A Low-Cost Digital XBT System and its Application to the Real-Time Computation of Dynamic Height

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ABSTRACT

An XBT interface is described for use with Commodore and other 6502 based microprocessors. This interface takes the form of a single circuit board mounted inside the microcomputer and is completely software controlled. The application of this digital XBT system to the real-time computation of density and dynamic heights, using historical or recent temperature–salinity relationships, is also described. Comparison between XBT and CTD measured temperatures from the Northeast Atlantic yield a mean temperature difference of −0.08°C and an rms temperature difference of 0.33°C for the upper 800 m. Examples of dynamic topography maps and a temperature section computed using this technique are also presented and comparison between objectively analyzed XBT and CTD dynamic topographies demonstrates the reliability of the method for mapping the baroclinic flow.

1. Introduction

The expendable bathythermograph (XBT) is becoming an increasingly important measurement tool in oceanography. It boasts the advantage that data may be collected rapidly while the ship is underway reducing the time to survey an area and yielding a much more synoptic picture of the ocean. Also the simplicity of the system means that it does not require sophisticated support equipment and data may be collected from a variety of ship types. Thus merchant "ships-of-opportunity" are now being widely used as XBT platforms to collect thermal structure data along well-traveled shipping routes.

For many years XBT data were recorded on analog strip charts which were subsequently digitized by hand. Recently the availability of microprocessor systems has made it possible to record the XBT data digitally on either tape or floppy disk and to compute real time derived quantities from these XBT temperature data. A distinct advantage of the digital systems is that they are not subject to the mechanical errors inherent in the analog recorders. Thus the digital systems don't require repeated mechanical calibration to define the error limits of the instrument. As evidence of the magnitude of the errors connected with the use of a variety of analog recorders, XBT data from a series of seven Atlantic research cruises were compared. Different recorders were used on these cruises and no special effort

was made to intercalibrate the systems. The mean temperature difference between 191 XBT and coincident CTD temperatures was 0.15°C with a standard deviation of 0.23°C for all seven cruises. This is comparable to the mean temperature difference of 0.13°C and a standard deviation of 0.11°C given for T7 (800 m) probes using a wide variety of analog XBT systems as reported by Heinmiller et al. (1983).

Another advantage of digital XBT systems is that no subsequent digitization of the analog traces is required to put the data into computer compatible form. This aspect of the analog XBT system was often the source of subtle errors introduced by the laborious hand digitizing of the analog traces. Thus the new digital systems save both in terms of manpower and avoiding errors as well as providing the capability for the real-time computation of derived quantities such as dynamic height (geopotential anomaly).

The recent expansion of XBT use in scientific programs, both from research vessels and ships-of-opportunity, requires the availability of computational capabilities to compute derived quantities in quasi-real-time. This paper describes such a system based on a 6502 based microprocessor. Specifically a procedure developed for estimating dynamic height will be described and results obtained with this system will be compared with reference data taken using more accurate CTD profiling systems. Examples of dynamic height maps and a section produced using such a system

will be presented. It is hoped that this description will stimulate other interested investigators to also build such a system for their own applications.

2. Other digital XBT systems

The microprocessor based XBT system discussed in this paper is not a particularly new development and similar systems have existed for quite a while. These digital systems range from the complex interface systems offered by commercial firms such as Sippican and Bathysystems to a simple digitization of the signal from a standard Sippican analog recorder (John Dugan, personal communication, 1985). A forerunner of the system described in this paper was developed at Oregon State University (OSU; Mesecar and Wagner, 1980). It was based on a Commodore microcomputer and was designed to simplify the preparation of radio "bathymessages" being sent from ships of opportunity. With the analog systems ship operators visually read off temperature–depth pairs which were sent by radio to shore. The microcomputer digital system produces direct values which save reading the analog traces. The system discussed by Mesecar and Wagner included an algorithm to automatically compose the bathy-message to be sent by radio.

More complex digital XBT recording systems are presently available from both Sippican and Bathysystems. These systems also use a microcomputer (HP-85) for data reduction and recording. The main advantage of these systems is that they are general data logging devices and can be used with a variety of other expendable profilers with the appropriate software.

