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AN AUTOMATED TACTICAL OCEANOGRAPHIC MONITORING SYSTEM

An automated prototype oceanographic monitoring system, developed by The Johns Hopkins University Applied Physics Laboratory, has been successfully demonstrated aboard a U.S. Navy submarine during an extended operational period. The system, consisting of commercial off-the-shelf data processing electronics and tailored oceanographic sensors, replaces time-consuming manual monitoring procedures that depend on inadequate sensors. Results show that the system can automatically indicate incipient changes in water-mass conditions in both open ocean and coastal environments, thereby enabling watchstanding personnel to improve the quality of information for tactical and ship's ballasting decisions. Automated oceanographic monitoring augments the Navy's existing capabilities to support submarines in joint, regional warfare operations, and offers new opportunities for the collection of scientifically sound oceanographic data in nontraditional operating areas of the world.

INTRODUCTION

As part of its new, post–Cold War mission, the Navy faces increased responsibility for supporting regional contingency operations. Although much is now known about the higher-latitude areas of the ocean, such as the Norwegian Sea, many politically unstable areas and their associated coastal regions are nontraditional operating areas for the Navy and have been little studied oceanographically. Variations in water properties (in both the open ocean and particularly in coastal waters) are important for naval operational decisions because they affect the performance of naval sensors. For effective tactical decision-making, the Navy must be able to monitor and act on significant changes in water-mass properties in real time.

Open ocean and coastal regions exhibit spatially and temporally varying environmental conditions over scales ranging from climatologically significant basin-scale water masses and currents to small ocean fronts, eddies, and local changes in water properties induced by coastal river runoff.[1] Huthnance highlights this complexity in a review of environmental conditions associated with coastal oceanographic regions and the recurring physical processes that give rise to that variability.[2] In particular, he points out the increasing number of forces and processes (not necessarily important in the open ocean) that affect the coastal water-mass conditions as the ocean bottom shoals rapidly towards the coast; these include unstable longshelf currents, the mixing of coastal and deepwater masses, tides, and the local effects of complex bathymetries.

IN SITU OCEANOGRAPHIC MONITORING— CURRENT PRACTICE

Conventional *in situ* monitoring of seawater properties is often inadequate to detect incipient changes in local water-mass conditions in real-time. Scientific vessels have historically acquired sea-surface data along the ship's track via automated data-logging devices, which consist of sensors immersed in seawater pumped into the ship's laboratory. Expendable sensor probes are often used while the vessel is under way to augment the sea-surface measurements with depth profiles of, for example, ocean temperature. Submarines and surface ships currently rely primarily on the data from these expendable probes to assess the local acoustic propagation conditions for the ship's sonar sensors. Such measurements, however, are pointwise and often infrequent, sometimes taken no more than once a day.

As the variability of mid-ocean water-mass conditions has become more apparent,[3-5] ship personnel have augmented intermittent depth-profile observations with manual readings and plots of injection temperatures of the propulsion system's cooling seawater (or other measured parameters such as sound speed, if available). Unfortunately, manually generated plots are time consuming to interpret and error prone because of deficiencies in onboard sensors and variances in recording methods.

TOMS—FUNCTIONAL OBJECTIVES

To address these problems, the Oceanographer of the Navy, in consultation with the Commander, Submarine Development Squadron TWELVE, initiated in 1989 the

development of a prototype, real-time, *in situ* submarine tactical oceanographic monitoring system (TOMS). The TOMS was conceived as an automated system that would enhance existing monitoring capabilities with critical improvements: a dedicated suite of oceanographic-quality sensors, automated data acquisition and processing, and a permanent local data archive to preserve the real-time observations for review and for use in running onboard computer predictions of acoustic sensor performance. The specific functional objectives for the submarine oceanographic monitoring system were

1. To automate manual oceanographic monitoring procedures

2. To enable faster recognition by the watch team of tactically significant changes in oceanographic conditions

3. To automate oceanographic data entry to computer-based tactical decision aids

4. To provide for routine, unattended oceanographic data collection and data archiving to support subsequent analysis and updates to Navy oceanographic databases.

The Applied Physics Laboratory was selected for the lead development activity in 1989 and tasked to produce a prototype concept demonstration system meeting the above criteria. The prototype TOMS was installed aboard a U.S. submarine for testing in March 1990 and has remained on the test platform for tactical evaluation in various operational exercises. The initial system trials clearly demonstrated the superior monitoring capabilities of the TOMS prototype.

TOMS—SYSTEM OPERATING CONCEPT

To develop a tactical oceanographic monitoring system for real-time detection of ocean fronts and associated changes in water-mass conditions, we first had to identify key front characteristics that were amenable to measurement. Table 1 lists some of the properties of ocean fronts that emerged from the literature (see Ref. 1, for example)

as candidate signatures exploitable by an automated oceanographic monitoring system.

On the basis of this review, we selected an initial suite of TOMS sensors for the prototype demonstration: fast-response temperature and conductivity sensors (to address items 1 and 5 in Table 1), a chlorophyll fluorometer (to address item 4), and a tap into the existing AN/BQH-1 shipboard seawater sound-velocity drum recorder (to address item 1). Later in the demonstration period, an optical backscatterometer (item 3) was added. The sensors were incorporated in the TOMS prototype, as described below, for operational testing aboard a Navy submarine.

