.15°C with a standard deviation of 0.47°C. In addition, the bias in the distribution of difference reverses, with 56.3% of the differences being negative, 40.3% positive, and 3.4% zero.

Finally, it is concluded from this analysis that a method of detecting malfunctioning XBT systems that produce visually acceptable XBT profiles is required.

TEMPERATURE ACCURACY OF 460-m SYSTEMS

This section contains the results of four studies that compare XBT measured temperatures at selected depths with average hydrocast and STD/SV measurements, quasi-simultaneous STD/SV measurements, and simultaneous thermistor chain measurements. The profiles whose calibration lines deviated from 16.7°C by more than ±0.34°C are not included in these studies.

COMPARISON WITH AVERAGE HYDROCAST AND STD/SV TEMPERATURES

The results of two studies that compared XBT measured temperatures with hydrocast and STD/SV measurements are discussed in this section. These studies included all visually acceptable XBT profiles made during the Gulf of Alaska experiments in water mass 2 and the transition water mass; during SUDS I 1972 in area C; during CAPER in water mass 2; and during RAPLOC/DEEPTOW when the ORB was at anchor. In these water masses, enough hydrocast and/or STD/SV measurements were made in the area and time interval over which the XBT profiles were themselves made to provide a reasonably accurate average temperature and an estimate of the standard deviation. The first study includes all visually acceptable profiles reaching a minimum depth of 200 m, and the second all visually acceptable profiles reaching 400 m and also having an independent surface temperature measurement.

Visually Acceptable Profiles Reaching 200 m

Comparisons were made at 200, 300, and 400 m. These depths were selected because they are below the thermocline where vertical temperature gradients and spatial and temporal variations are small. The analysis began with the computation of the differences between the XBT 200-, 300-, and 400-m temperatures and the appropriate average hydrocast and STD/SV temperatures listed in table 13.

The most accurate and the most extensive of the five sets of differences was obtained during the Gulf of Alaska experiments in water mass 2, where 65 STD/SV profiles were made in the same area and time interval over which 270 XBT profiles were made. In water mass 2, the 200-, 300-, and 400-m temperatures were extremely stable. The standard deviation of the average hydrocast and STD/SV measurements at these three depths was 0.04°C (see table 13). The second most accurate set of differences was obtained during the

RAPLOC/DEEPTOW experiments. These measurements were all made from the ORB at anchor. This data set consists of 11 STD/SV profiles made over the same time interval that 107 XBT profiles were obtained with two independent XBT systems.

The differences for the five sets of comparisons are summarized in appendix B, which contains tabulated statistical summaries for each of the data sets and plots which present 200-, 300-, and 400-m-depth positive and negative ogives for three subsets of differences — all visually acceptable profiles that include the profiles made when the Gulf of Alaska and CAPER XBT systems malfunctioned; profile set I; and profile set IA.* Listed in the tabulations are the number of differences, average differences, standard deviations, and the percentage of positive and negative differences. Table 28 is an attempt to summarize the Gulf of Alaska and CAPER comparisons for the sets of profiles that consist of all visually acceptable profiles. Table 28 supports the following observations:

a. The average differences are positive at all three depths, and are an increasing function of depth.

b. The standard deviation is about the same at all three depths.

c. At all three depths, more of the differences are positive than negative.

d. At all three depths, the largest differences are positive. Thus, for the data set of visually acceptable XBT profiles, it is concluded that, on the average, the recorded temperatures are higher and the vertical temperature gradients larger** than those measured by the hydrocast and STD/SV systems. These are the expected results if malfunctioning XBT systems are undetected.

The differences for profile set I, which consists of all XBT profiles except those differences associated with the malfunctioning system, are summarized in table 29. An inspection of the table 29 data for the Gulf of Alaska water mass 2 and transition water mass, and for the CAPER water mass 2, leads to the same observations. Thus, even with the omission of the profiles made with the two malfunctioning XBT systems, the average temperature and the average vertical temperature gradients remain systematically biased. For the SUDS I and the RAPLOC/DEEPTOW comparisons, the average difference was negative at one of the three depths; for the RAPLOC/DEEPTOW comparisons, the average difference was a decreasing, rather than increasing, function of depth. However, for both data sets, at all three depths, the largest differences were positive. This later observation tends to support the previous conclusions.

In an effort to eliminate the biasing profile, profile set I was separated into two subsets by using the accuracy criterion defined in the XBT system errors section. The criterion was modified by using the final system errors in place of the preliminary system errors. One subset included all differences that satisfied the criterion (profile set IA), and the other all differences that did not satisfy the criterion (profile set IB). The differences for profile set IA are summarized in table 30. An inspection of these data shows that for the Gulf of Alaska data set, the average differences still show a slight increase with depth and, for the SUDS I data set, a slight decrease with depth. For all five sets of data, the

*Profile set IA is a subset of profile set I. It is defined above.

**The mathematical convention that a positive number is larger than a negative number is used in this discussion. For example, a +0.12°C/100 m gradient is larger than a -0.22°C/100 m gradient.

OBSERVATIONS	GULF OF ALASKA, WATER MASS 2	GULF OF ALASKA, TRANSITION	CAPER, WATER MASS 2
1. Average differences are:			
a. Positive at all three depths	x	x	x
b. Negative at one depth			
c. An increasing function of depth	x	x	x
d. A decreasing function of depth.			
2. Standard deviation is about the same at all three depths.	x	x	x
3. At all three depths, more of the differences are:			
a. Positive than negative	x	x	x
b. Negative than positive.			
4. At all three depths, the largest differences are:			
a. Positive	x	x	x
b. Negative.			

Table 28. Comparison of average 200-, 300-, and 400-m average hydrocast and STD/SV temperature measurements with XBT profile measurements for all visually acceptable XBT profiles made during the Gulf of Alaska experiments in water mass 2 and in the transition water mass, and during CAPER in water mass 2

OBSERVATIONS	GULF OF ALASKA, WATER MASS 2	GULF OF ALASKA, TRANSITION	CAPER, WATER MASS 2	SUDS I 1972 AREA C	RAPLOC/DEEPTOW AT ANCHOR
1. Average differences are:					
a. Positive at all three depths	x	x	x	—	—
b. Negative at one depth	—	—	—	x	x
c. An increasing function of depth	x	x	x	—	—
d. A decreasing function of depth.	—	—	—	—	x
2. Standard deviation is about the same at all three depths.	x	x	x	x	x
3. At all three depths, more of the differences are:					
a. Positive than negative	x	x	x	—	—
b. Negative than positive.	—			.	—
4. At all three depths, the largest differences are:					
a. Positive	x	x	x	x	x
b. Negative.	—	—	—	—	—

Table 29. Comparison of average 200-, 300-, and 400-m hydrocast and STD/SV temperature measurements with XBT profile measurements for profile set I.

OBSERVATIONS	GULF OF ALASKA, WATER MASS 2	GULF OF ALASKA, TRANSITION	CAPER, WATER MASS 2	SUDS I 1972 AREA C	RAPLOC/DEEPTOW AT ANCHOR
1. Average differences are:					
a. Positive at all three depths	–	x	x	–	–
b. Negative at one depth	x	–	–	x	x
c. An increasing function of depth	x	x	–	–	–
d. A decreasing function of depth.	–	–	–	x	–
2. Standard deviation is about the same at all three depths.	x	x	x	x	x
3. At all three depths, more of the differences are:					
a. Positive than negative	–	x	x	–	–
b. Negative than positive.	–	–	–	–	–
4. At all three depths, the largest differences are:					
a. Positive	–	–	–	–	–
b. Negative.	–	–	–	–	–

Table 30. Comparison of average 200-, 300-, and 400-m hydrocast and STD/SV temperature measurements with XBT profile measurements for profile set 1A.

average values were close to zero, varying from –0.024°C to 0.088°C, with nine differences being positive and six differences negative. The standard deviations were small, varying from 0.07°C to 0.13°C.

Table 31 summarizes the number and percentage of the differences in profile sets I, IA, and IB. An inspection of these statistics shows that from 28.8% to 58.7% of the differences were in profile set IB, the set of differences that did not satisfy the accuracy criterion. For the set of all differences, the percentage was an increasing function of depth. It increased from 36.7% at 200 m to 45.6% at 400 m.

Depth,	Set I	Set IA		Set IB	
m	Number	Number	Percentage	Number	Percentage
Gulf of Alaska, Water Mass 2					
200	105	68	64.8	37	35.2
300	102	70	68.6	32	31.4
400	96	64	66.7	32	33.3
Gulf of Alaska, Transition Water Mass					
200	109	72	66.1	37	33.9
300	100	60	60.0	40	40.0
400	96	55	57.3	41	42.7
SUDS I 1972, Area C					
200	186	114	61.3	72	38.7
300	182	112	61.5	70	38.5
400	176	100	56.8	76	43.2
CAPER, Water Mass 2					
200	52	37	71.2	15	28.8
300	50	28	56.0	22	44.0
400	46	20	43.5	26	56.5
RAPLOC/DEEPTOW, at Anchor					
200	107	63	58.9	44	41.1
300	106	58	54.7	48	45.3
400	104	43	41.3	61	58.7
ALL DIFFERENCES					
200	559	354	63.3	205	36.7
300	540	328	60.7	212	39.3
400	518	282	54.4	236	45.6

Table 31. Number and percentage of differences in profile sets I, IA, and IB.

In summary, this analysis supports the preliminary conclusion that, unless biasing profiles are detected and removed from the profile set, on the average the XBT system records temperatures over the 200-to-400-m depth interval that are slightly higher, and vertical temperature gradients that are slightly larger, than those recorded by average hydrocast and STD/SV measurements made in the same water masses as the XBT profiles.

Of the 559 set I profiles reaching 200 m, 518 (92.7%) also reached 400 m. This question might be asked: Out of these 518 profiles, how many satisfied the 200-, 300-, and 400-m accuracy criteria at all three depths, at one depth, at two depths, and at none of the three depths? Table 32 summarizes these data. Shown for each water mass is the number of XBT profiles that satisfied the accuracy criteria at one, two, and three depths. Shown also are the total number and the percentage the total represents of the complete subset. Four points are of special interest:

a. Only 37.8% of the XBT profiles satisfied the accuracy criteria at all three depths.

b. 19.9% of the XBT profiles failed to satisfy the accuracy criteria at all three depths.

c. Of 126 profiles failing the accuracy criterion at one depth, the percentage failing the accuracy criteria at 200-, 300-, or 400-m was 32.5, 19.1, and 48.4, respectively.

d. Of 93 profiles that satisfied the accuracy criterion at one depth (failed the accuracy criteria at two depths), the percentage that satisfied the accuracy criteria at 200, 300, and 400 m was 51.6, 22.6, and 25.8, respectively.

	Number XBT Profiles Rejected at:							
	0 Depths		1 Depth		2 Depths		3 Depths	
	n	%	n	%	n	%	n	%
GULF OF ALASKA								
Water Mass 2	55	57.3	14	14.6	8	8.3	19	19.8
Transition	47	49.0	12	12.5	10	10.4	27	28.1
SUDS I 1972								
Area C	59	33.5	50	28.4	38	21.6	29	16.5
CAPER								
Water Mass 2	14	30.4	12	26.1	14	30.4	6	13.0
RAPLOC/DEEPTOW								
at Anchor	21	20.2	38	36.5	23	22.1	22	21.2
TOTAL	196	37.8	126	24.3	93	18.0	103	19.9

Table 32. Accuracy summary for 518 profile set I profiles reaching 400 m.

All Visually Acceptable Profiles Reaching 400 m and Having Independent Surface Temperature Measurements

The previous analysis suggested that temperatures and vertical temperature gradients in the 200-to-400-m layer were systematically biased when compared to average hydrocast and STD/SV measurements. This analysis considered all XBT profiles made in water masses where enough 200-, 300-, and 400-m hydrocast and STD/SV measurements were made to establish an average temperature and its variance. Not all of these profiles reached 400 m, which resulted in a different number of comparisons at each depth. This question might now be asked: Are the results of the preceding analysis influenced by having different numbers of comparisons at each depth?

A second question that arises: Are the temperatures and vertical temperature gradients also biased in the surface-to-200-m layer?

Insight into these questions may be gained by considering the subset of all profiles that reached 400 m and also had an independent surface temperature measurement. This subset consists of 528 profiles. The results of the analysis of this subset are summarized in appendix C and tables 33, 34, and 35. The format used is the same as for the preceding analysis.

Table 33, summarizing the results for the set of all visually acceptable Gulf of Alaska water mass 2 and transition water mass, as well as the CAPER water mass 2 profiles, supports the following observations:

a. At 200 , 300 , and 400 m, the results are similar to the results presented in table 28.

b. The XBT profiles measure a surface temperature that, on the average, is less than the independently measured temperature.

c. The surface-to-200-m temperature gradient, on the average, is biased positively with respect to the average hydrocast and STD/SV temperature measurements.

Thus, for the data set consisting of all visually acceptable profiles, the answer to the first question is no, and the answer to the second question is yes. In addition, on the average, the XBT profiles measured vertical temperature gradients from the surface to 400 m that were larger than those measured by the hydrocast and STD/SV systems. These, then, are the expected results if no procedures are used to detect malfunctioning systems.

It was shown previously that two of the XBT systems malfunctioned. Of the 528 visually acceptable profiles, 177 (33.5%) were made with the systems malfunctioning, and 351 (66.5%) were made with the systems not malfunctioning. The analysis of the 351 set I profiles is summarized in appendix C and table 34. An inspection of these data shows that:

a. At 200, 300, and 400 m, the results are similar to those presented in table 29 for the Gulf of Alaska and CAPER water mass 2 data sets, with minor differences associated with the other three data sets.

b. At the surface, the XBT system now measured a temperature higher than the independently measured temperature for four of the five data sets. For the Gulf of Alaska water mass 2 data set, the average surface difference was still negative.

Observations	GULF OF ALASKA, Water Mass 2	GULF OF ALASKA, Transition	CAPER, Water Mass 2
200, 300, and 400 m			
1. Average differences are:			
a. Positive at all three depths	x	x	x
b. Negative at one depth	—	—	—
c. An increasing function of depth	x	x	x
d. A decreasing function of depth.	—	—	—
2. Standard deviation is about the same at all three depths.	x	x	x
3. At all three depths, more of the differences are:			
a. Positive than negative	x	x	x
b. Negative than positive.		—	—
4. At all three depths, the largest differences are:			
a. Positive	x	x	x
b. Negative.	—	—	—
Surface			
1. Average difference is:			
a. Positive	—	—	—
b. Negative.	x	x	x
2. Surface to 200-m gradient is:			
a. Biased positively	x	x	x
b. Biased negatively.	—	—	—

Table 33. Comparison of average hydrocast and STD/SV temperature measurements with XBT profile measurements for all visually acceptable XBT profiles made during the Gulf of Alaska in water mass 2 and in the transition water mass, and during CAPER in water mass 2. XBT profiles reached 400 m and had an independent surface temperature measurement.

Observations	GULF OF ALASKA, Water Mass 2	GULF OF ALASKA, Transition	CAPER, Water Mass 2	SUDS I 1972 Area C	RAPLOC/DEEPTOW at Anchor
200, 300, and 400 m					
1. Average differences are:					
a. Positive at all three depths	x	x	x	–	–
b. Negative at one depth	–	–	–	x	x
c. An increasing function of depth	x	–	x	–	–
d. A decreasing function of depth.	–	–	–	–	–
2. Standard deviation is about the same at all three depths.	x		x	x	x
3. At all three depths, more of the differences are:					
a. Positive than negative	x	x	x	–	–
b. Negative than positive.	–	–	–	–	x
4. At all three depths, the largest differences are:					
a. Positive	x	x	x	–	x
b. Negative.	–		–	–	–
Surface					
1. Average difference is:					
a. Positive	–	x	x	x	x
b. Negative.	x	–	–	–	–
2. Surface to 200-m gradient is:					
a. Biased positively	x	x	x	–	–
b. Biased negatively.		–	–	x	x

Table 34. Comparison of average hydrocast and STD/SV temperature measurements with XBT profile measurements for profile set I, which consisted of XBT profiles reaching 400 m and had an independent surface temperature measurement.

Observations	GULF OF ALASKA, Water Mass 2	GULF OF ALASKA, Transition	CAPER, Water Mass 2	SUDS I 1972 Area C	RAPLOC/DEEPTOW at Anchor
1. Average differences are:					
a. Positive at all three depths	–	x	x	–	–
b. Negative at at least two depths	x	–	–	x	x
c. An increasing function of depth	x	x	–	–	–
d. A decreasing function of depth.	–	–	–	x	–
2. Standard deviation is about the same at all three depths.	x	x	x	x	x
3. At all three depths, more of the differences are:					
a. Positive than negative	–	x	x	–	–
b. Negative than positive.	-	–	–	–	–
4. At all three depths, the largest differences are:					
a. Positive	–	x	x	–	–
b. Negative.	–	–	–	–	x

Table 35. Comparison of average 200-, 300-, and 400-m hydrocast and STD/SV temperature measurements with XBT profile measurements for profile set 1A, which consisted of XBT profiles reaching 400 m and had an independent surface temperature measurement.

c. The vertical temperature gradient from the surface to 200 m is slightly greater than that measured by the hydrocast and STD/SV systems for the Gulf of Alaska and CAPER data sets, and slightly less for the SUDS I and RAPLOC/DEEPTOW data sets.

Thus, for this data set, the answer to the first question is yes, to the extent that there were minor differences associated with three of the data sets. The answer to the second question is also yes.

For completeness, the results of the analysis of the profile set IA profiles are summarized in appendix C and table 35. An inspection of these data shows that for all five data sets at all depths, the average differences were close to zero, varying from -0.023°C to 0.126°C with eight differences being positive and seven differences being negative. The standard deviations were also small, varying from 0.03°C to 0.11°C.

QUASISIMULTANEOUS XBT AND STD/SV MEASUREMENTS

The third accuracy study compares quasisimultaneous XBT and STD/SV profiles. A total of 66 pairs of profiles, made within 30 minutes or less of each other, were obtained during the Gulf of Alaska, SUDS I, CAPER, and RAPLOC/DEEPTOW experiments. These measurements are used to examine further the accuracy of the XBT measurements at the surface and at the 200-, 300-, and 400-m depths. All appropriate system errors were applied prior to obtaining the differences between the two measurements. The results of the comparisons were similar to those obtained from the first two studies.

The individual differences are tabulated in appendix D. Tabulated are the XBT numbers, the time in minutes between the beginning of the XBT and STD/SV measurements, and the differences for the four selected depths. If the difference is positive, the XBT temperature is higher than the STD/SV temperature, and if it is negative, the XBT temperature is lower than the STD/SV temperature. In the Gulf of Alaska and CAPER data sets, certain of the differences are underlined. These differences are associated with the XBT profiles acquired when the LEE and MOANA WAVE XBT systems malfunctioned. Recall that the malfunction of these systems was discovered from an analysis of the XBT surface temperature measurement accuracy.

Histograms of the differences listed in appendix D are shown in figure 27. The dot-shaded areas are associated with the measurements made during CAPER when the MOANA WAVE's XBT system malfunctioned, the line-shaded areas are associated with the measurements made during the Gulf of Alaska experiments, when the LEE's system malfunctioned, and the unshaded areas show the differences associated with the remaining profiles. An examination of figure 27 shows that at 200, 300, and 400 m, all but one of the large differences are associated with the profiles made by the malfunctioning systems, and that the differences associated with the Gulf of Alaska profiles obtained when the XBT system malfunctioned would not have been detected from these comparisons since these differences are similar in magnitude to the differences associated with the unshaded areas. The profile associated with the largest unshaded 200-, 300-, and 400-m positive differences shown in figure 27 is the Gulf of Alaska ES1-146 profile shown in figure 28. The "dots" in figure 28 are the temperatures measured by STD/SV 39. These measurements were made 30 minutes apart in the very stable water mass 2. Also shown are the differences between the two sets of measurements at the surface and at 200, 300, and

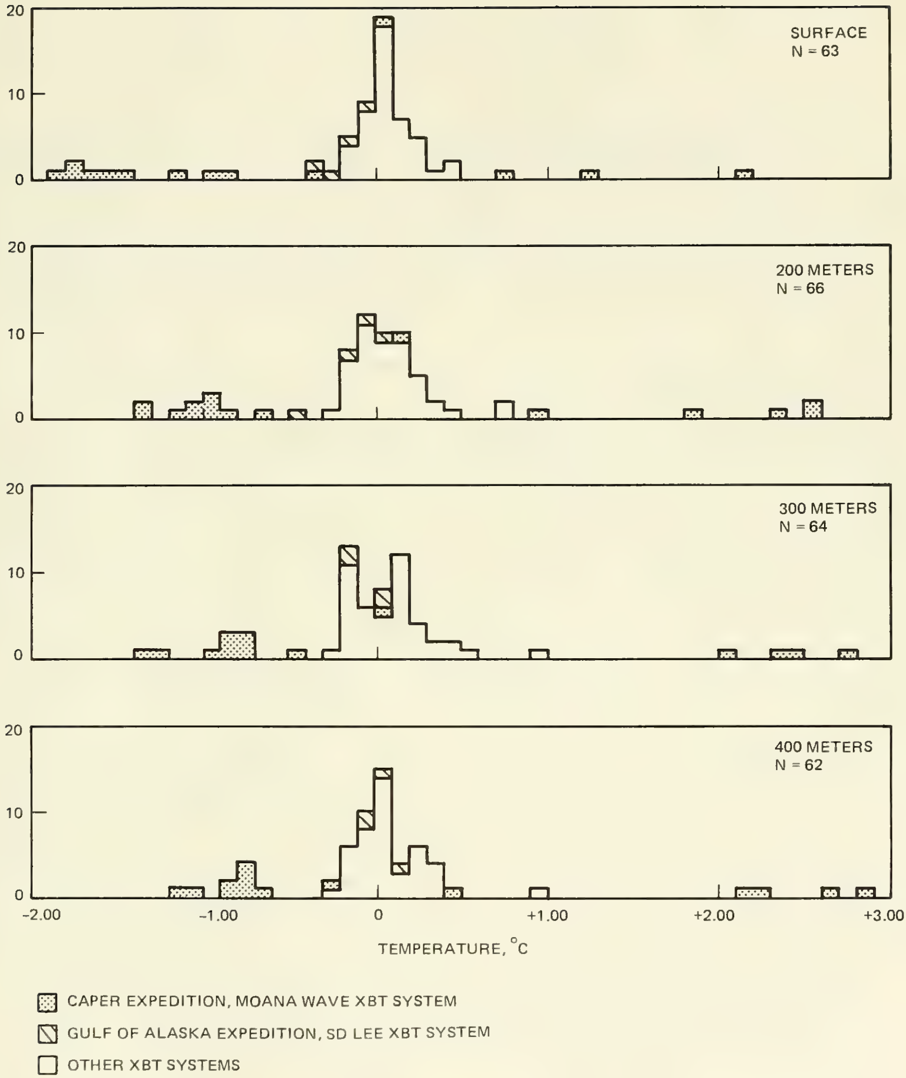

Figure 27. Differences between quasisimultaneous XBT and STD/SV temperatures.

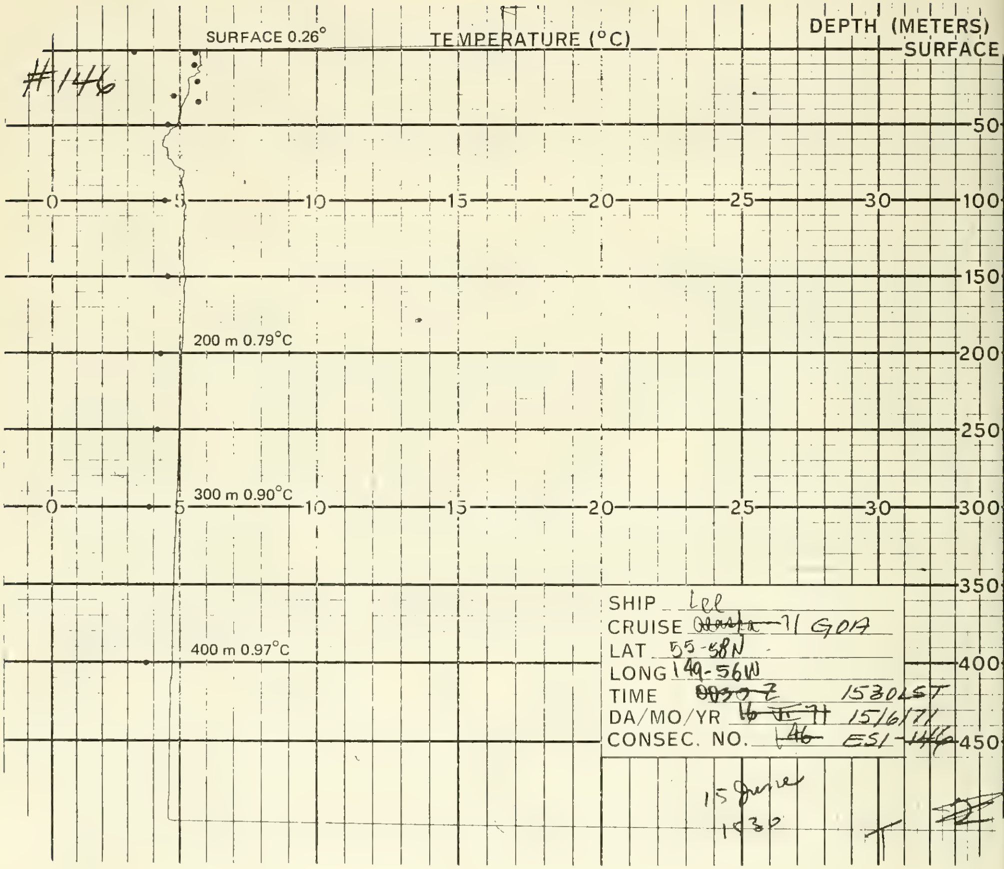

Figure 28. Comparison of Gulf of Alaska XBT ESI-146 (–) with STD/SV 39 (•) temperatures.

400 m. The two sets of measurements agree reasonably well from the surface to about 60 m. From 60 m to the maximum depth, the differences increase systematically from near zero to 0.97°C at 400 m. In an acoustic application, the difference between these two profiles is significant since the XBT profile suggests the presence of a depressed channel that is considerably stronger than the channel suggested by the STD/SV profile.

Table 36 presents a statistical summary for the set of all visually acceptable profiles and for profile set I for comparisons of surface, 200-, 300-, and 400-m measurements. For the set of all visually acceptable profiles, the results are similar to those obtained in the two studies previously discussed. The major difference is the standard deviations, which are somewhat larger than those listed in appendices B and C. For profile set I, the average differences are all positive and a greater percentage of differences is positive than was the case for all visually acceptable profiles. These data give additional evidence supporting the conclusion that, on the average, the XBT system measures temperatures slightly higher than those measured by other measuring systems.

Depth, m	Difference, °C			Percent	
	n	$\overline{\Delta T}$	s	Positive	Negative
	ALL VISUALLY ACCEPTABLE PROFILES				
0	63	-0.110	0.67	55.4	41.3
200	66	0.049	0.75	50.0	47.0
300	64	0.060	0.74	48.4	46.9
400	62	0.090	0.74	51.6	43.5
	PROFILE SET I				
0	46	0.060	0.16	67.4	28.3
200	46	0.082	0.21	56.2	39.1
300	45	0.077	0.22	55.6	40.0
400	43	0.073	0.20	58.1	34.9

Table 36. Summary of comparisons between quasisimultaneous XBT and STD/SV profiles.

COMPARISON WITH THERMISTOR CHAIN MEASUREMENTS

The fourth study compares simultaneous XBT and thermistor chain measurements. These measurements were made during the SUDS I experiments. On 23 February 1972, with the thermistor chain vertical in the water (zero tow speed), seven XBT profiles were attempted between 0650 and 0726 LST. On 12 February 1972 at 0428 LST, one XBT profile was made under similar circumstances. These pairs of measurements are the most accurate set considered in this study since they are as close to simultaneous in space and time as is possible to obtain at sea, and were made with the vessel hove to and drifting, and with the thermistor chain hanging vertically in the water. During the acoustic experiments, the LEE, towing the thermistor chain at three knots, made 153 XBT temperature profiles.

These XBT measurements are simultaneous with the scan of the thermistor chain, which began when the XBT probe was dropped. This discussion compares these simultaneous thermistor chain and XBT temperature measurements.

Recall that the thermistor chain is a towed device used for measuring temperatures every 10 seconds from the surface to a maximum depth of 242 m at 44 depths spaced 5.6 m apart. In addition, a sensor records the depth of the deepest thermistor. With the towing speed and the maximum depth known, the depth of each sensor may be computed. Unfortunately, during these measurements the depth sensor was inoperative. As a result, measurements of the thermistor chain sensors were not available. To obtain information on the sensor depths under tow at 3 knots, the average hydrocast and STD/SV temperatures recorded in areas A and C were compared with the average temperatures measured by the thermistor chain for all acoustic runs made in these two areas. Similar comparisons could not be made for area B since no hydrocast or STD/SV measurements were made in this area. The results of these comparisons are summarized in figures 29 and 30. The solid curve connects the average hydrocast and STD/SV temperatures at standard depths and at the maximum thermistor chain depth of 242 m. The horizontal bar connects the lowest and highest temperatures observed at the indicated depth. The dots are the average thermistor chain temperatures for each of the 44 sensors. The comparison for area C measurements suggests good agreement. The area A comparisons do not show good agreement. For depths greater than about 170 m, the average thermistor chain measurements are 0.1 to 0.2°C lower than the hydrocast and STD/SV average measurements; and at shallower depths, they are 0.2 to 0.7°C higher. However, all average thermistor chain measurements fall within the hydrocast and the STD/SV measured range of temperature. In the vicinity of the thermocline, good agreement would be observed if all thermistors were at a depth about 10 m shallower than assumed. To accomplish this, the deepest thermistor would have to be about 18 m shallower than the 242-m maximum depth. Experience in towing the chain suggests that this amount of shoaling could not occur at a 3-knot towing speed. For purposes of this study, it is concluded that accurate thermistor chain temperatures cannot be established for area A; thus only the measurements made in area C will be used in the following analysis.

Figure 31 presents the measurements associated with the single XBT profile taken on 12 February 1972. The left-hand figure is the average, for each of the 44 sensors, of nine scans of the thermistor chain made while XBT 81L was being recorded. The standard deviations for these average thermistor chain temperatures are small, varying from 0.00°C to 0.03°C. The right-hand figure is a plot, for each sensor, of the differences between the XBT measurement and the average thermistor chain measurement. The largest differences are associated with the thermocline, where small differences in depth cause large differences in temperature. The largest difference, –0.51°C at 96 m, can be accounted for by a 2-m depth difference. In the surface layer, 0 to 79 m, and below the thermocline, 135 to 242 m, the largest positive difference was 0.09°C, and the largest negative difference was 0.10°C. The average differences and standard deviation for the in-layer differences were 0.007°C and 0.04°C; for the below-thermocline difference they were 0.009°C and 0.04°C; and for all 35 in-layer and below-thermocline differences they were –0.002°C and 0.04°C. Note that the differences for the five deepest sensors are negative. The measurements made by this single XBT probe are in excellent agreement with those made by the thermistor chain.

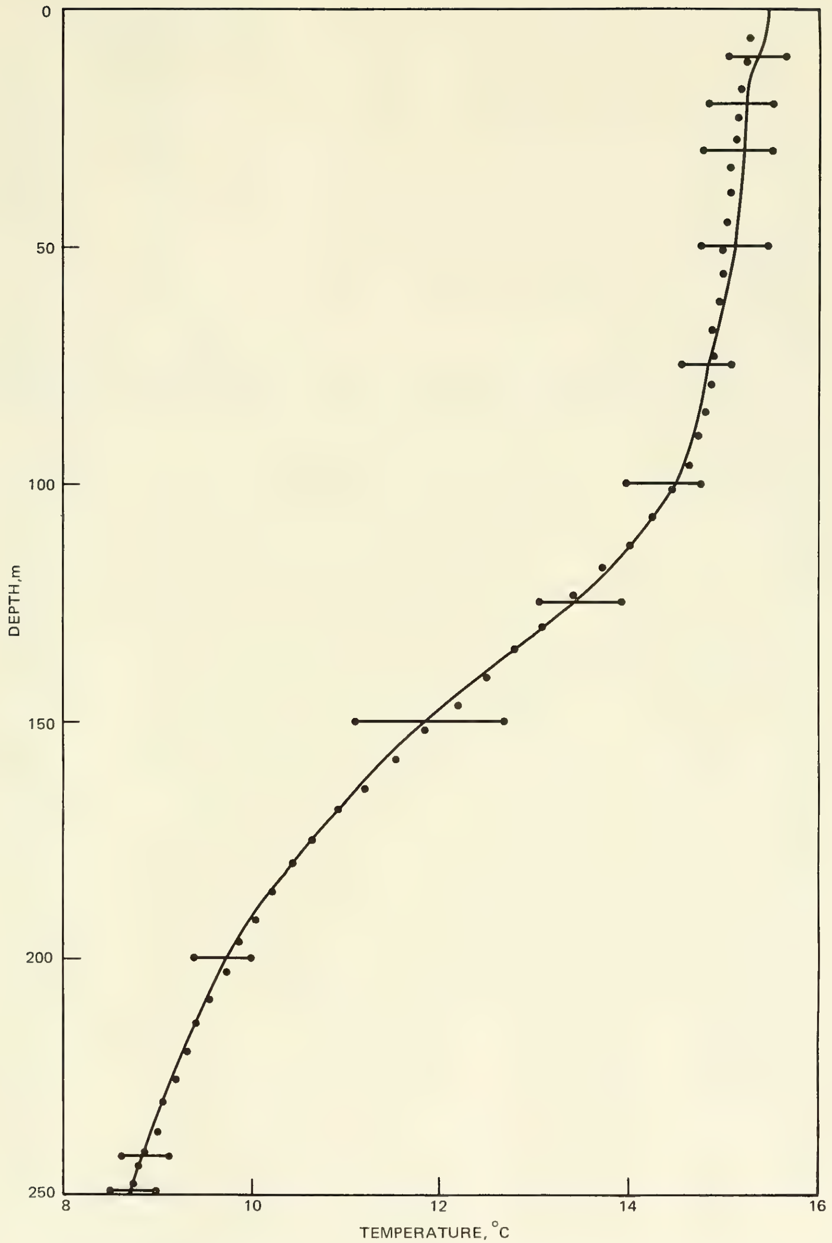

Figure 29. Comparison between average hydrocast and STD/SV and average thermistor chain temperatures for area C.

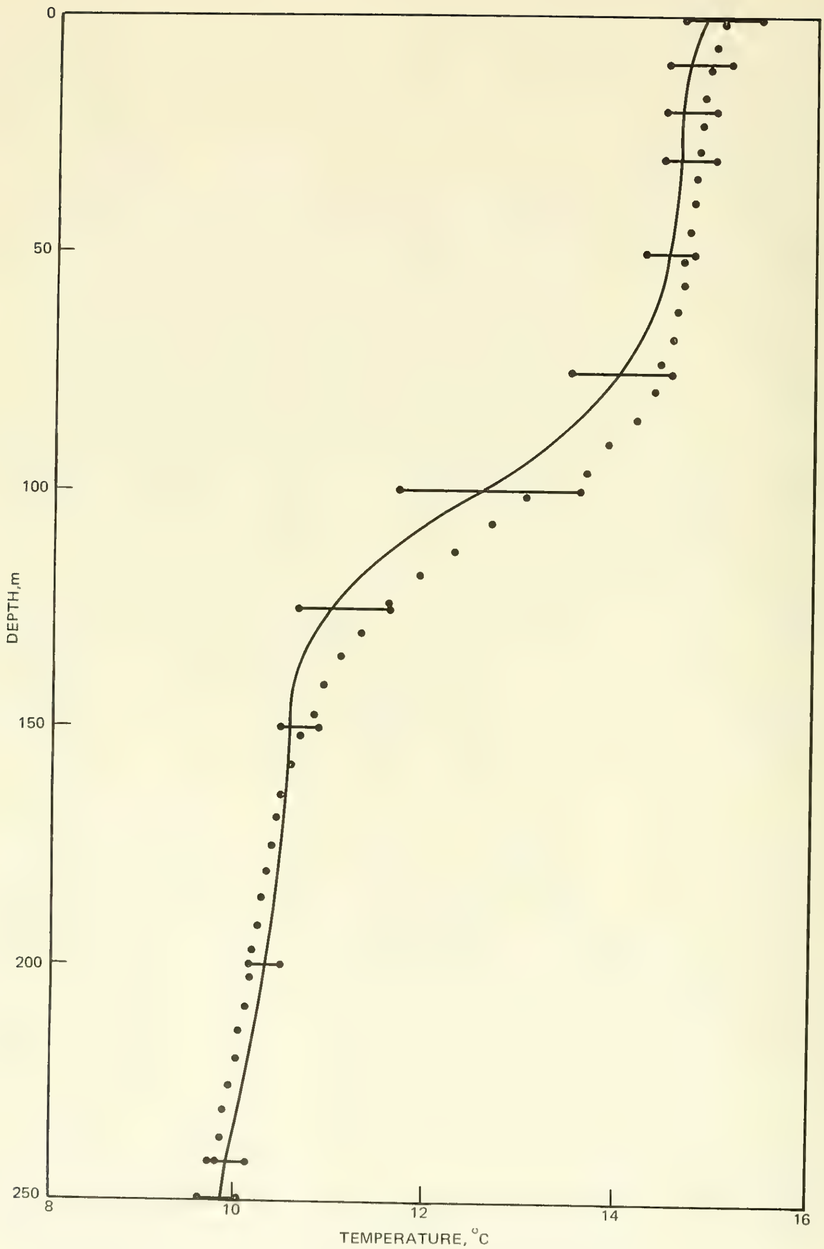

Figure 30. Comparison between average hydrocast and STD/SV and average thermistor chain temperatures for area A.

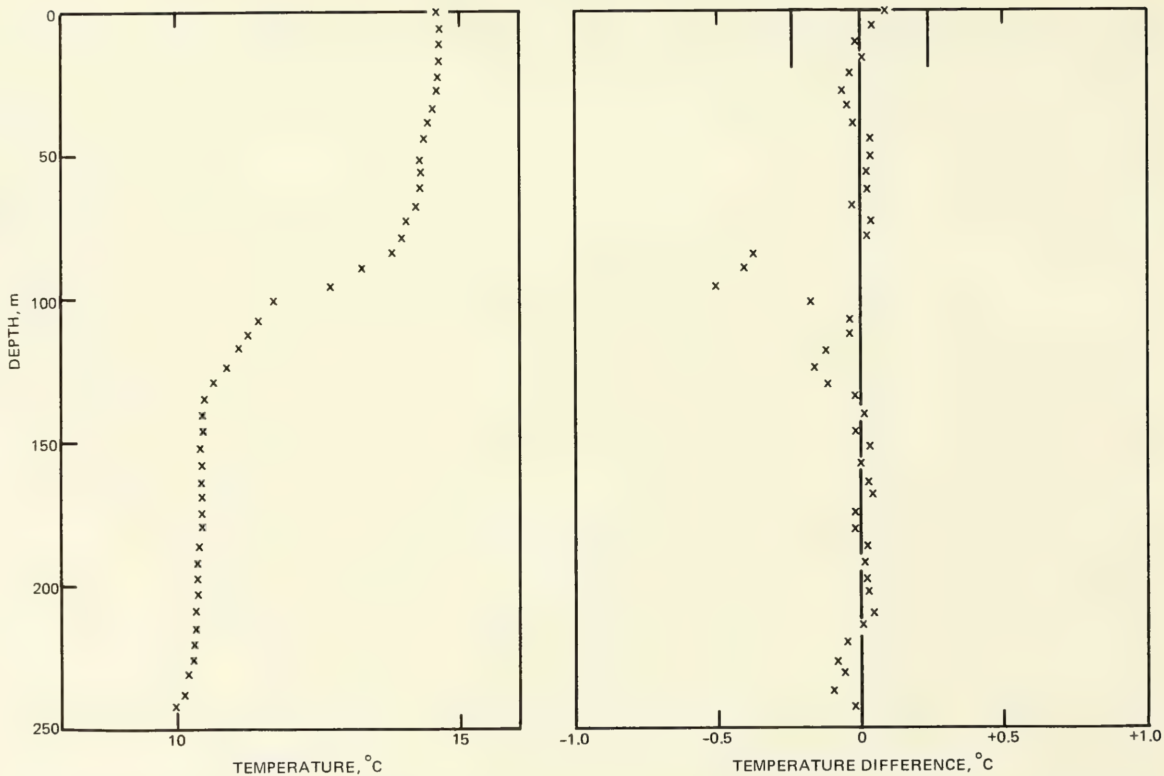

Figure 31. Comparison of SUDS I XBT 81L with average of nine thermistor chain scans made simultaneously with the XBT profile. Ship was hove to and drifting.