The primary advantage of the system discussed below is its relative low-cost of production. Like the OSU system, it uses a Commodore microcomputer (or possibly any other 6502 based microcomputer) which is significantly less expensive than the HP-85. The XBT interface itself is inexpensive to assemble. The Commodore system has computational power and flexibility similar to that of the HP-85 and its low cost allows one to add a disk drive with SBT data recording on floppy-disk rather than on cassette tape. Rapid access to the data on disk is needed for the quasi-real-time computation of derived quantities such as dynamic topography. Access to these derived quantities in near real-time was the purpose for developing this system and adds greatly to the ability to evaluate shipboard sampling programs while still in the field. Parameters such as density, dynamic height and sound velocity can be easily calculated by the system.

3. XBT interface

The central feature of our XBT system is the interface between the launcher and the microcomputer. The interface is built as a single circuit board which is mounted internal to the computer and is controlled strictly through software commands from the computer. This eliminates any physical contact through buttons or switches which can be accidently switched or may become mechanically defective. It also makes the conversion of the microcomputer to an XBT system almost physically transparent.

The only external evidence is the terminal block where the launcher cable leads are attached to the computer. Another advantage of this interface is that the internally mounted circuit board uses the same power supply as the microcomputer itself. Thus no added power source is needed for the interface.

The interface acts to convert the resistance value of the probe-thermistor to a digital temperature value. The primary component of this interface is an Intersic ICL 7109 12-bit binary A/D converter. On the interface board, shown as a block diagram in Fig. 1, (a more complete description of this interface can be found in Zenk et al., 1985), there are two sources of constant electrical current which give rise to voltage differences with the sea water itself and with the sea water through a thermistor connected in series. The voltage difference between points A and C is proportional to the resistance of the thermistor and is the system signal fed into the differential amplifiers. Here the voltage signal difference is increased before being sent to the A/D converter. The A/D converter translates the measured voltage difference, from the amplifiers, into a 12-bit digital word. The computer receives this information, plus additional status bits, in two parallel 8-bit words (first the high byte and then the low byte). From these 2 bytes the computer calculates the corresponding resistance loaded as a floating point quantity.

The interface senses the presence of a probe canister in the launcher when the circuit is closed, by the probe connection, and current flows through point B to connect with the signal driver. This value is constantly interrogated by the microprocessor for the presence of current after which it activates the trigger relay. The entry of the probe into sea water is sensed by the change in the resistance of the thermistor when it contacts the sea surface. For the software in use the limit is set at 700 ohms above which the probe is taken to be in sea water. The end of a cast is also sensed by the change in resistance of the thermistor which when below 700 ohms is considered to no longer be connected. If this occurs before the expected depth value the software reports that the copper wire is prematurely broken.

In the configuration shown in Fig. 1 this interface board connects directly to a 6502 based microprocessor. Thus the interface depends not only on the microprocessor for its power supply but also delivers a signal directly to the host computer. This interface can be modified (as described in Zenk et al., 1985) to produce a serial output (RS232C or other) which could then be fed into a serial port on any computer system. This generalization makes the interface compatible
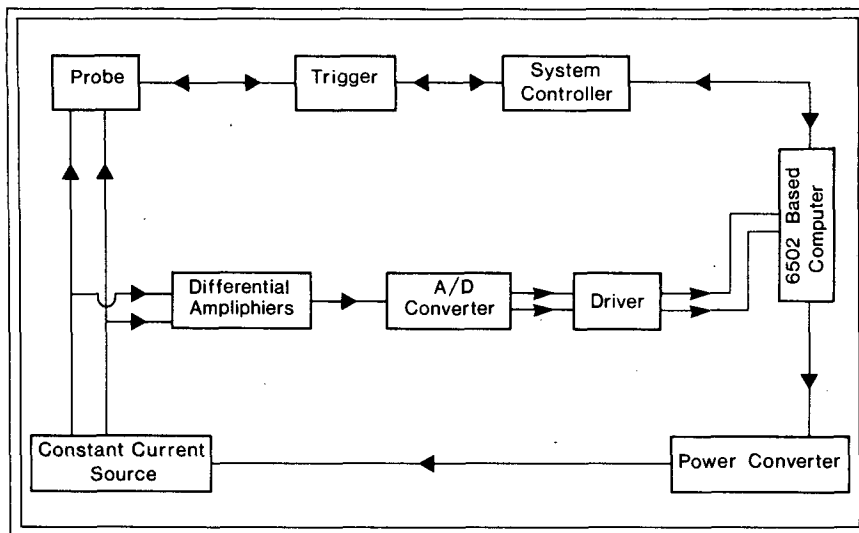
FIG. 1. Block diagram of XBT interface board for the Commodore 8032 Microcomputer.

with a wide variety of computers and makes the transition to 16-bit machines simple.