TOMS—SYSTEM DESCRIPTION

The TOMS prototype architecture consists of four principal components: a suite of dedicated oceanographic sensors installed on an expandable, external sensor bus; a central processing unit for data processing and archiving; an interface manager to network the processor to various existing ship's auxiliary sensors and systems; and operator interfaces and displays for system observation and control. The automatic oceanographic data products are available for transmission via an electronic interface to the ship's tactical systems, where they can be evaluated to determine the effects of the measured oceanographic environment on the ship's sensors. All components (except for the ship interface, printer, and tactical interface) are replicated in the system to minimize the likelihood of a single-point failure. The duplicate components can also serve as repair parts should a component fail at sea. The functional configuration of the TOMS prototype is illustrated in Figure 1 and discussed in more detail in the following sections.

External Sensor Bus

The external oceanographic sensors are connected to external data acquisition nodes (DAN's) on a full duplex

Table 1. Ocean frontal characteristics supporting automated detection.

|	Characteristics	Measurable parameter(s)	Approach
1.	Steeper horizontal gradient in physical properties across front	Temperature Sound speed Conductivity (salinity)	A sharp gradient in parameter over distance (sometimes less than 10 km) defines the frontal transition zone between the surrounding water masses.
2.	Steeper horizontal shear in surface current	Water velocity	A narrow band of high current velocity associated with the front increases ship set and drift.
3.	Reduced water clarity	Turbidity Optical backscatter Light attenuation Other measures of particulate loading in seawater	Mixing along the front supports increased biological activity levels. The higher particulate load results in increased turbidity levels, backscatter, and light attenuation.
4.	Biological activity	Chlorophyll Acoustic backscatter Acoustic ambient noise	Measurable parameters are higher near the front than in the surrounding water mass.
5.	Cross-frontal mixing	Temperature variances Conductivity variances	Mixing of water masses across the front produces localized patches of small-scale (0.01–10 km) variability in local temperature and conductivity, which can be measured with fast-response sensors.
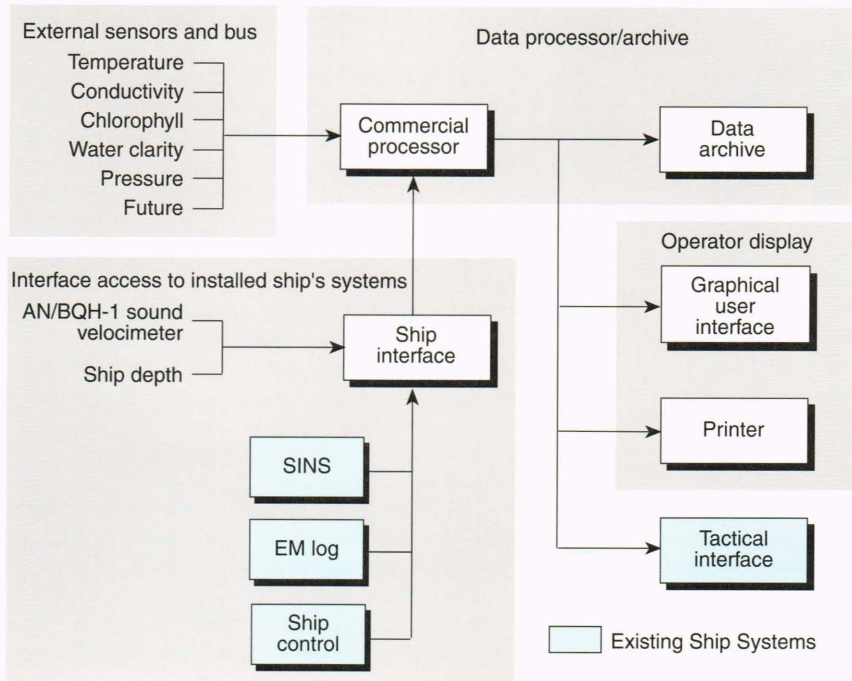
Figure 1. The tactical oceanographic monitoring system (TOMS) prototype architecture and installation configuration aboard the test submarine. The principal components of the system include the sensors in an external sensor bus, a commercial off-the-shelf central data processor with a data archive facility, a graphical user interface, and a ship systems interface for electronic access to the existing ship sound velocimeter, depth transducer, inertial navigation system (SINS), speed (electromagnetic—EM—log), and the control planes. The tactical interface permits direct input of data products to the submarine's tactical decision-supporting computer. The principal TOMS display is located between the two ship's control operators.
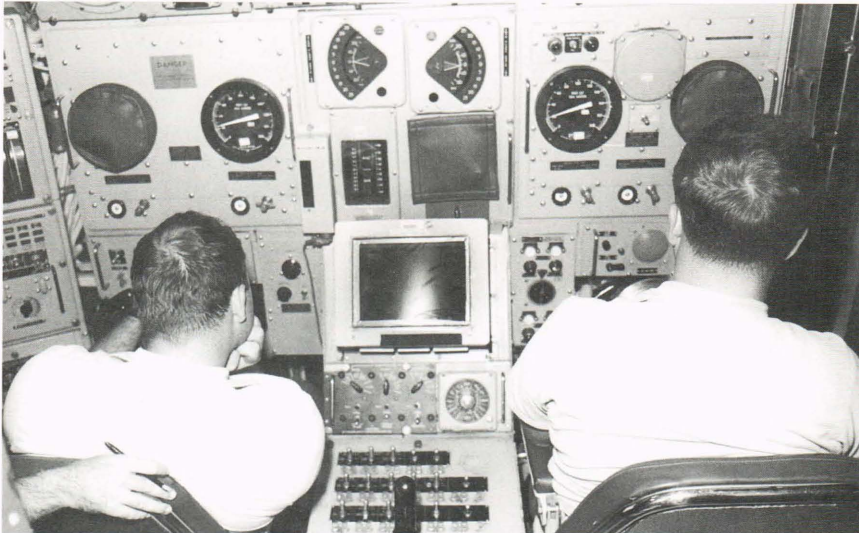
serial sensor bus via the RS-485 electrical standard. RS-485 is a differential signal communications architecture that allows multi-nodal serial communications over greater distances than the more common RS-232C standard, which imposes a 15-m maximum. Data rates are generally low enough to allow the serial bus to operate asynchronously at the bit communications level at 38.4K baud, further simplifying both the hardware and software interfaces.