On 23 February 1972 from 0650 LST to 0726 LST, with the LEE hove to and drifting and the thermistor chain hanging vertical in the water, seven XBT profiles were attempted. Of these seven attempts, one was a catastrophic failure, one was a partial success that yielded measurements to 90 m, and five were successes. Figure 32 summarizes the results of a comparison of these profiles with single thermistor chain scans, beginning at the same time the XBT probe was released. The XBT probe was at a depth of about 50 m by the time the thermistor chain completed its 10-s scan. The left-hand part of figure 32 is a plot of the six thermistor chain scans. In the near-surface layer, surface to 85 m, the observed variation in the thermistor chain temperature measurements was small, while in the thermocline, variations up to 0.80°C at 158 m were observed. The right-hand figure is a plot of the differences associated with the six pairs of measurements. Also shown is the XBT drop time in seconds. The average difference at each depth is shown by the symbol (x). Of a total of 237 differences, the largest positive difference was 0.12°C, and the largest negative difference was -0.52°C. All the larger negative differences were in the thermocline and could have resulted from small depth differences. Of major interest is that these six XBT probes, on the average, measured temperatures that were lower than those measured by the thermistor chain at all 44 sensor depths. The average of 237 differences was -0.07°C, with a standard deviation of 0.09°C. Out of the total of 237 differences, only 54 (22.8%) were positive, and 175 (73.8%) were negative. In the surface layer (surface to 85 m) and below the thermocline (220 to 242 m), layers where vertical temperature gradients are small, the largest positive difference was 0.12°C, and the largest negative difference was 0.21°C. The average difference and standard deviation for the in-layer differences was -0.063°C and 0.08°C; for the below-thermocline differences they were -0.046°C and 0.09°C; and for all 121 in-layer and below-thermocline differences, they were -0.060°C and 0.08°C.

Statistics for the individual XBT probes are summarized in table 37 for the in-layer, below-thermocline, and for the combined set of differences. In the layer all, or nearly all, of the differences were negative for four of the six probes, with the average differences varying from –0.041°C, XBT 278L, to –0.162°C, XBT 277L. Only XBT 275L measured an average positive difference. Note that this probe failed at 90 m. XBT 276L showed the best agreement with the thermistor chain with seven positive, seven negative, and two zero differences. Five of the six probes measured temperatures below the thermocline. The average differences for four of the five probes were negative, and for one probe it was positive. Thus the six probes used in this comparison show a marked propensity to measure temperatures that are less than those measured simultaneously by the thermistor chain. Only one of the six probes, XBT 276L, showed excellent agreement in the statistical sense. These measurements were made serially over a 26-min period on 23 February 1972. The biasing of the differences may be a consequence related to a "run" of consecutive XBT probes. Additional examples of biased results related to "runs" of probes will be discussed later.

During the station 3 and 4 experiments, 73 XBT profiles were attempted while the LEE towed the thermistor chain at a speed of 3 knots. Out of the 73 attempts, 62 (84.9%) were successes, two (2.7%) were partial successes, and nine (12.3%) were catastrophic failures. This study compares the 64 visually acceptable profiles with the thermistor chain scans that started at the same time the XBT probes were released.

An inspection of the differences for the individual profiles showed that at all depths greater than 34 m, the largest differences were associated with XBT 188L. The differences were all negative, varying from –0.43°C at 39 m to a very large difference of –3.08°C at

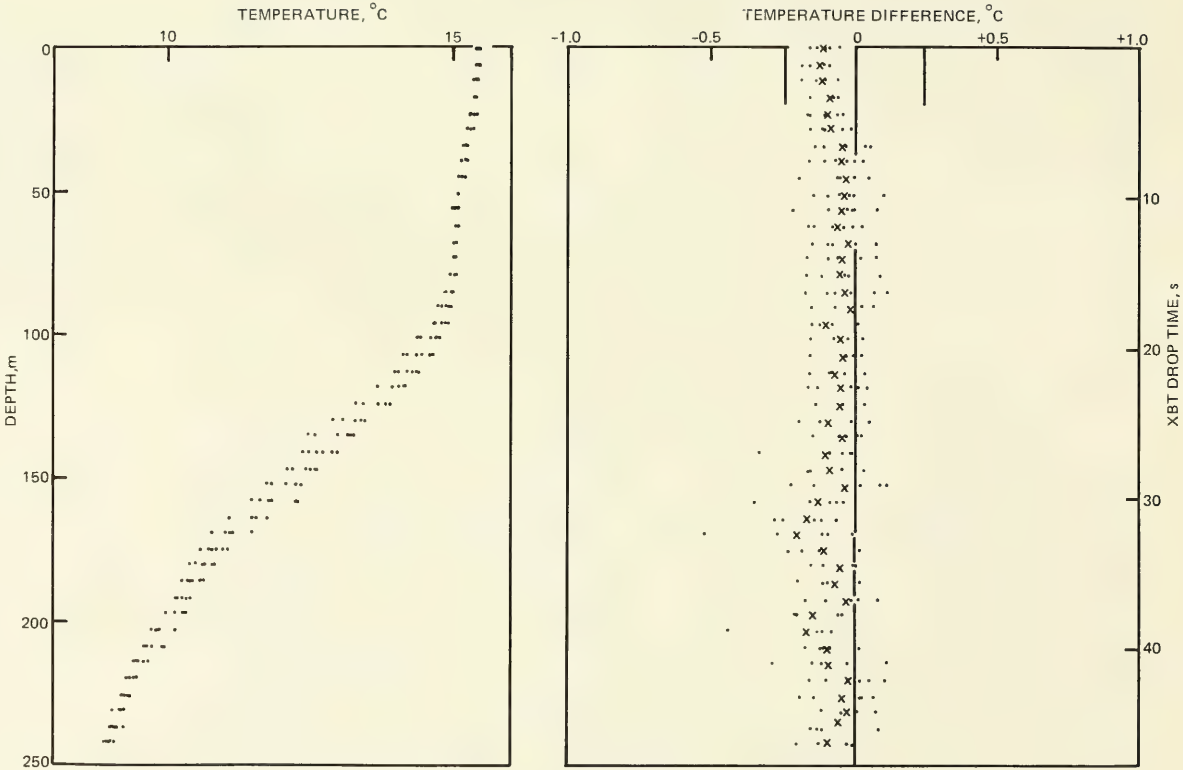

Figure 32. Comparison of six SUDS I XBT profiles with thermistor chain profiles taken at the same time the XBT probe was dropped. Ship was hove to and drifting.

XBT Number	°C			Number of Differences		
	n	$\overline{\Delta T}$	s	Postive	Zero	Negative
IN LAYER						
273L	16	-0.106	0.02	0	0	16
274L	16	-0.077	0.04	0	0	16
274aL	Catastrophic failure			–	–	–
275L	16	0.013	0.08	9	1	6
276L	16	-0.006	0.06	7	2	7
277L	16	-0.162	0.02	0	0	16
278L	16	-0.041	0.04	0	2	14
BELOW THERMOCLINE						
273L	5	-0.130	0.07	0	0	5
274L	5	-0.012	0.06	3	0	2
274aL	Catastrophic failure			–	–	–
275L		Partial success		–	–	–
276L	5	0.052	0.06	4	0	1
277L	5	-0.136	0.02	0	0	5
278L	5	-0.006	0.08	3	0	2
IN LAYER AND BELOW THERMOCLINE						
273L	21	-0.111	0.04	0	0	21
274L	21	-0.061	0.05	3	0	18
274aL	Catastrophic failure			–	–	–
275L	16	0.013	0.08	9	1	6
276L	21	0.008	0.06	11	2	8
277L	21	-0.156	0.02	0	0	21
278L	21	-0.030	0.05	3	2	16

Table 37. Summary of comparisons with thermistor chain measurements made with vessel hove to and drifting.

147 and 152 m. Figure 33 is a comparison of the two data sets. The "dots" are the 44 thermistor chain measurements superimposed on the XBT profile. If the XBT profile is displaced in depth by +50 m, the two sets of measurements are in good agreement. This suggests that the reason for this disagreement is that the recorder was not turned on until the probe was at a depth of 50 m. The poor agreement between XBT and thermistor chain temperatures is the result of operator error. This set of comparisons is not included in the discussion to follow.

The results of the comparisons of the remaining 63 profiles are summarized visually in appendix E. One figure is presented for each acoustic run. The left portion of each figure is a plot of the thermistor chain measurements. The symbol (x) is the average, and the length of the bar is two standard deviations of the number of scans shown in the upper left-hand corner. The "dots" in the right-hand figure are the differences between the XBT and the thermistor chain measurements for each thermistor chain depth and for each XBT profile made during the indicated run and in the indicated water mass or sound-speed profile

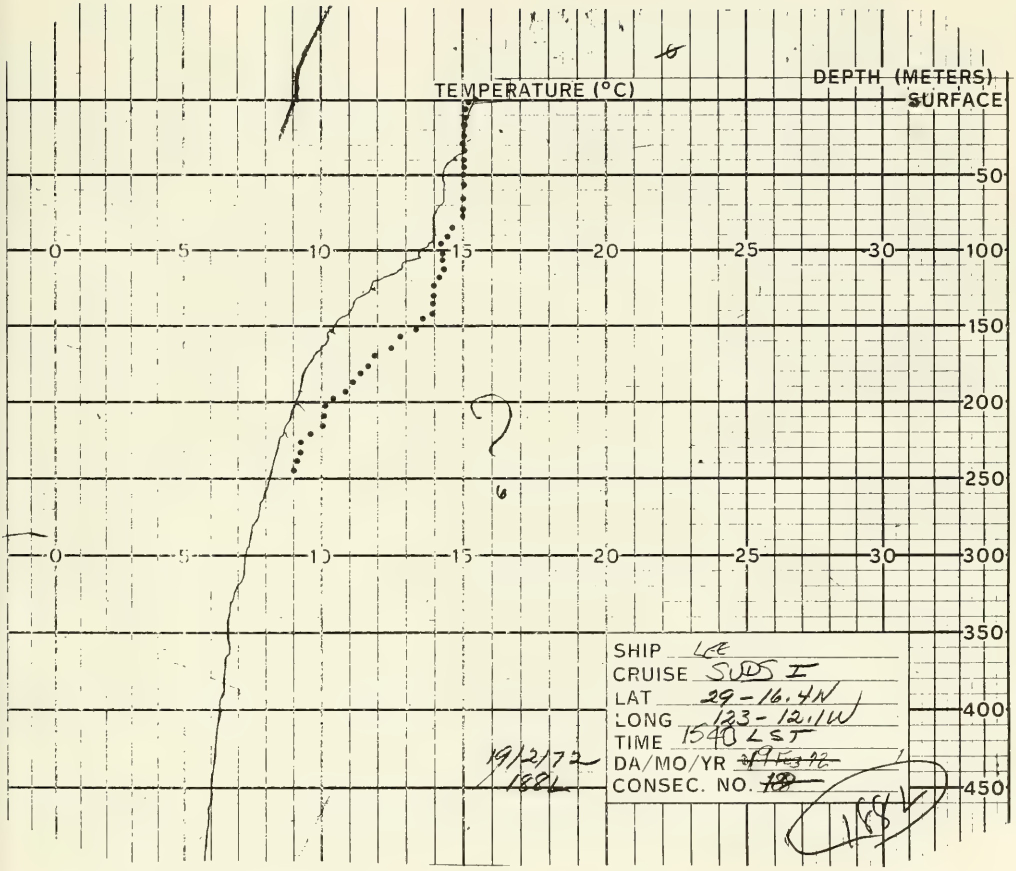

Figure 33. Temperature profiles for SUDS I XBT 188L and simultaneous thermistor chain profile.

volume. The number of XBT profiles plotted on each figure is indicated in the upper left of the right-hand figure.. The symbol (x) indicates the average value at each depth. Also shown in each plot are the wind conditions present during the run. An inspection of these figures shows that the distribution of the differences for station 4, runs 3 and 4, is quite different from the distribution of the differences for the other data sets. For station 4, run 3, the differences are nearly all positive, with all average differences being positive. In addition at all depths the largest positive differences, shown by the circled "dots," are associated with XBT 266L. The station 4, run 4, data set also contains one anomalous profile. The largest positive differences for depths greater than 40 m are all associated with XBT 269L. The differences for this XBT are also shown by the circled "dots." XBT 266L and 269L are shown in figures 34 and 35. An examination of these profiles provides little reason to consider them to be inaccurate. However, comparison with the thermistor chain data clearly shows them to be in error. The two profiles will not be included in the following analysis. Thus, of the original 64 visually acceptable profiles, 61 remain for further consideration.

Figure 36 is a composite plot of the differences for the remaining 61 XBT profiles. The "dots" are the individual differences, and the average difference for each depth is shown by the symbol (x). An inspection of the average thermistor chain plots in appendix E shows that the depth of the top of the thermocline, or the bottom of the near-surface mixed layer, is about 90 m. Note that all the above-thermocline average differences, except the surface difference, are positive, while all below-thermocline average differences are negative. Recall that the thermistor chain depth sensor was inoperative during these measurements, so that no independent thermistor chain sensor depths were measured. From indirect evidence based on average thermistor chain and hydrocast, and on STD/SV temperature measurements, it was previously concluded that the chain was vertical in the water during the 3-knot propagation loss runs, with the deepest temperature sensor at 242 m. Perhaps the bias in the below-thermocline differences may be attributed to the lack of validity of this conclusion. Since the vertical temperature gradient below the surface layer is not zero, the thermistor chain sensor would record a slightly higher temperature at a slightly shallower depth. Thus there remains a possibility that below-thermocline differences are not real but rather related to the assumption made regarding the depth of the sensors. Only the above thermocline differences are considered in the remainder of this discussion.

Table 38 lists for each depth in the near-surface layer the number of differences, the average difference, the standard deviation, and the number of positive, zero, and negative differences. Also shown are the statistics for all 1037 comparisons. The average of all differences was 0.04°C, standard deviation 0.13°C; 62.8% of the differences were positive, 35.3% negative, and 1.9% zero. Since the vertical temperature gradient associated with this data set is small, the reasoning used to explain the bias in connection with the thermocline differences is not applicable to these comparisons. Thus it is concluded that in this comparison of 61 underway XBT profiles with the thermistor chain, the XBT measures temperatures that are, on the average, slightly higher than the thermistor chain.

Statistics associated with the individual XBT measurements made in the surface to 90-m near-surface layer are tabulated in appendix F. Tabulated for each XBT are the average differences, the standard deviations, and the number of positive and negative differences. Note that some XBT numbers are missing. These profiles were made at times when the thermistor chain was not making measurements. Also shown are the station and

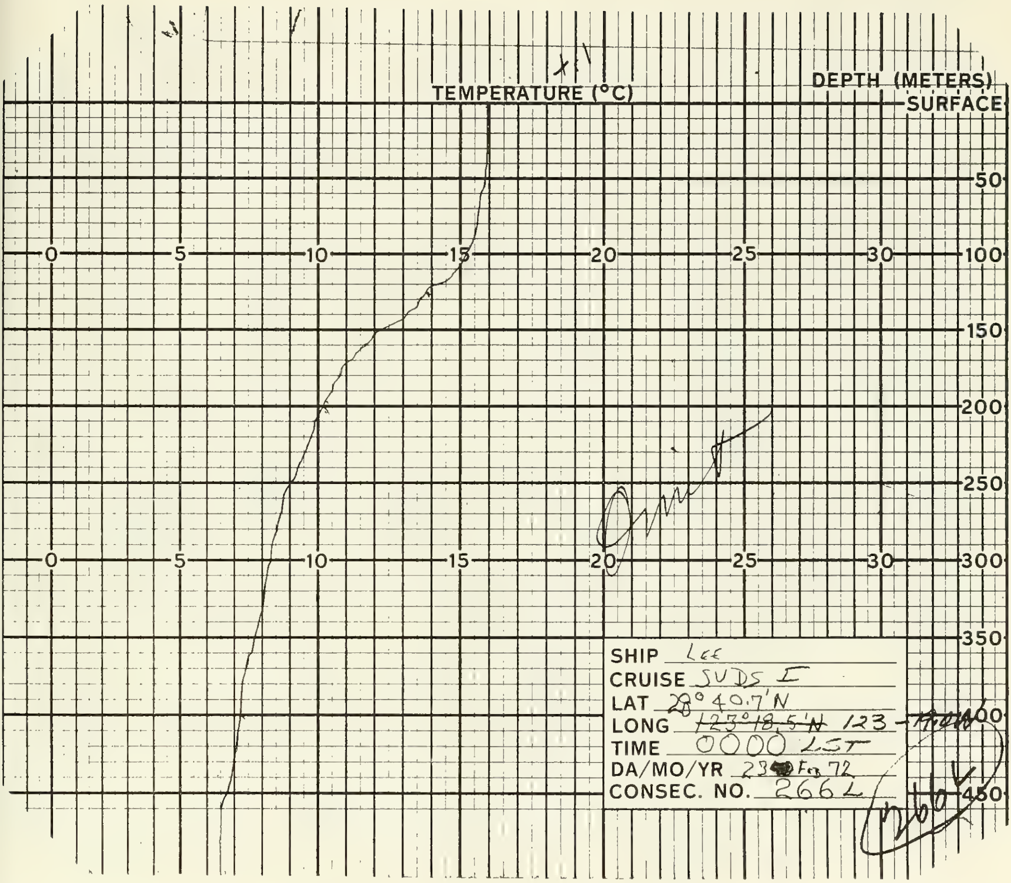

Figure 34. SUDS I XBT profile 266L.

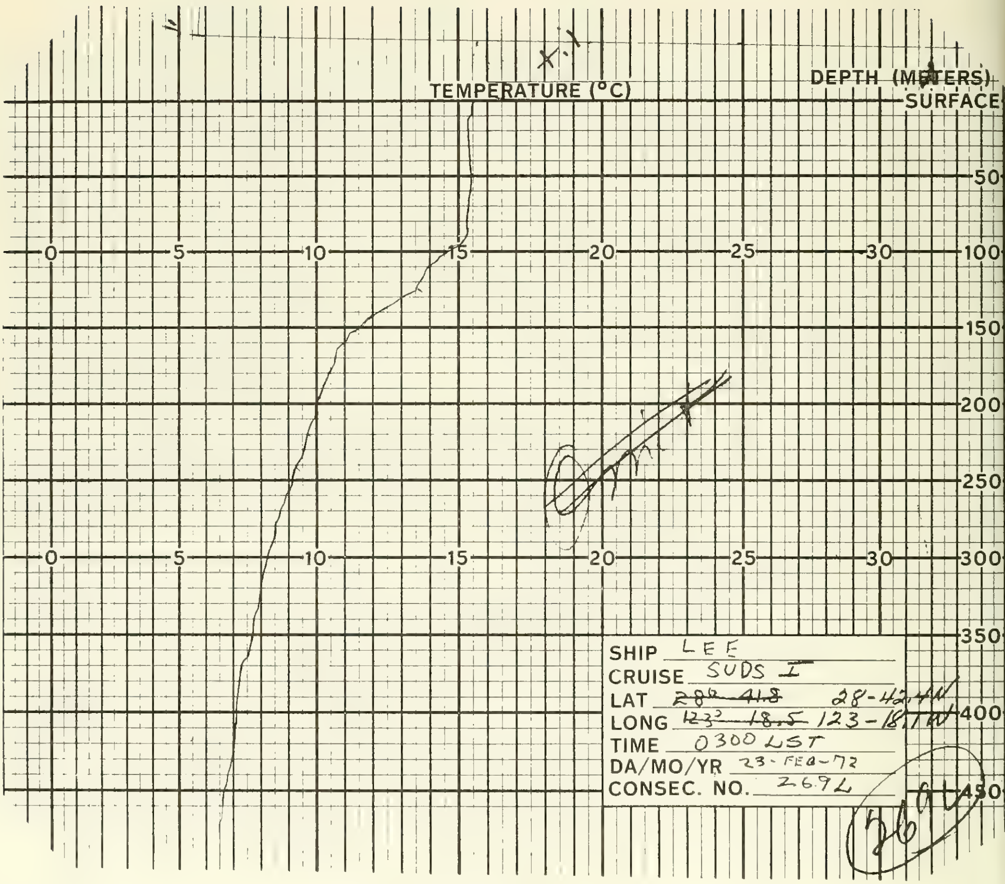

Figure 35. SUDS I XBT profile 269L.

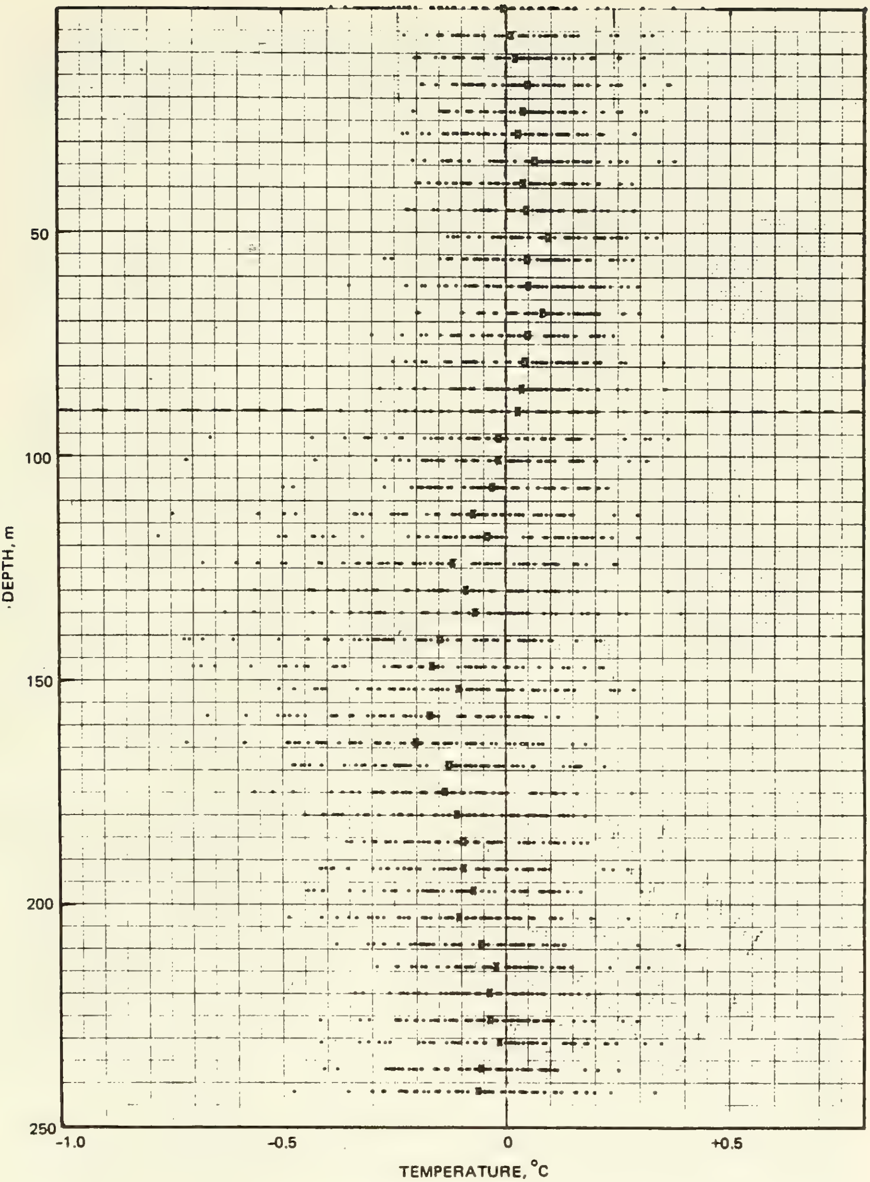

Figure 36. Summary of temperature differences between 61 simultaneous XBT profiles and thermistor chain scans made underway at 3 knots.

Depth, m	Number of Differences	Differences, °C		Number of Differences		
		$\overline{\Delta T}$	s	Positive	Zero	Negative
0	61	-0.01	0.16	30	0	31
6	61	0.01	0.12	30	0	31
11	61	0.02	0.12	33	1	27
17	61	0.04	0.13	39	1	21
23	61	0.03	0.12	39	0	22
28	61	0.02	0.12	37	0	24
34	61	0.06	0.13	41	1	19
39	61	0.04	0.11	40	1	20
45	61	0.04	0.12	40	2	19
51	61	0.09	0.11	47	2	12
56	61	0.04	0.12	39	0	22
62	61	0.05	0.13	42	1	18
68	61	0.08	0.11	45	4	12
73	61	0.05	0.13	41	1	19
79	61	0.04	0.13	40	1	20
85	61	0.03	0.12	35	2	24
90	61	0.02	0.15	33	3	25
All	1037	0.04	0.13	651	20	366
Percentage	100.0			62.8	1.9	35.3

Table 38. Statistical summary for SUDS I underway XBT and thermistor chain differences.

run numbers during which the profiles were made. An important feature of the appendix F data is the lack of randomness in the distribution of differences within a specific profile and in the time when consecutive profiles were made. For example, the average differences are positive for 18 consecutive profiles from 207L to 225L. For eight of the 18 profiles, all 17 differences were positive; for five of the profiles, 16 differences were positive. This set of 18 profiles includes all of the profiles made during station 3, runs 4 and 5, and two of the seven profiles made during station 3, run 3. The average differences for 10 profiles, XBT 245L to 256L, were all negative and for the 10 succeeding profiles, 257L to 268L, were positive. In this latter set, the individual differences for five consecutive profiles were all positive. This series also includes XBT 266L and 269L, which were previously eliminated from this analysis since early comparisons showed them to be erroneous.

The data listed in appendix F are associated with the same profiles plotted in appendix E. In the discussion of the appendix E plots it was noted that the distribution of the differences for station 4, runs 3 and 4, was different from the distribution of differences for the other data sets. It was also noted that two profiles, XBT 266L and 269L, were grossly in error and were not included in the station 4, runs 3 and 4, statistics presented in appendix F. Even with XBT 266L omitted from the station 4, run 3, data set the average difference for the remaining XBT profiles is quite different from all of the other runs. However, the average differences for the station 4, run 4, profiles, after omitting XBT 269L, are similar to the average differences for the XBT profiles taken during the other runs. The conclusion is that the profiles made during station 4, run 3, were measuring temperatures consistently higher than the thermistor chain measurements, with the average individual differences varying from 0.11°C to 0.25°C.

The data sets discussed above are additional examples of "runs" of consecutive probes measuring biased differences, which were previously observed in the discussion of table 37.

It is concluded from this analysis that many of the XBT profiles made by the XBT system used in this study measured temperatures that, on the average, showed good agreement with simultaneous thermistor chain measurements. However, of particular concern are the observed biases resulting from the non-random distribution of the differences both with respect to measurements made by an individual probe and with respect to "runs" of the consecutive probes.

SUMMARY

XBT measured temperatures are compared with average hydrocast and STD/SV measurements, quasisimultaneous (made within 30 minutes of each other) STD/SV measurements, and simultaneous thermistor chain measurements.

Two different XBT data sets were compared with the average hydrocast and STD/SV measurements. The first was the set of 826 visually acceptable profiles that reached a minimum depth of 200 m. The second was the set of 528 visually acceptable profiles that all reached 400 m and also had an independent surface temperature measurement. For the first set, comparisons were made at 200, 300, and 400 m. These depths were selected since, for depths greater than 200 m, vertical temperature gradients are small. For the second set, comparisons were made at the surface and at 200, 300, and 400 m.

The analysis of the first data set showed that in the absence of independent temperature measurements to detect XBT profiles made when an XBT system malfunctioned, the XBT system measures, on the average, temperatures that are higher and vertical temperature gradients that are larger than those measured by the hydrocast and STD/SV systems. Previous analysis of surface temperature accuracy showed that two of the XBT systems used in making the profiles malfunctioned. With the eliminations of these profiles from the data set, a reanalysis of the remaining 559 profiles still supported the above conclusion. Thus, even with the omission of demonstrated erroneous profiles made when an XBT system malfunctioned, there remained enough erroneous profiles to bias systematically the average temperature and the average vertical temperature gradient. In an effort to purge the data set of the biasing profiles, accuracy criteria based on the average hydrocast and STD/SV measurements were defined. Using these criteria, the data set was divided into one subset of 354 profiles that satisfied the criteria and another subset of 205 profiles that did not satisfy the criteria. The differences at all three depths for the data set that satisfied the accuracy criteria were normally distributed with mean near zero and standard deviations of 0.07°C to 0.13°C. Once the biasing profiles are identified and removed from the data set, the remaining profiles accurately measure the temperature. The biasing profiles were detectable only with the aid of independent 200-, 300-, and 400-m temperature measurements.

The results at 200, 300, and 400 m of the analysis of the set of profiles that reached 400 m and also had an independent surface temperature were similar to those obtained in the previous analysis. For the set of 528 visually acceptable profiles, the XBT measured a surface temperature that, on the average, was 0.15°C less than the independently measured surface temperatures. This resulted in an average positive temperature gradient bias in the surface-to-200-m layer. Analysis of the 351 profiles remaining after the elimination of the profiles made with the two malfunctioning XBT systems showed that at the surface, the XBT profiles measured a temperature slightly higher than the independently measured temperature; that at 200, 300, and 400 m, the XBT profile still measured temperatures slightly higher than the average hydrocast and STD/SV measurements; and that the vertical temperature gradient from the surface to 200 m was slightly biased.

Quasisimultaneous XBT and STD/SV profiles were obtained during the Gulf of Alaska, SUDS I, CAPER, and RAPLOC/DEEPTOW experiments. A total of 66 pairs was obtained. These measurements were used to further examine the accuracy of the XBT measurements at the surface and at 200, 300, and 400 m. All measurements were made with the vessel hove to and drifting or, in the case of the RAPLOC/DEEPTOW measurements, at anchor. Of the 66 XBT profiles, 20 were made when the XBT systems malfunctioned during the Gulf of Alaska and CAPER experiments. Recall that the system malfunctions were only detected because independent surface temperatures were available. The statistics for all the differences for each depth were very similar to the results obtained from the two previous analyses. The major difference was that the standard deviations were somewhat larger for this study. The statistics for the differences associated with the profiles made when the systems were not malfunctioning are also similar to the statistics for the two previous studies.

During SUDS I simultaneous XBT and thermistor chain measurements were made with the vessel both hove to and underway at 3 knots. Comparisons were made at 44 depths spaced 5.6 m apart from the surface to 242 m, the maximum depth of thermistor chain measurements. While hove to and drifting, eight XBT profiles were attempted. Of the eight, one was a catastrophic failure, one was a partial success, and six were successes. For the seven profiles making measurements in the near-surface layer, the average values for 16 comparisons were negative for five of the profiles and positive for two profiles. One of the latter was the profile that was a partial success, having failed at 90 m. For the six profiles making measurements below the layer, the average values were negative for five profiles and positive for one. It was concluded that the seven probes used in this comparison measured temperatures from the surface to 242 m that were slightly lower than those measured by the thermistor chain. Only two of the six probes showed excellent agreement in the statistical sense. The biasing of the differences may be related to a "run" of consecutive probes.

During the SUDS I stations 3 and 4 experiments, 73 XBT profiles were attempted while the vessel was underway at 3 knots. Of the 73 attempts, 62 were successes, two were partial successes, and nine were catastrophic failures. Comparisons, at the 44 thermistor chain sensor depths, of the 64 successful and partially successful profiles with single thermistor chain temperature scans starting at the same time the XBT probe was released, showed that three profiles were grossly in error and these were eliminated from the data set. Further analysis of the remaining 61 profiles suggested that in the thermocline, below the near-surface layer, the thermistor chain was measuring temperatures slightly higher than the XBT measurements. This possibly resulted from a slight shoaling of the thermistor sensors as a result of the 3-knot towing speed. Since the thermistor chain depth sensor was inoperative, it was not possible to check this conclusion. Comparisons of the

XBT measurements with the thermistor chain measurements at the 17 sensor depths in the near-surface layer where vertical temperature gradients were small showed that the 61 XBT profiles measured temperatures slightly higher than the thermistor chain. The average of 1037 comparisons was 0.04°C, with a standard deviation of 0.13°C; 62.8% of the differences were positive, 35.3% negative, and 1.9% zero. These results are consistent with those obtained from the hydrocast and STD/SV, as well as the quasisimultaneous STD/SV comparisons. In addition, a serial tabulation of the average differences, standard deviations, and the number of positive and negative differences for each of the 61 XBT profiles, showed temperature measurement biases both with respect to measurements made by individual XBT probes and with respect to "runs" of consecutive probes.

DISCUSSION OF PROFILES WITH LARGE DIFFERENCES

The analyses presented in the previous section were concerned primarily with average temperature differences. The results suggested that, on the average, the XBT system measured temperatures in the surface-to-400-m depth interval that were slightly higher and vertical temperature gradients that were slightly larger than those measured by hydrocast, STD/SV, and thermistor chain systems. In many applications, however, the concern is not with average values but rather with the use and interpretation of individual, or a short series of individual, profiles. This section discusses these biases with respect to individual profiles.

For the set of 559 profiles containing no profiles made with malfunctioning systems (profile set I) and reaching a minimum depth of 200 m, the 200-, 300-, and 400-m temperatures for 54 (9.7%) of the profiles exceeded the average hydrocast and STD/SV temperatures by more than or equal to ±0.50°C at one or more of the three depths.* These XBT profiles are listed in appendix G. Also listed are the 200-, 300-, and 400-m differences in °C and the 200–300-m and 300–400-m linear temperature gradient biases in °C/100 m. An examination of the data presented in appendix G shows that of the eight 460-m XBT systems used to make the 559 profiles, seven measured 200-, 300-, or 400-m temperatures that exceeded the average hydrocast and STD/SV temperatures by more than or equal to ±0.50°C at one or more of the three depths. Of the 51 profiles extending to 400 m, the differences for 41 (80.4%) profiles were positive at all three depths; for only five (9.8%) profiles they were all negative; and for the remaining five (9.8%) profiles they were mixed in sign. The XBT profiles measured, over the 200- to 400-m depth interval, a positive gradient bias for 15 profiles and a negative gradient bias for 18 profiles.

At 200 m, 46 (85.2%) of the differences were positive and eight (14.8%) were negative. The comparable numbers at 300 m are 47 (88.7%) and six (11.3%); at 400 m, the comparable numbers are 44 (86.3%) and seven (13.7%). In addition, more of the larger differences are positive. For example, at 400 m, three differences are greater than 1.00°C, with the largest difference being 3.02°C, while the largest negative difference was –0.37°C. For the 200–300-m depth interval, 21 (39.6%) of the temperature gradient biases were positive, 30 (56.6%) negative, and two were zero with more of the larger gradient biases being positive. For the 300–400-m depth interval, 26 (51.0%) of the temperature gradient

*The use of a difference of ±0.50°C is arbitrary. The intent was to select a subset of profiles that measured temperatures obviously different from the average hydrocast and STD/SV temperatures.

biases are positive and 25 (49.0%) negative. Again, for this layer, more of the larger gradient biases are positive.

Table 39 lists the largest positive and negative temperature differences and the XBT profile which measured these differences, and table 40 lists similar information for the temperature gradient biases. The largest 200-, 300-, and 400-m positive temperature differences were all measured, at anchor from the ORB, by XBT 55A during RAPLOC/DEEPTOW. The largest 200-m negative differences were measured by XBT 66A during RAPLOC/DEEPTOW, and the largest 300- and 400-m negative differences were measured by XBT 188L during SUDS I. The largest 200–300-m positive temperature gradient bias was measured by XBT 81D taken during CAPER, and the largest positive 300–400-m bias was measured by XBT 55A taken during RAPLOC/DEEPTOW. Note that XBT 55A was made during RAPLOC/DEEPTOW from the ORB at anchor. The largest negative gradient bias in the 200–300-m depth interval was measured during SUDS I by XBT 128D, and the largest negative 300–400-m bias by XBT 134D also during SUDS I and by XBT 44B during RAPLOC/DEEPTOW. Facsimiles of the XBT profiles listed in tables 39 and 40, as well as facsimiles of the XBT profiles measuring the second largest positive and negative differences at each depth, are included in appendix G. An inspection of these profiles suggests that in the absence of other information, such as average hydrocast and STD/SV temperature measurements, these profiles are all visually acceptable. There is little reason to suspect that they contain errors as large as this analysis suggests.

Depth, m	Largest Positive		Largest Negative	
	XBT Number	Difference, °C	XBT Number	Difference, °C
200	R/D 55A	2.01	R/D 66A	-0.73
300	R/D 55A	2.33	SUDS 188L	-0.66
400	R/D 55A	3.02	SUDS 188L	-0.37

Table 39. Tabulation of largest positive and negative temperature differences.

Depth, m	Largest Positive		Largest Negative	
	XBT Number	Bias, °C/100 m	XBT Number	Bias, °C/100 m
2-300	CAPER 81D	0.96	SUDS 128D	-0.73
3-400	R/D 55A	0.69	SUDS 134D	-0.33
			R/D 44B	-0.33

Table 40. Tabulation of largest positive and negative temperature gradient biases.

Of special interest is figure 37, which combines facsimiles of the RAPLOC/DEEPTOW XBT profiles 55A and 54A on a common XBT chart. XBT 55A is the profile, listed in tables 39 and 40, with the largest positive 300–400-m positive gradient bias. In contrast, XBT 54A, taken 1 hour before XBT 55A, satisfied the accuracy criteria at all three depths. The differences for XBT 54A were 0.11°C at 200 m, -0.05°C at 300 m, and -0.10°C at 400 m. Without the additional information provided by the hydrocast and STD/SV

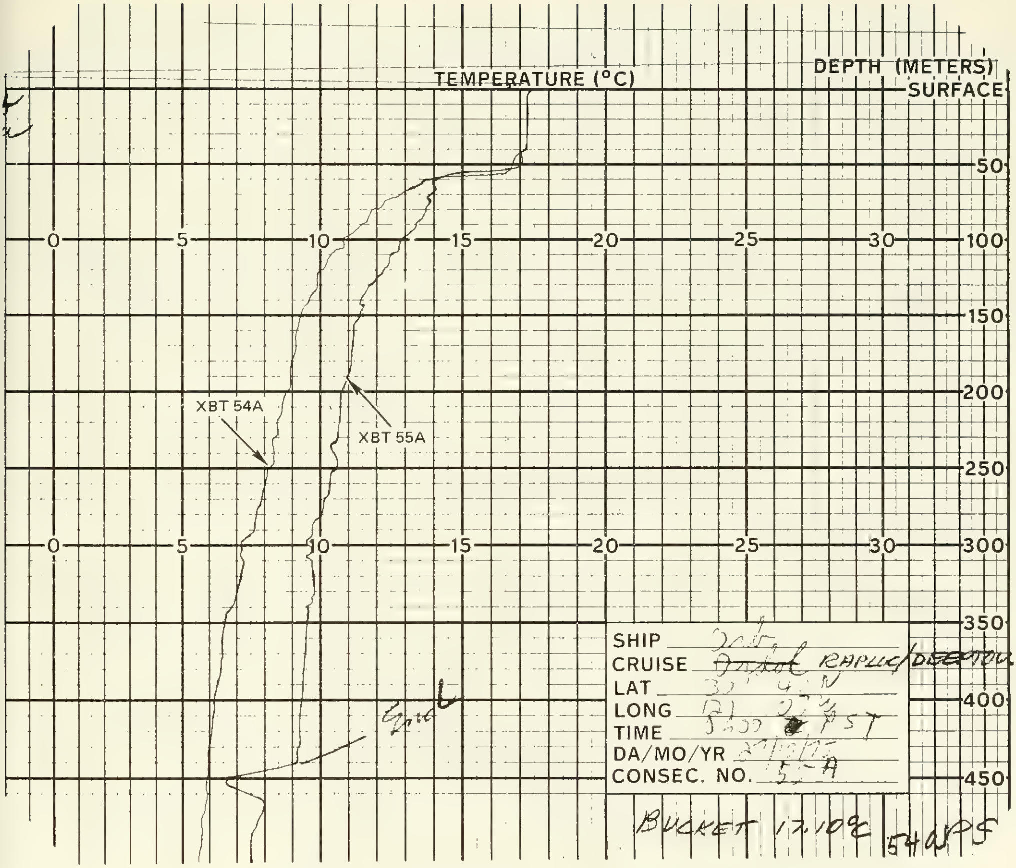

Figure 37. RAPLOC/DEEPTOW XBT profiles 54A and 55A.

measurements, there would be no reason to consider the XBT 55A profile incorrect at depths less than 440 m. Of special interest to underwater acoustics is the vertical temperature gradient biasing nature of the differences, with the differences increasing with increasing depth from about 60 to 440 m.