4. Calibrating the XBT interface

Both installation and calibration of the XBT interface were simplified with a system test unit. This "test box" consisted of a set of resistances that could be selected by a switch or a variable resistor. The calibration temperatures for the resistances used are given in Table 1. The calibration procedure consists of setting the A/D reference voltage, balancing the current sources and setting the differential amplifier gains. To balance the current sources the "test box" is connected to points A, B and C (Fig. 1) in place of the XBT probe. The "test box" is then used to balance the currents in branches A and C. A similar procedure is used to equalize the effects of the two differential amplifiers. This procedure is described more fully in Zenk et al. (1985).
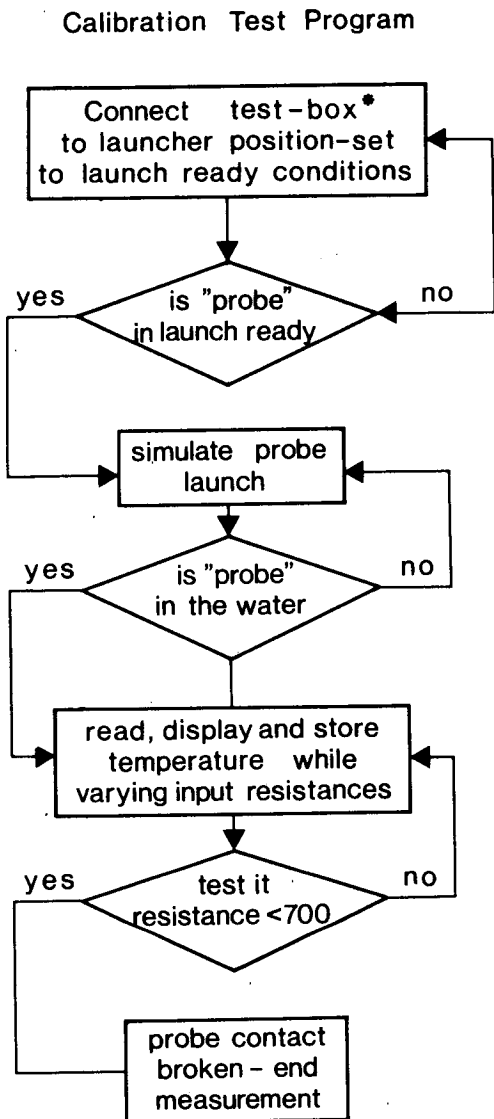
TABLE 1. Correspondence between resistance and temperature.

Resistance (ohms)	Temperature (°C)
17 500	−1.35
15 000	1.67
12 500	5.32
10 000	9.90
7 145	17.06
6 153	20.34
5 000	25.01
4 166	29.22
3 750	31.71
3 334	34.52

Now that the system has been set up, the "test box" can be used, in conjunction with a test program, to determine if the XBT system is operating or not and to check the temperature settings at various set resistance values. A flow chart of the test program is given in Fig. 2. With the test program loaded and running the "test box" can be used to test the system for its response to a probe being loaded into the launcher and launched. With the probe in launched mode the "test box" can be used to either generate the fixed resistances given in Table 1 or a variable resistor can be employed to cover the entire resistance/temperature range in question. The fixed resistances, however, are used to compute the coefficients of a quadratic fit between the measured digital values and resistance. For this reason 10 resistance values (Table 1) are used which cover the entire range of temperatures. Since each A/D converter behaves slightly differently this calibration procedure must be carried out for each XBT interface. From these values corresponding to Table 1 a quadratic least-squares fit is made between the recorded digital values and the matching resistances. The resulting three coefficients A_0, A_1, and A_2 are then used in the XBT data collection software to convert the measured digital values into resistances which are then converted to temperature. After the digital values have been listed for the "test box" resistances the test program can be terminated.