The system sensor capacity is designed to be expandable. The RS-485 standard allows up to 32 nodes on the network, each capable of accommodating up to four sensors. The network can be readily extended by the addition of RS-485 repeater stations, or the addition of another sensor bus. This design facilitates the rapid prototyping of future sensors, and allows system expansion to support additional requirements with minimal re-engineering.

Of the two independent serial connections on the bus, one is dedicated to commands directed to the external nodes, and the other to returning data and other command responses. As shown in Figure 2, the communications architecture consists of an internal DAN bus interface (DBI) and the external DAN nodes. The DBI acts as the "bus master" and is the only transmitter allowed on the command path. The DAN nodes transmit responses to commands onto the return data bus for reception internally at one or more data-processing stations; no unsolicited communications are allowed on the return data path. This scheme allows for a simpler network design with no need for complicated collision avoidance hardware or software algorithms.

The DBI transmits synchronous commands in a broadcast fashion, directing each node to acquire and buffer data. Then, once a second, without interfering with the
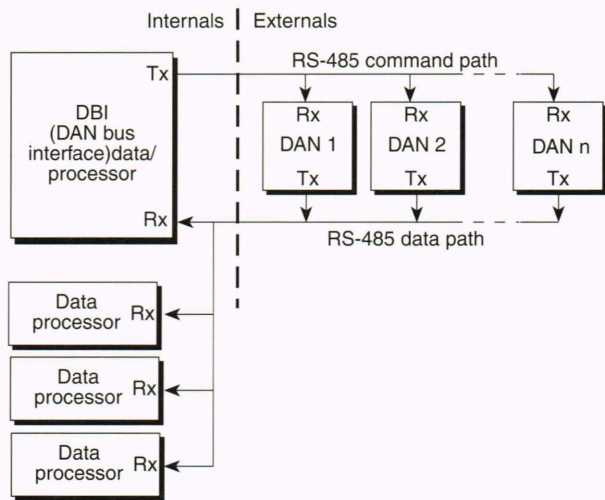
Figure 2. External sensor bus architecture. The external oceanographic sensors are connected to a robust, expandable external sensor bus interface through a sequence of external data acquisition nodes (DAN's) via an RS-485 electrical standard-based network. The internal DAN bus interface transmits commands to the DANs and transmits their responses to the data processors. The number of DAN's is essentially open-ended, allowing the number and types of external sensors to be expanded without detrimental impact on the rest of the internal system architecture.

consistency of new sample commands, it sequentially requests each node to dump its 1-s buffer. The result is consistent concurrent sampling over all DAN node sensors and a high utilization of the communications bandwidth

of the return data path with minimal transmission overhead.

The DBI supports other types of commands for general system operations, such as a request for calibration coefficients for converting raw binary data to the engineering units endemic to the specific sensor suite of the DAN node. Each DAN contains, in nonvolatile memory, its own sensor's calibration coefficients, which vary because of the subtle differences in the DAN electronics and sensing elements. Thus, nodes on a DAN bus can be replaced at any time without internal software modifications to the calibration information or adverse impact on the quality of the data displayed and archived in its native units. This capability greatly simplifies field maintenance procedures.

Sensors

Two sets (for redundancy) of dedicated TOMS oceanographic sensors are located high in the sail (see Fig. 3) in a specially fabricated seawater access port, where the water flow is unaffected by boundary layer turbulence associated with either the hull or control surfaces. Figure 3 shows the sensor modules housing the sensors and types of sensors.