In summary, a set of profiles (from profile set I) that reached a minimum depth of 200 m and whose temperatures exceeded the average hydrocast and STD/SV temperatures by equal to or more than ±0.50°C at 200, 300, or 400 m, was compiled. This set contained 54 profiles, which was 9.7% of the total set of 559 profiles used in this analysis. An examination of these data showed positive differences as large as 3.02°C, negative differences as large as -0.73°C, positive temperature gradient biases as large as 0.96°C/100 m, and negative temperature gradient biases as large as -0.73°C/100 m.

TEMPERATURE ACCURACY OF 1830-m SYSTEMS

During the CAPER and RAPLOC/DEEPTOW experiments, a limited number of XBT profiles was obtained with two different 1830-m XBT systems. During RAPLOC/DEEPTOW, 18 profiles were made from the ORB at anchor, and during CAPER, eight profiles were made from the FLIP at anchor in a three-point moor. Although the sample of 26 profiles is small, a discussion of these measurements provides some preliminary information on the performance of the 1830-m system.

During the RAPLOC/DEEPTOW experiments, simultaneous surface temperatures were also measured by a bucket thermometer concurrent with 10 XBT profiles and by the CTD/SV system concurrent with three profiles. These 13 comparisons showed excellent agreement between the XBT surface temperatures and the independently measured temperatures. The average of the 13 differences was 0.005°C, with the differences varying from -0.14°C to +0.12°C.

A visual examination of the RAPLOC/DEEPTOW 1830-m profiles showed that seven (38.9%) profiles were catastrophic failures, three (16.7%) profiles were successes, and seven (38.9%) profiles were partial successes. For one profile, the calibration correction was 1.12°C, greatly exceeding the maximum allowed value of ±0.34°C. Figure 38 is a copy of XBT 14C, one of the successful profiles; ie, visually acceptable to the maximum depth of 1830 m. The differences between the XBT measured and the average CTD/SV measured temperatures for the three successful profiles are listed in table 41. For all comparisons except XBT 14C at 500 m, the differences were less than ±0.24°C.

The seven XBT profiles classified as catastrophic failures (ie, no usable temperature measurements for depths greater than 50 m) were so classified because of indications that the wiring insulation failed in the first 50 m of the profile. Figure 39 is a copy of XBT 9C, one of the catastrophic failures. At 10 m there is an abrupt increase in temperature, or a "glitch," which suggests that the insulation was beginning to fail. However, at 30 m it appears that the insulation had "healed" and that the probe was recording valid temperatures. As the measurement proceeded, the insulation appeared to fail at 110, 850, 938, and 1635 m, but in each instance seemed to recover and record valid temperatures until the insulation failed completely at 1720 m. The other six catastrophic failures showed similar characteristics. There is a temptation to consider XBT 9C a valid profile over depth intervals between the apparent insulation failures. In fact, XBT 9C was originally classified as a partial success. Table 42 lists the differences for the profiles originally considered partial successes and subsequently reclassified as catastrophic failures on the basis of an

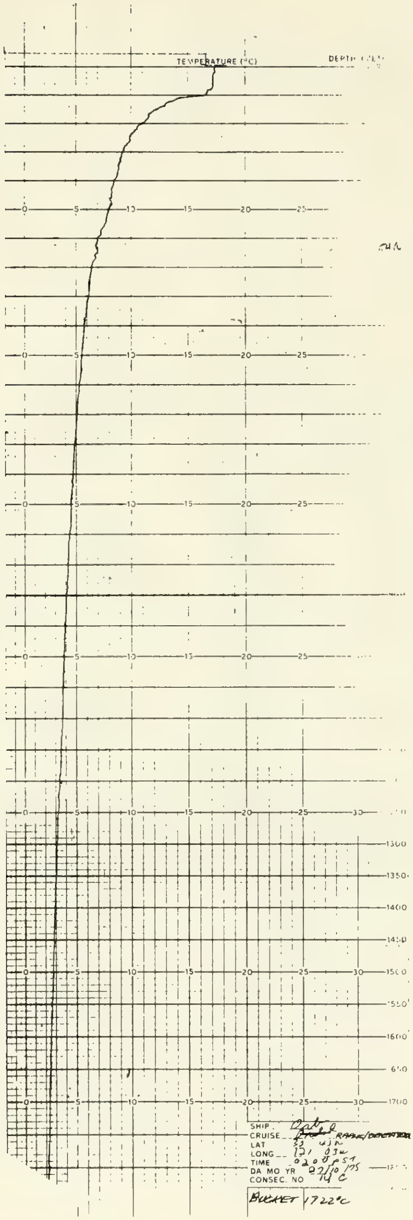

Figure 38. RAPLOC/DEEPTOW 1830-m XBT profile 14C.

Depth, m	Temperature Difference, °C		
	3C	5C	14C
200	-0.06	0.03	-0.22
250	-0.03	-0.11	0.05
300	0.09	-0.03	-0.22
400	-0.07	-0.09	-0.21
500	-0.01	0.07	-0.25
600	-0.06	-0.09	-0.18
800	-0.04	-0.03	-0.17
1000	0.02	0.06	0.01
1200	0.03	-0.01	0.01
1500	-0.11	0.03	-0.14

Table 41. Comparison of successful 1830-m RAPLOC/DEEPTOW XBT profiles with average CTD/SV temperatures.

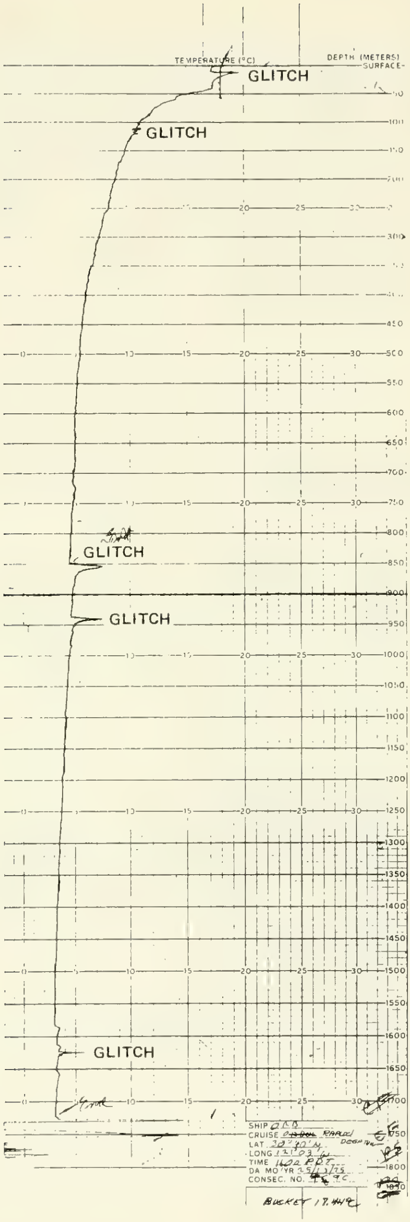

Figure 39. RAPLOC/DEEPTOW 1830-m XBT profile 9C.

Depth, m	Temperature Difference, °C						
	6C	9C	11C	12C	13C	16C	17C
200	-0.25	0.03	0.17	0.13	0.09	-0.31	-0.12
250	0.00	0.21	0.25	0.28	0.28	0.15	0.47
300	0.02	0.01	0.15	0.53	0.30	0.18	0.35
400	-0.07	-0.22	-0.09	-0.13	-0.06	-0.28	0.18
500	-0.06	-0.17	-0.06	-0.21	-0.17	-0.26	0.06
600	-0.09	-0.12	-0.12	-0.22	-0.15	-0.17	0.06
800	-0.11	0.15	–	-0.14	-0.12	–	0.01
1000	–	0.63	–	-0.07	-0.17	–	-0.01
1200	–	0.51	–	0.45	-0.15	–	–
1500	–	0.38	–	0.36	-0.07	–	–

Table 42. Comparison of 1830-m RAPLOC/DEEPTOW XBT profiles classified as catastrophic failures with average CTD/SV temperatures.

indication of insulation failure in the upper 50 m. An inspection of the differences listed in table 42 shows that XBT 9C and XBT 12C measured temperatures at 1200 and 1500 m that were considerably higher than the CTD/SV temperatures. For the remaining five XBT profiles, the differences were within ±0.24°C of the average CTD/SV temperatures for 28 (75.9%) of 37 comparisons. Thus it appears that the accuracy of temperature measurements made at depths greater than the first indication of insulation failure are questionable – sometimes they may be accurate and sometimes they may be inaccurate.

Of the seven profiles finally classified as partial successes, all had one or more "glitches" at depths greater than 50 m and less than 1830 m. Figure 40, a copy of XBT 19C, is an example of such a profile. Small "glitches" are observed at depths of 90, 560, 610, and 1010 m. In spite of the indications of insulation failure, the profile appears to record acceptable temperatures to the maximum depth. Profile 19C was finally classified as a partial success since the recorded temperatures are suspect for depths greater than 90 m, the depth of the first indication of insulation failure. Table 43 lists, for depths greater than 200 m, the differences for the profiles finally classified as partial successes. Also shown for each profile is the depth of the first "glitch".

Thus, for this set of measurements, it is concluded that the use of measurements made by probes exhibiting an apparent temporary insulation failure depends upon the importance of the measurement in a particular application. However, if the measurements are used for depths greater than the first indication of insulation failure, the accuracy of the measurements should be suspect.

Since no independent temperature measurements were made concurrent with the FLIP XBT measurements, an analysis of their accuracy is not possible. Of the eight profiles made by the FLIP, one was classified as a catastrophic failure since it recorded a "glitch" at 29 m. The remaining seven were classified as successes since they were visually acceptable to the maximum depth of 1830 m. An intercomparison of these seven profiles showed that XBT 2F recorded temperatures for depths greater than 250 m were consistently lower

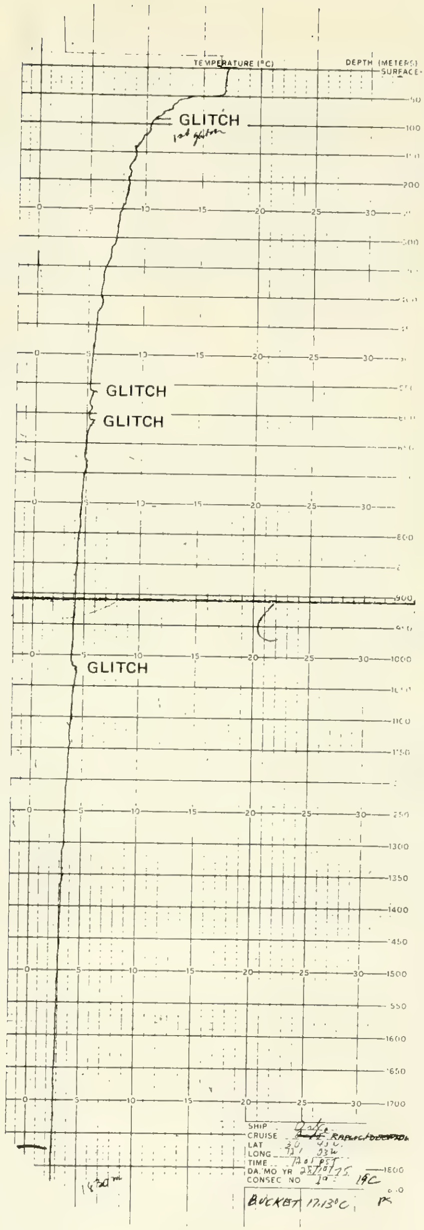

Figure 40. RAPLOC/DEEPTOW 1830-m XBT profile 19C.

Depth, m	Temperature Difference, °C						
	4C	7C	8C	10C	15C	18C	19C
200	0.37	–	-0.06	–	-0.07	-0.13	–
250	0.14	–	0.03	–	0.07	0.20	–
300	0.30	–	0.17	–	0.14	0.25	–
400	0.08	–	-0.13	–	-0.11	-0.11	–
500	0.01	–	-0.06	–	-0.27	–	–
600	0.05	–	–	–	-0.31	–	–
800	0.03	–	–	–	-0.23	–	–
1000	–	–	–	–	-0.22	–	–
1200	–	–	–	–	-0.15	–	–
1500	–	–	–	–	–	–	–
Depth of first "glitch," m	872	105	588	55	1400	436	90

Table 43. Comparison of 1830-m RAPLOC/DEEPTOW XBT profiles classified as partial successes with average CTD/SV temperatures.

than the other six profiles and XBT 4F recorded temperatures consistently higher than the other profiles over the depth interval from 400 to 800 m. These seven profiles were made at widely spaced time intervals over a 10-day period. Since this area is known to contain warm and cold water masses, or eddies, such variations in temperature are not unexpected. Thus, on the basis of information available, there is no reason to question the validity of seven of the eight profiles.*

In summary, of a total of 26 1830-m XBT profiles, 10 (38.5%) were classified as successes; eight (30.8%) as catastrophic failures; seven (26.9%) as partial successes; and one exceeded the calibration correction of ±0.34°C. In spite of apparent temporary insulation failure, most of the profiles finally classified as catastrophic failures and partial successes appeared to record valid temperatures at depths greater than the first indication of insulation failure.

*This type of insulation failure, an abrupt increase in temperature over a small depth interval followed by an apparent "healing" of the insulation failure and a return to recording what appears to be a correct temperature, was first identified during the analysis of the 1830-m profiles. A visual re-examination of the 460-m set I profiles showed that this type of insulation failure also occurred when the 460-m probes were used. The re-examination showed indications of this type of failure in 6.9% (101 out of 1458) of the 460-m set I profiles. In comparison, 15 out of 18 RAPLOC/DEEPTOW 1830-m profiles and one out of eight CAPER profiles showed this type of insulation failure, which suggests that this type of failure is more likely to occur when 1830-m probes are used than when 460-m probes are used.

COMPARISON OF SIMULTANEOUS XBT MEASUREMENTS

From 10–18 December 1972, simultaneous XBT measurements were made during the ORB-3 experiments, in which two independent 460-m XBT systems were used. The probe launchers were located about 30 feet apart. Another set of simultaneous XBT measurements was obtained from 17–28 October 1975 during the RAPLOC/DEEPTOW experiments. Two 460-m and one 1830-m XBT system were used to make these measurements. The two 460-m launchers were located about 5 feet apart, with the 1830-m launcher located about 45 feet from the 460-m launchers. For both data sets, probes were launched just a few seconds apart – the time it took for the observer to walk from one launcher to the other(s).

SIMULTANEOUS 460-m XBT PROFILES

During the ORB-3 experiments, a total of 49 pairs of 460-m XBT profiles were attempted from the ORB – 20 in transit to the experimental area at 5 knots and 29 at anchor during the experiments. The number of visually acceptable pairs (both profiles extending to depths greater than 50 m) was 45 – 18 under tow and 27 at anchor. During the RAPLOC/DEEPTOW experiments, a total of 47 pairs of 460-m profiles were attempted. The number of visually acceptable pairs was 45. All profiles were made from the ORB at anchor.

In this study, temperature comparisons will be made at standard hydrocast depths from the surface to 400 m. The depths of the near-surface layer, or top of the thermocline, also will be compared. Temperature differences between two profiles are dependently related to differences in measuring temperature and depth. In the near-surface layer, or above the thermocline where vertical temperature gradients are small or non-existent, the differences are due almost solely to the accuracy of the measured temperature. In the thermocline, where vertical temperature gradients are large, the temperature differences result primarily from errors in measuring depth. Below the thermocline, where vertical temperature gradients are smaller than in the thermocline and larger than in the near-surface layer, temperature differences are the result of errors in measuring both temperature and depth.

The temperature and layer depth differences (arbitrarily system A minus system B) for the ORB-3 under-tow and at-anchor measurements and for the RAPLOC/DEEPTOW measurements are tabulated in appendix H. From the surface to the horizontal line, the differences are below the thermocline; and for all differences between the horizontal lines, the differences are in the thermocline. An asterisk after the XBT profile pair number indicates pairs which agree to within ±0.34°C for comparisons made above and below the thermocline.*

The data tabulated in appendix H are summarized in figure 41. The left-hand pair are for the ORB-3 measurements, and the right-hand pair are for the RAPLOC/DEEPTOW measurements. The upper portion of each pair is a plot of the differences at each standard

*If the standard deviation of an XBT temperature measurement is ±0.12°C, then the standard deviation of the difference between two simultaneous XBT temperature measurements is $\pm\sqrt{0.12^2 + 0.12^2}$, or ±0.17°C, and two standard deviations is ±0.34°C.

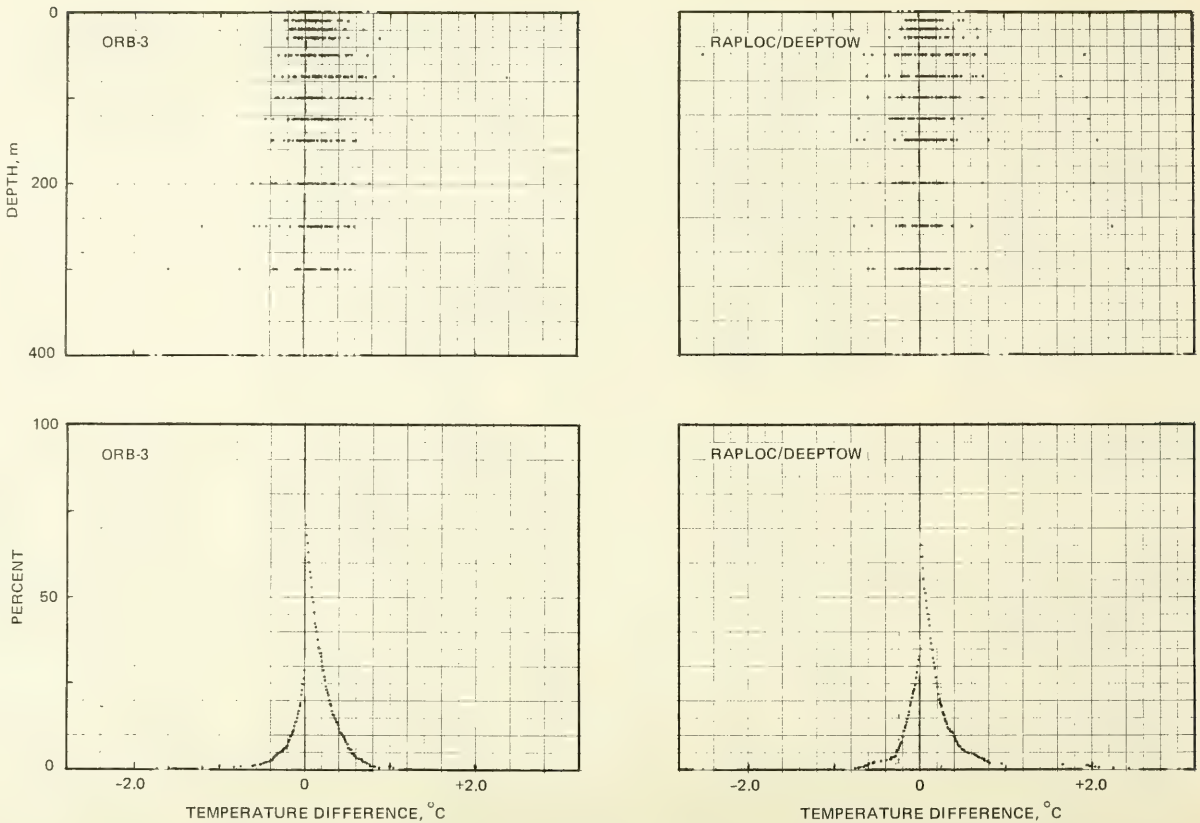

Figure 41. Summary of differences between simultaneous 460-meter XBT profiles.

hydrocast depth, and the lower portion contains ogives of the set of positive and the set of negative differences. By coincidence, more of the differences are positive than negative for both sets of data, since the sign of the difference depends on which system is arbitrarily chosen as the reference.

Table 44 lists pertinent statistics for the above-, in-, and below-thermocline subsets of differences, as well as for the set of all differences. Listed are the number of differences, the average difference and its standard deviation, and the percentage of differences that exceeded ±0.34°C. The most accurate temperature measurements are made above the thermocline, where vertical temperature gradients are small or nonexistent. As shown in table 44, for the 223 ORB-3 measurements made above the thermocline, the average difference was 0.09°C, with a standard deviation of 0.18°C. For the 180 RAPLOC/DEEPTOW measurements, the comparable numbers are 0.08°C and 0.14°C, respectively. In the ORB-3 subset, 71.4% of the differences were positive and 24.7% negative. The comparable percentages for the RAPLOC/DEEPTOW subset were 71.1% and 24.4%, respectively.

	ORB-3	RAPLOC/DEEPTOW
ABOVE THERMOCLINE		
Number of differences	223	180
Average, °C	0.09	0.08
Standard deviation, °C	0.18	0.14
Percent:		
Greater than +0.34°C	7.6	3.9
Less than -0.34°C	<0.1	<0.1
IN THERMOCLINE		
Number of differences	134	179
Average, °C	0.18	0.11
Standard deviation, °C	0.34	0.44
Percent:		
Greater than +0.34°C	25.4	21.2
Less than -0.34°C	3.0	6.1
BELOW THERMOCLINE		
Number of differences	186	214
Average, °C	0.06	0.07
Standard deviation, °C	0.33	0.43
Percent:		
Greater than +0.34°C	15.6	8.4
Less than -0.34°C	9.1	3.7
ALL DIFFERENCES		
Number of differences	543	
Average, °C	0.10	0.08
Standard deviation, °C	0.29	0.37
Percent:		
Greater than +0.34°C	14.7	11.0
Less than -0.34°C	4.1	3.5

Table 44. Comparison of simultaneous XBT profiles taken during the ORB-3 and RAPLOC/DEEPTOW experiments.

Some additional observations, based on the data of appendix H and table 44, are of interest:

1. The ORB-3 differences for 26 (57.8%) of the 45 pairs were less than or equal to ±0.34°C at all above- and below-thermocline depths, and for the RAPLOC/DEEPTOW differences the comparable number was 36 (80.0%) of the 45 pairs. For the combined data set of 90 XBT pairs, 62 (68.9%) of the pairs had differences less than or equal to ±0.34°C at all above- and below-thermocline depths. For the remaining 28 (31.1%) of the pairs, the differences were greater than ±0.34°C at one or more depths.

2. For the combined data set of 90 pairs, the differences were all less than or equal to ±0.34°C in the near-surface layer for 79 (87.8%) of the pairs, in the thermocline for 46 (51.7%) of the pairs, and below thermocline for 61 (71.8%) of the pairs.

3. For the combined data set of 90 pairs, the differences at all comparison depths were less than or equal to ±0.34°C for 43 (47.8%) of the pairs.

4. For the 45 ORB-3 profiles, the layer depth differences were less than ±5 m for 40 (88.9%) of the pairs, and for the 45 RAPLOC/DEEPTOW profiles, the comparable number was 41 (91.1%) of the pairs. For the combined data set of 90 pairs, the near-surface layer depth differences were less than or equal to ±5 m for 81 (90.0%) of the pairs and exceeded ±5 m for nine (10.0%) of the pairs.

Figure 42 is an ogive of the absolute value of the 1116 simultaneous XBT temperature differences measured at standard hydrocast depths from the surface to 400 m during the ORB-3 and RAPLOC/DEEPTOW experiments. The absolute value is used since the signs of the differences are arbitrary. This figure shows the percentage of the 1116 comparisons of simultaneous XBT measurements that exceeded a given difference. For example, 16.6% exceeded 0.34°C.

The preceding discussion was concerned primarily with the statistics of the differences between simultaneous pairs of XBT profiles. The following discussion presents and considers selected specific pairs of profiles, and supports the previous discussion.

An inspection of the ORB-3 data listed in appendix H shows that for XBT pair 47, the differences were greater than 0.34°C at all depths except the surface and 400 m, and for XBT pair 12 they were greater than 0.48°C at all depths except the surface. For these two comparisons, system A recorded a higher temperature than system B. Figure 43 shows superimposed temperature profiles for these two comparisons. Note the large differences in the near-surface layer where the temperature is nearly isothermal. In each case at least one of the profiles must be incorrect.

Average below-thermocline differences were greater than or equal to ±0.50°C for four XBT pairs—XBT pair 46 (-1.05°C), XBT pair 54 (-0.58°C), XBT pair 12 (0.54°C), XBT pair 47 (0.50°C). XBT pairs 46 and 54 are presented in figure 44. These pairs show how near identical agreement from 40 to 160 m for XBT pair 46 and from the surface to 190 m for XBT pair 54. However, for depths greater than 160 m and 190 m, respectively, the differences increase to as much as -1.74°C at 400 m for XBT pair 46 and -0.84°C at 400 m for XBT pair 54. In the figure 44 comparisons, system B measured temperatures higher than system A.

An inspection of the RAPLOC /DEEPTOW comparisons listed in appendix H shows that some of the largest below-thermocline differences are associated with pairs 33 and 38, which are presented in figure 45. Pair 33 shows minor differences in the near-surface

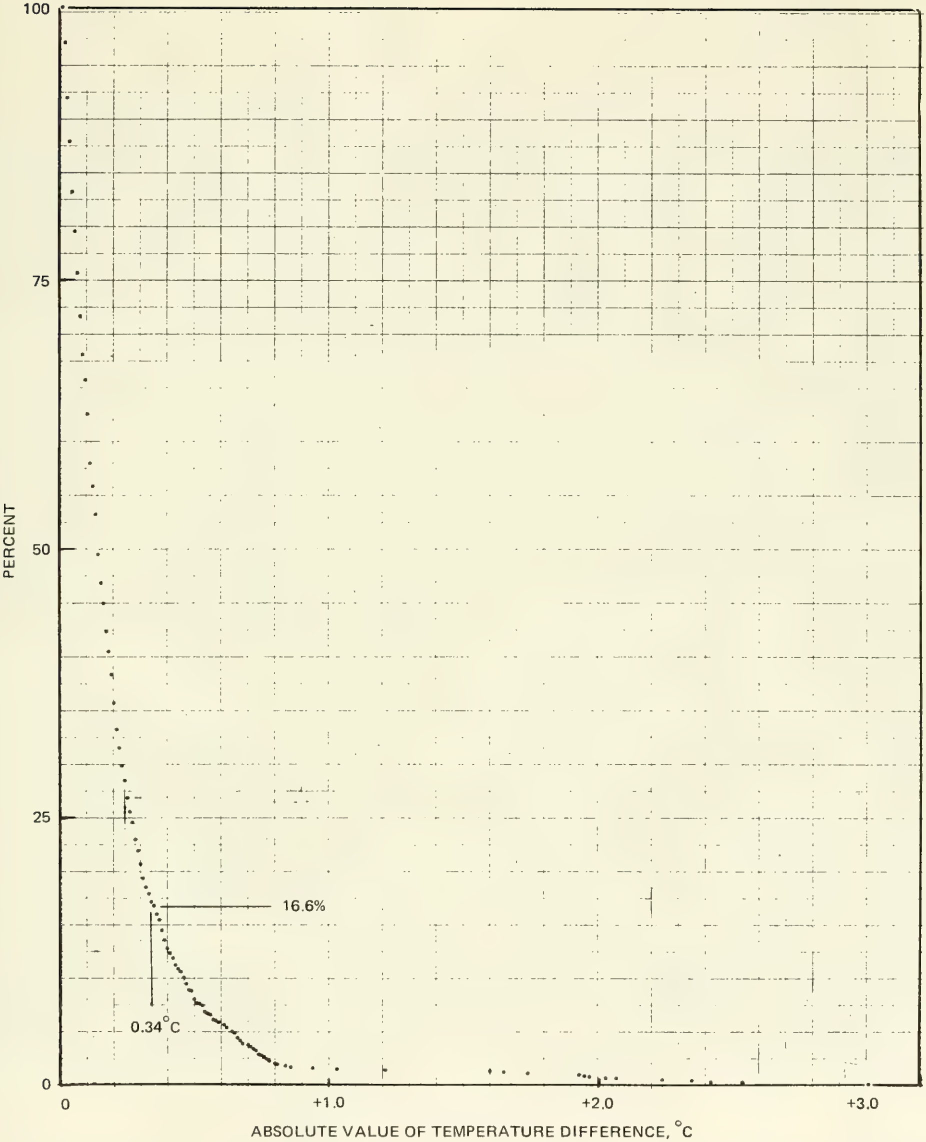

Figure 42. Ogive of the absolute value of 1116 simultaneous XBT temperature differences measured at standard hydrocast depths from the surface to 400 meters during the ORB-3 and RAPLOC/DEEPTOW experiments.

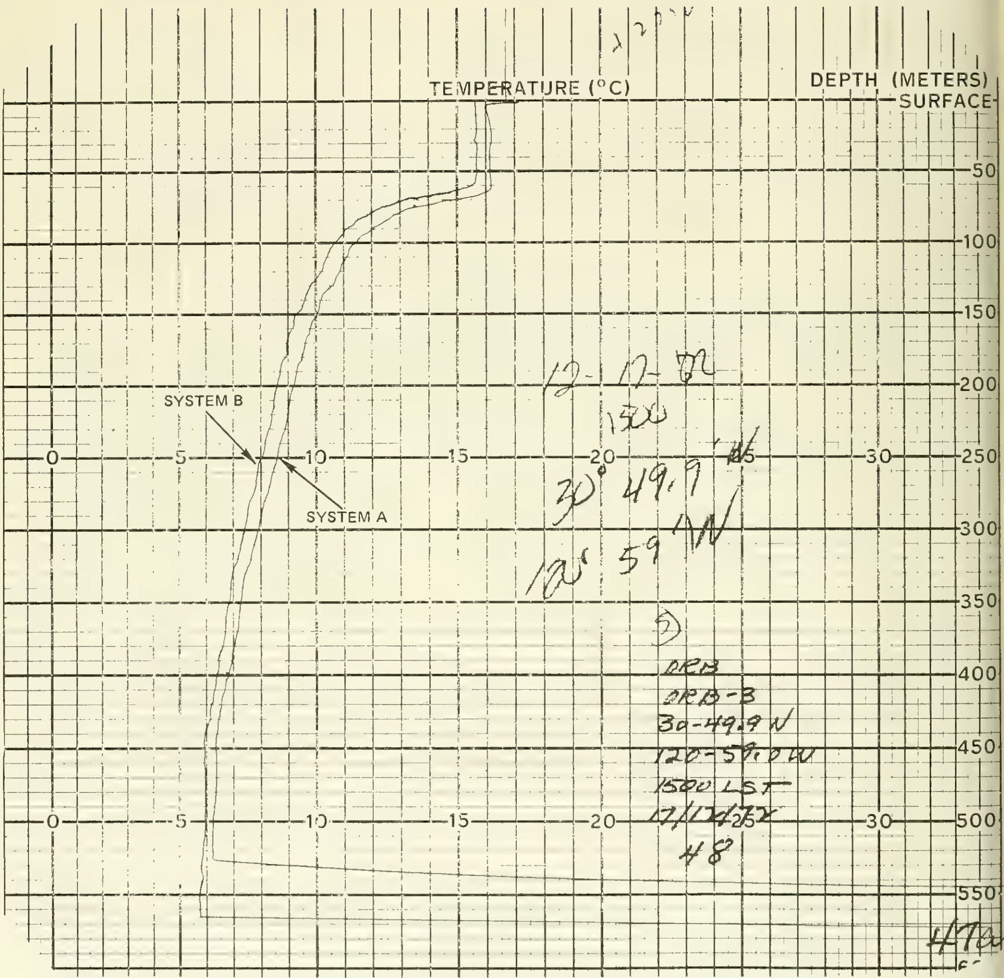

Figure 43a. Temperature profiles for ORB-3 XBT pair 47.

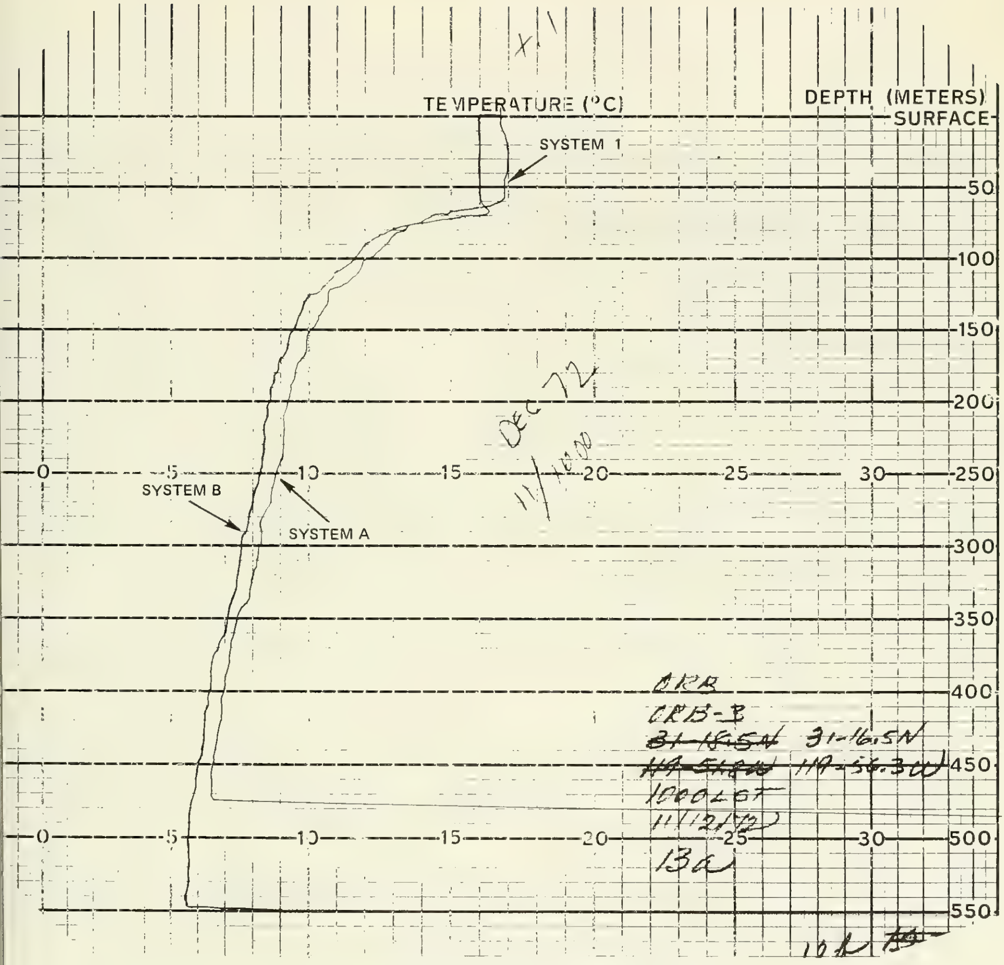

Figure 43b. Temperature profiles for ORB-3 XBT pair 12.

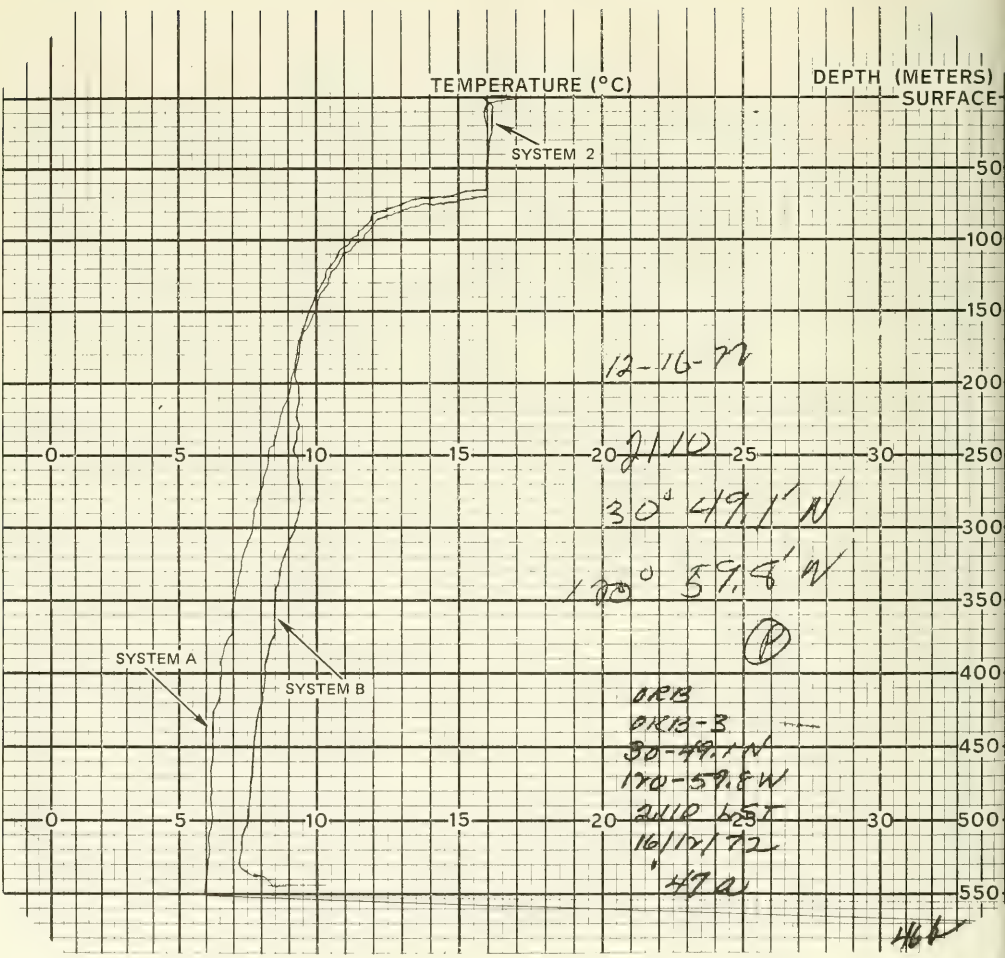

Figure 44a. Temperature profiles for ORB-3 XBT pair 46.

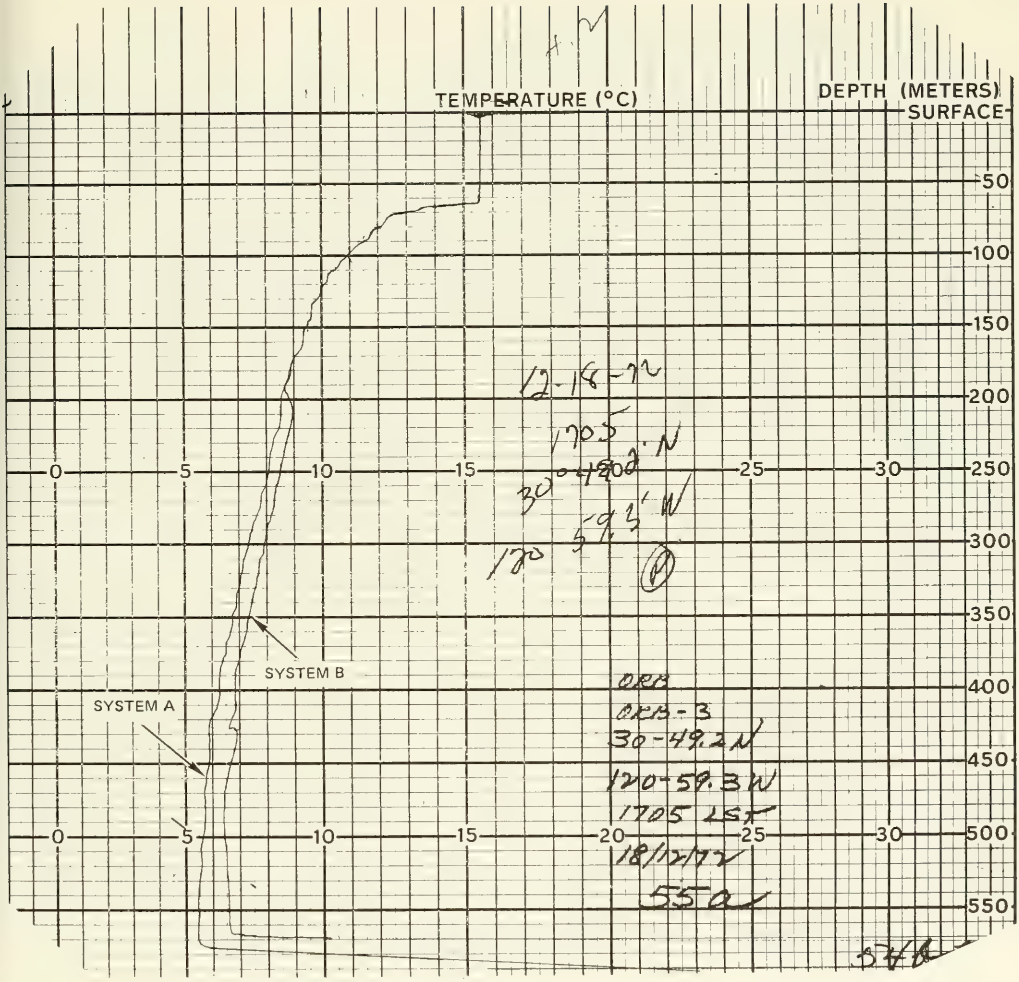

Figure 44b. Temperature profiles for ORB-3 XBT pair 54.