5. Temperature–depth computation

In order to convert the resistance values to temperature a logarithmic formula was used following the results of Steinhart and Hart (1968) that demonstrated

Calibration Test Program

Connect test-box* to launcher position-set to launch ready conditions

yes — is "probe" in launch ready — no

simulate probe launch

yes — is "probe" in the water — no

read, display and store temperature while varying input resistances

yes — test it resistance <700 — no

probe contact broken – end measurement

*
Test-box simulates probe presence and launch as well as selected input resistances

FIG. 2. Flow chart of test program.

the accuracy of such a logarithmic fit for a thermistor. The formula is

$$T = [1.34079 \times 10^{-3} + \ln(R) \times (2.1604 \times 10^{-1}$$
$$+ \ln(R) \times 2.38522 \times 10^{-6})^{-1}] - 273.15 \quad (1)$$

where T is temperature in °C and R is resistance in ohms. (This formula is less accurate for Arctic tem-

perature ranges as is discussed by Joyce et al., 1976). With the 12-bit A/D conversion this system has a temperature resolution better than 0.01°C. With proper calibration this digital system should not contribute added inaccuracy to this temperature measurement. Thus the overall temperature accuracy depends on the consistency of the individual thermistors in the XBT probes. While Sippican publishes a value of ±0.2°C statistics from samples of thermistor batches (Emery, 1978) have shown a precision of ±0.06°C.

The depth calculation follows the formula given by Sippican (1970)

$$D = 6.472t - 0.00216t^2 \quad (2)$$

where D is the depth in m and t is the elapsed time in seconds. No effort has been made to correct for some of the fall rate errors described in Heinmiller et al. (1983).

6. Temperature comparison

To evaluate the accuracy of data from this digital XBT system, relative to CTD data, a series of 41 XBT profiles were collected midway between 42 CTD casts each separated by 15 km. These data were all collected in July 1984 in the Northeast Atlantic west of the Rockall Channel. The temperature comparison was performed by taking the depth of each one degree Celsius isotherm, from the microcomputer printout of the XBT data and relating it to the temperature read at that depth from the adjacent CTD listings. The generally most similar neighboring CTD temperature profile was selected for the statistical comparison with the XBT profile in an effort to minimize the effects of spatial variability.

Depending on the mean observed vertical temperature range this procedure resulted in temperature differences being calculated for a maximum of 10 levels within the nominal 800 m depth of the "deep blue" (T7) XBT probes being used. This procedure yielded a different number of isotherm comparisons per depth level depending on the local vertical temperature gradient (Fig. 3, Table 2). This approach was considered favorable, however, in that it minimizes the effects of spatial variability on the statistical comparison.

Overall the values of 0.08°C for the mean temperature difference and 0.33°C for the rms difference are quite small; this is particularly true if we consider that the profiles, used in this comparison, were not taken simultaneously. Thus the mean and rms differences represent maximum values and similar truly simultaneous comparisons should have yielded even smaller differences. Unfortunately no such set of simultaneous XBT/CTD measurements, using this digital XBT system, was available. The fact that the mean difference for this comparison (0.08°C) was smaller than the 0.1
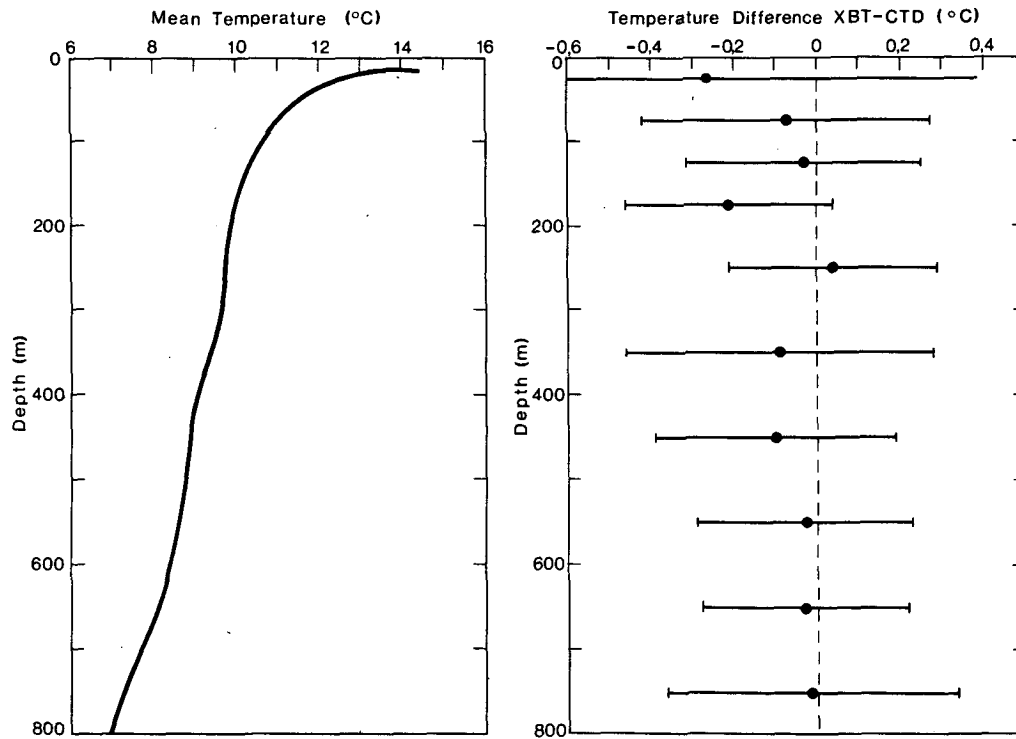
FIG. 3. Mean temperature profile (left) for the set of XBT–CTD comparison data; (right) mean temperature
difference and standard deviation between XBT and CTD profiles.