The five dedicated oceanographic sensors measure temperature, seawater conductivity, chlorophyll, optical backscatter, and pressure. Sensor analog-to-digital signals are processed external to the submarine's pressure hull, minimizing electrical connections through the hull and significantly reducing external electrical noise contamination of the low-level analog sensor signals.
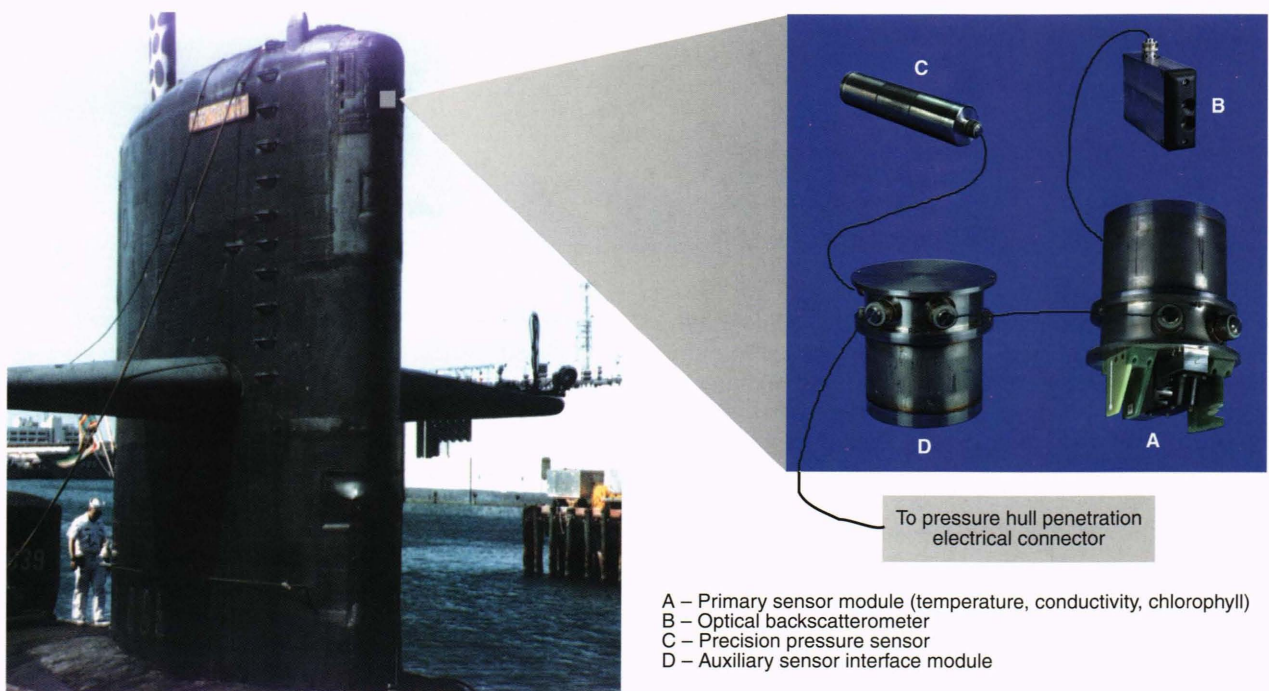

A – Primary sensor module (temperature, conductivity, chlorophyll)
B – Optical backscatterometer
C – Precision pressure sensor
D – Auxiliary sensor interface module

Figure 3. External sensor installation configuration showing one of two sets of oceanographic sensors. The sensors (A, B, C) are installed in a recessed compartment in the top leading edge of the submarine sail. Sensors B and C are located separately from the primary sensor module A. An auxiliary sensor interface module D serves as the system's expandable external sensor bus node and also houses sensor electronics for formatting and grooming the data before transmitting them to the internal system through a dedicated pressure hull penetrator.

Temperature

Each of the TOMS' twin sensor modules contains two commercially available thermistors for temperature sensing: a fast-response glass bead thermistor with a 20-ms thermal time constant and a metal-cased glass bead thermistor with a response time of 120 ms. The fast-response sensor resolves small-scale seawater temperature variations, and the slower one provides data for bulk-property calculations, such as seawater density and sound speed. The temperature sensor circuit design is similar to one developed by APL for use in oceanographic towed thermistor chain systems to examine small-scale oceanographic temperature fluctuations; it was redesigned for the TOMS to support extended, unattended use at sea.[6] The thermistor output is pre-emphasized at high frequencies before digitization to improve signal-to-noise levels at high sampling frequencies. After digitization and de-emphasizing, the sensitivity of the fast-response temperature sensor is $2.8 \times 10^{-6}\,°C/Hz^{1/2}$ in a 6-Hz bandwidth. The metal bead thermistor outputs data at 1 Hz.

Seawater Conductivity

Seawater conductivity is used by the TOMS as a direct measure of oceanographic water-mass properties, and as the basis for various derived parameters (such as salinity, sound speed, and seawater density). The conductivity sensor evolved from a four-electrode, planar contact cell developed by APL for oceanographic towed instrumentation chains.[7] The housing for the conductivity cells was designed to minimize fouling during long-term (on the order of six months) use at sea.

The sensor design represents a trade-off between sensitivity and calibration stability. The long-term stability of the redesigned sensor is 0.005 S/m and the sensitivity is $3 \times 10^{-7}\,(S/m)/Hz^{1/2}$ in a bandwidth of 6 Hz (S = siemens). Sensitivity (the ability to measure small-scale spatial variations in seawater conductivity) was given early design priority to ensure accurate measurement of local variations in seawater properties over periods of six months or more. Long-term static calibration maintenance is a challenge. Fouling, corrosion, and other degrading effects of long-term immersion in seawater cause drifts in the absolute calibration of conventional conductivity sensors. This drift must be determinable to ensure the reliability of the calculated seawater bulk properties, such as sound speed and density. Future conductivity sensor development work will focus on this issue.

Chlorophyll

Chlorophyll is an indicator of near-surface biological activity. Such activity can result from the nutrient-rich admixture of water masses along open ocean and coastal ocean fronts, coastal upwelling, river outflow, or the marginal ice zone edge during seasonal daylight periods. Chlorophyll is of interest because the active acoustic reverberation may be correlatable with direct measurements of the relative biological loading.