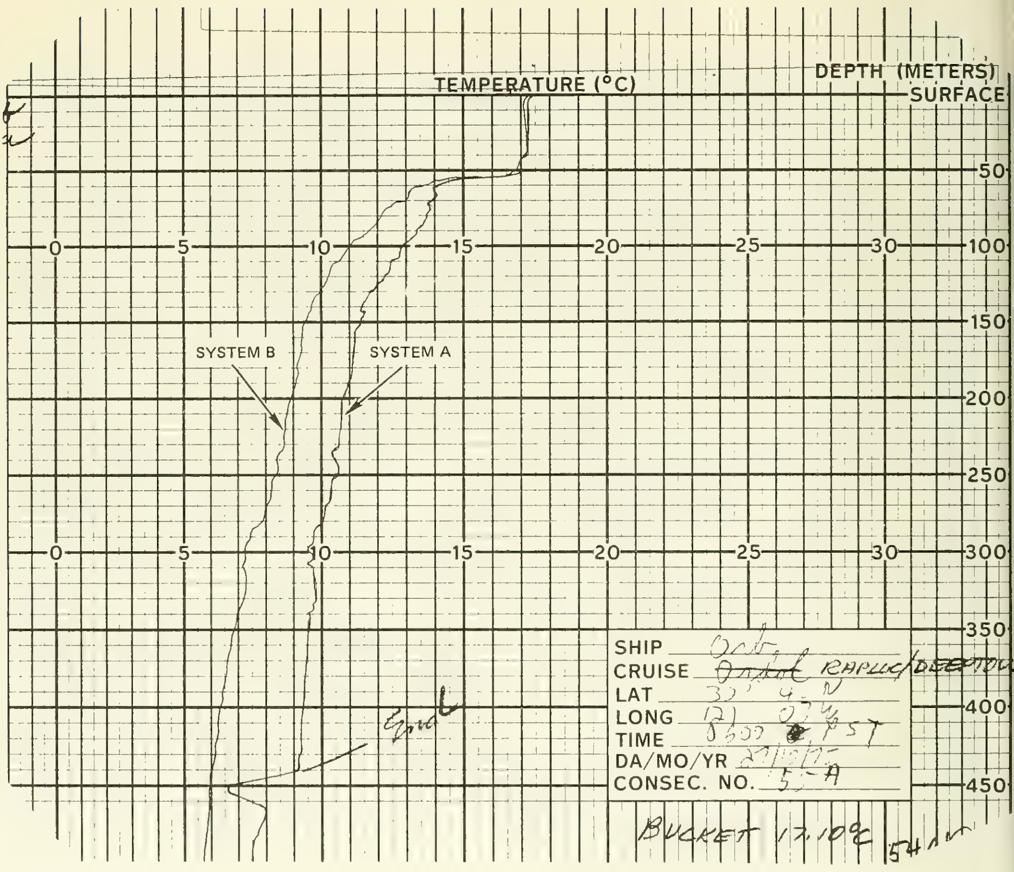

Figure 45a. Temperature profiles for RAPLOC/DEEPTOW XBT pair 33.

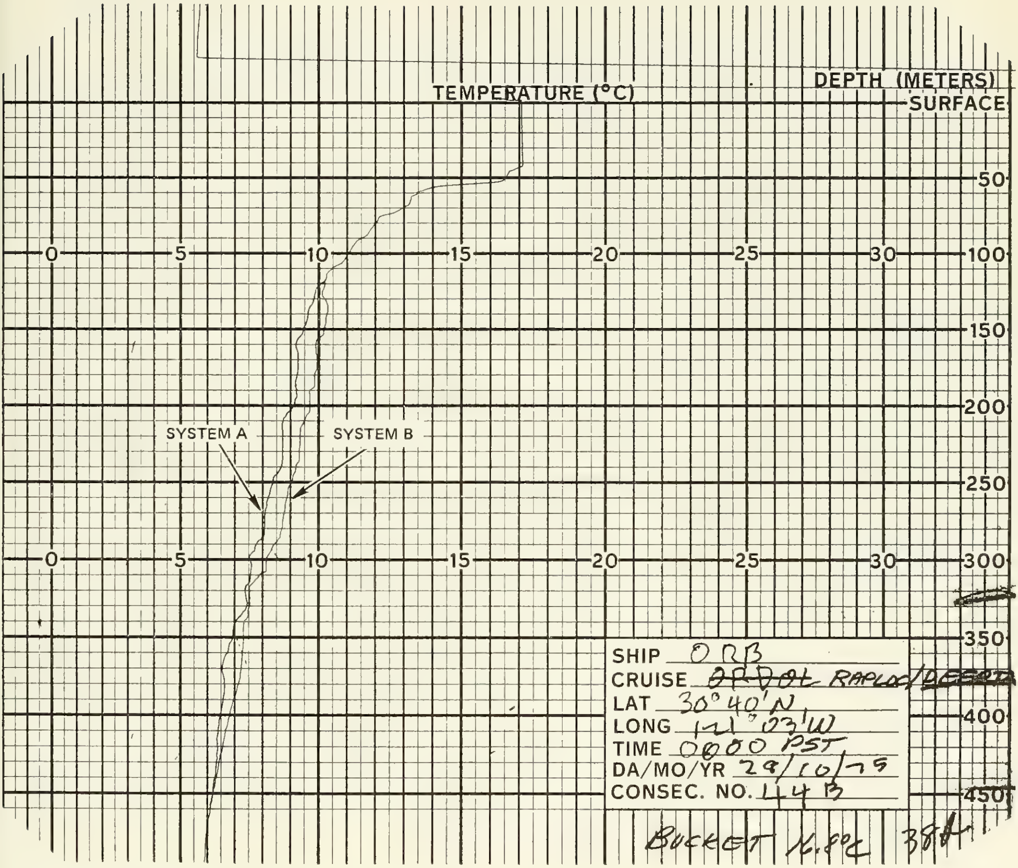

Figure 45b. Temperature profiles for RAPLOC/DEEPTOW XBT pair 38.

layer with identical agreement in the thermocline. However, below the thermocline they begin to differ, with the difference being an increasing function of depth. At 400 m, the difference was 3.01°C. Pair 38 shows identical agreement from the surface to 115 m. At 115 m, the two profiles begin to differ, with the difference being a variable function of depth. Figures 45a and 45b exhibit characteristics similar to those shown by two of the ORB-3 comparisons (figure 44). The major difference is that for XBT pair 38 (figure 45b), the differences do not diverge with depth.

RAPLOC/DEEPTOW XBT pairs 4 and 39 exhibited a marked difference in the above-thermocline comparisons as well as in the below-thermocline comparisons. These two comparisons are shown in figure 46.

Remember, all profile pairs shown in figures 43–46 were simultaneous pairs made by using two independent XBT systems whose launchers, in the case of the ORB-3 measurements, were located 30 feet apart and, in the case of the RAPLOC/DEEPTOW measurements, were located 5 feet apart. All of the measurements except the one presented in figure 43b were made from the ORB at anchor.

Table 45 shows the average temperatures for each XBT system for the 26 ORB-3 and the 36 RAPLOC/DEEPTOW XBT pairs whose differences met the accuracy specification at all comparison depths above and below the thermocline ("starred" comparisons in appendix H). For both data sets, system A, on the average, measured slightly higher temperatures than system B. All average differences, even the in-thermocline differences, are well within the ±0.34°C accuracy specification. It is concluded that when the biasing profiles are detected and removed from a data set, excellent agreement between the remaining profiles is reached.

Note in figures 43–46 that the left-hand profiles, except possible ORB-3 pairs 47 and 54 (figures 43a and 44b), agree better with the average temperatures listed in table 45 than the right-hand profiles. This suggests that, in at least three cases, the right-hand profiles are the incorrect profiles. This is important since the temperature errors introduced into these sets of XBT profiles are systematic, biasing, and nonrandom. The implications are obvious.

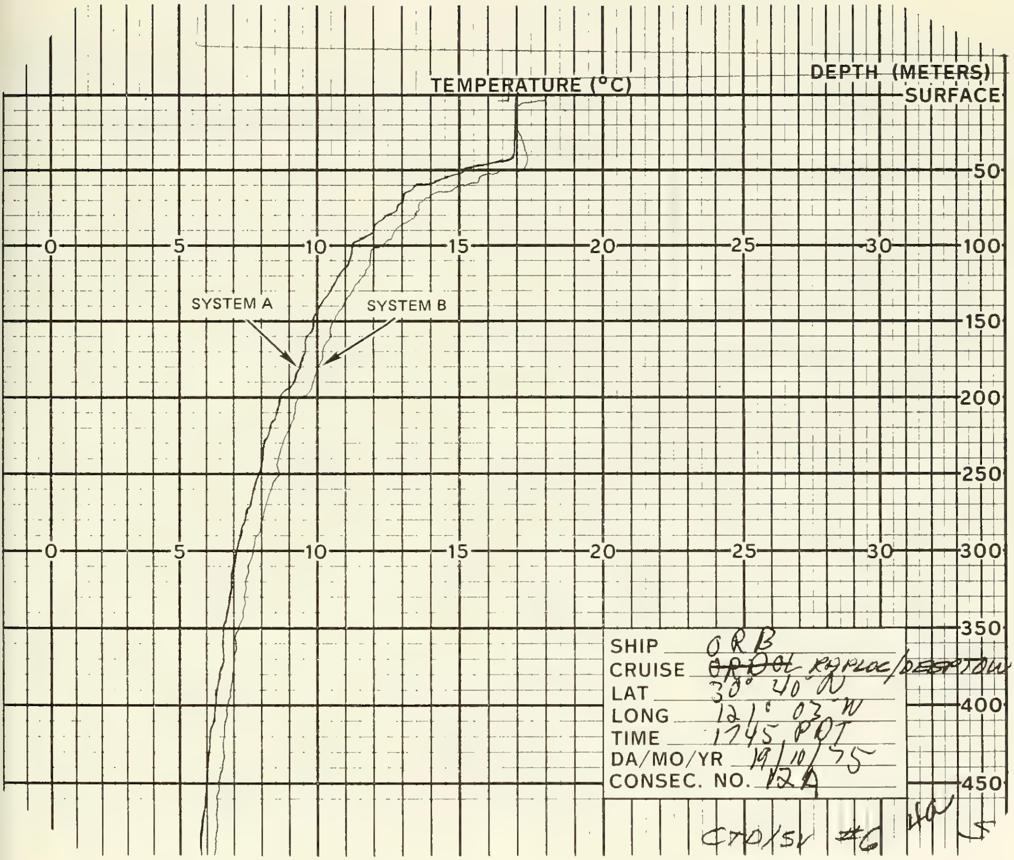

Figure 46a. Temperature profiles for RAPLOC/DEEPTOW XBT pair 4.

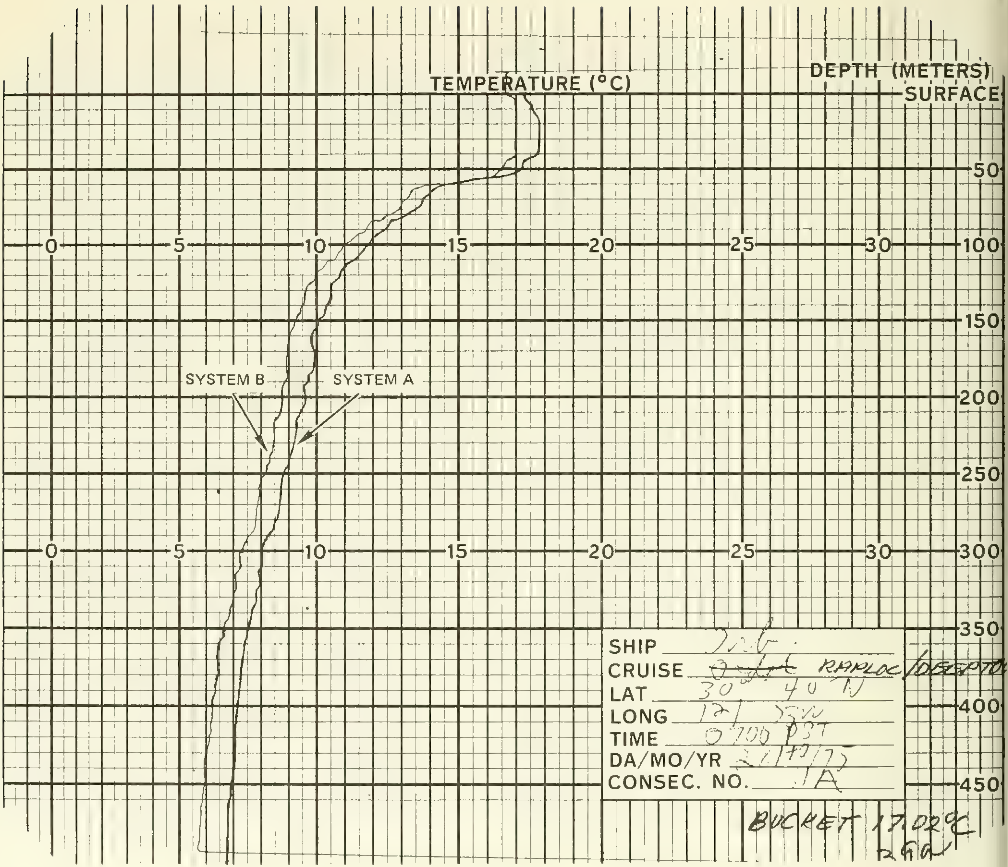

Figure 46b. Temperature profiles for RAPLOC/DEEPTOW XBT pair 39.

Depth, m	Temperature, °C					
	ORB-3			RAPLOC/DEEPTOW		
	System A	System B	Difference	System A	System B	Difference
0	16.16	16.13	0.03	17.10	17.05	0.05
10	16.19	16.13	0.06	17.06	17.01	0.05
20	16.22	16.14	0.08	17.05	16.98	0.07
30	16.23	16.17	0.06	17.01	16.95	0.06
50	16.17	16.15	0.02	15.68	15.68	0.00
75	12.56	12.40	0.16	12.45	12.36	0.09
100	10.99	10.97	0.02	11.08	10.98	0.10
125	10.20	10.15	0.05	10.12	10.11	0.01
150	9.73	9.63	0.10	9.44	9.46	-0.02
200	8.90	8.85	0.05	8.69	8.69	0.00
250	8.23	8.16	0.07	8.04	8.07	-0.03
300	7.58	7.60	-0.02	7.18	7.17	0.01
400	6.43	6.42	0.01	6.12	6.13	-0.01
Layer depth	57	58	-1	38	37	1

Table 45. Comparison of XBT pairs satisfying the accuracy specification for comparisons above and below the thermocline.

SIMULTANEOUS 1830-m AND 460-m XBT PROFILES

During the RAPLOC/DEEPTOW experiments, 1830-m XBT profiles were obtained simultaneously with 460-m profiles taken on two different 460-m systems. This section compares the 1830-m profiles (system C) with the 460-m profiles (systems A and B). During the experiment, 18 sets of simultaneous profiles were attempted. Of the 18 system C profiles, seven failed catastrophically; the calibration correction for one exceeded 0.34°C and therefore was not used. This left 10 system C visually acceptable XBT profiles taken simultaneously with 10 system A and 10 system B profiles. All profiles were made from the ORB at anchor. Comparisons are made at standard hydrocast depths.

The temperature and layer depth differences for system C versus system A and for system C versus system B are presented in tables 46 and 47, respectively. The asterisk after the XBT profile pair number indicates pairs which agreed to within ±0.34°C for all above- and below-thermocline depths. Of a total of 20 comparisons, 15 (75.0%) pairs met the accuracy criteria at all above and below thermocline depths. For 17 pairs, the layer depth differences were less than or equal to ±5 m.

Of a total of 238 comparisons, 143 (60.0%) differences were negative and 88 (37.0%) were positive. This means that system C measured temperatures that were lower than those measured by systems A and B. Table 48 lists pertinent statistics for the above-, in-, and below-thermocline subsets of differences, as well as statistics for the set of all differences.

Depth, m	XBT Profile Pair (System C – System A)				
	1*	2	3*	4*	5*
0	0.01	-0.19	-0.09	-0.14	-0.13
10	0.10	-0.08	0.02	-0.19	-0.18
20	0.04	-0.06	-0.04	-0.24	-0.33
30	-0.06	-0.15	-0.04	-0.29	-0.34
50	0.89	-0.32	-0.02	-0.08	-0.38
75	0.34	0.10	0.13	-0.07	0.04
100	0.02	0.08	0.08	-0.11	-0.27
125	0.06	0.20	0.08	0.00	-0.32
150	0.15	0.28	-0.01	-0.25	-0.27
200	-0.13	0.52	0.04	-0.07	-0.32
250	-0.22	0.19	0.11	0.04	-0.22
300	-0.04	0.24	0.26	0.06	0.00
400	-0.16	0.14	0.11	-0.06	-0.18
Layer depth	3	6	4	2	-2

Depth, m	XBT Profile Pair (System C – System A)				
	6*	7*	8*	9*	10*
0	0.01	0.07	-0.14	-0.24	-0.13
10	-0.03	0.13	-0.13	-0.19	-0.14
20	-0.07	0.03	-0.18	-0.23	-0.15
30	-0.17	-0.01	-0.22	-0.22	-0.26
50	0.07	-0.06	-0.26	-0.13	2.40
75	–	-0.29	-0.26	-0.14	0.31
100	–	-0.18	-0.14	-0.27	-0.23
125	–	-0.06	-0.34	-0.15	-0.16
150	–	-0.10	-0.18	-0.24	-0.12
200	–	0.04	-0.20	-0.15	-0.18
250	–	0.01	-0.12	0.03	0.09
300	–	0.15	0.17	-0.04	0.15
400	–	0.15	-0.03	-0.13	-0.27
Layer depth	2	1	2	1	5

Table 46. Temperature (°C) and layer depth (m) differences between simultaneous 1830-m and 460-m XBT profiles obtained during RAPLOC/DEEPTOW.

Depth, m	XBT Profile Pair (System C – System B)				
	1	2*	3*	4	5*
0	0.03	-0.13	-0.08	-0.15	0.13
10	0.22	-0.18	0.01	-0.29	-0.08
20	0.17	-0.11	-0.05	-0.38	-0.17
30	0.07	-0.21	0.04	-0.46	-0.27
50	-0.08	0.40	0.02	-0.63	-0.22
75	0.52	-0.09	0.09	-0.48	0.00
100	0.26	-0.18	0.11	-0.33	-0.20
125	0.25	-0.07	0.14	-0.29	–
150	0.35	0.00	-0.04	-0.40	–
200	0.09	0.24	-0.06	-0.30	–
250	-0.04	-0.09	0.11	-0.17	–
300	0.26	0.04	0.26	-0.23	–
400	0.13	0.01	0.08	-0.14	–
Layer depth	4	1	0	2	2

Depth, m	XBT Profile Pair (System C – System B)				
	6*	7*	8	9	10*
0	-0.03	0.22	0.03	-0.08	-0.03
10	0.03	0.27	0.00	-0.04	-0.13
20	-0.06	0.13	0.00	-0.14	-0.13
30	-0.21	0.09	0.02	-0.19	-0.29
50	-0.19	0.50	-0.05	-0.44	-0.14
75	–	0.37	0.18	-0.27	-0.05
100	–	0.52	0.12	-0.49	-0.27
125	–	0.00	-0.16	-0.34	-0.23
150	–	0.11	-0.03	-0.40	-0.29
200	–	0.05	0.11	-0.32	-0.24
250	–	0.09	0.02	-0.27	-0.09
300		0.18	0.36	-0.29	-0.04
400	–	0.15	0.10	-0.32	-0.17
Layer depth	2	6	6	2	3

Table 47. Temperature (°C) and layer depth (m) differences between simultaneous 1830-m and 460-m XBT profiles obtained during RAPLOC/DEEPTOW.

	Above Thermocline	In Thermocline	Below Thermocline	All Differences
SYSTEM C versus SYSTEM A				
Number of differences	40	37	45	122
Average difference, °C	-0.12	0.02	-0.02	-0.04
Standard deviation, °C	0.12	0.47	0.18	0.29
Percent:				
Greater than +0.34°C	0.0	5.4	2.2	2.5
Less than -0.34°C	0.0	2.7	0.0	<0.1
SYSTEM C versus SYSTEM B				
Number of differences	40	36	40	116
Average difference, °C	-0.06	-0.05	-0.03	-0.05
Standard deviation, °C	0.16	0.29	0.20	0.22
Percent:				
Greater than +0.34°C	0.0	13.9	5.0	6.0
Less than -0.34°C	5.0	11.1	5.0	6.9
ALL DIFFERENCES				
Number of differences	80	73	85	238
Average difference, °C	-0.09	-0.02	-0.02	-0.04
Standard deviation, °C	0.14	0.39	0.19	0.26
Percent:				
Greater than +0.34°C	0.0	9.6	3.5	4.2
Less than -0.34°C	2.5	6.8	2.4	3.8

Table 48. Comparison of simultaneous 1830-m and 460-m XBT profiles taken during the RAPLOC/DEEPTOW experiments.

For all sets of statistics, except the in-thermocline system C versus system A differences, the average difference was slightly negative. For the set of all 238 differences, the average difference was -0.04°C, with 4.2% of the differences greater than +0.34°C and 3.8% less than -0.34°C. The extreme differences were -0.63°C and 2.40°C. Thus, on the average, the 1830-m system measured temperatures slightly lower than temperatures measured by the two 460-m systems.

Table 49 shows the average temperatures for the 15 XBT pairs whose differences met the accuracy specification of ±0.34°C at all comparison depths above and below the thermocline (designated by asterisk in tables 46 and 47). All average differences, even the in-thermocline differences, are well within the accuracy specification. The agreement between the two sets of profiles is excellent.

Depth, m	Temperature, °C					
	System C	System A	Difference	System C	System B	Difference
0	17.05	17.14	-0.09	17.04	17.03	0.01
10	17.01	17.07	-0.06	17.00	16.99	0.01
20	16.93	17.06	-0.13	16.91	16.98	-0.07
30	16.86	17.04	-0.18	16.83	16.98	-0.15
50	16.19	15.92	0.27	15.84	15.78	0.06
75	12.56	12.56	0.00	12.48	12.42	0.06
100	11.10	11.24	-0.14	11.14	11.14	0.00
125	10.18	10.29	-0.11	10.19	10.23	-0.04
150	9.42	9.54	-0.12	9.47	9.53	-0.06
200	8.64	8.76	-0.12	8.71	8.68	0.03
250	7.97	8.00	-0.03	7.95	7.95	0.00
300	7.32	7.23	0.09	7.31	7.20	0.11
400	6.15	6.21	-0.06	6.18	6.16	0.02
Layer depth	42	40	2	41	39	2

Table 49. Comparison of 1830-m and 460-m simultaneous RAPLOC/DEEPTOW XBT pairs meeting the ±0.34°C accuracy specification for comparisons above and below the thermocline.

ANALYSIS OF XBT PROFILES TRANSMITTED TO FLEET NUMERICAL WEATHER CENTER FOR OPERATIONAL USE

During the SUDS I 1972 experiments, the DE STEIGUER routinely digitized and transmitted XBT temperature data to the Fleet Numerical Weather Center (FNWC), Monterey, CA. These measurements were used as inputs to FNWC synoptic predictions of propagation loss and Fleet sonar performance. These operational predictions are used by the Fleet in day-to-day operations. This section discusses the accuracy of the data transmitted to FNWC.

From 8–23 February 1972, the DE STEIGUER digitized and transmitted XBT temperature measurements to the FNWC. During this period, 31 profiles were attempted and three failed catastrophically. The remaining 28 were judged visually acceptable by the observer prior to digitization and transmission. Of the 28 profiles 15 were made in area C, where enough hydrocast and STD/SV measurements were made to establish an average 200-, 300-, and 400-m temperature. The following summarizes an analysis of the 200-, 300-, and 400-m temperatures in terms of the accuracy criteria established for area C.* Preliminary system error is replaced by the final system error.

*See step 4 of the section, Procedure for Determining XBT System Error.

Number of XBT profiles transmitted:	15 (100.0%)
Number partial successes:	2 (13.3%)
Number reaching 400 m:	13 (86.7%)

Of those reaching 400 m, the number satisfying the accuracy criteria at all three depths was three (or 23.1%); at two depths was two (or 15.4%); at one depth was three (or 23.1%); and at no depth was five (or 38.5%). To restate, of 13 area C XBT profiles reaching 400 m, only 23.1% satisfied the accuracy criteria at three depths below the thermocline; 38.5% did not satisfy the criteria at any of the three depths; the balance, 38.5%, did not satisfy the criteria at one or two of the three depths. Yet, all 13 profiles were deemed acceptable XBT traces by the observer and transmitted to FNWC as inputs to operational acoustic parameter predictions.

The above 13 XBT profiles are a subset of a set of 47 profiles to a depth of 400 m that were made by the DE STEIGUER in area C during the SUDS I experiments. Of the 47 profiles, 10 (21.3%) satisfied the accuracy criteria at all three depths, 41 (29.8%) did not satisfy the accuracy criteria at all three depths, and 23 (48.9%) did not satisfy the accuracy criteria at one or two depths. These statistics are somewhat similar to the statistics for the 13 profiles transmitted to the FNWC, which suggests that the subset is a random sample drawn from the total set of 47 profiles.

Table 50 lists the differences between the 200-, 300-, and 400-m XBT temperatures and the average hydrocast and STD/SV temperatures for the profiles transmitted to the FNWC. The differences varied from -0.36°C to 1.09°C, with four (9.3%) of the 43 differences greater than 0.50°C.

Depth, m	95D	96D	97D	98D	99D	102D	108D	112D	115D
200	CF	0.17	0.10	0.53	0.46	0.02	CF	-0.10	-0.04
300		-0.08	-0.11	-0.12	0.35	-0.09		-0.16	-0.12
400		-0.11	0.01	0.30	0.26			-0.15	

Depth, m	122D	125D	128D	131D	137D	141D	144D	148D
200	0.58	-0.29	1.09	-0.25	-0.08	-0.36	-0.36	0.34
300	0.40	-0.15	0.36	-0.08	-0.05	-0.23	-0.16	0.38
400	0.44	-0.04	0.70	-0.22	-0.16	-0.23	-0.31	0.17

Table 50. Summary of 200-, 300-, and 400-m temperature differences between XBT and average hydrocast and STD/SV temperatures for SUDS I XBT profiles taken by the DE STEIGUER in area C and transmitted to FNWC.

Figures 47 and 48 are facsimiles of two of the area C profiles that were transmitted to the FNWC during the SUDS I experiments. Shown in the inset are the 200-, 300-, and 400-m temperatures (T) and the difference between these temperatures as well as the average hydrocast and STD/SV temperatures (ΔT). Figure 47 is a facsimile of XBT 97D taken in area C on 19 February 1972 at 0400 PST and satisfying the 200-, 300-, and 400-m accuracy criteria. Figure 48 is a facsimile of XBT 128D, which was taken in area C on 21 February 1972 at 2200 PST and does not satisfy the 200-, 300-, and 400-m accuracy criteria. At 200-, 300-, and 400-m, the XBT temperatures were 1.09°C, 0.37°C, and 0.70°C higher than the average hydrocast and STD/SV temperatures. The 200–300-m temperature gradient bias is –0.72°C, and the 300–400-m temperature gradient bias is +0.33°C. These temperature biases convert to sound speed gradient biases of about –2.2 and +1.0 m/s/100 m, respectively.

In conclusion, if this sample of 13 XBT profiles is representative of the data being transmitted to FNWC on a routine basis, the inclusion of many visually acceptable but actually erroneous measurements must certainly have an adverse effect on the accuracy of the acoustic predictions based on these measurements as inputs to the predictions. Certainly, some procedure or technique of detecting such measurements prior to their use as inputs to predictions is required.

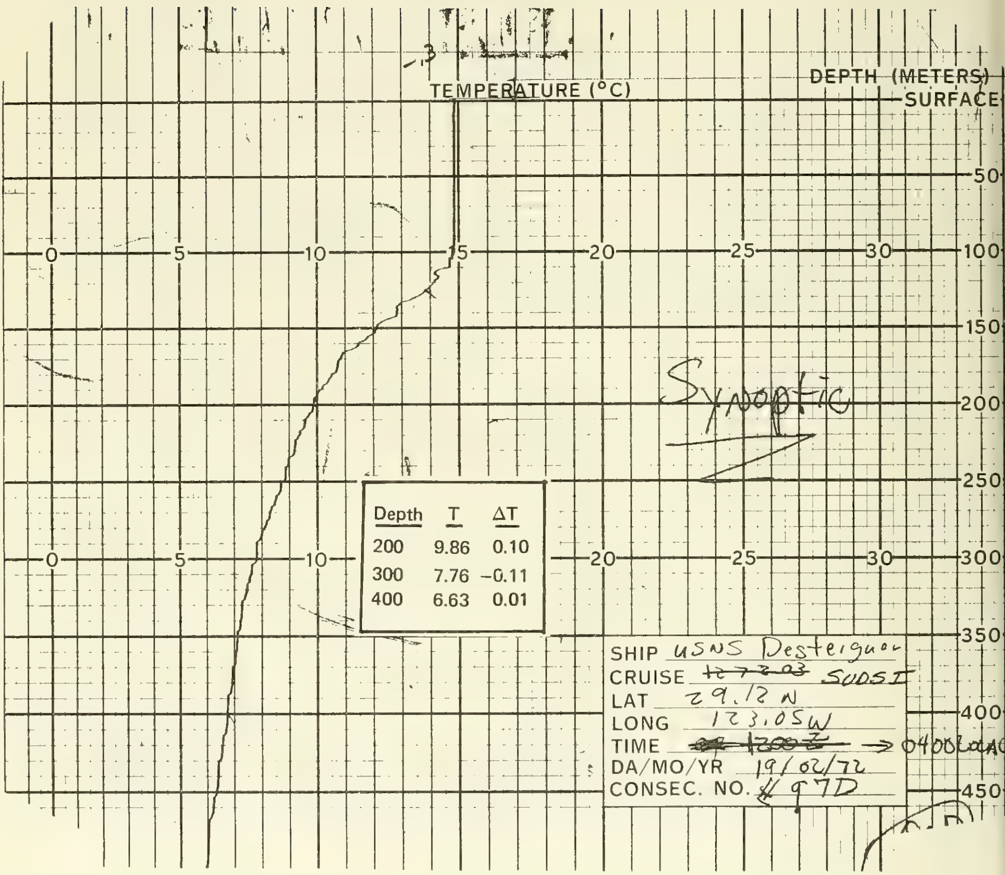

Figure 47. Example of an XBT profile (97D) satisfying the accuracy criteria at 200, 300, and 400 meters and transmitted to FNWC during the SUDS I experiments.

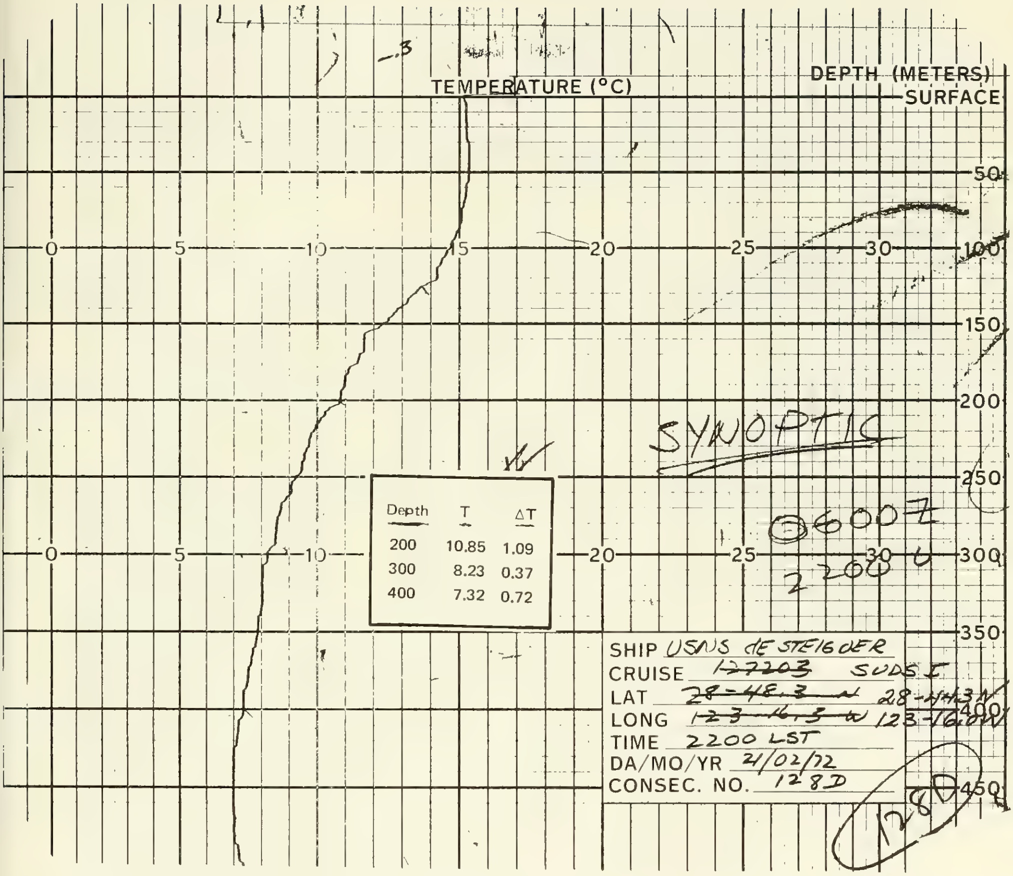

Figure 48. Example of an XBT profile (128D) not satisfying the accuracy criteria at 200, 300, and 400 meters and transmitted to FNWC during SUDS I experiments.

SUMMARY

During six acoustic experiments conducted between 1971 and 1975, a total of 1978 XBT temperature profiles were acquired – 26 by means of 1830-m XBT systems and 1961 by means of 460-m systems. Included were special sets of measurements that provided data bases for absolute and relative accuracy studies. The measurements were made on eleven 460-m and two 1830-m systems from four ships and two research platforms. In addition, independent temperatures were measured by using hydrocasts, STD/SV, thermistor chain, surface towed thermistors, and bucket thermometers.

It is common practice to read XBT analog records visually with a temperature accuracy of ±0.2°C and a depth accuracy of ±2 m. In this study, all XBT records were read with a Hewlett-Packard 9864A Digitizer that has a temperature resolution of ±0.05°C and a depth resolution of ±0.94 m.

XBT PERFORMANCE

The following is a summary of the performance of the XBT systems used to provide the data for this study.

	460 m		1830 m	
Profiles attempted	1961	100.0%	26	100.0%
Catastrophic failures	126	6.4%	8	30.8%
Miscellaneous failures	52	2.7%	0	0.0%
Partial successes	212	10.8%	8	30.8%
Successes	1571	80.1%	10	38.4%
Visually acceptable	1783	90.9%	18	69.2%

where the above categories are defined as follows:

Catastrophic failure – No usable measurements for depths greater than 50 m.

Miscellaneous failure – Failed because of operator error, wire blowing against ship, etc.

Partial success – Visually acceptable to a depth greater than 50 m but less than the maximum depth.

Success – Visually acceptable to maximum depth.

Visually acceptable – The sum of the successes and partial successes. No basis for rejecting as incorrect based on a visual inspection of the analog record.

SYSTEM MEASUREMENT ERRORS

STD/SV, CTD/SV, SVTP, XBT, thermistor chain, towed thermistor, and bucket thermometer temperatures were compared with hydrocast measurements to determine the corrections required to bring these measurements into agreement with the hydrocast measurements. These corrections are referred to as the system errors.

The system errors for the STD/SV, CTD/SV, SVTP, and thermistor chain systems were all small – varying from -0.03°C to 0.02°C. The errors for the towed thermistor and the bucket thermometers were slightly larger – varying from -0.11°C to 0.08°C. The system error for the towed thermistor, used during the Gulf of Alaska experiments, changed from 0.08°C to -0.11°C between the measurements made during the A2 experiments and those made during environmental survey 2. This may have resulted from a recalibration of the system between the two sets of measurements.

Some of the XBT system errors were substantial – varying from -0.19°C to 0.23°C. These errors are fixed. To be certain that the absolute value of the temperatures recorded by a given XBT system is accurate, it appears necessary to determine the XBT system error. To do this, independent and simultaneous temperature measurements are required. In the absence of these latter measurements, the absolute value of the XBT recorded temperature is questionable to within approximately ±0.2°C.

SURFACE TEMPERATURE ACCURACY OF 460-m SYSTEMS

Independent surface temperature measurements were made at the same time XBT profiles were made during the Gulf of Alaska, SUDS I, CAPER, and RAPLOC/DEEPTOW experiments. A few measurements were made by using the hydrocast and STD/SV systems. Most of the measurements were made by means of a towed thermistor (Gulf of Alaska), thermistor chain (SUDS I), and bucket thermometers (CAPER and RAPLOC/DEEPTOW). A total of 736 XBT profiles were made, together with one or more independent and simultaneous surface temperature measurements.

The purpose of these measurements was to check the surface temperature measurement accuracy of visually acceptable XBT profiles. As the analysis proceeded, a secondary purpose was realized. This was to use the independent measurements as detectors of malfunctioning XBT systems. Two malfunctioning systems were detected. The first system was used to make the Gulf of Alaska measurements. Comparison of the XBT surface temperatures with the towed thermistor temperatures showed that the XBT system began to malfunction when making XBT profile 166. Of a total of 327 profiles, the accuracy of the XBT surface temperature was questionable for 162 (49.5%) profiles. The malfunction of this system was not detected until the preparation of this study some 6 years after the data were published. The second system was used by the MOANA WAVE during the CAPER experiments. Comparison of the XBT surface temperature with the bucket temperatures showed that the MOANA WAVE XBT system began to malfunction when making XBT profile 46. Of a total of 138 profiles, the accuracy of the surface temperature was questionable for 103 (74.6%) profiles. The cause, or causes, of either of the malfunctions are not known. The malfunction of these two systems would not have been discovered if independent surface measurements had not been made.

An analysis of the 400-m temperatures showed that the malfunctioning systems did not shift the profile by a fixed amount. The 400-m differences were not the same magnitude as the surface differences.

Once the profiles made when the XBT systems were malfunctioning were detected and removed from the data set, the XBT and independently measured surface temperatures were in agreement. The average of 467 comparisons was 0.02°C with a standard deviation of 0.15°C. The distribution of the differences was slightly biased, with 56.5% being positive, 38.6% negative, and 4.9% zero.

All XBT profiles used in this analysis were originally classified as visually acceptable profiles. In the absence of independently measured surface temperatures, all 736 XBT surface temperatures would have been considered valid. In that event, the statistics would have been markedly altered, with the average difference being –0.15°C with a standard deviation of 0.47°C. In addition, the bias in the distribution of differences would have been reversed, with 56.3% of the differences being negative, 40.3% positive, and 3.4% zero.

TEMPERATURE ACCURACY OF 460-m SYSTEMS

XBT measured temperatures are compared with average hydrocast and STD/SV measurements, quasisimultaneous STD/SV measurements, and simultaneous thermistor chain measurements.

Two studies compared the average hydrocast and STD/SV measurements with XBT profile measurements. The first study was based on a set of 826 visually acceptable profiles that reached a minimum depth of 200 m and the second on a set of 528 visually acceptable profiles that all reached 400 m and also had an independent surface temperature measurement. For the first study, comparisons were made at 200, 300, and 400 m since, at these depths, vertical temperature gradients are small. The second study made comparisons at the surface and at 200, 300, and 400 m.