to 0.13°C given by Heinmiller et al. (1983), and also
smaller than the 0.15°C difference given earlier for si-
multaneous comparisons between CTD temperatures
and XBT profiles from analog recorders, suggests that
the digital system provides some improvement in the
quality of the observations. The somewhat higher rms
difference of 0.33°C, as compared to Heinmiller et al.'s
value of 0.18°C and even the 0.23°C for the earlier
analog data comparison, is likely due to the spatial
variations of the thermal structure inherent in the

present comparison data. Future, more simultaneous
comparisons, will hopefully confirm improvement
even in terms of the rms differences.

7. Inferring salinity

Since the XBT system measures only the vertical
temperature profile it is necessary to supply added sa-
linity information in order to calculate quantities such
as density and dynamic height (geopotential anomaly).
In many regions of the ocean it is possible to infer
salinity from mean or ideal temperature–salinity
(T–S) relationships (Emery and Dewar, 1982; Siedler
and Stramma, 1983; Flierl, 1978; Zantopp and Lea-
man, 1984). In higher latitudes of the North Pacific,
Emery and O'Brien (1978) demonstrated that T–S re-
lationships did not lead to meaningful dynamic height
values but instead mean salinity profiles (S–Z) could
be used to infer salinity from depth. A similar analysis
for the North Atlantic is given in Emery and Dewar
(1982). Thus software was developed to use historical
mean T–S and S–Z curves to infer salinity primarily
for the computation of dynamic height. In order to
compare with locally observed T–S relationships an
option was built into the program to enter a newly
observed T–S curve (say from a nearby CTD cast) for
the salinity inference. It should be noted here that it

TABLE 2. Comparison between 41 XBT and CTD casts from
Poseidon III in the area west of the Rockall Channel (54°N, 18°W).

Depth (m)	Mean temperature difference (°C)	Temperature difference standard deviation (°C)
25	−0.26	0.64
75	−0.07	0.35
125	−0.03	0.28
175	−0.21	0.25
250	0.04	0.25
350	−0.09	0.37
450	−0.10	0.29
550	−0.03	0.26
650	−0.03	0.25
750	−0.01	0.35

would be a simple extension to compute sound velocity in this same program.

8. Computation of dynamic height

The traditional definition of the dynamic depth anomaly is the integral of specific volume over a pressure interval. As discussed by Montgomery and Wooster (1954) this procedure is favored over that of integrating density over geopotential since it allows one to operate with a specific depth interval. These authors also argue that the pressure corrections to specific volume can be neglected in the upper 1000 m and thus introduce a specific volume anomaly with the pressure terms omitted, called the thermosteric anomaly. Nevertheless most oceanographers still use the more cumbersome formulation and either include all of the specific volume terms or use a modern equation of state to compute all of these specific volumes. At the same time the computer routines generally compute sigma-t to represent density. It would be computationally economical if a method were developed to compute geopotential anomaly directly from sigma-t without the computation of specific volume anomalies. Such a calculation would only be valid for the upper layer ($\leqslant$1000 m) which includes the maximum depth of the T7 (or deep blue) XBT probe ($\leqslant$800 m).