The chlorophyll sensor is a miniaturized fluorometer designed at APL.[8] The fluorometer generates a bright, high-voltage halogen light beam at 430 nm (the absorption wavelength band of chlorophyll-a) which traverses a fixed-length water path. A red-extended gallium arsenide-phosphide photodetector captures light transmitted at 670 nm (the emission wavelength of chlorophyll molecules) and generates a signal proportional to the level of chlorophyll in the water. The fluorometer incorporates a self-calibrating circuit that compensates for variations in the halogen light bulb output. The sensor light paths are shielded so that the light will not be visible to an outside observer.

The fluorometer signal-to-noise ratio levels (sensitivities) are comparable to laboratory chlorophyll fluorometer standards. In the early TOMS prototype designs, we emphasized the measurement of relative chlorophyll concentrations. However, the oceanographic community is keenly interested in developing zero-reference calibration standards for the chlorophyll sensor so that absolute chlorophyll concentrations can be measured and compared with extant scientific data.

Optical Backscatter

The optical backscatter of seawater, which is related to water turbidity (transparency), is difficult to measure *in situ*. The optical geometry of the sensor and the heterogeneity of the scattering components (which also varies spatially) force trade-offs among sensor size, measurement sensitivity, and sample size.

The APL backscatterometer is a compact underwater instrument designed to measure blue backscatter at a sampling rate of 1 Hz (M. J. Jose and A. B. Fraser, pers. comm., 29 March 1991). The sensor assembly houses an incandescent lamp which is filtered to produce a beam of blue light ($\approx$480 nm) 8° wide by 12° high. A photodetector (located above the lamp beam) is oriented so that its imaging beam (with the same angular dimensions as the transmitted beam) intersects the transmitted beam at an angle of 9°. This crossed-beam geometry is a compromise between keeping measurements close to the 180° backscatter angle and keeping them as narrow as possible. Thus, the backscatterometer has enhanced sensitivity to small changes in average scatter when the sampled volume is close to the sensor, in this case approximately 16 cm from the unit. Since the transmitted beam is modulated at 16 Hz, the returned scatter signal can be bandpass filtered to minimize noise from external light sources (for example, the Sun). The sensor has a broad sensing range of 0.0 to $0.01/sr \cdot m^{-1}$, permitting it to operate over the range of backscatter values characteristic of both open, clear ocean (typically near $4 \times 10^{-4}/sr \cdot m^{-1}$) and coastal (above $2 \times 10^{-3}/sr \cdot m^{-1}$) regions.

Precision Pressure

The external sensors are complemented by a commercially available precision pressure sensor, which independently verifies the depth of the observations when depth data from the ship's sensors differ from those measured by the TOMS sensors. The differences are due to calibration ambiguities noted early in the test period in the operation of the submarine's existing twin pressure transducers.

Data Recording and Archiving

The TOMS utilizes a commercially manufactured ship systems interface manager to access selected ship's sensors. The interface manager monitors up to 20 channels of ship's data at 1 Hz and transmits them to the TOMS processor over an RS-232C interface. The data monitored include ship position and attitude (ship hull roll and pitch) from the submarine's inertial navigation system (SINS), keel depth, seawater sound speed (from the AN/BQH-1 sound velocimeter), control surface positions (planes and rudder), and ship's speed (from the electromagnetic ship's speed log).

The TOMS manages three separate types of archival record structures for time- and position-tagged data. Data used in supporting real-time monitoring/display applications are recorded in display data records at 5-s intervals (0.2 Hz). Platform parameters (optical backscatter and chlorophyll) are recorded at 1-s intervals (1 Hz) and stored in the ship's data records. The high-resolution TOMS sensor data (temperature and conductivity) are recorded in sensor data records at 16 Hz. These data constitute the master archive and are available to the user as read-only records.

Internal System Description

Data Processing

For the TOMS prototype demonstration, we used a commercially available Apple Macintosh IIci computer as the system's central processing unit (see Fig. 1). This unit was selected because of its high-speed data and graphics processing capacity, as well as its small footprint (important for installation aboard submarines). An optical disk drive in the submarine's control room serves as the master data archive supporting real-time data acquisition. Approximately one week's data can be placed on each side of the optical disk (~1 Mbyte of data per day). Using a second optical disk drive, the sonar supervisor can review previously recorded data without interrupting data acquisition and display management in the control room. A high-resolution color graphics printer provides hard copy and is accessible from either the control room or the sonar room.

Operator Interfaces and Displays

The principal TOMS display is located between the two ship's control operators (shown seated at their stations in Fig. 1) on the sail/stern planes control console. The location is ideal, offering both the officer of the deck and the diving officer ready, but unobtrusive, visual access to the oceanographic monitoring display. The sonar supervisor has access to a second display in the sonar room. The two displays operate independently, allowing each to be set to the format best suited for the specific watchstanding support required. For example, the officer of the deck might view a short-time window (15 min) to monitor ballasting conditions, while the sonar supervisor watches over a longer period to monitor sonar system performance during an entire watch.