The first study showed that, in the absence of independent temperature measurements to detect XBT profiles made when an XBT system malfunctioned, the XBT system measures, on the average, temperatures that are higher and vertical temperature gradients that are larger than those measured by the hydrocast and STD/SV systems. Eliminating the profiles made when the two XBT systems malfunctioned, a reanalysis of the remaining 559 profiles still supported the above conclusion. Thus, even with the omission of obviously erroneous profiles made when XBT systems malfunction, there remain enough erroneous profiles to bias systematically the average temperature and the average vertical temperature gradient. Using an accuracy criterion based on the average hydrocast and STD/SV measurements, the data set was divided into a subset of 354 profiles that satisfied the criterion and one of 205 profiles that did not satisfy the criterion. The differences at all three depths for the data set that satisfied the criterion were normally distributed with mean near-zero and standard deviations of 0.07°C to 0.13°C. Once the biasing profiles were identified and removed from the data set, the remaining profiles accurately measured the temperature. The biasing profiles were detectable only with the aid of independent 200-, 300-, and 400-m temperature measurements.

The results of the second study were similar to those obtained in the first study. For the set of 528 visually acceptable profiles, the XBT measured a surface temperature that, on the average, was 0.15°C less than the independently measured surface temperature. This results in an average positive temperature gradient bias in the surface-to-200-m, layer. Analysis of the 351 profiles that remained after the elimination of the profiles made with the two malfunctioning XBT systems showed that, at the surface, the XBT profiles measured a temperature slightly higher than the independently measured temperature. At 200, 300, and 400 m, the XBT profile still measured temperatures slightly higher than the average hydrocast and STD/SV measurements. In addition, the vertical temperature gradient from the surface to 200 m was slightly biased.

A total of 66 pairs of quasisimultaneous XBT and STD/SV profiles were used to examine further the accuracy of the XBT measurements at the surface and at 200, 300, and 400 m. All measurements were made with the vessel hove to and drifting or at anchor.

Of the 66 profiles, 20 were made when the XBT systems malfunctioned. The statistics for all the differences for each depth were very similar to the results obtained from the first two studies. The major difference was that the standard deviations were somewhat larger for this study. The statistics for the differences associated with the profiles made when the systems were not malfunctioning were also similar to the statistics for the first two studies.

Simultaneous XBT and thermistor chain measurements were made with the vessel both hove to and underway at 3 knots. Comparisons were made at 44 depths spaced from the surface to 242 m, the maximum depth of the thermistor chain. From a study of these measurements, it was concluded that the probes used measured temperatures from the surface to 242 m that were slightly less than those measured by the thermistor chain. The biasing of these differences may be related to using a "run" of eight consecutive probes. While underway at 3 knots, 73 XBT profiles were attempted. Comparisons of the 64 successful and partially successful profiles with single thermistor chain temperature scans that started at the same time the XBT probe was released showed that three profiles were grossly in error and these were eliminated from the data set. Analysis of the remaining 61 profiles suggested that below the near-surface layer, the thermistor chain measured temperatures slightly higher than the XBT measurements. This possibly resulted from a slight shoaling of the thermistor sensors as a result of the 3-knot towing speed. Since the thermistor chain depth sensor was inoperative, it was not possible to check this conclusion. Comparisons of the XBT measurements with thermistor chain measurements made in the near-surface layer showed that the 61 XBT profiles measured temperatures slightly higher than the thermistor chain. The average of 1037 comparisons was 0.04°C with a standard deviation of 0.13°C; 62.8% of the differences were positive; 35.3% were negative; and 1.9% were zero. These results are consistent with those obtained from the hydrocast and STD/SV as well as the quasisimultaneous STD/SV comparisons. In addition, a serial tabulation of the average differences, standard deviations, and the number of positive and negative differences for each of the 61 XBT profiles showed temperature measurement biases both with respect to measurements made by individual XBT probes and with respect to "runs" of consecutive probes.

PROFILES WITH LARGE DIFFERENCES

The analyses summarized above were concerned primarily with average temperature differences. The results suggested that, on the average, the XBT system measured temperatures in the surface-to-400-m depth interval that were slightly higher, and vertical temperature gradients that were slightly larger, than those measured by hydrocast, STD/SV, and thermistor chain systems. In many applications, the concern is not with average values but rather with the use and interpretation of individual, or a short series of individual, profiles. A set of profiles that reached a minimum depth of 200 m and whose temperature exceeded the average hydrocast and STD/SV temperatures by more than ±0.50°C at 200, 300, or 400 m was compiled. This set contained 54 profiles, which was 9.7% of the total set of 559 profiles. This set does not include the profiles made with the malfunctioning XBT systems. An examination of these data showed positive differences as large as 3.02°C, negative differences as large as −0.73°C, positive temperature gradient biases as large as 0.96°C/100 m, and negative temperature gradient biases as large as −0.73°C/100 m.

TEMPERATURE ACCURACY OF 1830-m SYSTEMS

During the CAPER and RAPLOC/DEEPTOW experiments, twenty-six 1830-m XBT profiles were attempted. Of the eight profiles made during CAPER, one was a catastrophic failure and seven were successes. Of the 18 profiles made during RAPLOC/DEEPTOW, seven were catastrophic failures, three were successes, seven were partial successes, and one exceeded the calibration correction of ±0.34°C. The eight catastrophic failures were all related to an apparent temporary insulation failure in the upper 50 m of the profile. Since no independent temperatures were measured concurrent with the CAPER XBT measurements, an analysis of their accuracy was not possible. However, on the basis of information available, there was no reason to question the validity of the seven visually acceptable profiles. An examination of the RAPLOC/DEEPTOW 1830-m profiles showed that in spite of apparent temporary insulation failure, some of the catastrophic failures and partial successes appeared to record valid temperatures for some depth intervals. However, comparison with CTD/SV measured temperatures showed that several of these profiles measured temperatures markedly different from the CTD/SV temperatures for depths greater than that of the first indication of insulation failure. For the three successful XBT profiles, the temperatures measured at standard hydrocast depths from 200 to 1500 m were compared with the average CTD/SV measured temperatures. The differences varied from −0.25°C to 0.09°C.

COMPARISON OF SIMULTANEOUS XBT PROFILES

During the ORB-3 and RAPLOC/DEEPTOW experiments, 96 pairs of simultaneous 460-m XBT profiles were attempted from the ORB, with 20 pairs made under tow at 5 knots and 76 at anchor. During the RAPLOC/DEEPTOW experiments, eighteen 1830-m profiles were attempted simultaneously with 460-m profiles taken on two different 460-m systems. The number of visually acceptable pairs of 460-m profiles was 90, and the number of visually acceptable triplets was 10. These data were used to examine the relative accuracy of 460-m and 1830-m XBT systems. Temperatures at standard hydrocast depths and near-surface-layer depths were compared. Comparisons were made for depths in the near-surface layer, in the thermocline, and below the thermocline.

The 460-m comparisons showed that 43 (47.8%) pairs of the 90 pairs satisfied the ±0.34°C accuracy specification at all comparison depths; 62 (68.9%) satisfied the accuracy specifications at all in-layer and below-thermocline depths; and 28 (31.1%) pairs did not satisfy the accuracy specification at one or more in-layer and below-thermocline depths. For nine (10.0%) pairs, the near-surface-layer depth difference exceeded the ±5-m accuracy specification; for 81 (90.0%) pairs, it was less than the accuracy specification. For both sets of comparisons, considerably more differences were positive than negative.

In each set of comparisons, one of the systems consistently measured a higher temperature than the other. Of a total of 1116 comparisons, the absolute value of the differences exceeded 0.34°C for 16.6% of the comparisons.

An examination of individual pairs of profiles showed that many of the pairs differed by large amounts. Some pairs measured large differences starting in the near-surface layer, with the difference being a variable function of depth; while other pairs agreed identically in the near-surface layer and began to differ at some depth below the thermocline, with the difference being an increasing function of depth. Figures 43 to

46 contain eight pairs of profiles that illustrate the nature of these differences. For example, one pair showed minor differences in the near-surface layer and identical agreement in the thermocline. However, below the thermocline they began to differ, with the difference being an an increasing function of depth. At 400 m, the difference had increased to 3.01°C. Generally, when pairs of profiles exhibited large differences, the profile measuring the higher temperature was the incorrect profile. This is important since, if undetected, the temperature errors of these profiles are systematic, biasing, and nonrandom.

Comparison of ten 1830-m profiles with two sets of simultaneous profiles made on two different 460-m systems showed that 15 (75.0%) pairs of the 20 pairs agreed to within ±0.34°C at all above and below-thermocline comparison depths. For 17 (85.0%) pairs, the layer depth difference was less than or equal to ±5 m. On the average, the 1830-m system measured temperatures that were slightly lower than the temperatures measured by the two 460-m systems.

PROFILES TRANSMITTED TO FLEET NUMERICAL WEATHER CENTER

During the SUDS I 1972 experiments, the DE STEIGUER routinely digitized and transmitted XBT temperature data to the Fleet Numerical Weather Center (FNWC), Monterey, CA, where they were used as inputs to predictions of propagation loss and Fleet sonar performance. From 8–23 February 1972, 31 profiles were attempted, with three being catastrophic failures. The remaining 28 profiles were judged to be visually acceptable by the observer and were digitized and transmitted. Of the 28 profiles, 15 were made in area C where enough hydrocast and STD/SV measurements had been taken to establish an average 200-, 300-, and 400-m temperature. Of these 15 profiles, 13 reached 400 m. Of the 13, the number satisfying the accuracy criteria at all three depths was three (or 23.1%); at two depths was two (or 15.4%); at one depth was three (or 23.1%); and at no depth was five (or 38.5%). Thus, out of 13 profiles reaching 400 m, only 23.1% satisfied the accuracy criteria at all three depths, and 38.5% did not satisfy the criteria at any of the three depths. Yet, all 13 profiles were deemed acceptable by the observer and transmitted to FNWC as inputs to operational acoustic parameter predictions. In addition, the differences varied from −0.36°C to 1.09°C, with four (9.3%) of the 43 differences greater than +0.50°C.

CONCLUSIONS

Evidence has been presented to support the following conclusions concerning the accuracy of XBT temperature measurements:

- XBT system errors varied from −0.19°C to 0.23°C. To determine these errors independent and simultaneous temperature measurements are required. In the absence of such measurements, the absolute value of the XBT recorded temperature is questionable to approximately ±0.2°C.

- Properly functioning XBT systems may develop malfunctions while making a series of profiles and produce visually acceptable, but erroneous, temperature profiles. Other information, such as independent temperature measurements, is required to detect and identify such malfunctioning 460-m XBT systems. In these studies independent surface temperatures were measured concurrently with 736 visually acceptable XBT profiles made on seven different 460-m systems. Surface temperature comparisons showed that two of the systems, after making a series of accurate profiles, malfunctioned. Comparison of 400-m temperatures showed that the malfunction did not result in a simple temperature displacement of the profile. Consequently, it produced profiles having systematic errors in the vertical temperature gradients. The profiles made after the system malfunctioned were visually acceptable profiles. Of 736 profiles 36.5 percent were made by the malfunctioning systems.

- Of a total of 1961 attempted 460-m profiles, the following percentages apply:

  Visually acceptable to the maximum depth. 80.1%
  Partially successful 10.8%
  Catastrophic failures 6.4%
  Miscellaneous failures . . . . .2.7%.

- Of a total of 518 460-m XBT profiles made when the XBT systems were not malfunctioning, only 37.8 percent of those reaching 400 m satisfied 200-, 300-, and 400-m accuracy criteria at all three depths and 19.9 percent failed to satisfy the accuracy criteria at all three depths (see table 32). The accuracy criteria were based on average hydrocast and STD/SV temperatures.

- Comparison of XBT temperatures with average hydrocast and STD/SV temperatures, quasisimultaneous STD/SV temperatures, and thermistor chain temperatures taken underway at 3 knots showed that the 460-m XBT systems measured, on the average, temperatures that were higher and vertical temperature gradients that were larger than those measured by the other systems. Once the profiles associated with the large differences were identified and removed from the data set, the remaining profiles accurately measure the temperature. For this data set, the average differences were near zero with standard deviations of 0.07°C to 0.13°C.

- Of a total of 559 profiles made when the XBT systems were not malfunctioning and also were reaching a minimum depth of 200 m, the 200-, 300-, or 400-m temperatures for 54 (9.7 percent)of the profiles exceeded the average hydrocast and STD/SV temperatures by more than or equal to ±0.50°C at one or more of the three depths.

- The data set included 26 attempts to make 1830-m XBT profiles. Of the 26 attempts, 10 were successes, 7 were partial successes, 8 were catastrophic failures, and one exceeded the calibration correction. The catastrophic failures were so classified because of apparent temporary insulation failure in the upper 50 m. The measurements made at depths greater than the apparent insulation failures for some profiles appear accurate. However, use of these measurements without other confirming measurements for depths greater than the first insulation failure may result in some risk.

- "Runs" of consecutive XBT profiles were observed in which the temperature measurements are accurate within prescribed limits. However, the measurements do not vary randomly within these limits and form a statistical run of biased data.

- Comparison of 90 pairs of simultaneous visually acceptable 460-m XBT profiles at standard hydrocast depths indicated the following:

47.8% satisfied a ±0.34°C accuracy specification at all comparison depths.

68.9% satisfied the accuracy specification at all in-layer and below-thermocline depths.

31.1% did not satisfy accuracy specifications at one or more depths.

90.0% of the near-surface-layer depth differences satisfied the accuracy specification for depth.

10.0% of the near-surface-layer depth differences did not satisfy the accuracy specification for depth.

- Of a total of 1116 comparisons of simultaneous pairs of XBT temperatures, the absolute value of the differences exceeded two standard deviations of the manufacturer's specified accuracy for 16.6 percent of the comparisons.

- An examination of individual simultaneous pairs of visually acceptable 460-m profiles showed that many of the pairs differed by large amounts. Some of the pairs measured large differences starting in the near-surface layer, with the differences being a variable function of depth, while others agreed identically in the near-surface layer and began to differ at some depth below the thermocline, with the difference being an increasing function of depth.

- During the SUDS I experiments, 28 XBT profiles were judged by the observer to be visually acceptable and were digitized and transmitted to the Fleet Numerical Weather Center where they were used as inputs to predictions of Fleet sonar performance. Of the 28 profiles, 15 were made in area C, where enough hydrocast and STD/SV measurements were taken to establish an average 200-, 300-, or 400-m temperature. Of the 15, 13 reached a depth of 400 m. Of those reaching 400 m, the percentages satisfying the 200-, 300-, and 400-m accuracy criteria at the various depths were as follows:

All three depths:	3, or 23.1%
Two depths:	2, or 15.4%
One depth:	3, or 23.1%
No depths:	5, or 38.5%.

If this sample of 13 XBT profiles is representative of the data being transmitted to FNWC on a routine basis, the inclusion of many visually acceptable but actually erroneous measurements must certainly have an adverse effect on the accuracy of the acoustic predictions based on these measurements as inputs to the predictions.

RECOMMENDATIONS

- As a result of its review of these studies, the Sippican Corp suggests that the following procedure be used for those applications requiring retention of full available system accuracy.

> ". . . calibrate with an A2A test canister whenever (1) a new roll of chart paper is installed, (2) at four-hour intervals during continuing drops, and (3) whenever the 2-second, mid-scale

calibrate trace exceeds ±.1°C from 16.7°C. In addition, a once per day check using an A4 XBT test box provides a quick indication of incipient launcher leakage before it becomes severe enough to affect system accuracy."

The preceding should be standard operating procedure for all users of Sippican's XBT systems. If this is not possible, independent surface measurements should be made simultaneously with each XBT profile. These measurements may be used to check whether or not an XBT system is properly functioning.

- When a system malfunction is recognized while making measurements keep intact the configuration of the system. Contact Sippican Corporation upon return to port to investigate the cause of the system malfunction.
- Enter the identification number of the XBT probe carton on the XBT log.
- When it is recognized that a system has malfunctioned while making measurements, the configuration of that system should be kept intact. The Sippican Corp should be contacted promptly after the vessel returns to port, so that the cause of the system malfunction can be investigated.
- Modify the XBT system to include a depth sensor that would measure a single depth independent of the drop time and provide an indication of this depth on the analog record. This measurement could be used to correct for depth bias.
- Develop a method or technique for identifying visually acceptable but gradient-biasing XBT profiles before they are used in any application and before they are archived.
- Implement a precision digitizer and/or a more accurate analog display in the recording system of the XBT system. The accuracy of a good profile (ie, one free from problems) warrants the use of an improved recorder.
- Investigate possible causes of XBT system malfunctions. Once the cause, or causes, are identified, modify the XBT system to eliminate the causes.
- Conduct similar studies based on measurements made by means of several XBT systems and following the Sippican operating procedure. These new data sets may be used to determine whether the new procedure corrects the anomalies revealed in the present studies.

SIPPICAN RESPONSE TO THE ANDERSON REPORT

In response to the report, EXPENDABLE BATHYTHERMOGRAPH (XBT) ACCURACY STUDIES, by E. R. Anderson, outlining various temperature-depth inaccuracies found with Sippican's XBT system, a brief summary of the major XBT system error sources is outlined below.

(1) Recorder

Zero (Adjustment)
Full Scale (Adjustment)
Response Time
Chart Paper

(2) Launcher

Insulation Leakage

(3) Probe

Wire Resistance Unbalance
Wire Insulation Leakage
Thermistor Offset/Slope
Thermistor Insulation Leakage

Installation of an A2A test canister in the launcher provides an overall system test for (1) and (2) above. If the results of this test indicate that no setting of the zero and full-scale adjustments for –1.1°±.1° and 34.4°C±.1°, respectively, result in a 16.7°±.1°C mid-scale reading, then a 100 VDC high pot check of launcher leakage resistance (normally done on a monthly basis) would be in order to determine a probable launcher leakage resistance condition of considerably less than 100MΩ. Alternatively, testing with an A4 XBT test box will also indicate the presence of excessive launcher leakage.

Many times in the report the phrase, "accuracy criteria," in regard to XBT temperature is used without specific reference to actual value. It is assumed from the analysis on page 19, Vol. I of Mr. Anderson's report that ±.24°C (two standard deviations of assumed value of ±.12°) is meant.* Sippican specifies the system with a stated worst case temperature accuracy of ±.2°C (±.1°C for the probe and ±.1°C for a properly *maintained* and *calibrated* recorder). Such calibration will provide a read-out within ±.1°C at –1.1°C, +16.7°C and +34.4°C when checked with an A2A test canister. Because it is possible that a shift in gain can occur that will affect high temperature readings twice as much as mid-scale readings, and very little at low temperatures, the practice of using the mid-scale calibration value as a correction is questionable. It's better than no correction but obviously more "chancey" than recalibrating the system. For a simple zero offset error, the practice is reasonably acceptable since it applies almost equally across the total temperature span. ("Almost" because of the chart nonlinear temperature compensation used to correct for the thermistor-series resistor "S" curve nonlinearity of .8°C at about .8°C and 24.°C).

The procedure Sippican would use for those applications requiring retention of full available system accuracy is to calibrate with an A2A test canister whenever (1) a new roll of chart paper is installed, (2) at four-hour intervals during continuing drops, and (3) whenever the 2-second, mid-scale calibrate trace exceeds ±.1° from 16.7°C. In addition, a once per day check using an A4 XBT test box provides a quick indication of incipient launcher leakage before it becomes severe enough to affect system accuracy.**

Assuming a correctly-maintained and adjusted launcher-recorder system, then a series of probe drops will reflect probe wire/thermistor problems as follows:

- Wire Resistance Unbalance

May be either up or down scale error depending on which lead has higher resistance; will have more noticeable effect at higher temperatures where thermistor

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*See author's note A.

**See author's note B.

resistance change per degree is less. Sippican hand-tailors each probe lead resistance match to less than .03°C error at 25°C.

- Wire Insulation Leakage

Generally, (although not always) produces up-scale error, since a leak in the "A" lead will have more effect than a similar leak in "B"; will have more noticeable effect at cold temperatures where thermistor resistance is higher and is more susceptible to high shunting resistance. Normal wire insulation leakage contributes less than .03°C error at −1.1°C.

- Thermistor Offset

May be either up or down scale and results in a temperature reading that is always more or less than actual by about the same amount.

- Thermistor Slope

Little or no error around 25°C, increasing in either up or down scale direction as end scale temperatures are approached. Typical sum of offset and slope errors is .1°C max. over the 0°C to 30°C span.

- Thermistor Insulation Leakage

Always up scale and more noticeable at cold temperatures where thermistor resistance is high.

Because Sippican normally in-line production tests each XBT for an accuracy of ±.1°C at room temperature, most of the field failures result from wire and thermistor insulation leakage which will tend to bias failures heavily in an up-scale direction.

With the aforementioned error sources in mind, the following discussion relates to the "Summary of Results" in Mr. Anderson's report.

(1) Two out of eleven 460-m systems malfunctioned to produce erroneous but visually acceptable temperature errors *after* making accurate drops and yielded 36.5% of total data that was outside stated system error.

Comment:

We suspect leakage resistance of launcher and launcher cable was too low. This is normally result of salt water penetration of cable or launcher through physical damage to the launcher or cable. It is visually detectable by installing an A2A test canister in launcher and testing as described on page 11 of Volume I of Mr. Anderson's report. It may be compensated, if not excessive, by recalibrating zero and full scale. It is definitely established by the recommended monthly Reference Standard Leakage Test B-1 of Table 5-4, page 5-4 of R-603, Instruction Manual for XBT System or by testing with an A4 XBT test box.

Effects of low-leakage resistance do tend to bias readings upscale by a greater amount at colder temperatures.

(2) Only 80.1% of 460 m system drops would have been visually acceptable.

Comment:

Normal acceptance rate is 90% or better for 460 m probes that are two years old or less. Older probes will fail at a higher rate due to aging of wire and thermistor insulation. If a customer experiences an abnormally high probe failure rate, Sippican will provide replacement units providing the data and circumstances indicate that defective probes less than two years old were responsible.

(3) Only 37.8% of a total of 518, 460 m system drops satisfied "accuracy criteria" (±.24°C)* at all three depths of 200 m, 300 m and 400 m and 19.9% failed accuracy criteria at all three depths.

Comment:

Accuracy of the system exists in two frames of reference depth and temperature. Sippican states temperature accuracy at ±.2°C (±.1°C probe and ±.1°C recorder) and depth accuracy at ±15 feet or ±2%, whichever is larger.

Any apparent temperature error at specific depth is the result of both real temperature error and depth induced temperature error, if a gradient exists around that depth. For this reason, Sippican would establish system accuracy by measuring temperature and depth at the start and/or finish of a known zero-gradient temperature/depth feature, rather than an indicated temperature at an apparent depth, to eliminate the added apparent temperature error resulting actually from depth error.**

In addition, as mentioned above, probes that are out of two-year warranty may exhibit greater error than the assigned ±.1°C over the 460 m depth range because of gradual wire and thermistor insulation degradation with time.

(4) XBT temperatures and temperature-depth gradients are higher than those measured by other systems.***

Comment:

In general, probes older than two years may have thermistor and wire leakage levels that influence temperature readings. Insufficient wire and thermistor insulation resistance will produce, in a majority of cases, *higher* temperature readings. Furthermore, as more wire becomes wetted, e.g., at greater depths, its insulation leakage becomes greater and exhibits greater effects on the readings, usually in an up-scale direction. Hence, actual temperature error would be expected to increase in an up-scale direction with depth for out of warranty XBT probes.

Unless the gradient being measured was positive, e.g., *increasing* temperature with *increasing* depth, the effect of wire leakage would seem to be to *reduce* the actual gradient rather than increase it.

(5) Of 559 profiles made that reached at least 200 m when neither of the two recorder systems that malfunctioned were contributing errors, 9.7% (54) exceeded average hydrocast and STD/SV temperatures by ⩾.5°C at one or more of the sampled depths of 200 m, 300 m, or 400 m.

Comment:

A number of these units might be expected to fail because of normal production tolerance on wire and thermistor insulation resistance. However, a quantity approaching

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*See author's note A.

**See author's note C.

***See author's note D.

10% is considered excessive and indicative of either insulation degradation with age or possibly the result of data points taken at a gradient.*

(6) Of eight, 1830 m probe drops from FLIP in 1974, seven were successful, while in 1975, of eighteen, 1830 m probe drops from the ORB, only three were successful.

Comment:

Because the length of the 1830 m probe wire link is four times that of the 460 m probe, a higher failure rate is normally expected. Typically, Sippican experiences a success rate of around 80% for this probe. The excessively high failure rate due to apparent wire leaks during the ORB drop infers a possible problem stemming from the launch platform, e.g., a high platform, perhaps, allowing a combination of wind and/or sea action to rub the wire link against the ship's hull or mooring lines of other devices. However, the good success rate (over 90%) for the two 460 m systems seems to rule out such a problem source (assuming launch conditions were similar for all three systems).

One additional source of problem can be accumulation of salt buildup and debris around the lip of the launcher bell-mouth. If a third launcher, separate from the more successful 460 m drops, were used for the 1830 m attempt, the possible presence of such encrustation around the bell mouth, coupled with wind and/or water motion, could have produced some of the early failures experienced. Sippican suggests weekly inspection and soft-cloth cleaning of the launcher mouth to prevent such problems.

Finally, the possibility does exist that a group of faulty probes were encountered. Assuming that the possibilities cited were not the cause of failure and that the probes were less than two years old, Sippican's policy of replacement includes the 1830 m probe as well as the 460 m.**

(7) "Runs" of XBT profiles that measure within specifications but with a bias in one direction rather than a random distribution.

Comment:

Besides occurring because of a miscalibrated recorder, such "runs" can also result from the following causes.

The thermistors employed in the probes are manufactured by a batch lot process yielding several thousand at a time. The process produces units that are very similar *within* a batch for slope. The units are then individually ground to value at one temperature, which is periodically reset to centerline value after some degree of in-tolerance drift. Either or both of these variances can produce thermistor lots that are within specification but exhibit bias on one side or the other.

(8) Individual units of "many" simultaneous pair drops showed excessive differences in temperature at depth.

Comment:

A total of 90 out of 96 paired drops were visually acceptable (93.8%). Comparisons were made at fixed apparent depth increments of 200 m, 300 m, and 400 m

*See author's note C.

**See author's note E.

and differences were noted. Because normal system depth errors of ±2% or ±15 feet can produce resulting apparent temperature errors at depths located within rapid temperature changes, care must be *used to select temperatures within a mixed layer.** Typically, Sippican would expect up to .4°C worst case temperature disagreement between simultaneous probe drops in the same constant temperature body of water, exclusive of depth-induced temperature errors.

Of the trace results in relatively constant temperature water, 76 pairs showed essential agreement to within .4°C. Trace 47 (Figure 43A) is an example of a marginal failure to this criteria, where one appears to measure about .2°C low and the other about .2°C high. The total acceptable probe pair drops expressed as a percent is 76/96 X 100 = 79.2%, statistically close to the expected value for a 90% reliable probe of (.9 X .9) 81%.

It should be expected that the great majority of failures will occur in an upscale direction (as was noted by the author) if the failure is caused by poor insulation quality and will become more noticeable with depth as more insulation is exposed.

(9) Out of 15 probe drops made in water of known temperature profile, only 13 provided visually acceptable data to 400 m and of the 13, only 3 provided temperature data to the "accuracy criteria" at each of three monitored depths at 200, 300, and 400 m.**

Comment:

Assuming Drop 128D (Figure 48) is a typical example of profiles failing at all three depths, the following conclusions may be drawn.

Based on knowledge of expected depth-temperature results from previous drops, this profile exhibits a consistent upscale reading with visible "rounding" in the surface mixed layer, indicating possible excess leakage in either wire, probe, or launcher. Since some earlier and later profiles did not exhibit this anomaly, it is concluded that the error can be probably attributed to poor wire or thermistor insulation. Because the failure is not catastrophic but rather marginal, insulation degradation with age is suspect.

The following discussion relates to "Recommendations" suggested by the author.

- Make routine surface measurements as a check on XBT system.

A preferred method would seem to be more extensive use of A2A test canister and A4 test box to detect system maintenance and calibration problems.

- Log I/D of probe carton.

Excellent recommendation. Questions relating to "bad" 460 m probes (and up to 10% can fall in this category) versus "out-of-warranty" probes could be immediately settled if this were adopted.

- Contact Sippican when system malfunctions for analysis and repair.

Excellent suggestion. Questions relating to launcher leakage and recorder performance can be settled much more expeditiously.

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*See author's note C.

**See author's note A concerning accuracy criteria.

- Incorporate a depth sensor in test probes.

Possible, but only with extensive design effort. When feasible, suggest location over bottom of known depth and use of "glitch" occurring on chart paper as probe strikes bottom as a depth check indicator.*

- Identify possible "bad" traces before archiving data.

Possible, through use of "second drops" in questionable cases. Still requires training in judgement and/or supplying information on what trace *should* look like; definitely a recommendation to pursue.

- Eliminate causes of XBT system "failure."

From the preceding discussion it appears that more extensive use of A2A and A4 testers will eliminate most of the apparent system failures encountered. The new MK8 recorder performs more "self-checking" but still requires a test canister to "know" the launcher is "OK." As long as a launcher is required, a test canister should be used as often as possible when full system accuracy is required.

- Implement a precision digitizer and/or a more accurate display.

Sippican MK8 or AN/BQH-7 systems provide precise recording of full digital data on cassette storage for ease of data handling and includes a self-calibrated strip chart display

AUTHOR'S NOTES RELEVANT TO SIPPICAN RESPONSE

NOTE A

In this section, Procedure for Determining XBT System Error, 200-, 300-, and 400-m *temperature accuracy criteria intervals* are defined. For convenience, these intervals are referred to in the text as *accuracy criteria*. The *accuracy criterion*, as defined, is a variable, being a function of depth, the average hydrocast temperature, and its variability (table 13), the XBT system error (table 16), and the manufacturer's stated absolute value of the accuracy of the XBT system converted to a standard deviation. The accuracy criterion is not assumed to be ±0.24°C, a constant, but takes into account the variability present in the various water masses where the hydrographic casts and XBT measurements were made.

For example, in the Gulf of Alaska at 200 m in water mass 2, the standard deviation of 65 hydrographic cast measurements was 0.04°C, while in water mass 7 it was 0.67°C for eight measurements (table 13). Thus the accuracy criterion at 200 m in water mass 2 was 3.88 – 4.12°C and in water mass 7 was 4.11 – 5.47°C. If an XBT profile measured a 200-m temperature in water mass 2 that was within the above interval (0.24°C), it satisfied the criterion. Likewise, if a measurement made in water mass 7 was within the appropriate interval (1.36°C), it also satisfied the accuracy criterion.

NOTE B

At the time of this analysis the procedure, recommended by Sippican and concerning the use of the calibration line on the XBT profile for determining the measured

*See author's note F.

temperature, is discussed in the section, Procedure for Determining XBT System Error. The author agrees that the procedure Sippican now recommends will materially improve the accuracy of XBT measured temperatures. In the future, this should become a part of the standard operating procedure for making XBT measurements.

NOTE C

The author recognizes the importance of a depth error on the temperature at any depth, and that its contribution to the temperature error is a function of the magnitude of the vertical temperature gradient at the depth under consideration. The 200-, 300-, and 400-m depths were selected for comparison since, for all data sets, these were below the thermocline where vertical gradients are small.

Using Sippican's depth error of ±15 ft (4.6 m) from the surface to 230 m and ±2% for depths greater than 230 m, temperatures were measured at 200 ±4.6, 300 ±6.0, and 400 ±8.0 m for selected XBT profiles made in each of the water masses where measurements were made. The vertical temperature gradients at 200, 300, and 400 m were computed from these measurements. In the following tabulation of these gradients, the units are °C/m.

	Depth, m		
	200	300	400
GULF OF ALASKA			
Water mass 2	0.000	0.001	0.004
Water mass 7	-0.007	0.000	-0.001
Transition water mass	0.001	0.001	0.001
SUDS I 1972			
Area A	-0.009	-0.007	-0.004
Area C	-0.038	-0.012	-0.005
ORB 3	-0.017	-0.018	-0.007
ORB 4	-0.009	-0.014	-0.007
CAPER			
Water mass 1	-0.024	-0.013	-0.020
Water mass 2	-0.010	-0.013	-0.017
Water mass 3	-0.001	-0.008	-0.016
RAPLOC/DEEPTOW	-0.024	-0.004	-0.005

It is believed that the overall contribution of the system depth error to the temperature error at 200, 300, and 400 m is minor compared to other factors contributing to the observed temperature differences.

NOTE D

Result 4 states "Comparison of XBT temperatures with average hydrocast and STD/SV temperatures, quasisimultaneous STD/SV temperatures, and thermistor chain temperatures taken under way at 3 knots shows that the 460-m XBT systems measure on the average temperatures that are *higher* and vertical temperature gradients that are *larger* than those measured by other systems." Note the use of the words *larger* and *higher*. The mathematical convention that a positive number is *larger* than a negative number is used in this paper. Thus a ±0.12°C/100-m gradient is *larger* than a –0.22°C/100-m gradient. If the temperature differences are a positive increasing function of depth, the *absolute value* of the gradient is reduced. However, if the above convention is used, the mathematical value of the gradient becomes larger. Thus there is no contradiction. The author agrees with the Sippican comment. It is a matter of definition of terms.

NOTE E

The simultaneous XBT measurements made on the ORB were by J. R. Lovett of NOSC. The 1830-m probes used were purchased from Sippican especially for this set of measurements. No problems with wind, high seas, or salt buildup around the lips of the launchers were encountered. However, according to J. R. Lovett, "The short deck cable used with the 1830-m probes constrained the location of the launcher to a position about 15 ft from an ORB cable. This adverse location probably accounted for most of the catastrophic failures encountered with these deep probes." The relative location of the launchers is noted in the section, Comparison of Simultaneous XBT Measurements.

NOTE F

Since each XBT probe has its individual rate-of-fall characteristic, this suggestion can be used only where water depths are less than 460 m or 1830 m, depending on the type of probe used. Since many measurements are made in water depths greater than these, the author feels that the incorporation of some simple sensor that would make one depth measurement at some depth, such as 400 m, would greatly improve the validity of the assumption that depth can be determined from the fall time and, if there were a disagreement between the two measurements, would provide a first-order depth correction.

REFERENCES

1. Spilhaus, A. F., A Bathythermograph, *Journal of Marine Research,* v 1, p 95-100, 1938.

2. Arthur D. Little, Inc, *Experimental Evaluation of Expendable Bathythermographs,* Dept of the Navy, Bureau of Ships, NObsr-93055, Project Ser No SF-101-03-21, Task 11353, November 1965.

3. Arthur D. Little, Inc, *Expendable Bathythermograph (XBT) System Evaluation for Tactical Sonar Application,* Dept of the Navy, Naval Ship Systems Command, NObsr-93055, Project Ser No SF-101-03-21, Task 11353, August 1966.

4. Naval Research Laboratory Memorandum Report 3612, *Subtle T4 XBT Malfunctions,* by J. P. Dugan and A. F. Schuetz, September 1977.

5. Naval Underwater System Center, Letter report Ser 8431-17, 13 February 1978.

6. Naval Undersea Center TP 301, v II, *Gulf of Alaska Sonar Tests. April–August 1971: STD/SV, SVTP, and XBT Data Report,* by E. R. Anderson and J. R. Lovett, August 1972.

7. Naval Undersea Center TP 465, v I–V, *Surface-Duct Sonar Measurements (SUDS I-1972): Oceanographic Measurements*, by E. R. Anderson, February 1976.

8. Reference available to qualified requesters.

9. Reference available to qualified requesters.

10. Naval Undersea Center TP 485, *Combined Acoustic Propagation in EASTPAC Region (Exercise CAPER): Sound-Speed Profiles,* by E. R. Anderson and P. G. Hansen, September 1975.