The derivation of such a formula is very straightforward and follows from the definition of dynamic depth. Using sigma-t (σ_t) as a pressure independent density value the formula for the dynamic depth anomaly is

$$\Delta D = \frac{g}{1028}\left[(z_2 - z_1) \times 28.13 - \int_{z_1}^{z_2} \sigma_t\, dz\right] \quad (3)$$

where g is the acceleration of gravity (in cm s^{-2}) and the depth z is in m. The dynamic depth anomaly (ΔD), in this equation, is in units of m^2 s^{-2} and must be divided by 10 to get the traditional unit of dynamic meters.

As a test of the accuracy of this equation a sample calculation was carried out using data from a table in Sverdrup et al. (1942). Values of temperature, salinity, sigma-t and dynamic depth anomaly (ΔD_{Sv}), taken from this example are in Table 3. Also included in this table are the dynamic depths computed using Eq. (3) (ΔD_d), along with the differences between ΔD_{Sv} and ΔD_d. As expected, the difference between these two dynamic depths increases with depth as the neglected pressure terms become more important. Down to 500 m, however, the difference is only 1.4 dyn cm. Since spatial differences of the dynamic height values are of most interest, and errors can be expected to cancel, this error level was considered tolerable and dynamic height was routinely computed with this equation in the XBT system software. There is a considerable computational savings in using this method which is

TABLE 3. Examples of the computation of dynamic depth anomalies (station E.W. Scripps I-8, Lat. 32°57'N, Long. 122°07'W, February 17, 1938, see Sverdrup et al., 1942, Table 61).

Depth (m)	Temp. (°C)	Salinity (‰)	σ_t	ΔD_{Sv}[a] (dyn m^{-1})	ΔD_d[b] (dyn m^{-1})	Difference[c]
0	14.22	33.25	24.81			
10	13.72	0.24	0.91	0.310	0.0311	−0.0001
25	0.71	0.24	0.91	0.0769	0.0772	−0.0003
50	0.35	0.30	25.03	0.1521	0.1525	−0.0004
75	9.96	0.57	0.86	0.2162	0.2165	−0.0003
100	0.38	0.84	26.17	0.2667	0.2668	−0.0001
150	8.82	0.98	0.37	0.3557	0.3555	0.0002
200	0.48	34.09	0.51	0.4372	0.4361	0.0011
250	0.30	0.16	0.59	0.5140	0.5114	0.0026
300	7.87	0.20	0.69	0.5868	0.5824	0.0044
400	0.07	0.20	0.80	0.7233	0.7144	0.0089
500	6.14	0.26	0.97	0.8473	0.8331	0.0142
600	5.51	0.35	27.12	0.9568	0.9365	0.0203
800	4.65	0.42	0.28	1.1478	1.1138	0.0340
1000	3.99	0.44	0.36	1.3178	1.2682	0.0496
1200	0.52	0.52	0.48	1.470	1.4035	0.0665
1400	0.07	0.54	0.54	1.606	1.5218	0.0842
1600	2.69	0.56	0.59	1.733	1.6295	0.1035
1800	0.37	0.59	0.64	1.850	1.7276	0.1224
2000	0.13	0.64	0.69	1.957	1.8163	0.1407
3000	1.62	0.63	0.76	2.437	2.2023	0.2347
4000	0.50	0.70	0.81	2.877	2.5312	0.3458

[a] ΔD_{Sv} is calculated using the specific volume anomaly (Sverdrup et al., 1942, p. 409).
[b] ΔD_d is calculated from Eq. (3).
[c] Difference is $\Delta D_{Sv} - \Delta D_d$.

important when working with relatively slow micro-computers.