The operator has access to the TOMS control functions through a graphical user interface controlled by an industrial-quality trackball. An unretouched example of the TOMS operator display is shown in Figure 4. The system can provide up to three graphical displays, or "strip charts," of real-time data or previously recorded data from the data archive. Real-time data plotting is animated, scrolling from right (most recent time) to left. The operator may select pulldown menus along the top of the screen to configure the system display; options include independent displays of any of the available data in any of the three strip charts, as well as dynamic scaling of the charts themselves in both the horizontal and vertical directions. Observation periods from 15 min to 24 h are available, depending on the operator's tactical interest. Frequently used system commands are represented as macro command soft-key "buttons" along the bottom of the screen. These macro functions, activated by a simple "point-and-click" of the cursor, include commands for capturing a depth profile, switching between real-time and archived (both strip chart and depth profile) data, and capturing a color screen. A depth profile display format, also available, sorts the measured data into depth bins. The profiles, most useful when the submarine makes an extended depth excursion, are independently archived and available for later retrieval. The ship's position and the time period of the data on the screen appear in the text boxes to the right of the (operator-selected) measurement data.

The example provided in Figure 4 shows (from top to bottom) time history plots of seawater temperature, conductivity, and sound speed during coastal training operations near the Aleutian Islands in March 1991. The most recent sound-speed measurement (taken off the submarine's AN/BQH-1 sound velocimeter) appears in the data box to the right of the temperature strip chart. The sharp changes in measured seawater properties (i.e., changes of 2.5°F in temperature, 0.13 S/m in conductivity, and 18 ft/s in sound speed) indicate a coastal front at approximately 00:45 as the submarine entered the Gulf of Alaska during a coastal transit. (The prototype TOMS display data are in English units of measure, as is current practice aboard U.S. submarines.)

OPERATIONAL ISSUES

The Ocean-Front Detection Process

Consider a ship passing through a canonical ocean front from the cold-water side to warmer water, as shown in Figure 5A. Manual temperature measurements at discrete time intervals are indicated by the triangles on the hypothetical temperature plot along the ship's track, shown in Figure 5B. The time required to interpret the plot (and recognize that a front had been crossed) would depend on the frequency of the measurements, the magnitude of the temperature change across the front, and how far the ship was traveling. Automated, continuous measurements, represented by the continuous temperature line, greatly facilitate plot interpretation and frontal feature identification.

Clearly, the ocean is not nearly so well behaved as Figure 5 suggests. Figure 6 shows the track of the TOMS test submarine as 'it transited coastal waters from the
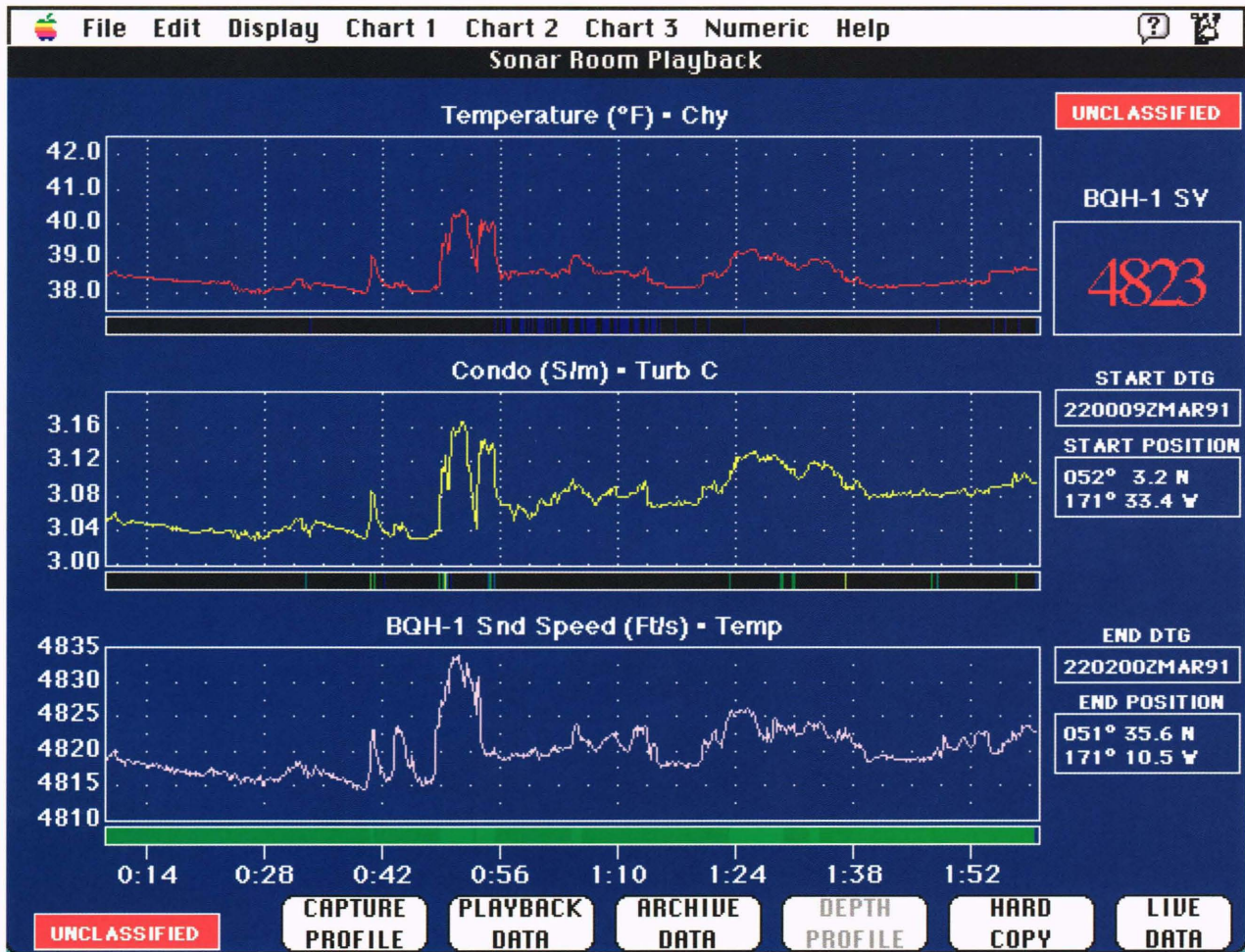
Figure 4. Example of the tactical oceanographic monitoring system (TOMS) display generated during the Aleutian Islands coastal transit. Pulldown menu options are shown along the top and macro soft-key commands along the bottom. English units of measure are used in the prototype TOMS system to conform to current practice aboard U.S. submarines.