11. Reference available to qualified requesters.

APPENDIX A

Programs to Digitize XBT Records

```
10 REM                        F*JCFhM TO READ 460 AND 760 METER XBT (TYPES T4,T6
20 REM                        TO AT STANDARD DEPTHS.  PRINTER OUTPUT.
30 REM                        SYSTEM SPECIFICATIONS:
40 REM                             HP9830A (2K R/W)
50 REM                             HP9866A PRINTER
60 DIM D[24],T[24]
70 DIM A$[50],B$[50],C$[50],D$[50]
80 DISP "ENTER CRUISE NAME";
90 INPUT A$
100 DISP "XBT NO.";
110 INPUT B$
120 DISP "  ENTER LATITUDE LONGITUDE";
130 INPUT D$
140 DISP "DATE/TIME";
150 INPUT C$
160 DISP "ENTER SYSTEM ERROR";
170 INPUT C1
180 REM                       READING STANDARD DEPTH FROM TABLE
190 FOR N=1 TO 24
200 READ D[N]
210 NEXT N
220 REM                       CORRECT FOR SKEWNESS OF GRAPH
230 DISP "0 DEPTH,35 T=?"
240 WAIT 3000
250 ENTER (9,*)X,Y
260 IF Y=0 THEN 280
270 GOTO 330
280 FOR I=1 TO 5
290 BEEP
300 WAIT 300
310 NEXT I
320 GOTO 230
330 M=0
340 IF Y 0.5 AND ABSX<0.5 THEN 1100
350 Z=SQR(X*X+Y*Y)
360 X5=X/Z
370 Y5=-Y/Z
380 A=6.55/Z
390 REM STOP FOR GRID TEST  TO  1000
400 FOR N=1 TO 24
410 T[N]=1E+06
420 NEXT N
430 REM                       TEMPERATURE CORRECTION
440 DISP "TEMP 16.7 ?"
450 WAIT 3000
460 ENTER (9,*)X,Y
470 C=-(FNT(X)-16.7)
480 REM                       DEPTH CORRECTION
490 DISP "SURFACE POINT"
500 WAIT 3000
510 ENTER (9,*)X,Y
520 E1=X
530 E2=Y
540 E=-Y*X5-X*Y5
550 GOTO 590
560 REM                       ENTER TABLE DATA
570 ENTER (9,*)X,Y
580 IF Y 0.5 AND ABSX<0.5 THEN 680
590 D=FNDY
600 FOR N=1 TO 24
610 IF ABS(D[N]-D)>1 THEN 650
620 WRITE (9,*)
```

```
630 T[N]=FNTX+C+C1
640 GOTO 570
650 NEXT N
660 GOTO 570
670 REM                      PRINT TABLE
680 WRITE (15,1170)
690 PRINT TAB10,"CRUISE:                    "A$
700 PRINT TAB10,"XBT NO.:                   "B$
710 PRINT TAB10,"DATE TIME:                 "C$
720 PRINT TAB10,"LATITUDE LONGITUDE:        "D$
730 PRINT
740 WRITE (15,1150)
750 PRINT
760 FOR N=1 TO 6
770 WRITE (15,1140)D[N],T[N],D[N+6],T[N+6],D[N+12],T[N+12],D[N+18],T[N+18]
780 NEXT N
790 PRINT
800 PRINT
810 IF M=1 THEN 870
820 DISP "LAYER DEPTH -? OR REENTER DATA POINTS "
830 WAIT 3000
840 WRITE (9,+)
850 ENTER (9,+)X,Y
860 IF Y.0.5 AND ABS( [illegible] THEN 570
870 WRITE (15,1140)"LAYER DEPTH:                     "FNDY
880 WRITE (15,1160)"LAYER DEPTH TEMPERATURE:         "FNT[illegible]+C1
890 WRITE (15,1160)"TEMPERATURE CORRECTION:          "C
900 X=E1
910 E=0
920 WRITE (15,1140)"DEPTH CORRECTION:                "FNDE2
930 WRITE (15,1160)"SYSTEM ERROR:                    "C1
940 WRITE (15,1170)
950 RESTORE
960 GOTO 100
970 END
980 DEF FND(Y)
990 Y1=-Y/[illegible]5-X+Y5-E
1000 REM            [illegible] IS THE VALUE OF Y AT 450M
1010 REM            [illegible] DEPTH EQUATION
1020 D=97.0788*Y1-0.40[illegible]
1030 RETURN D
1040 END
1050 DEF FNT(
1060 X=[illegible]5-X+Y[illegible]
1070 X=[illegible]-5.6287E-04[illegible]
1080 X=[illegible]140)+5.9-40
1090 RETURN X
1100 M=1
1110 GOTO 680
1120 DATA 0,10,20,30,[illegible],150,200,250,300,400,450,500,600,700,750
1130 DATA 800,1000,1200,[illegible]
1140 FORMAT 10X,F4.0,[illegible],2,6X,F4.0,2X,F6.[illegible]
1150 FORMAT 10X,"D(M)   [illegible]   D(M)   [illegible]   D(M)   [illegible]"
1160 FORMAT 10X,F6.2
1170 FORMAT 4
1180 END
1190 REM                   GRID TEST PROGRAM"
1200 E=0
1210 ENTER (9,+)X,Y
1220 PRINT "(X,Y)=("X","Y")DEPTH="FNDY"   TEMP="FNTX
1230 GOTO 1210
```

```
10 REM                          PROGRAM TO READ 1630 [illegible] (TYPE T5)
20 REM                          [illegible] OUTPUT
30 REM                          [illegible] SPECIFICATIONS
40 REM                              HP9810A [illegible]
50 REM                              HP9866A PRINTER
60 DIM D[24],[illegible]
70 DIM A$[50],B$[50],[illegible]
80 DISP "ENTER CRUISE NAME"
90 INPUT A$
100 DISP "LATITUDE [illegible]"
110 INPUT D$
120 DISP "XBT NO.";
130 INPUT B$
140 DISP "DATE TIME";
150 INPUT C$
160 DISP "ENTER [illegible] ERROR"
170 INPUT C1
180 REM                         [illegible] STANDARD DEPTH FROM TABLE
190 FOR N=1 TO 24
200 READ D[N]
210 NEXT N
220 REM                          [illegible] FOR [illegible]NESS OF GRAPH
230 DISP "0 DEPTH [illegible]"
240 WAIT 5000
250 ENTER (9,+)X,Y
260 M=0
270 IF Y<0.5 AND ABS(X)<0.5 THEN [illegible]
280 [illegible]=SQR(X*X+Y*Y)
290 A=6.55/[illegible]
300 DISP "1500 METERS [illegible]"
310 WAIT 5000
320 ENTER (9,+)X,Y
330 Z=SQR(X*X+Y*Y)
340 S5=-Y/Z
350 [illegible]
360 REM                          [illegible] FOR GRID TEST [illegible]
370 FOR N=1 TO 24
380 [illegible][N]=1E+06
390 NEXT N
400 REM                          TEMPERATURE CORRECTION
410 DISP "TEMP [illegible]"
420 WAIT 5000
430 ENTER (9,+)X,Y
440 [illegible]
450 REM                          DEPTH CORRECTION
460 DISP "SURFACE [illegible]"
470 WAIT 5000
480 ENTER (9,+)X,Y
490 [illegible]=X
500 [illegible]=Y
510 [illegible]
520 GOTO 560
530 REM                          ENTER TABLE DATA
540 ENTER (9,+)X,Y
550 IF Y<0.5 AND ABS(X)<0.5 THEN 650
560 [illegible]
570 FOR N=1 TO 24
580 IF [illegible] THEN 620
590 NEXT N
600 [illegible]
610 GOTO 540
620 NEXT N
```

```
630 GOTO 640
640 REM [illegible] TABLE
650 WRITE (15,1140)
660 PRINT TAB10,"CFU [illegible]
670 PRINT TAB10,"BT [illegible] BS
680 PRINT TAB10,"DATE [illegible]
690 PRINT TAB10,"LATITUDE [illegible]
700 PRINT
710 WRITE (15,1100)
720 PRINT
730 FOR N=1 TO 6
740 WRITE (15,1110)[illegible]
750 NEXT N
760 PRINT
770 PRINT
780 IF M=1 THEN 640
790 DISP "WATER DEPTH [illegible]
800 WAIT 1000
810 WRITE (9,[illegible]
820 ENTER (9,[illegible]
830 IF [illegible] 0.5 AND ABS([illegible]
840 WRITE (15,1130)[illegible]
850 WRITE (15,1120)[illegible]
860 WRITE (15,1120)[illegible]
870 [illegible]=E1
880 E=0
890 WRITE (15,1110)[illegible]
900 WRITE (15,1120)[illegible]
910 WRITE (15,1140)
820 RESTORE
830 GOTO [illegible]20
840 END
950 DEF FND(Y)
960 Y1=[illegible]5-[illegible]-E
970 REM [illegible] DEPTH EQUATION
980 D=102.4128*Y1-0.[illegible]
990 RETURN D
1000 END
1010 DEF FNT([illegible]
1020 X=[illegible]5-[illegible]+Y5[illegible]+H
1030 Z=[illegible]5.6[illegible]E-0[illegible]
1040 [illegible]=[illegible]40[illegible]5[illegible]40
1050 RETURN [illegible]
1060 M=1
1070 GOTO 650
1080 DATA [illegible],20,[illegible]
1090 DATA 800,1050,[illegible]
1100 FORMAT 10[illegible]
1110 FORMAT 10X,F4.0,[illegible]
1120 FORMAT 10X,F6.2
1130 FORMAT 10X,F4.0
1140 FORMAT 4
1150 END
1160 REM                    GRID TEST PROGRAM"
1170 E=0
1180 ENTER (9,[illegible]
1190 PRINT "[illegible]
1100 GOTO 1180
```

APPENDIX B

Difference Between Average Hydrocast and STD/SV and XBT Profile Measurements

GULF OF ALASKA Experiments

Water Mass 2

Depth, m	Differences, °C n	$\overline{\Delta T}$	s	Percent Positive	Negative
ALL VISUALLY ACCEPTABLE PROFILES					
200	270	0.068	0.27	50.0	48.1
300	263	0.100	0.29	51.0	44.9
400	255	0.122	0.29	58.0	39.2
PROFILE SET I					
200	105	0.069	0.20	55.2	41.9
300	102	0.078	0.18	57.8	38.2
400	96	0.086	0.18	64.6	31.8
PROFILE SET IA					
200	68	–0.015	0.07	39.7	55.9
300	70	–0.003	0.07	41.3	50.0
400	64	0.016	0.07	54.7	39.1

GULF OF ALASKA Experiments

Transition Water Mass

Depth, m	Differences, °C n	$\overline{\Delta T}$	s	Percent Positive	Negative
ALL VISUALLY ACCEPTABLE PROFILES					
200	153	0.104	0.28	60.8	39.2
300	142	0.135	0.22	73.2	23.9
400	137	0.147	0.21	74.5	24.8
PROFILE SET I					
200	109	0.114	0.26	63.3	36.7
300	100	0.127	0.18	77.0	19.0
400	96	0.137	0.18	79.2	19.8
PROFILE SET IA					
200	72	0.006	0.11	52.8	47.2
300	60	0.034	0.08	66.7	26.7
400	55	0.036	0.08	65.5	32.7

CAPER Experiments

Water Mass 2

Depth, m	Differences, °C n	$\overline{\Delta T}$	s	Percent Positive	Negative
ALL VISUALLY ACCEPTABLE PROFILES					
200	110	0.125	0.93	60.0	38.2
300	105	0.198	0.90	64.8	35.2
400	98	0.202	0.89	57.1	41.8
PROFILE SET I					
200	52	0.146	0.15	82.7	13.5
300	50	0.207	0.21	92.0	8.0
400	46	0.211	0.26	78.3	19.6
PROFILE SET IA					
200	37	0.063	0.09	75.7	18.9
300	28	0.088	0.10	85.7	14.3
400	20	0.017	0.08	50.0	4.50

SUDS I 1972 Experiments

Area C

Depth, m	Differences, °C n	$\overline{\Delta T}$	s	Percent Positive	Negative
PROFILE SET I					
200	186	0.043	0.28	56.5	42.5
300	182	-0.006	0.22	40.1	57.7
400	176	0.034	0.22	47.2	51.7
PROFILE SET IA					
200	114	0.009	0.13	53.5	44.7
300	112	-0.024	0.09	34.8	61.6
400	100	-0.019	0.08	37.0	61.0

RAPLOC/DEEPTOW Experiments

At Anchor

Depth, m	Differences, °C			Percent	
	n	$\overline{\Delta T}$	s	Positive	Negative
PROFILE SET I					
200	107	0.098	0.34	57.0	41.1
300	106	0.065	0.35	53.8	44.3
400	104	-0.001	0.39	36.5	62.5
PROFILE SET IA					
200	63	-0.003	0.10	49.2	47.6
300	58	0.008	0.09	55.2	41.4
400	43	-0.016	0.07	41.9	55.8

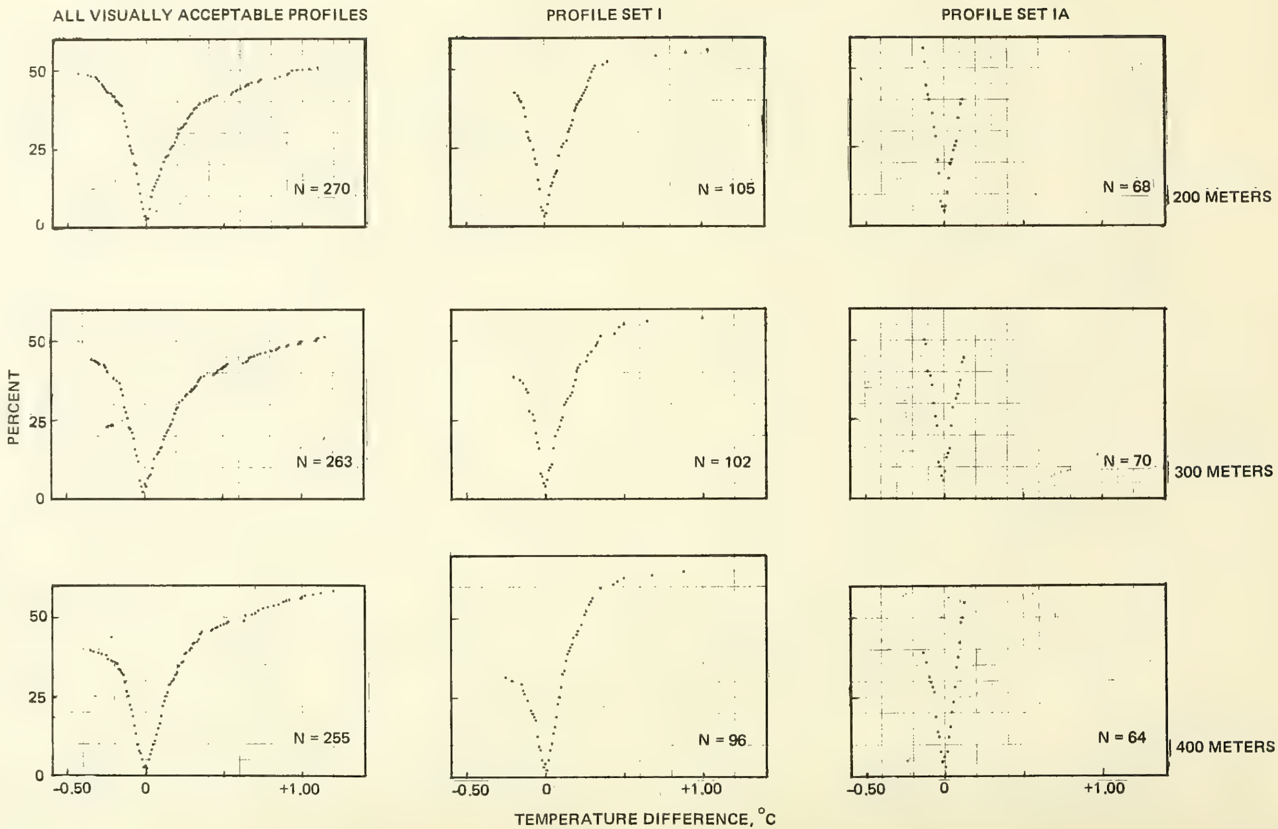


Figure B-1. Positive and negative ogives of Gulf of Alaska water mass 2 temperature differences between average hydrocast and STD/SV and XBT profile measurements.

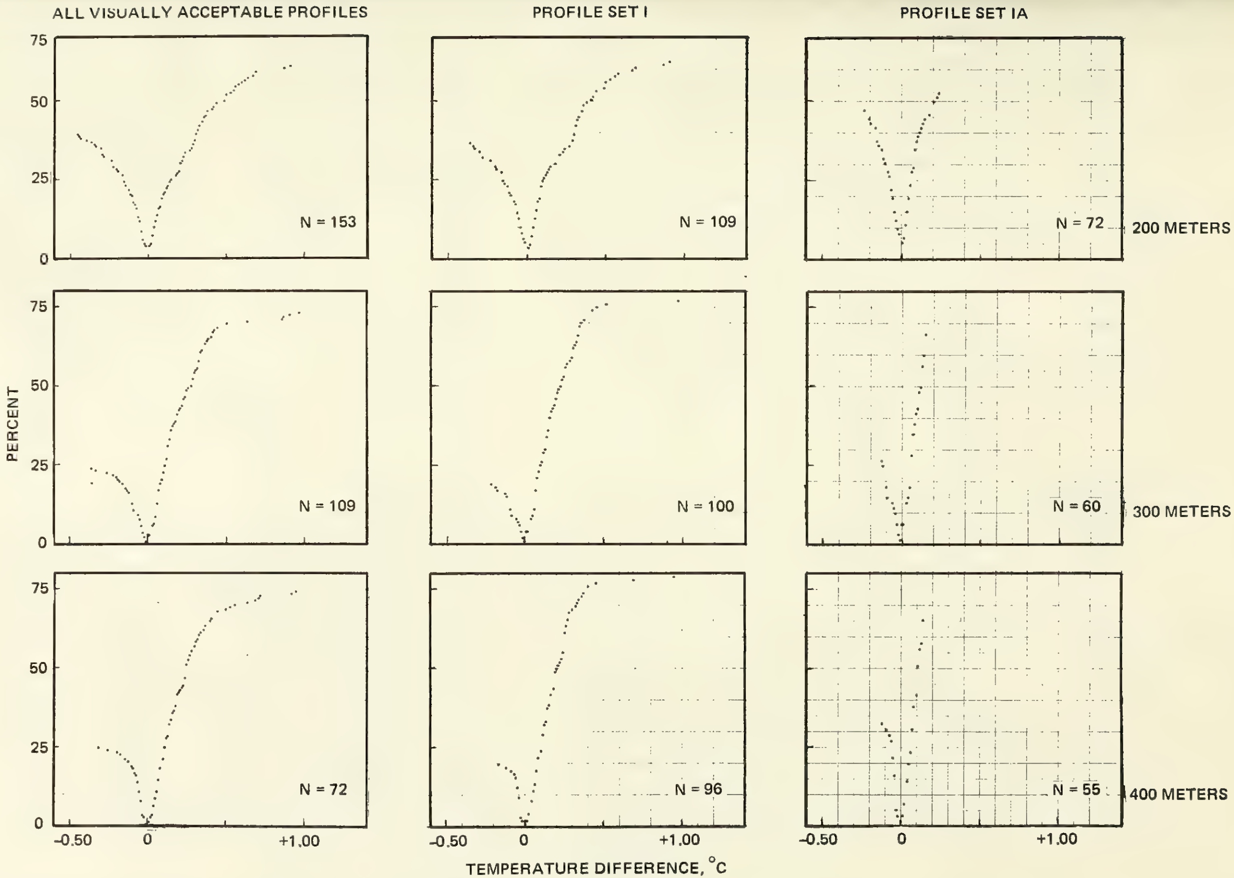


Figure B-2. Positive and negative ogives of Gulf of Alaska transition water mass temperature differences between average hydrocast and STD/SV and XBT profile measurements.

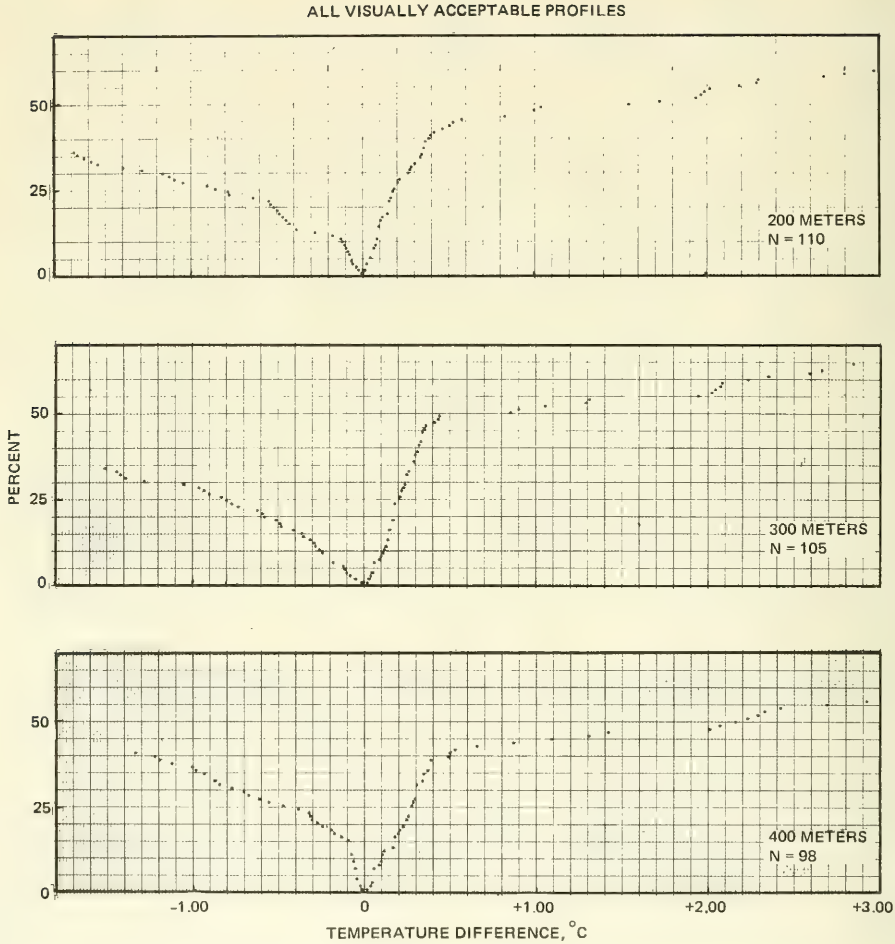


Figure B-3. Positive and negative ogives of CAPER water mass 2 temperature differences between average hydrocast and STD/SV and XBT profile measurements.

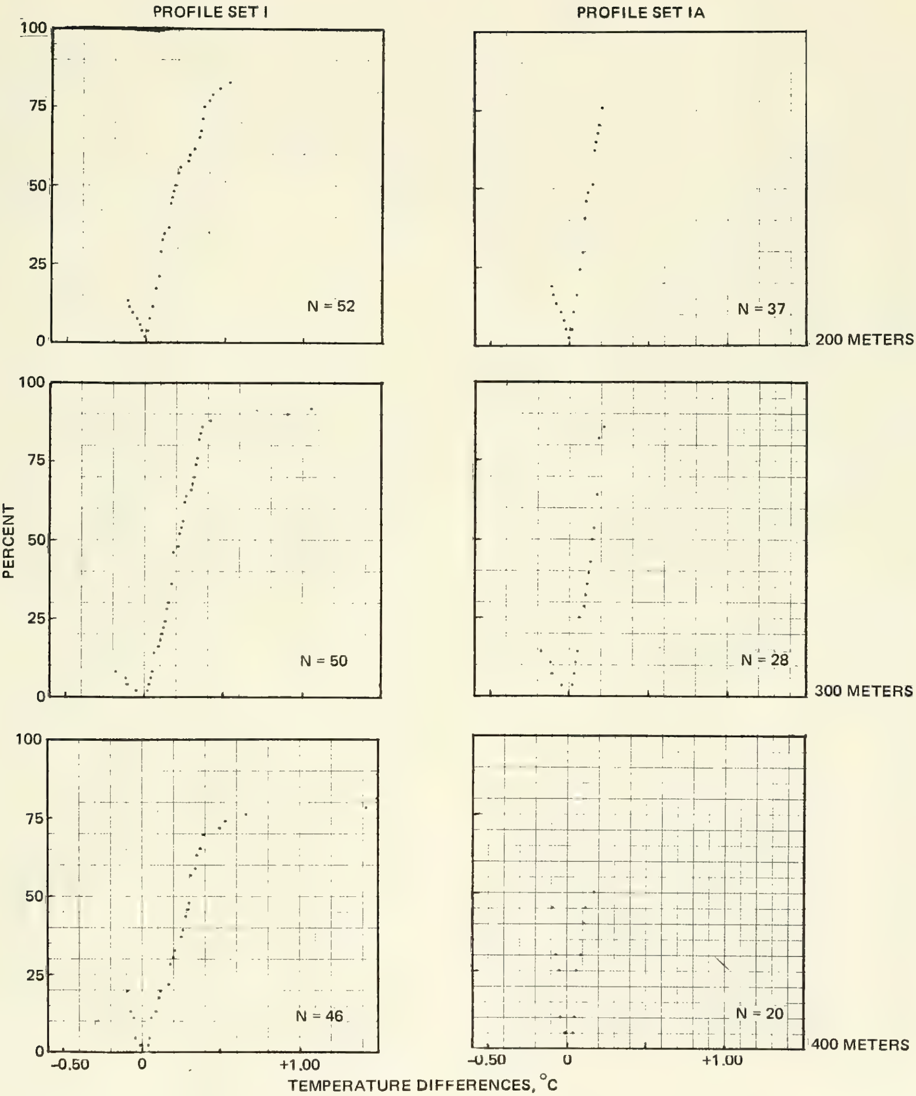


Figure B-3 (Cont'd).

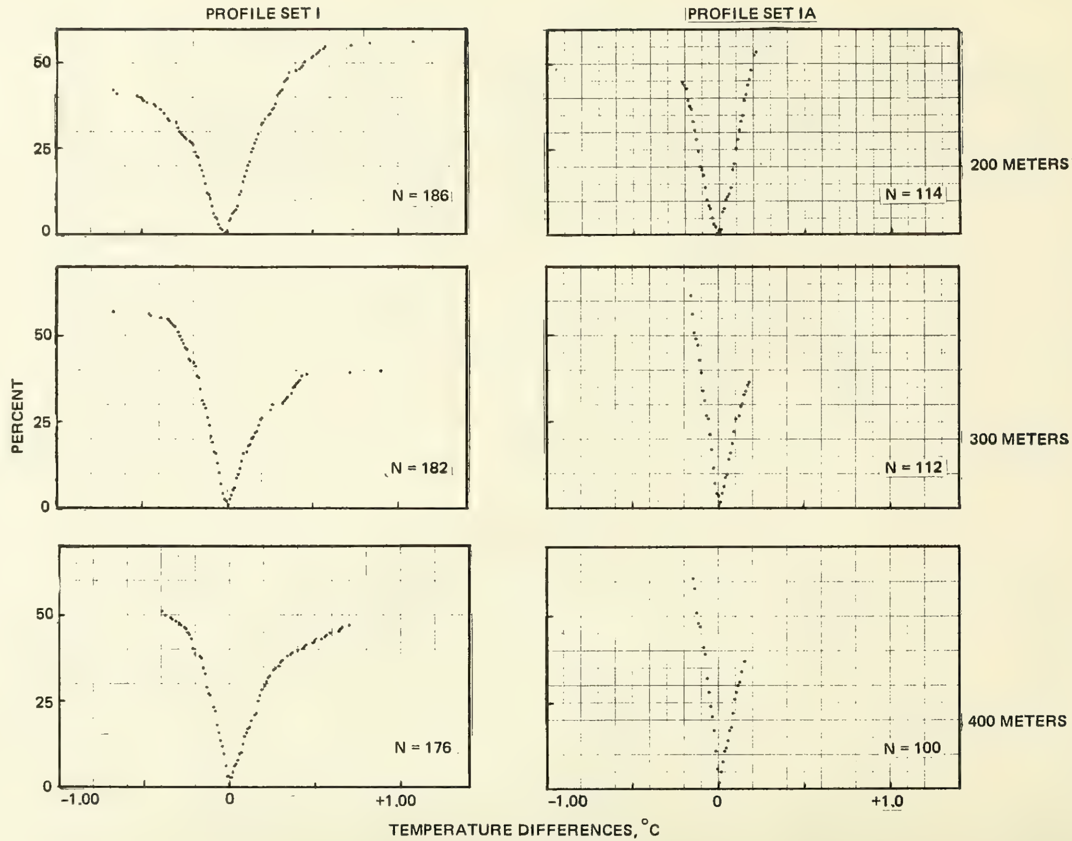


Figure B-4. Positive and negative ogives of SUDS I 1972 area C temperature differences between average hydrocast and STD/SV and XBT profile measurements.

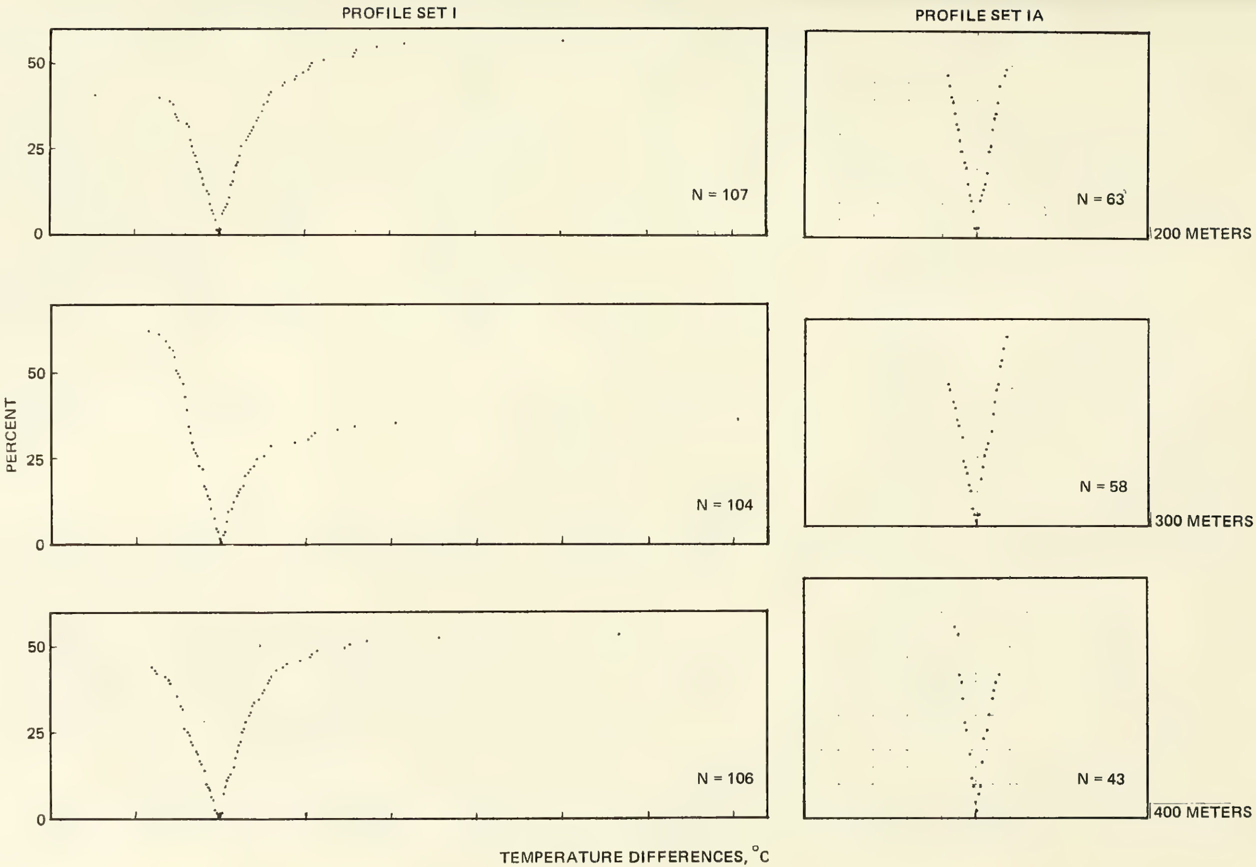


Figure B-5. Positive and negative ogives of RAPLOC/DEEPTOW at anchor temperature differences between average hydrocast and STD/SV and XBT profile measurements.

APPENDIX C

Difference Between Average Hydrocast and STD/SV and XBT Profiles Extending to 400 Meters and Having an Independent Surface Temperature Measurement

GULF OF ALASKA Experiments

Water Mass 2

Depth, m	Differences, °C n	$\overline{\Delta T}$	s	Percent Positive	Negative
ALL VISUALLY ACCEPTABLE PROFILES					
0	179	-0.163	0.21	24.0	72.1
200	179	0.064	0.22	53.1	45.8
300	179	0.103	0.26	55.9	39.7
400	179	0.127	0.26	63.1	33.0
PROFILE SET I					
0	82	-0.040	0.14	39.0	54.9
200	82	0.034	0.12	53.7	45.1
300	82	0.043	0.13	53.7	40.2
400	82	0.050	0.12	61.0	43.1
PROFILE SET IA					
200	60	-0.014	0.07	41.7	56.7
300	65	-0.001	0.07	46.2	47.7
400	60	0.013	0.07	53.3	40.0

GULF OF ALASKA Experiments

Transition Water Mass

Depth, m	Differences, °C n	$\overline{\Delta T}$	s	Percent Positive	Negative
ALL VISUALLY ACCEPTABLE PROFILES					
0	92	-0.077	0.23	37.0	60.9
200	92	0.113	0.28	64.1	35.9
300	92	0.147	0.23	76.1	21.7
400	92	0.155	0.21	79.3	19.6
PROFILE SET I					
0	63	0.024	0.16	52.4	44.4
200	63	0.161	0.26	76.2	23.8
300	63	0.142	0.18	82.5	14.3
400	63	0.135	0.16	82.5	15.9
PROFILE SET IA					
200	41	0.039	0.10	65.9	34.1
300	36	0.046	0.07	75.0	19.4
400	37	0.047	0.07	73.0	24.3

CAPER Experiments

Water Mass 2

Depth, m	n	$\overline{\Delta T}$	s	Positive	Negative
	Differences, °C			Percent	
ALL VISUALLY ACCEPTABLE PROFILES					
0	62	-0.245	1.00	37.1	62.9
200	62	0.146	1.10	51.6	46.8
300	62	0.185	1.09	50.0	50.0
400	62	0.255	1.07	54.8	45.2
PROFILE SET I					
0	11	0.106	0.19	72.7	27.3
200	11	0.123	0.10	100.0	0.0
300	11	0.167	0.09	100.0	0.0
400	11	0.217	0.10	100.0	0.0
PROFILE SET IA					
200	8	0.076	0.06	100.0	0.0
300	8	0.126	0.06	100.0	0.0
400	3	0.087	0.03	100.0	0.0

SUDS I 1972 Experiments

Area C

Depth, m	n	$\overline{\Delta T}$	s	Positive	Negative
	Differences, °C			Percent	
PROFILE SET I					
0	115	0.043	0.14	60.9	33.9
200	115	0.026	0.24	58.3	39.1
300	115	-0.074	0.23	35.7	63.5
400	115	-0.025	0.25	38.3	60.9
PROFILE SET IA					
200	76	0.018	0.11	57.9	38.2
300	64	-0.020	0.09	40.6	57.8
400	69	-0.011	0.09	39.1	59.4

RAPLOC/DEEPTOW Experiments

At Anchor

Depth, m	Differences, °C n	$\overline{\Delta T}$	s	Percent Positive	Negative
PROFILE SET I					
0	80	0.053	0.15	62.5	28.8
200	80	0.002	0.35	42.5	55.0
300	80	0.038	0.36	47.5	50.0
400	80	–0.026	0.41	30.0	70.0
PROFILE SET IA					
200	50	–0.020	0.09	41.2	54.9
300	42	–0.003	0.10	50.0	45.2
400	29	–0.023	0.07	37.9	62.1

APPENDIX D

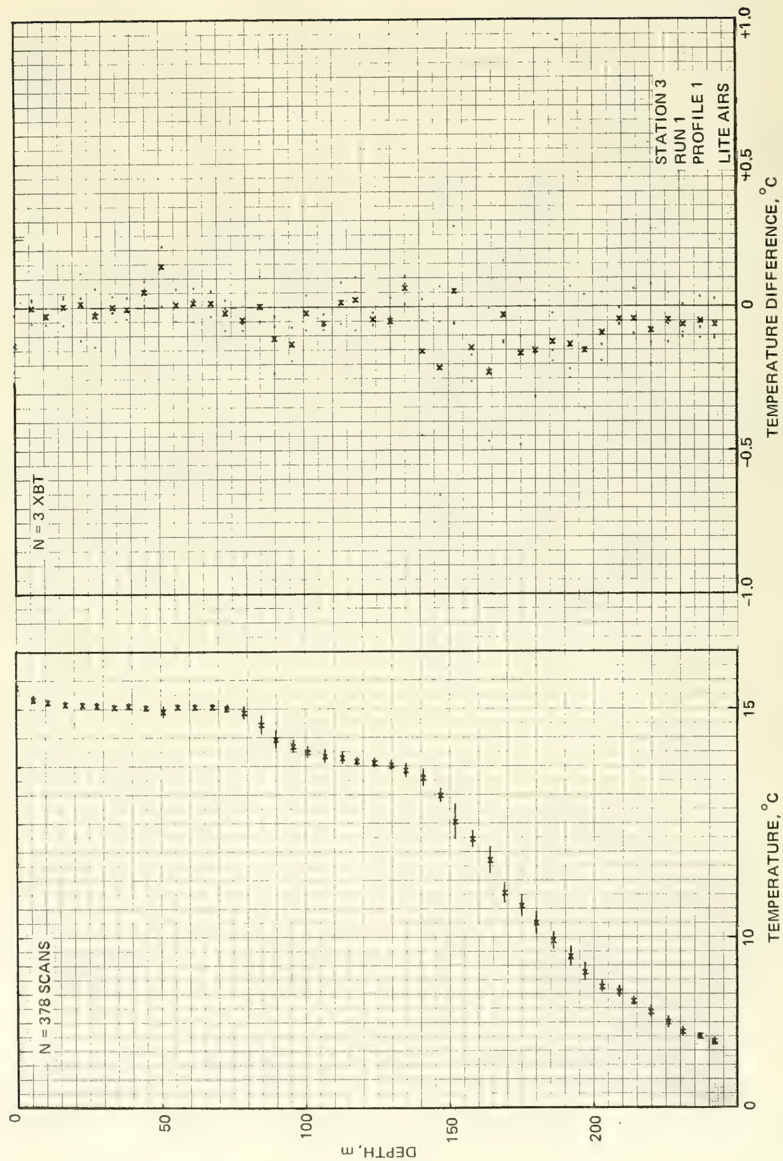
Differences Between Quasisimultaneous XBT and STD/SV Measurements

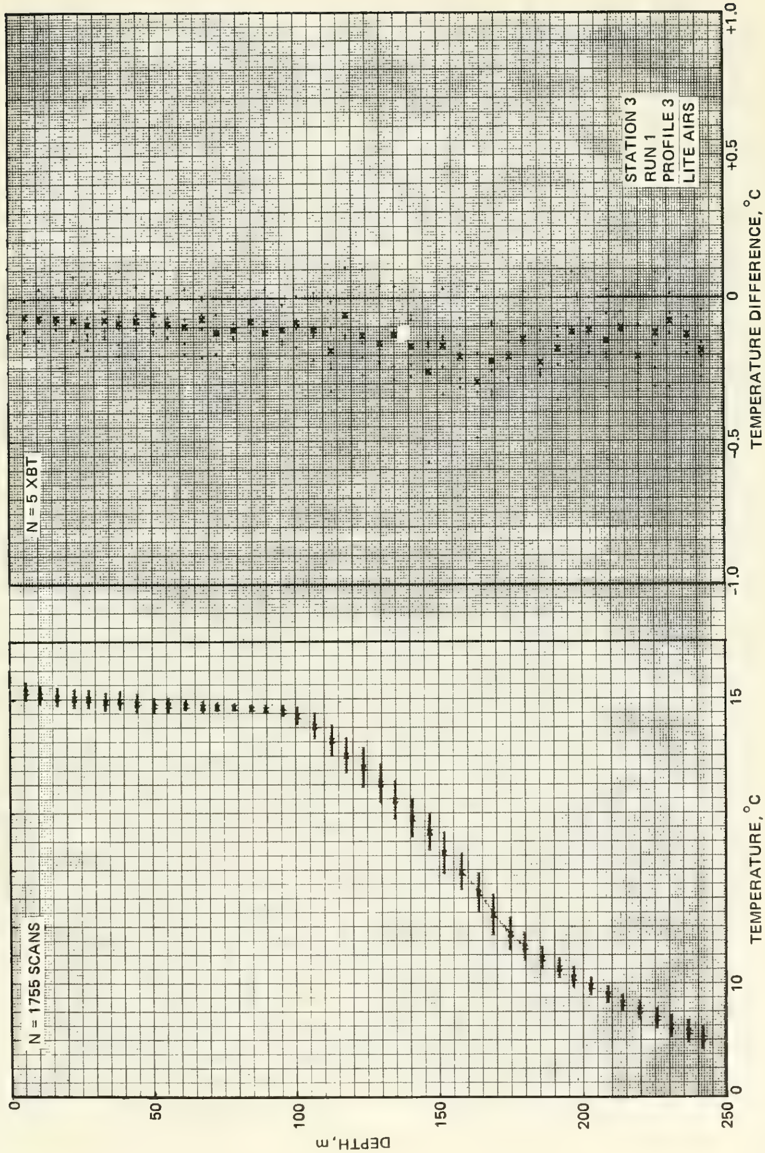
XBT No.	Time Difference, min	Temperature Difference, °C Surface	200	300	400
GULF OF ALASKA					
A1-40	0	0.15	0.03		
43	5	0.41	0.33	0.33	0.29
A2-18	30	-0.13	-0.06	-0.05	0.03
21	0	-0.15	-0.10	-0.02	-0.05
23	22	-0.10	-0.03	0.35	0.33
ES1-10	30	-0.09	0.13	0.11	0.07
26	30	-0.10	0.00	0.06	0.00
31	30	0.11	-0.03	-0.01	0.02
42	30	-0.05	-0.07	-0.01	0.01
49	0	0.05	0.01	0.09	0.00
56	30	-0.08	-0.17	-0.10	-0.11
68	15	-0.11	0.09	0.15	0.15
78	30	0.06	0.00	0.00	-0.03
84	10	0.28	0.09	-0.13	-0.07
89	30	-0.34	-0.06	-0.12	-0.05
97	30	-0.10	0.14	0.13	0.08
102	30	0.04	0.34	0.25	0.20
117	20	-0.14	0.17	0.10	0.07
124	25	0.28	0.15	0.11	0.14
129	20	0.19	0.21	0.17	0.21
138	15	0.31	0.16	0.24	0.20
146	30	0.26	0.79	0.90	0.97
152	0	0.11	-0.01	0.16	0.13
A4-31	30	-0.13	-0.18	-0.12	-0.06
ES2-35	10	-0.40	0.03	0.02	0.11
49	25	-0.07	-0.41	-0.12	-0.08
52	28	-0.30	-0.09	0.00	0.02
SUDS I 1972					
81L	13	0.04	-0.07	-0.18	
235L	15	0.08	0.18	0.10	0.31
241L	20	0.27	-0.01	0.14	-0.21
CAPER					
28M	30	0.07	0.15	0.52	0.33
29M	25	0.12	0.22	0.40	0.24
30M	0	0.22	0.22	0.25	0.03
33M	21	-0.03	0.08	0.10	0.06
55M	8	-0.83	-1.02	-0.98	-0.79
69M	2	-1.64	-0.97	-0.87	-0.85
71M	10		-1.39	-1.34	-1.19