9. Examples of derived quantities

As an example of the data produced by such a system an XBT temperature section between Lisbon, Portugal and the Azores is shown in Fig. 4 along with the corresponding horizontal profile of 0/500 db dynamic height. In this region the T-S relationship is fairly tight (Siedler and Stramma, 1983; Emery and Dewar, 1982) and can be reliably used to infer salinity for density and dynamic height calculations. The dynamic height in Fig. 4 together with the characteristic slopes of the 15°C-isotherm reflect the meridional current systems off Portugal. Due to the lack of an appropriate T-S relationship in the upwelling region of the continental shelf, the dynamic height east of 11°W may be questionable (we used extrapolated T-S values). Nevertheless, we recognize, progressing from east to west, the southbound Portugal Current next to a counter current or eddy feature. A southward drift between 15° and 21°W is reflected by the steep increase of the dynamic height around 22°W. This signature is indicative of the meandering Azores Current being a persistent feature in that region (Käse et al., 1985; Siedler et al., 1985).

A real advantage of this system is that surveys can be carried out much more rapidly with this XBT system as the ship is continuously underway. The value of also being able to see the corresponding geopotential field
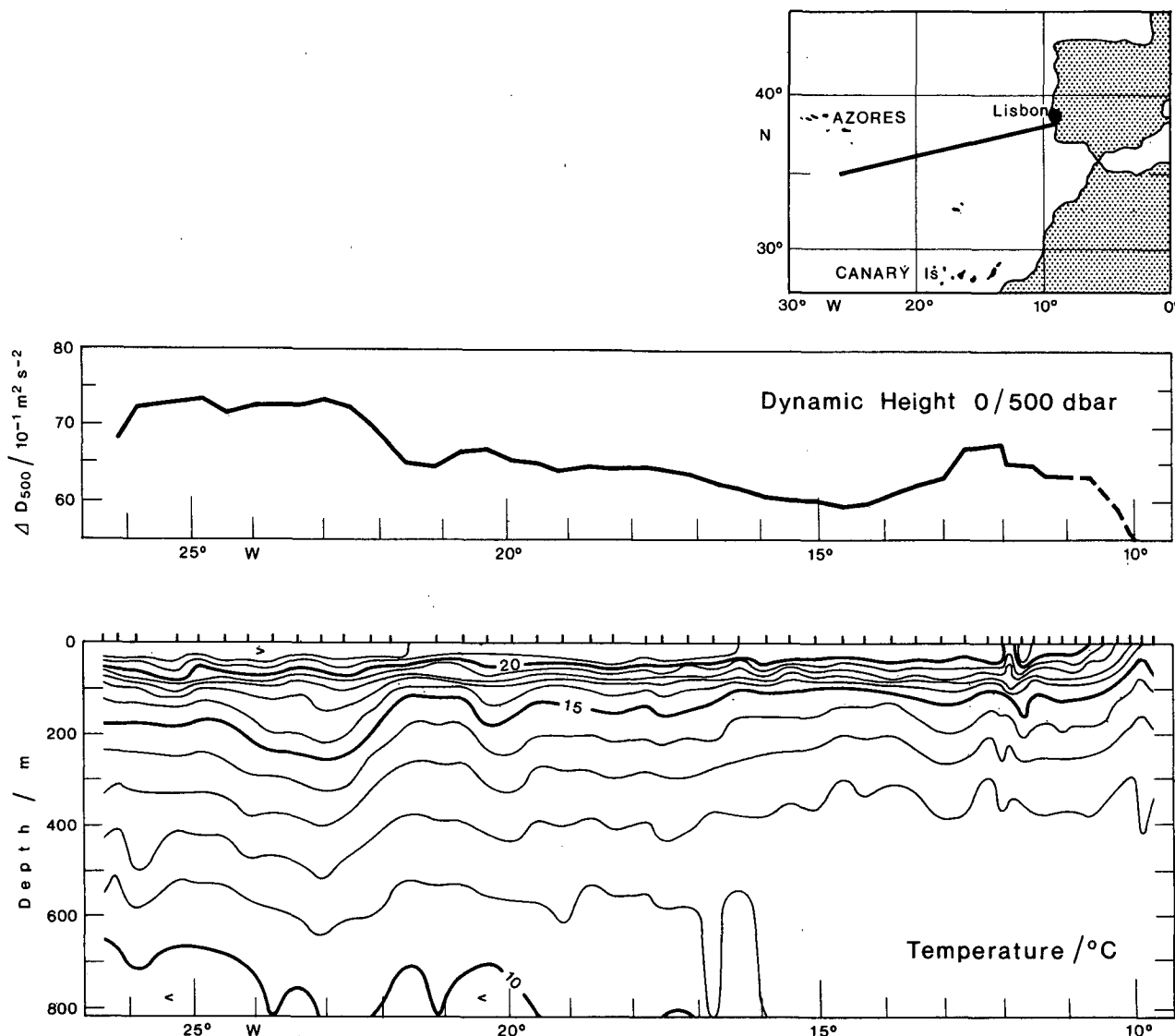