Bering Sea side of the Aleutians into the North Pacific. (The data presented in Fig. 4 were obtained over a period of about two hours on 22 March 1991 during this transit period.) The waters along the north coast of the Aleutians are characterized by nearly uniform cold temperatures and seawater conductivity (salinity) gradually decreasing near the coast. On the Pacific side of the islands, temperature and salinity increase sharply. Such water-mass variations are common in coastal waters and can affect not only the performance of a ship's sensors but also the operation of the platform itself. In this example, the 18-ft/s change in seawater sound speed shown on the TOMS display (Fig. 4, bottom trace) as the submarine passed through the front translates into a static submarine trim compensation adjustment of about 5000 pounds of variable ballasting.

Correcting for Errors Induced by Vertical Motion of a Submarine

In the foregoing examples, we assumed a submarine operating at constant depth. But when a submarine moves vertically through the water column, it can experience variations in properties such as temperature, salinity, and turbidity that are very similar to those caused by horizontal water-mass variations. To clearly interpret the measurements, we must account for these variations induced by change of depth.

The TOMS implements a simple, effective procedure to compensate observed values for platform-induced ambiguities related to depth changes. Specifically, the system captures and archives (upon the operator's prompt) a reference depth profile of any of the system-measured parameters, which can then be compared with actual *in situ* measured values. Differences between subsequent measurements and the reference profile at the same depth represent a measure of the horizontal variation in water-mass conditions—a direct indication of ocean water-mass variations.

This depth-motion compensation process is graphically illustrated in Figure 7. Results of the process are defined as "compensated values," since they indicate estimated horizontal changes in the values rather than the actual measured parameters. The magnitude and the sense (negative for a transition to a colder water mass)
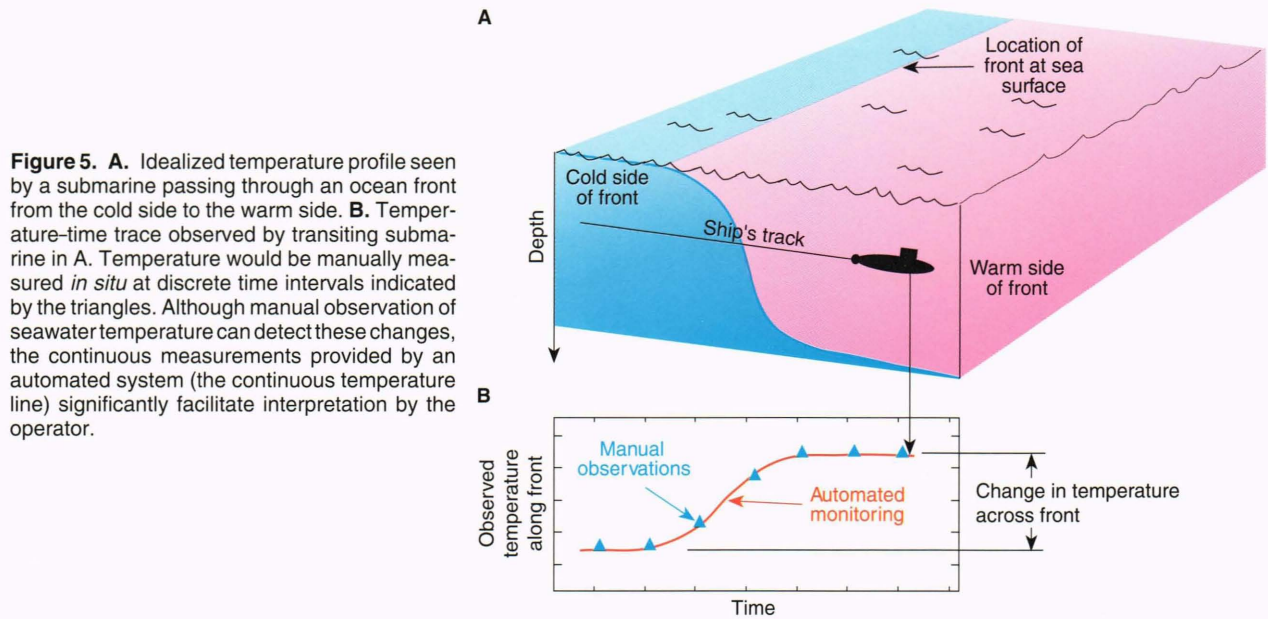
A

Figure 5. A. Idealized temperature profile seen by a submarine passing through an ocean front from the cold side to the warm side. **B.** Temperature–time trace observed by transiting submarine in A. Temperature would be manually measured *in situ* at discrete time intervals indicated by the triangles. Although manual observation of seawater temperature can detect these changes, the continuous measurements provided by an automated system (the continuous temperature line) significantly facilitate interpretation by the operator.