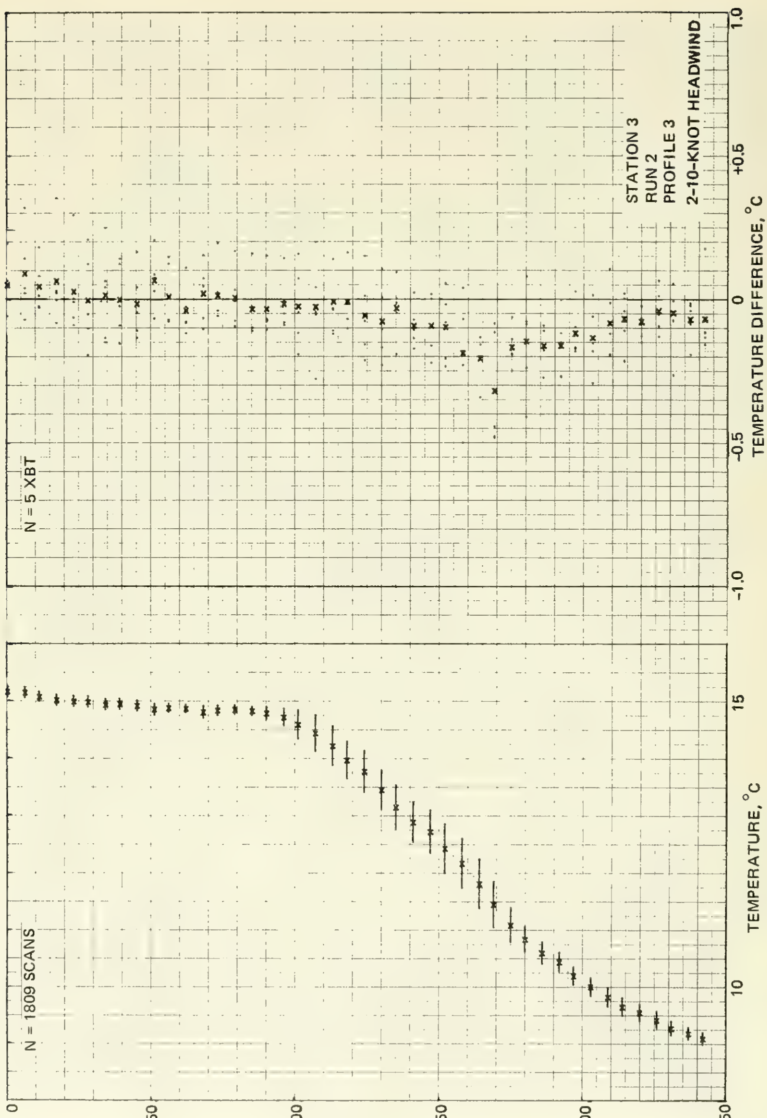
XBT No.	Time Difference, min	Temperature Difference, °C			
		Surface	200	300	400
CAPER (Continued)					
72M	15		-1.31	-1.27	-1.08
76M	5	-0.96	0.19	0.04	0.40
78M	2	0.04	0.91		
81M	16	2.19	2.59	2.49	2.66
83M	0		2.56	2.70	2.88
87M	25	1.27	2.36	2.38	2.25
94M	6	0.72	1.85	2.00	2.18
96M	0	-1.71	-0.68	-0.42	-0.22
101M	0	-1.48	-1.08	-0.90	-0.78
103M	15	-1.72	-0.88	-0.89	-0.83
104M	15	-1.88	-1.16	-0.77	-0.73
107M	5	-1.19	-0.97	-0.80	-0.65
110M	17	-1.60	-0.94	-0.76	-0.79
RAPLOC/DEEPTOW					
10A	5	0.11	0.25	0.16	0.09
11A	0	0.14	0.75	-0.15	-0.07
12A	0	0.07	-0.26	-0.14	0.01
18A	10	0.02	-0.18	-0.20	-0.15
19A	5	0.05	0.05	0.00	-0.03
20A	6	0.01	-0.12	-0.20	-0.16
21A	3	0.49	0.10	-0.12	-0.12
30A	5	0.00	0.40	0.24	0.30
7B	5	0.05	-0.02	-0.17	-0.09
8B	0	0.08	0.05	0.05	0.06
9B	0	0.07	0.21	0.41	0.27
10B	10	0.07	-0.18	-0.21	-0.17
11B	5	-0.06	-0.05	-0.05	-0.02
12B	6	0.00	-0.14	-0.20	-0.13
13B	3	0.03	-0.11	-0.16	
14B	5	0.01	0.16	0.17	0.00

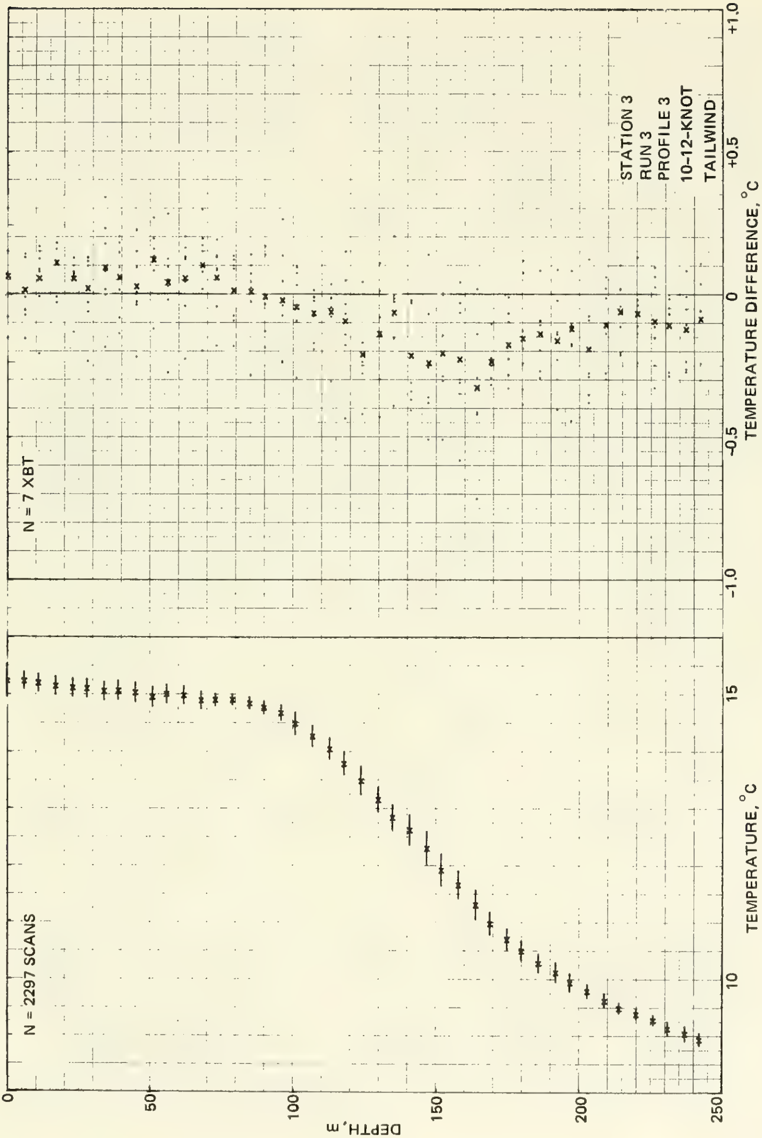
APPENDIX E

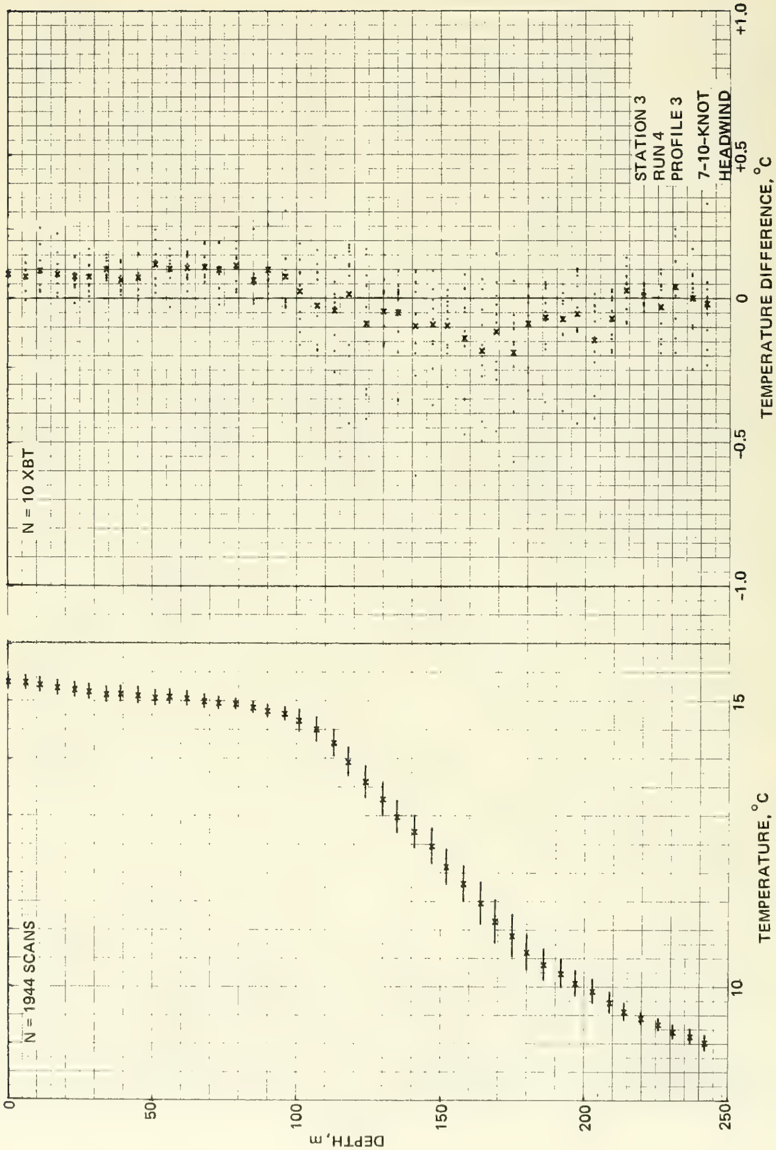
Temperature Differences Between Simultaneous XBT and Thermistor Chain Measurements

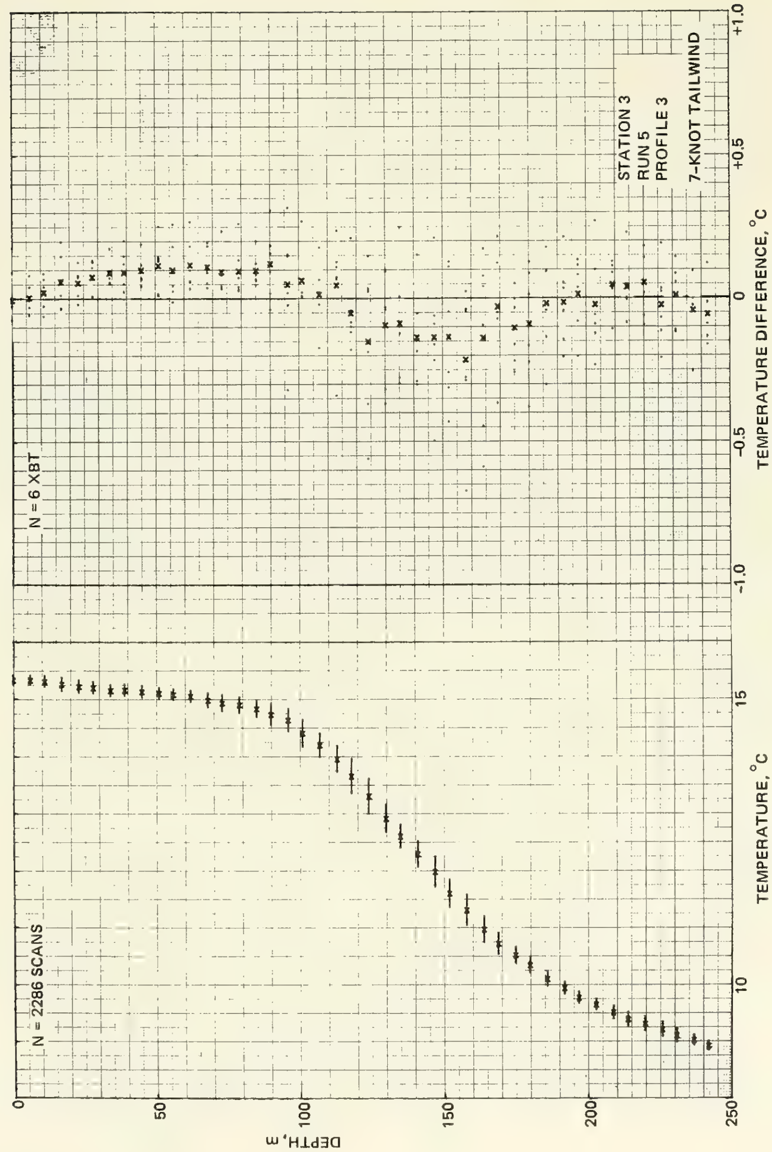

N = 378 SCANS
N = 3 XBT
STATION 3
RUN 1
PROFILE 1
LITE AIRS
DEPTH, m
0
50
100
150
200
TEMPERATURE, °C
0
10
15
TEMPERATURE DIFFERENCE, °C
−1.0
−0.5
0
+0.5
+1.0

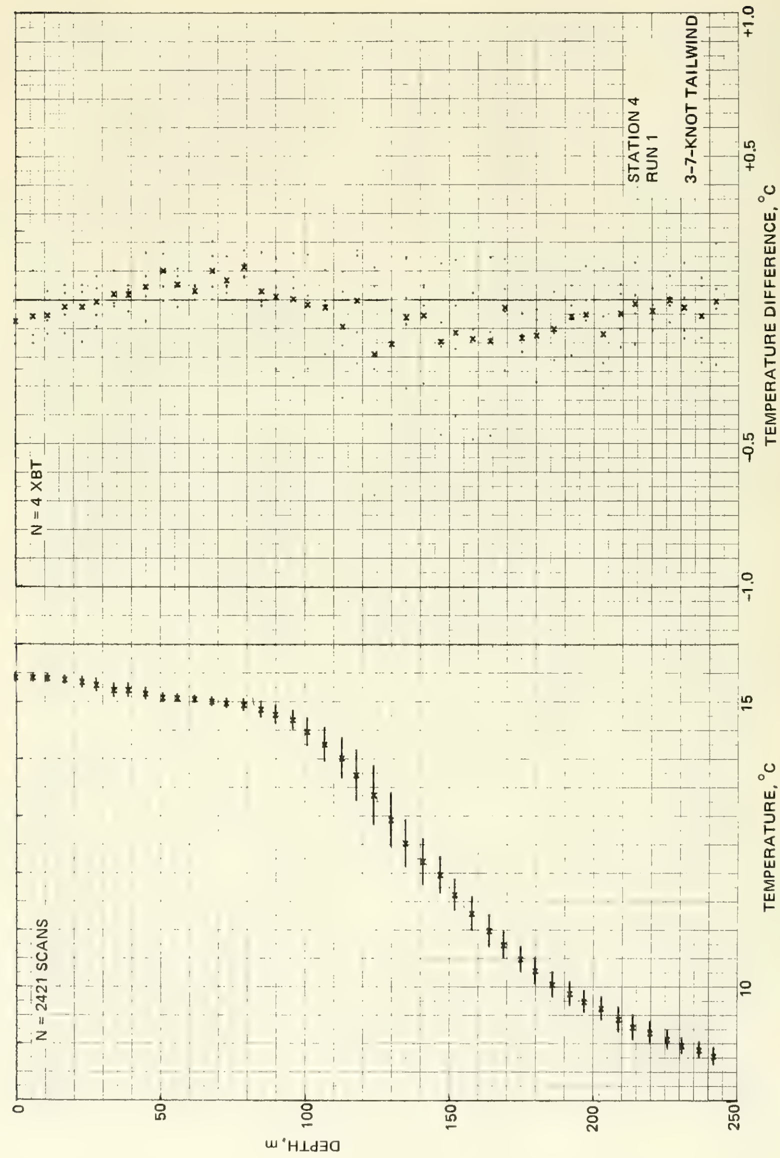

N = 1755 SCANS
N = 5 XBT
STATION 3
RUN 1
PROFILE 3
LITE AIRS
TEMPERATURE, °C
TEMPERATURE DIFFERENCE, °C
DEPTH, m
0
50
100
150
200
250
10
15
-1.0
-0.5
0
+0.5
+1.0


N = 1809 SCANS
N = 5 XBT
STATION 3
RUN 2
PROFILE 3
2-10-KNOT HEADWIND
DEPTH, m
0
50
100
150
200
250
TEMPERATURE, °C
10
15
TEMPERATURE DIFFERENCE, °C
-1.0
-0.5
0
+0.5
1.0

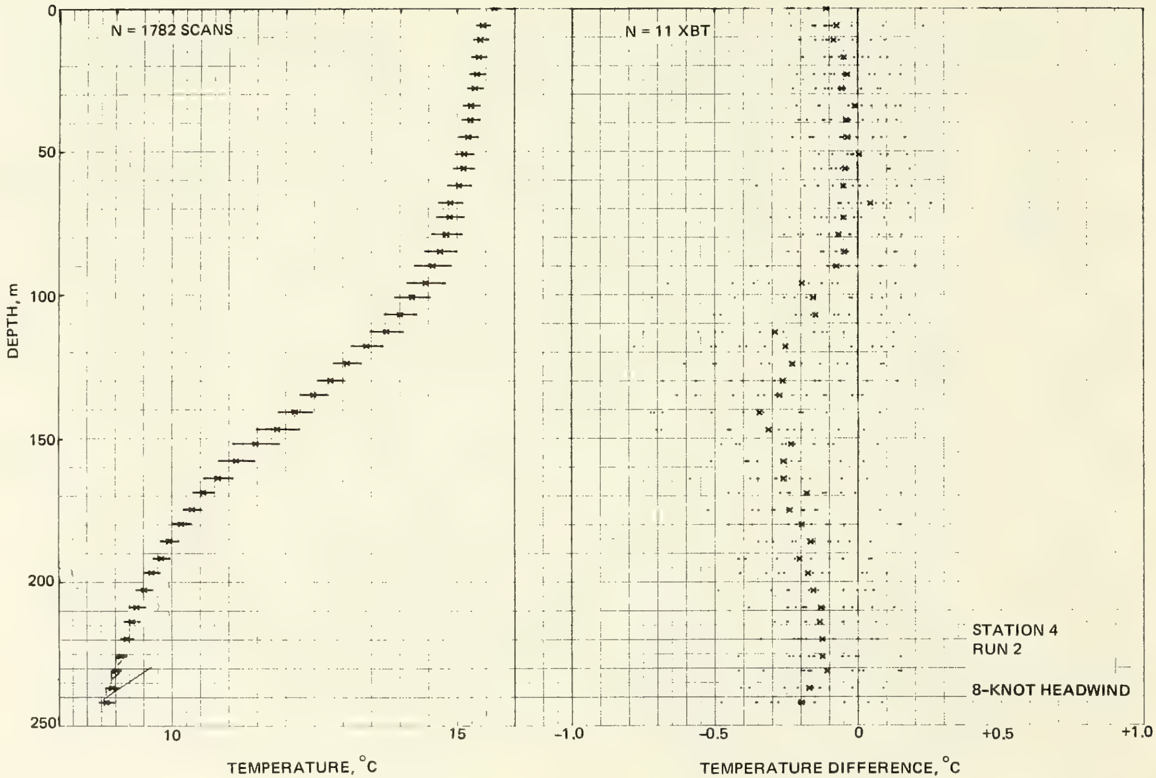

N = 7 XBT
N = 2297 SCANS
STATION 3
RUN 3
PROFILE 3
10-12-KNOT
TAILWIND
TEMPERATURE DIFFERENCE, °C
TEMPERATURE, °C
DEPTH, m
-1.0
-0.5
0
+0.5
+1.0
10
15
0
50
100
150
200
250

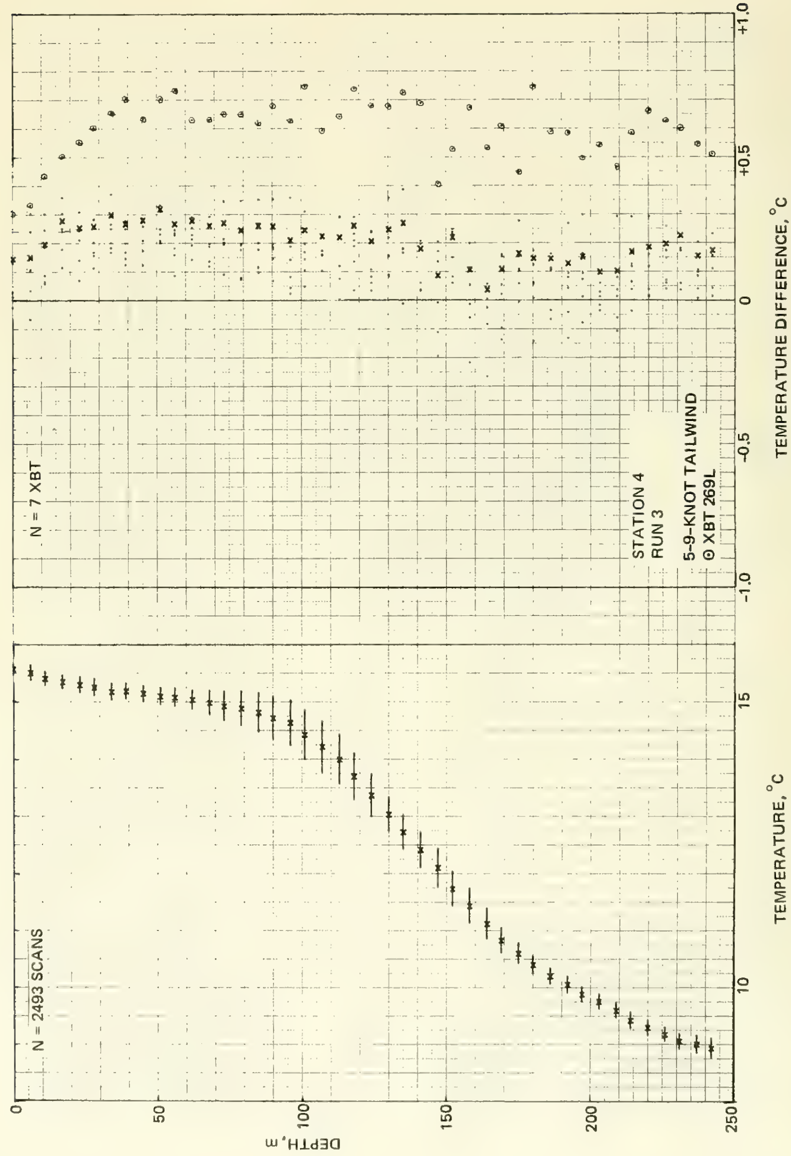

N = 1944 SCANS
N = 10 XBT
STATION 3
RUN 4
PROFILE 3
7-10-KNOT
HEADWIND
DEPTH, m
0
50
100
150
200
250
TEMPERATURE, °C
10
15
TEMPERATURE DIFFERENCE, °C
-1.0
-0.5
0
+0.5
+1.0

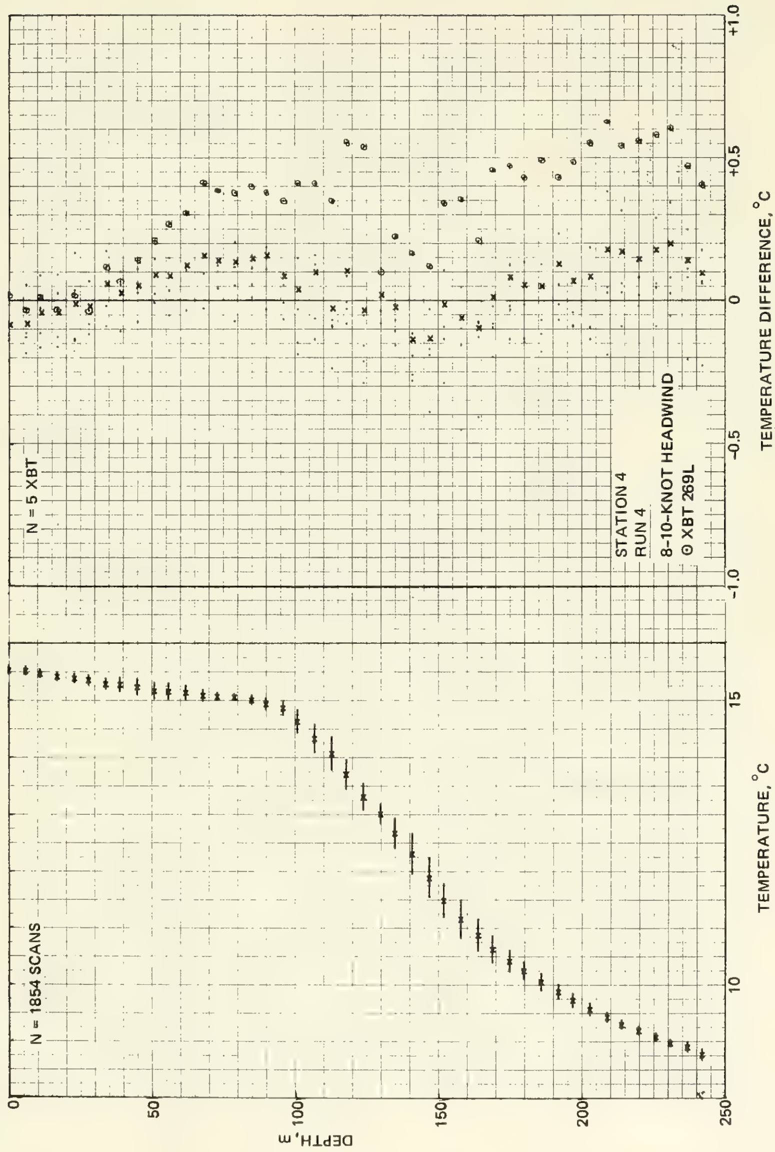

STATION 3
RUN 5
PROFILE 3
7-KNOT TAILWIND
N = 6 XBT
N = 2286 SCANS
TEMPERATURE DIFFERENCE, °C
TEMPERATURE, °C
DEPTH, m
+1.0
+0.5
0
-0.5
-1.0
15
10
0
50
100
150
200
250



N = 2421 SCANS
N = 4 XBT
STATION 4
RUN 1
3-7-KNOT TAILWIND
DEPTH, m
0
50
100
150
200
250
TEMPERATURE, °C
10
15
TEMPERATURE DIFFERENCE, °C
-1.0
-0.5
+0.5
+1.0


N = 1782 SCANS
N = 11 XBT
DEPTH, m
0
50
100
150
200
250
10
15
TEMPERATURE, °C
-1.0
-0.5
0
+0.5
+1.0
TEMPERATURE DIFFERENCE, °C
STATION 4
RUN 2
8-KNOT HEADWIND


N = 2493 SCANS
N = 7 XBT
STATION 4
RUN 3
5-9-KNOT TAILWIND
⊙ XBT 269L
TEMPERATURE, °C
TEMPERATURE DIFFERENCE, °C
DEPTH, m
0
50
100
150
200
250
10
15
-1.0
-0.5
0
+0.5
+1.0


N = 1854 SCANS
N = 5 XBT
STATION 4
RUN 4
8-10-KNOT HEADWIND
⊖ XBT 269L
TEMPERATURE, °C
TEMPERATURE DIFFERENCE, °C
DEPTH, m
0
50
100
150
200
250
10
15
−1.0
−0.5
0
+0.5
+1.0

APPENDIX F

Statistical Summary for Comparisons from the Surface to 90 m of Simultaneous XBT Profiles and Thermistor Chain Scans Made Underway at 3 knots

	XBT Number	Difference, °C Average	Standard Deviation	Number of Differences: Positive	Negative
Station 3 run 1	186L	0.03	0.06	12	5
	187L	0.00	0.10	10	7
	189L	-0.05	0.07	3	14
	190L	-0.18	0.07	0	17
	191L	0.04	0.05	14	3
	192L	-0.11	0.06	1	16
	193L	-0.08	0.06	1	16
	194L	-0.11	0.04	0	17
Station 3 run 2	196L	-0.08	0.06	1	16
	197L	0.20	0.07	17	0
	198L	-0.03	0.06	7	10
	199L	-0.03	0.06	7	10
	200L	0.03	0.07	10	7
Station 3 run 3	201L	0.06	0.09	11	6
	202L	-0.01	0.07	6	11
	204L	0.12	0.05	16	1
	205L	0.19	0.09	17	0
	206L	-0.18	0.06	0	17
	207L	0.14	0.03	17	0
	208L	0.03	0.06	12	5
Station 3 run 4	209L	0.09	0.05	17	0
	210L	0.08	0.04	16	1
	211L	0.17	0.06	17	0
	212L	0.10	0.04	17	0
	213L	0.05	0.05	16	1
	214L	0.09	0.04	16	1
	215L	0.08	0.04	17	0
	216L	0.17	0.06	17	0
	217L	0.10	0.04	17	0
	218L	0.04	0.05	12	5
Station 3 run 5	219L	0.08	0.04	16	1
	220L	0.11	0.07	14	3
	222L	0.19	0.07	17	0
	223L	0.01	0.05	10	7
	224L	0.07	0.04	16	1
	225L	0.03	0.04	14	3
Station 4 run 1	243L	0.08	0.05	16	1
	244L	0.07	0.09	13	4
	245L	-0.01	0.07	7	10
	246L	-0.05	0.09	9	11

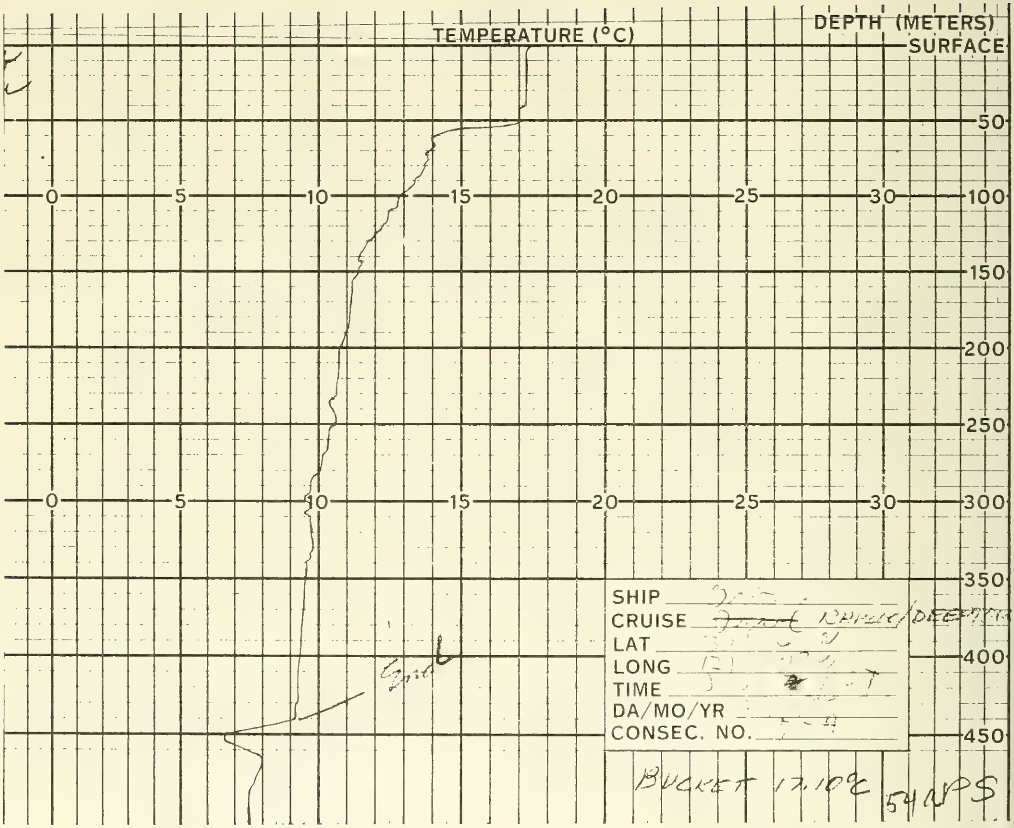
	XBT Number	Difference, °C: Average	Difference, °C: Standard Deviation	Number of Differences: Positive	Number of Differences: Negative
Station 4 run 2	249L	-0.10	0.07	2	15
	250L	-0.20	0.08	0	17
	251L	-0.02	0.07	5	12
	252L	-0.12	0.12	2	15
	253L	-0.02	0.11	6	11
	254L	-0.18	0.09	0	17
	255L	-0.06	0.06	2	15
	256L	-0.09	0.07	1	16
	257L	0.12	0.07	16	1
	259L	0.05	0.09	14	3
	260L	0.12	0.07	16	1
Station 4 run 3	261L	0.17	0.06	17	0
	262L	0.11	0.08	15	2
	263L	0.17	0.07	17	0
	264L	0.25	0.06	17	0
	265L	0.25	0.07	17	0
	267L	0.23	0.11	17	0
Station 4 run 4	268L	0.09	0.04	17	0
	270L	-0.02	0.13	8	9
	271L	0.08	0.10	14	3
	272L	-0.05	0.07	4	13

APPENDIX G

Temperature Differences and Gradient Biases for Selected XBT Profiles

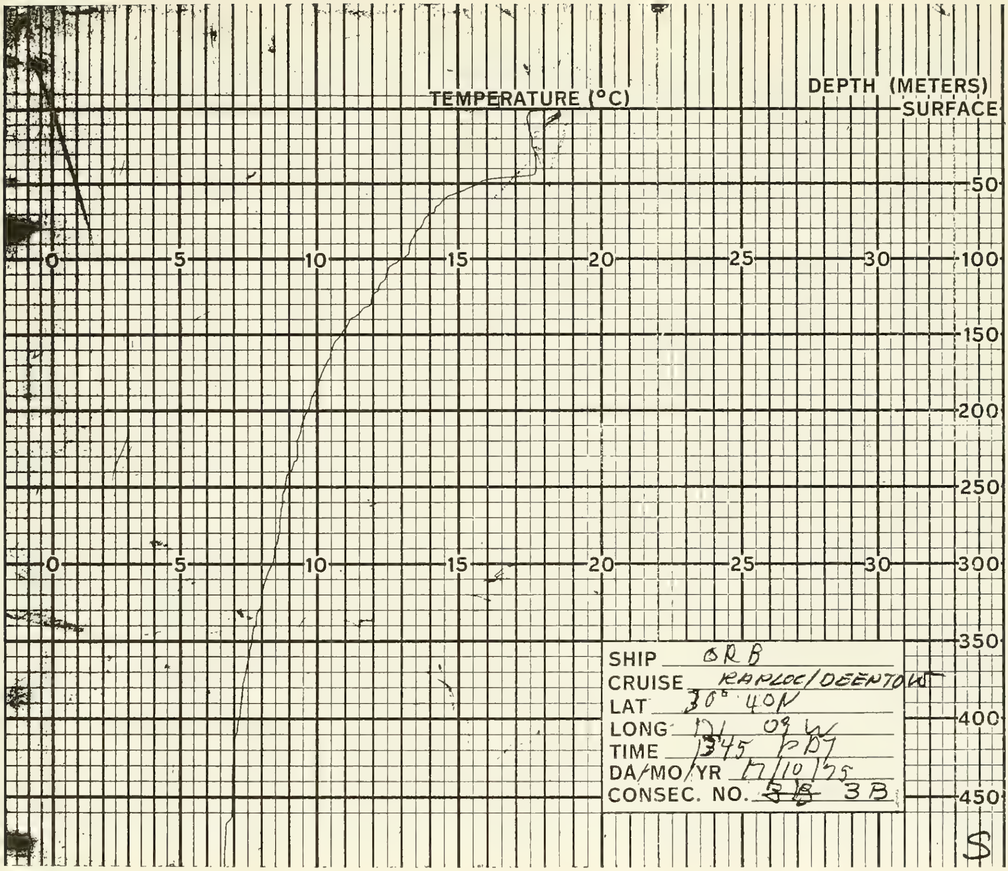
XBT Number	Temperature Difference °C			Temperature Gradient Biases °C/100 m	
	200 m	300 m	400 m	200–300 m	300–400 m
GULF OF ALASKA water mass 2					
IT-18	1.04	1.00	0.88	–0.04	–0.12
IT-21	0.71	0.65	0.68	–0.06	0.03
IT-23	0.30	0.47	0.50	0.17	0.03
ES1-65	0.90	0.50	0.43	–0.40	–0.07
GULF OF ALASKA transition water mass					
IT-30	0.58	0.35	0.26	–0.23	–0.09
IT-32	0.69	0.21	0.19	–0.48	–0.02
A2-2	0.50	0.25	0.24	–0.25	–0.01
A2-14	0.31	0.51	0.69	0.20	0.18
ES1-2	0.67	0.45	0.25	–0.22	–0.20
ES1-2a	0.69	0.31	0.40	–0.38	0.09
ES1-13	0.53	0.37	0.30	–0.16	–0.07
ES1-16	0.56	0.37	0.32	–0.19	–0.05
ES1-146	0.91	0.97	0.95	0.06	–0.02
ES1-158	0.87	0.19	0.26	–0.68	–0.07
A3-6	0.50	0.30	0.24	–0.20	–0.06
SUDS I 1972 area C					
186L	0.55	0.20	0.08	–0.35	–0.12
188L	–0.66	–0.66	–0.37	0.00	0.29
214L	0.50	0.27	0.15	–0.23	–0.12
252L	–0.50	–0.23	–0.14	0.27	0.09
256L	–0.66	–0.31	–0.20	0.35	0.11
266L	0.43	0.42	0.54	–0.01	0.12
269L	0.35	0.39	0.56	0.04	0.17
271L	0.15	0.47	0.50	0.32	0.03
282L	–0.04	0.05	0.64	0.09	0.59
98D	0.53	–0.12	0.30	–0.41	0.42
100D	0.73	0.44	0.43	–0.39	–0.01
103D	0.50	0.72	0.66	0.22	–0.06
110D	–0.64	–0.27	–0.29	0.37	–0.02
122D	0.58	0.40	0.44	–0.18	0.04
127Da	0.36	0.41	0.59	0.05	0.18
128D	1.09	0.36	0.70	–0.73	0.34
132D	0.54	0.43	0.65	–0.11	0.22
134D	0.51	0.90	0.57	0.39	–0.33
70C	0.57	0.03	–0.08	–0.54	–0.11
86C	–0.52	–0.30	–0.05	0.22	0.25
100C	0.84				

XBT Number	Temperature Difference °C 200 m	300 m	400 m	Temperature Gradient Biases °C/100 m 200–300 m	300–400 m
CAPER water mass 2					
56D	0.34	0.32	0.66	–0.02	0.34
58D	0.17	0.17	0.53	0.00	0.36
81D	0.09	1.05		0.96	
83D	0.02	0.90	1.42	0.88	0.52
102D	0.52	0.35	–0.07	–0.17	–0.42
RAPLOC/DEEPTOW at anchor					
3A	0.49	0.76	0.51	0.27	–0.25
4A	0.54	0.57	0.55	0.03	–0.02
24A	0.78	0.39	0.43	–0.39	0.04
25A	0.53	0.28	0.29	–0.25	0.01
27A	0.79	0.47		–0.32	
31A	0.61	0.28	0.17	–0.33	–0.11
43A	0.52	0.25	0.13	–0.27	–0.12
50A	–0.19	0.53	0.68	0.72	0.15
55A	2.01	2.33	3.02	0.32	0.69
61A	0.80	0.73	0.78	–0.07	0.05
68A	–0.73	0.15	0.25	0.88	0.10
3B	1.08	1.28	1.02	0.20	–0.26
44B	0.92	0.86	0.53	–0.06	–0.33



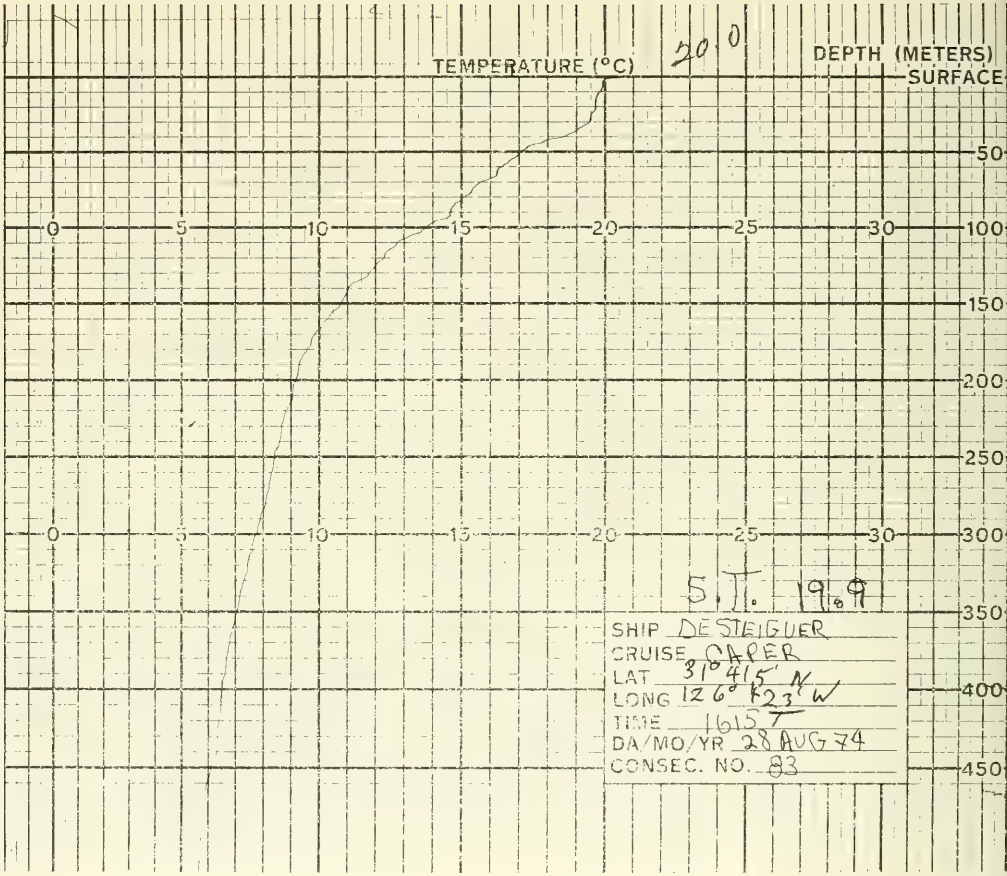
RAPLOC/DEEPTOW XBT 55A: Largest positive differences at 200, 300, and 400 m
Largest 300–400-m positive gradient bias