FIG. 4. Vertical XBT temperature section and horizontal 0/500 db dynamic height profile between Lisbon, Portugal and the Azores.
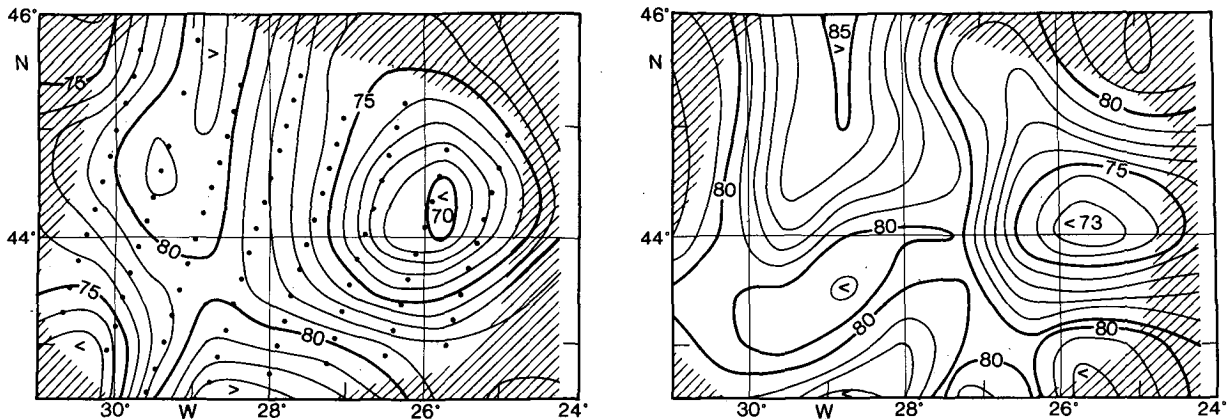
FIG. 5. Objectively analyzed dynamic topography (dyn m) maps for XBT profiles (left) and CTD profiles (right). In each map the boundary shaded region indicates where the analysis error is greater than 2.5×10^{-4}.

in research vessel operations is that rapid surveys can help to dictate where more intensive measurements should be made.

As an example of how well such an XBT geopotential anomaly survey compares with one made using only the more accurate CTD casts we present the maps of Fig. 5. Here near simultaneous CTD and XBT casts were collected at each station within the survey. Using mean T-S relationships the XBT data were provided with matching salinity profiles, converted to 50/800 db dynamic heights and mapped using objective analysis (Hiller and Käse, 1983). Using the CTD data separately, similar 50/800 db geopotential anomaly maps were constructed with objective analysis. These two maps are plotted together in Fig. 5; here the dashed background lines indicate the region where the objective analysis error becomes significant and the maps are less reliable. The overall structure is common to both maps which demonstrates the utility of using the XBT data alone to survey the baroclinic structure. The main feature is the strong low in the central right portion of the survey. Both the spatial structure and the strength (geopotential difference) of this feature are well estimated by the XBT survey relative to the CTD map. Some differences are apparent in the lower left portion of the surveys which do affect the overall circulation pattern. Care must be taken here, however, where the boundary effects of the objective analysis procedure become important. Other comparisons, from this same geographic region (not shown here), demonstrate the correspondence between geopotential anomaly maps, based on XBT measurements, and the trajectories of satellite tracked drifting buoys (Krauss and Meincke, 1982).

10. Summary

A low-cost digital XBT system, based on a microcomputer, is described and the application of such a system to the real-time computation of geopotential anomaly is considered. Not only does such a digital system avoid the problems of time and error associated with the analog XBT systems but the low-cost of the system discussed makes it possible to install such equipment on a variety of ship-of-opportunity platforms for XBT data collection.

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