Calibration correction:	0.09°C
200-m difference:	2.01
300-m difference:	3.02
200–300-m gradient bias:	0.32°C/100 m
300–400-m gradient bias:	0.69



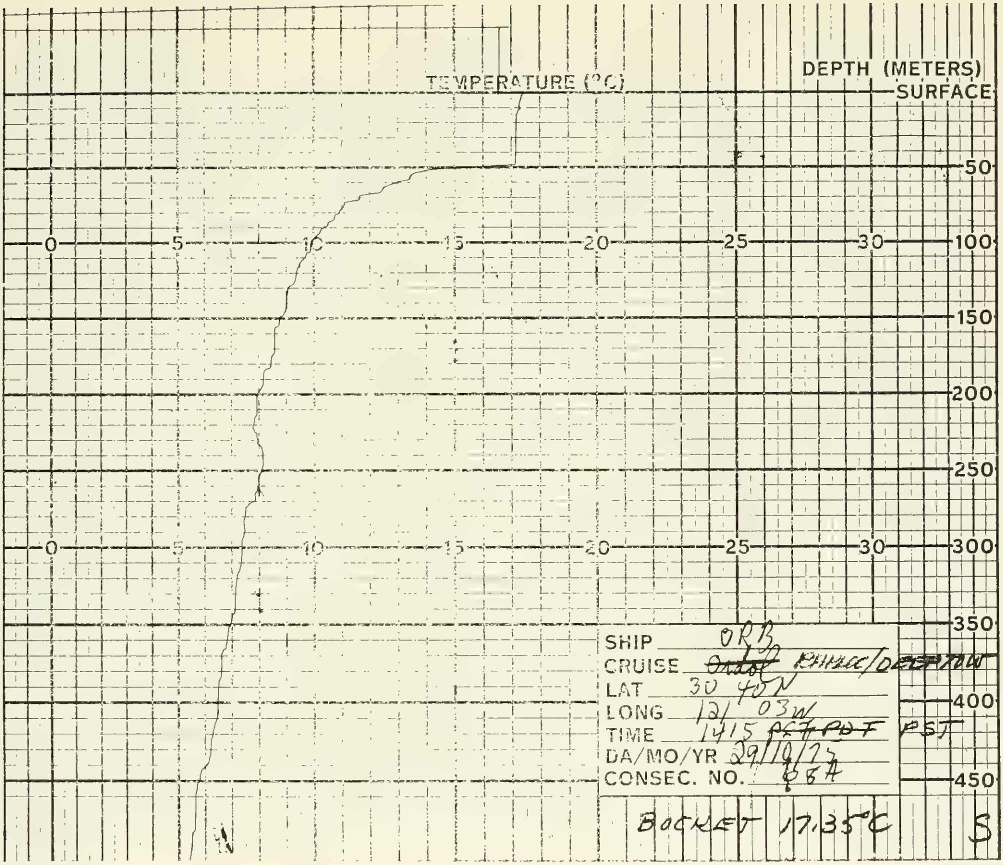
RAPLOC/DEEPTOW XBT 3B: Second largest positive difference at 300 m

Calibration correction:	0.26°C
200-m difference:	1.08
300-m difference:	1.28
400-m difference:	1.02
200–300-m gradient bias:	0.20°C/100 m
300–400-m gradient bias:	–0.26



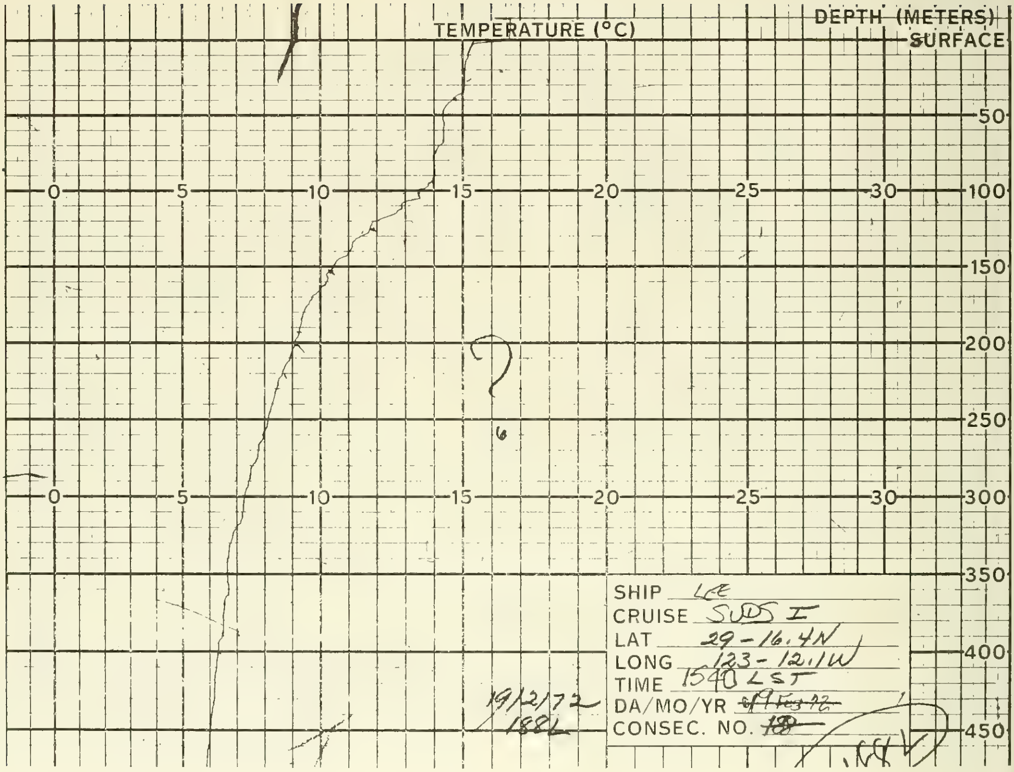
CAPER XBT 83D: Second largest positive difference at 400 m

Calibration correction:	–0.11°C
200-m difference:	0.02
300-m difference:	0.90
400-m difference:	1.42
200–300-m gradient bias:	0.88°C/100 m
300–400-m gradient bias:	0.52



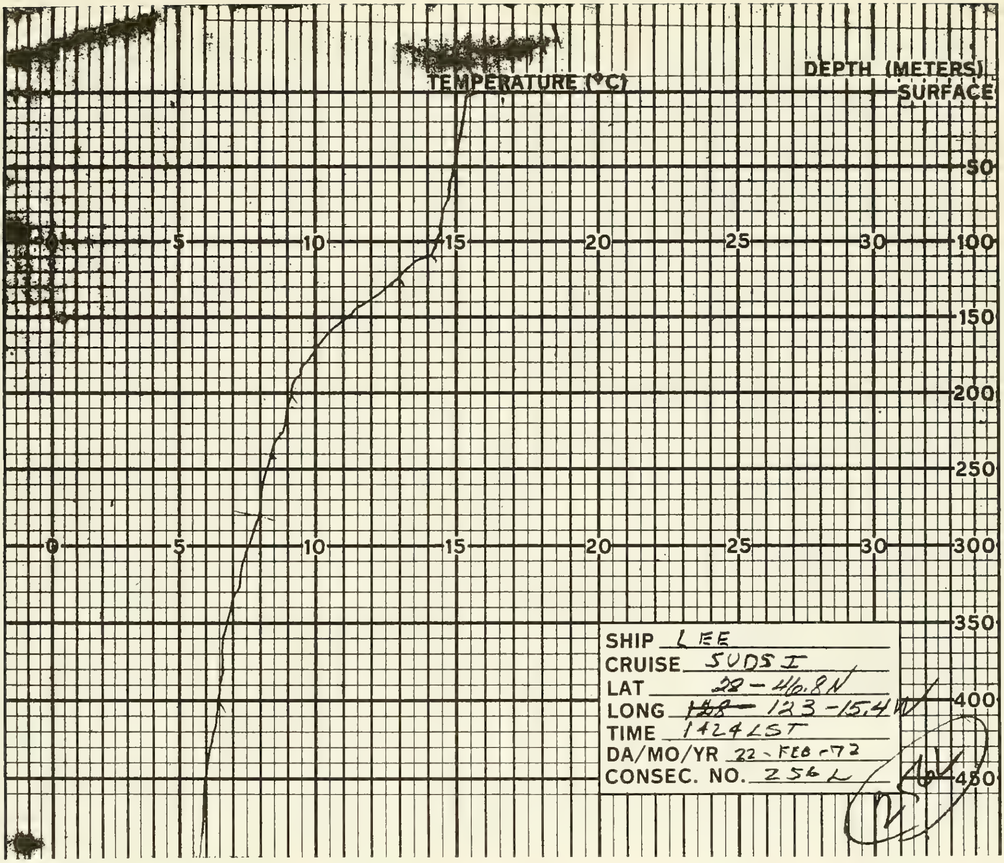
RAPLOC/DEEPTOW XBT 68A: Largest negative difference at 200 m

Calibration correction:	0.08°C
200-m difference:	–0.73
300-m difference:	0.15
400-m difference:	0.25
200–300-m gradient bias:	0.32°C/100 m
300–400-m gradient bias:	0.69



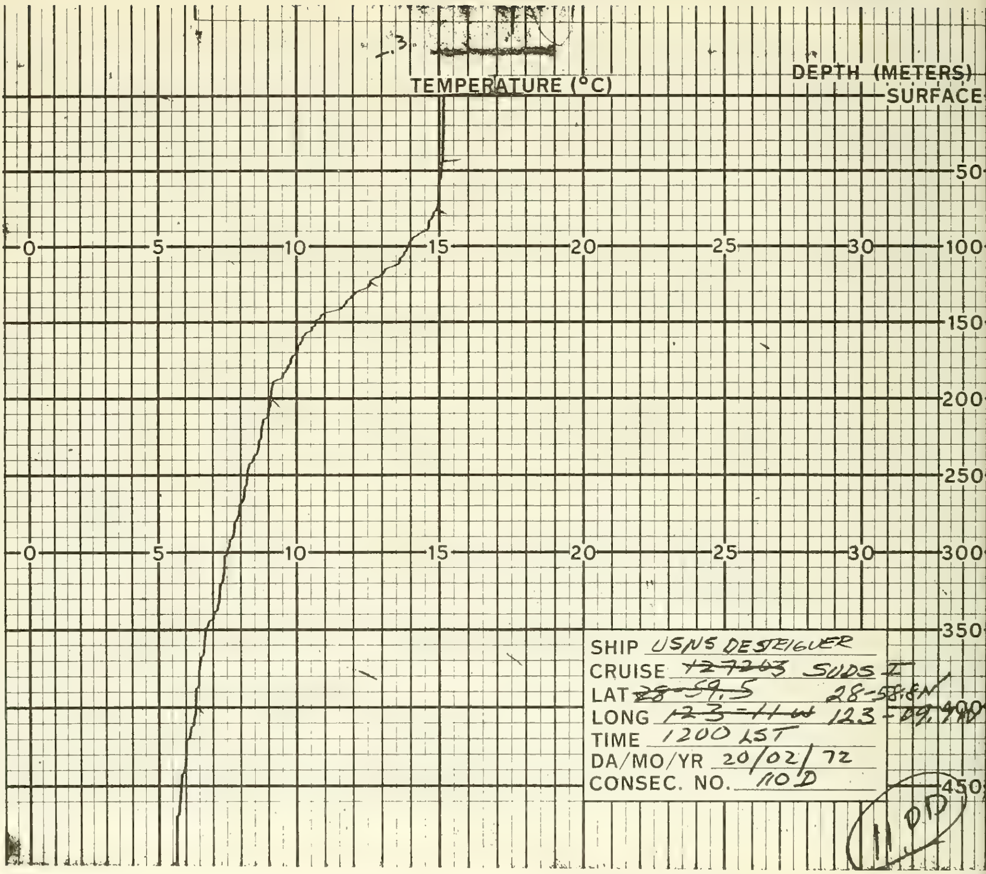
SUDS I 1972   XBT 188L: Largest negative difference at 300 and 400 m
Second largest negative difference at 200 m

Calibration correction:	0.04°C
200-m difference:	–0.66
300-m difference:	–0.66
400-m difference:	–0.37
200–300-m gradient bias:	0.00°C/100 m
300–400-m gradient bias:	0.29



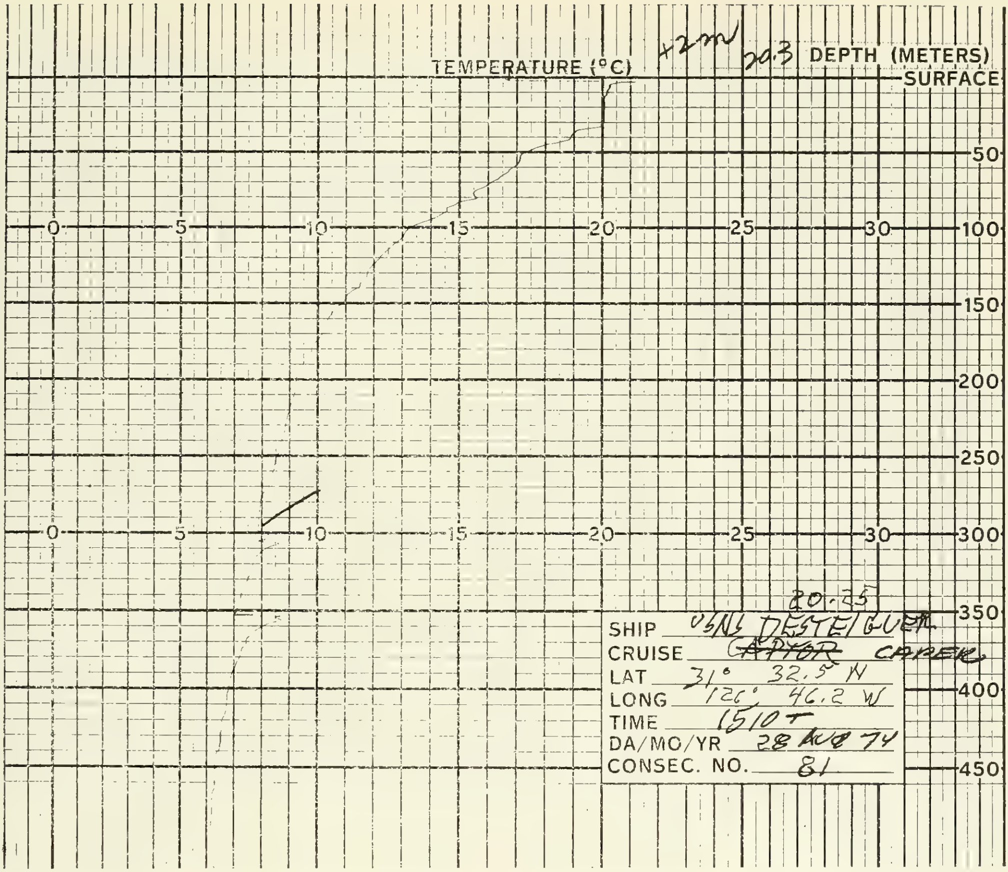
SUDS I 1972   XBT 256L: Second largest negative difference at 200 m

Calibration correction:	–0.01°C
200-m difference:	–0.66
300-m difference:	–0.31
400-m difference:	–0.20
200–300-m gradient bias:	0.35°C/100 m
300–400-m gradient bias:	0.11



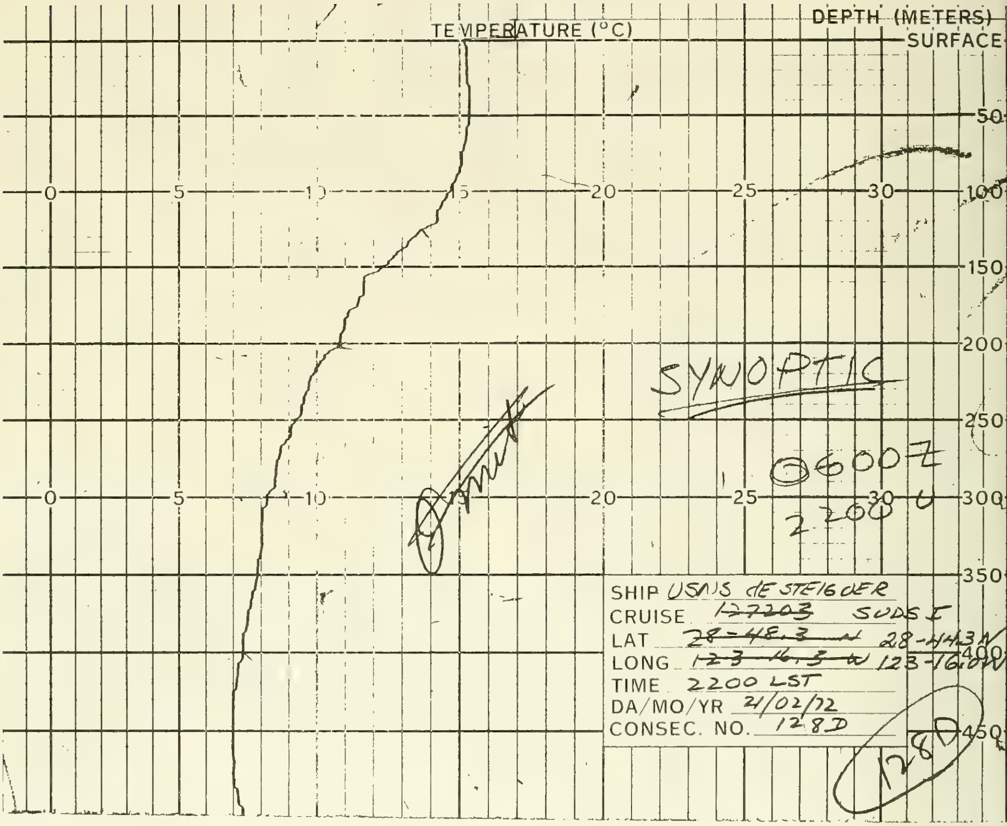
SUDS I 1972 XBT 110D: Second largest negative difference at 400 m

Calibration correction:	–0.25°C
200-m difference:	–0.64
300-m difference:	–0.27
400-m difference:	–0.29
200–300-m gradient bias:	0.37°C/100 m
300–400-m gradient bias:	–0.02



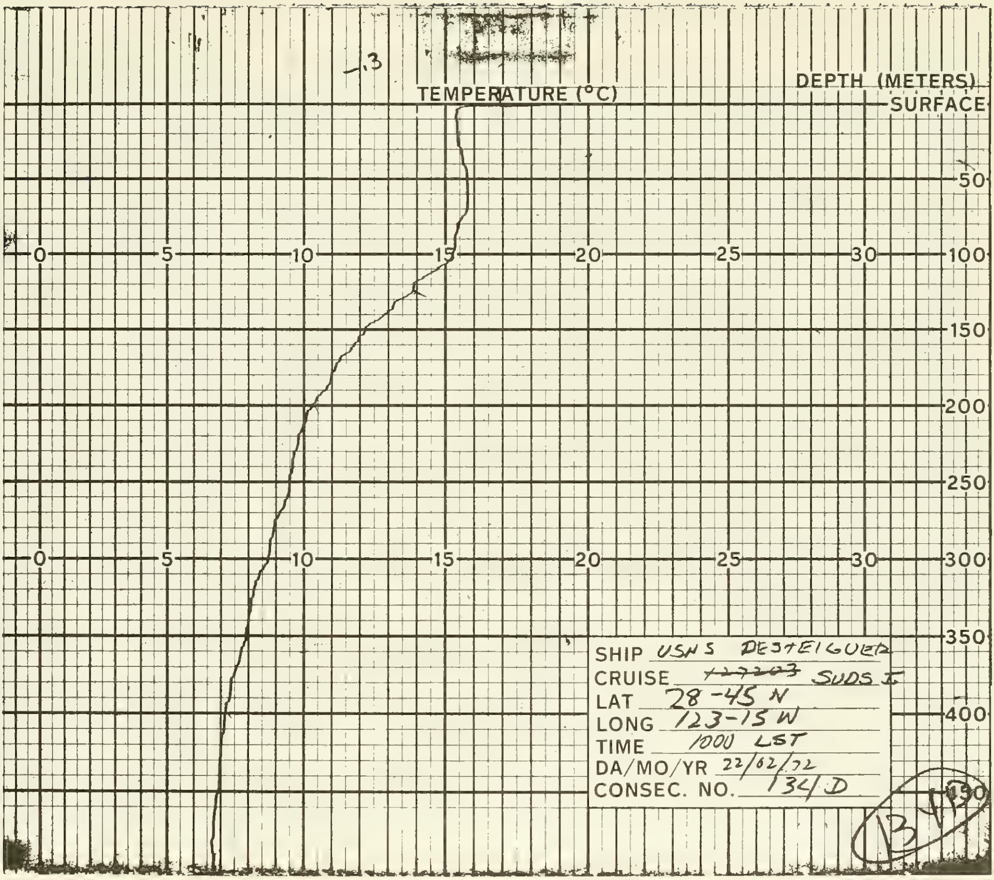
CAPER XBT 81D: Largest 200–300 m positive gradient bias

Calibration correction:	–0.04°C
200-m difference:	0.09
300-m difference:	1.05
400-m difference:	–
200–300-m gradient bias:	0.96°C/100 m
300–400-m gradient bias:	–



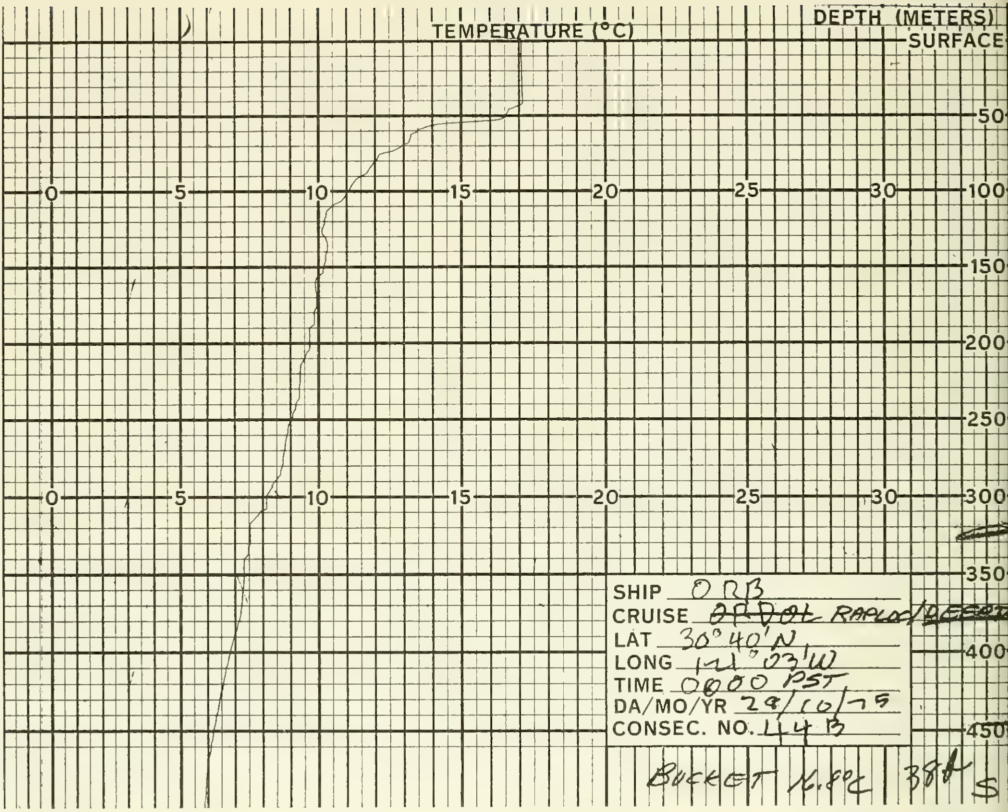
SUDS I 1972 XBT 128D: Largest 200–300 m negative gradient bias
Second largest positive difference at 200 m

Calibration correction:	–0.29°C
200-m difference:	1.09
300-m difference:	0.36
400-m difference:	0.70
200–300-m gradient bias:	–0.73°C/100 m
300–400-m gradient bias:	0.34



SUDS I 1972 XBT 134D: Largest 300–400 m negative gradient bias

Calibration correction:	–0.24°C
200-m difference:	0.51
300-m difference:	0.90
400-m difference:	0.57
200–300-m gradient bias:	0.39°C/100 m
300–400-m gradient bias:	–0.33



RAPLOC/DEEPTOW XBT 44B: Largest 300–400 m negative gradient bias

Calibration correction:	–0.01°C
200-m difference:	0.92
300-m difference:	0.86
400-m difference:	0.53
200–300-m gradient bias:	–0.06°C/100 m
300–400-m gradient bias:	–0.33

APPENDIX H

Comparison of Simultaneous XBT Measurements

Temperature (°C) and Isothermal Layer Depth (m) Differences Between Simultaneous XBT Measurements Taken at 5 knots During ORB-3

Depth, m	XBT Profile Pair 1*	2	3*	6*	7*	9*	10	11*	12
0	0.00	0.02	0.06	0.04	0.02	0.03	–0.10	–0.18	0.21
10	0.09	0.09	0.19	0.06	0.17	0.09	–0.09	–0.12	0.49
20	0.03	0.25	0.21	0.13	0.23	0.21	–0.07	–0.17	0.67
30	–0.09	0.30	0.32	0.10	0.13	0.13	–0.05	–0.22	0.86
50	–0.03	0.38	0.21	0.04	0.09	–0.24	–0.32	–0.18	0.72
75	–0.12	0.70	0.12	0.49	0.04	–0.15	–0.13	0.31	0.81
100	–0.01	0.56	–0.04	–0.05	–0.02	–0.10	–0.04	0.07	0.75
125	–0.05	0.27	0.27	–0.15	0.03	–0.21	0.31	0.18	0.76
150	–0.15	0.30	0.06	–0.20	0.03	–0.07	0.25	0.29	0.56
200	–0.19	0.46	–0.04	0.01	0.00	–0.06	0.09	0.16	0.56
250	–0.18	0.51	–0.03		0.07		0.38	0.29	0.57
300	–0.11	0.47	0.07		0.09			0.20	0.53
400		0.58			0.00			0.20	0.49
Layer Depth	–1	3	–3	–1	0	–1	1	–1	–2

Depth, m	XBT Profile Pair 14	15	16*	17	18*	19*	20	21*	22*
0	0.28	–0.42	0.09	0.07	–0.01	0.10	0.23	0.15	0.07
10	0.23	–0.25	0.12	0.10	0.09	0.07	0.28	0.13	0.06
20	0.14	–0.07	0.14	0.09	0.09	0.04	0.27	0.07	–0.05
30	0.20	0.06	0.11	0.07	0.03	0.02	0.27	0.05	0.06
50	0.11	0.01	0.06	0.05	0.09	0.02	0.25	0.10	0.09
75	2.35	0.62	–0.27	–0.20	0.28	0.36	0.27	0.65	–0.03
100	0.65	0.43	0.42	0.38	0.17	–0.01	0.21	0.19	0.01
125	0.31	0.28	0.20	0.25	0.16	–0.13	0.35	0.19	–0.05
150	0.39	0.19	0.08	0.43	0.30		0.22	0.14	
200	0.31	0.33	0.14	0.35	0.23		0.24	0.24	
250	0.24	0.20	0.15	0.39	0.32		0.26	0.18	
300	0.23			0.21	0.30		0.39	0.26	
400	0.30			0.38			0.26	0.18	
Layer Depth	6	0	–2	–3	5	–2	–2	–3	1

Temperature (°C) and Isothermal Layer Depth (m) Differences Between Simultaneous XBT Measurements Made at Anchor During ORB-3

Depth, m	XBT Profile Pair								
	24*	25*	26	27	28*	29*	30	31*	32
0	0.33	0.02	0.22	0.01	0.07	0.02	0.23	0.05	-0.20
10	-0.01	-0.02	0.37	0.10	0.00	0.18	0.17	0.10	-0.16
20	-0.01	-0.01	0.46	0.14	0.08	0.18	0.17	0.04	-0.19
30	0.00	-0.01	0.49	0.39	0.13	0.09	0.22	-0.07	-0.14
50	-0.03	0.06	0.53	0.27	0.10	0.01	0.18	-0.04	-0.18
75	0.40	0.53	0.81	0.45		0.23	0.37	0.14	-0.13
100	0.22	0.30	0.53	0.22		0.10	0.44	-0.04	-0.32
125	-0.02	0.37	0.46	0.21		0.11	0.27	-0.01	-0.21
150	-0.09	0.19	0.38	0.24		0.04	0.37	0.01	-0.25
200	-0.04	0.08	0.23	0.21		-0.03	0.22	-0.03	-0.39
250	-0.03	0.12	0.50	0.08		0.07		0.03	-0.53
300	-0.09	0.12		0.24		-0.05		-0.05	-0.36
400	-0.07	0.10		0.14		-0.12		0.07	-0.49
Layer Depth	0	1	-1	-1	3	2	6	1	-5

Depth, m	XBT Profile Pair								
	33*	34*	37*	38*	39*	42*	43	44*	45*
0	0.05	-0.08	0.04	-0.01	0.02	0.11	0.72	-0.04	-0.05
10	0.01	0.01	0.00	0.04	0.02	0.06	0.10	0.00	0.04
20	0.01	0.01	0.01	0.10	0.07	0.21	0.30	0.03	0.04
30	0.10	0.00	0.03	0.12	0.12	0.16	0.34	0.08	0.04
50	0.30	-0.01	-0.10	-0.06	0.06	0.20	0.47	-0.04	0.03
75	0.10	0.00	0.13	0.11	0.16	0.10	0.45	0.08	0.29
100	-0.12	-0.07	0.03	0.08	0.06	0.14	0.49	0.05	0.08
125	0.14	-0.02	0.07	0.00	0.00	0.19	0.42	0.13	0.02
150	0.14	-0.03	0.00	0.03	0.05	0.19	0.45	0.10	0.06
200	0.09	-0.02	0.03	0.04		0.12	0.55	0.06	0.00
250	0.14	0.10	-0.01	-0.01		0.16	0.52	0.05	0.09
300	0.13	0.00	0.03	-0.06		0.04	0.36	0.01	-0.09
400	0.01	-0.05	0.02	-0.10		0.07	0.33	0.28	-0.18
Layer Depth	-4	-3	-1	-2	-2	0	1	-2	7

Depth, m	XBT Profile Pair								
	46	47	48	49	50*	52	53*	54	55
0	0.00	0.26	0.16	0.28	0.04	–0.14	–0.05	–0.06	–0.01
10	–0.22	0.41	0.25	0.13	0.13	0.02	–0.03	–0.07	0.03
20	–0.16	0.45	0.34	0.02	0.18	–0.13	–0.02	–0.08	0.18
30	–0.09	0.39	0.14	0.11	0.13	–0.14	–0.05	–0.12	0.19
50	0.00	0.47	0.16	0.35	0.03	–0.20	–0.11	–0.02	0.33
75	0.49	1.03	–0.37	0.23	0.04	–0.05	0.13	–0.13	0.66
100	0.17	0.66	–0.35	0.06	–0.02	–0.26	0.13	–0.18	0.58
125	0.02	0.70	–0.47	0.10	–0.12	–0.38	–0.08	–0.20	0.53
150	–0.10	0.59	–0.40	0.07	–0.02	–0.38	0.07	–0.19	0.44
200	–0.62	0.75	–0.34	0.03	–0.08	–0.35	0.06	–0.52	0.35
250	–1.21	0.47	–0.45	0.09	–0.07	–0.30	–0.05	–0.59	0.32
300	–1.60	0.38	–0.33	0.05	–0.08	–0.37	–0.06	–0.76	0.27
400	–1.74	0.31	–0.27	0.02	–0.15	–0.29	–0.13	–0.84	0.21
Layer Depth	–1	4	–7	1	–3	2	4	–2	8

Temperature (°C) and Isothermal Layer Depth (m) Differences Between Simultaneous XBT Measurements Made at Anchor During RAPLOC/DEEPTOW

Depth, m	XBT Profile Pair								
	1*	2	3*	4	5*	6*	7*	8	9
0	0.02	0.06	0.06	0.00	−0.05	0.11	0.01	0.46	−0.01
10	0.12	0.10	0.00	−0.11	0.10	0.01	−0.01	0.46	0.05
20	0.13	0.15	−0.05	−0.20	0.08	0.10	−0.01	0.40	0.20
30	0.13	0.24	−0.06	−0.35	0.08	0.17	0.08	0.39	0.33
50	0.03	0.77	−0.28	−0.65	−0.25	0.36	0.05	0.64	0.51
75	0.18	0.34	−0.19	−0.62	−0.03	0.15	−0.04	0.42	0.62
100	0.14	0.37	−0.26	−0.61	0.00	0.25	0.03	0.41	0.43
125	0.19	0.40	−0.27	−0.71	−0.08	0.10	0.06	0.29	0.39
150	0.20	0.37	−0.29	−0.65	−0.06	0.02	−0.03	0.28	0.39
200	0.22	0.27	−0.31	−0.47	0.00	0.10	0.02	0.21	0.24
250	0.18	0.23	−0.28	−0.56	−0.09	0.04	0.00	0.13	0.21
300	0.30	0.33	−0.20	−0.55	0.01	0.05	0.00	0.04	0.17
400	0.29	0.18	−0.13	−0.26	0.02	−0.01	−0.03		0.30
Layer Depth	1	−2	−7	−3	−2	−1	−4	1	4

Depth, m	XBT Profile Pair								
	10*	11*	12*	13*	14*	15*	16*	17*	18*
0	−0.01	−0.01	0.12	0.26	−0.12	0.05	0.03	0.05	0.24
10	0.00	−0.10	0.16	0.10	−0.05	0.10	0.10	0.16	0.16
20	−0.04	−0.14	0.04	0.16	0.07	0.20	0.16	0.12	0.02
30	0.02	−0.17	0.12	0.07	0.13	0.30	0.19	0.13	−0.12
50	0.02	−0.55	0.08	0.16	−0.20	0.64	0.42	0.45	0.31
75	0.27	−0.41	0.11	−0.04	−0.02	0.48	0.20	0.12	0.09
100	0.21	−0.22	0.14	0.07	−0.04	0.42	0.30	0.10	0.06
125	0.13	−0.29	0.01		−0.07	0.37	0.19	0.03	0.15
150	0.17	−0.15	0.05		−0.04	0.31	0.12	0.00	0.09
200	0.17	−0.23	0.16		0.03	0.15	0.11	0.03	0.16
250	0.13	−0.21	0.03		0.04	0.25	0.09	0.01	0.17
300	0.13	−0.29	0.09		−0.10	0.13	0.07	−0.09	0.05
400	0.10	−0.08	0.01		−0.14	0.16	0.09	0.03	−0.01
Layer Depth	2	0	−1	4	0	2	0	2	2

Depth, m	XBT Profile Pair								
	19*	20*	21*	22	23*	24*	25*	26*	27*
0	-0.04	-0.05	0.00	0.01	0.10	0.19	0.00	0.09	0.28
10	0.06	0.00	-0.01	0.02	0.07	0.27	0.01	0.10	0.00
20	0.01	0.15	0.02	0.03	0.10	0.19	0.07	0.17	0.01
30	-0.04	0.10	-0.05	0.11	0.12	0.16	-0.03	0.03	0.03
50	-0.26	-0.01	-0.11	0.19	0.17	0.00	-0.41	0.06	0.37
75	-0.22	0.18	0.29	0.24	0.20	0.12	-0.15	0.02	0.38
100	-0.19	0.24	0.46	0.46	0.19	0.10	-0.07	0.03	0.20
125	-0.25	0.13	0.22	0.27	0.12	-0.01	-0.11	0.04	0.07
150	-0.16	0.07	0.24	0.43	0.16		-0.13	-0.10	-0.07
200	-0.28	0.17	0.11	0.40	0.07		-0.14	-0.08	-0.08
250	-0.24	0.06	0.08	0.37	0.08		-0.09	-0.01	0.02
300	-0.20	0.16	0.22	0.29	0.00		-0.10	0.01	-0.11
400	-0.17	0.26	0.02	0.27	0.03		-0.06	-0.05	-0.12
Layer Depth	0	2	10	2	-4	-2	2	0	0

Depth, m	XBT Profile Pair								
	28	29*	30*	31*	32*	33	34*	35*	36*
0	0.09	0.15	0.06	0.08	0.17	0.13	-0.20	0.00	0.10
10	0.24	0.14	0.06	0.04	0.13	0.20	-0.15	-0.06	0.05
20	0.21	0.10	0.09	0.05	0.18	0.14	-0.09	-0.06	0.01
30	0.19	0.10	0.08	0.02	0.24	0.12	-0.04	-0.02	-0.03
50	0.03	0.56	1.93	0.15	0.21	0.33	0.32	-0.14	-0.05
75	-0.03	0.66	0.74	-0.14	0.44	1.65	0.07	-0.02	0.05
100	0.00	0.73	0.42	-0.35	0.36	1.95	-0.03	-0.04	0.02
125	-0.07	0.06	0.49	-0.29	0.18	1.97	-0.13	-0.22	0.04
150	0.02	0.27	0.10	-0.03	0.15	2.07	-0.13	-0.14	0.01
200	-0.06	0.01	0.05	-0.24	0.31	2.03	-0.17	-0.13	0.00
250	0.38	0.08	-0.06	-0.18	0.14	2.24	-0.06	-0.23	0.00
300	0.78	0.03	-0.05	-0.23	0.19	2.42	-0.05	-0.11	-0.22
400	0.94	0.00	-0.06	-0.12	0.13	3.01	-0.13	-0.15	-0.02
Layer Depth	-6	5	6	0	4	-1	0	3	-1

Depth, m	XBT Profile Pair								
	37*	38	39	40*	41*	42*	43*	44*	45*
0	0.06	0.05	0.21	0.14	-0.11	0.16	0.19	0.10	-0.25
10	-0.16	-0.06	0.51	0.14	-0.10	0.15	0.19	0.01	0.06
20	-0.22	-0.10	0.67	0.20	-0.11	0.09	0.25	0.02	0.16
30	-0.13	-0.10	0.68	0.10	-0.11	0.03	0.30	-0.03	0.11
50	-0.26	-0.15	0.54	0.23	-0.17	-0.29	0.14	-2.54	-0.19
75	0.03	0.24	0.49	0.16	-0.18	-0.13	0.27	-0.36	0.01
100	-0.06	-0.01	0.71	0.09	-0.12	-0.22	0.41	-0.04	0.01
125	-0.13	-0.32	0.73	0.12	-0.35	-0.19	0.24	-0.07	-0.03
150	-0.13	-0.73	0.80	0.11	-0.30	-0.16	0.23	-0.17	-0.02
200	-0.20	-0.67	0.73	0.02	-0.22	-0.16	0.11	-0.07	0.10
250	-0.18	-0.77	0.61	-0.06	-0.20	-0.20	0.19	-0.18	-0.04
300	-0.15	-0.61	0.65	0.01	-0.22	-0.25	0.17	-0.19	-0.02
400	-0.20	-0.29	0.78	0.00	-0.16	-0.19	0.28	0.05	0.01
Layer Depth	3	-1	-2	2	-4	1	3	-2	-2