B
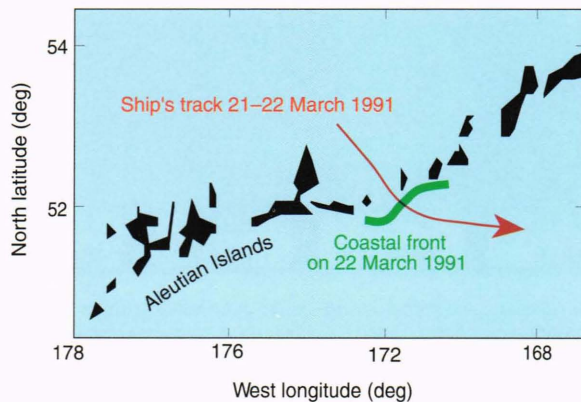
Figure 6. Actual ship's track and location of the coastal front corresponding to the data of Figure 4. The sharp changes in water-mass properties associated with the front affect both sensor performance and ship operation.

of the difference between the reference profile and the measured conditions have been shown to reliably indicate incipient changes in water-mass conditions.

MONITORING EXAMPLES

During 1991, the TOMS test submarine participated in an exercise in the North Pacific Ocean, transiting from Hawaii to the Gulf of Alaska and back. Drawing on Navy land-based ocean forecast facilities that integrate synoptic oceanographic and meteorological satellite data, we anticipated nine frontal zones over the route, generally associated with the locations of the large-scale climatological fronts. We thus had an excellent opportunity to evaluate the *in situ* performance of TOMS for a variety of operational and environmental conditions. We subsequently detected 46 ocean-front features with a significant cross-frontal sound speed signature—that is, showing at least a 3-m/s difference in sound-speed over a distance

of less than 50 km. Other observed features with smaller sound-speed signatures or those that extended continuously over distances greater than 50 km were not considered.

Figure 8 maps the ocean fronts detected at the submarine's depth during the exercise transit periods. Red dots represent warm-front crossings, green dots the transitions to colder water-mass conditions. The climatological mean positions of the North Pacific subtropical and subarctic fronts (from Roden[9]) are also shown. During the submarine's transit to its exercise area, we detected clusters of fronts not only in the vicinity of the climatological mean frontal locations but also well away from those locations. We also observed a stepwise transition from the warm, tropical low-latitude ocean regions to the subarctic along the ship's track, consistent with the structure reported by Fedorov.[1] The northeast Pacific track exhibited greater upper ocean complexity than the track north from Hawaii.

Each of the TOMS-detected fronts indicated in Figure 8 was examined in detail and characterized by the measured change in its water-mass properties (temperature, conductivity, sound speed, and chlorophyll-a) across the front. All of the fronts had sound-speed, temperature, and conductivity signatures. Some exhibited changes in chlorophyll-a concentration (indicative of elevated biological activity) as well. Figure 9 summarizes the resulting distribution of observed frontal sound-speed strengths. The most frequently observed frontal features had a mean sound-speed signature of approximately 3.4 m/s. The mean sound-speed signature of all 46 fronts was 4.9 m/s. These observations indicate a complex pattern of water-mass variability that can be characterized only by a ship employing automated monitoring systems.

Coastal-Front Observations

Although the TOMS-equipped submarine has spent most of its operational time in deep water, the system has
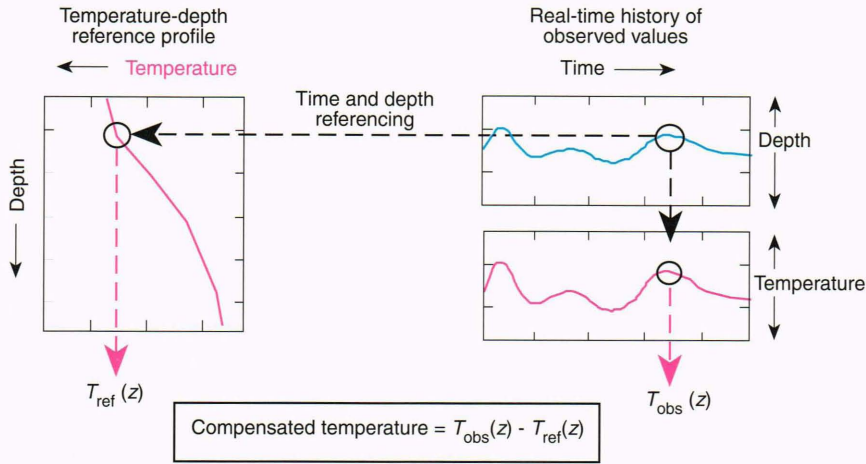
Figure 7. Compensating for changes in water temperature and submarine sound speed induced by depth changes. The tactical oceanographic monitoring system (TOMS) captures a reference depth profile of temperature and stores it for future comparison to real-time temperature data. A significant difference (i.e., 1–2°C) between the two temperatures at the same depth indicates a new water mass.
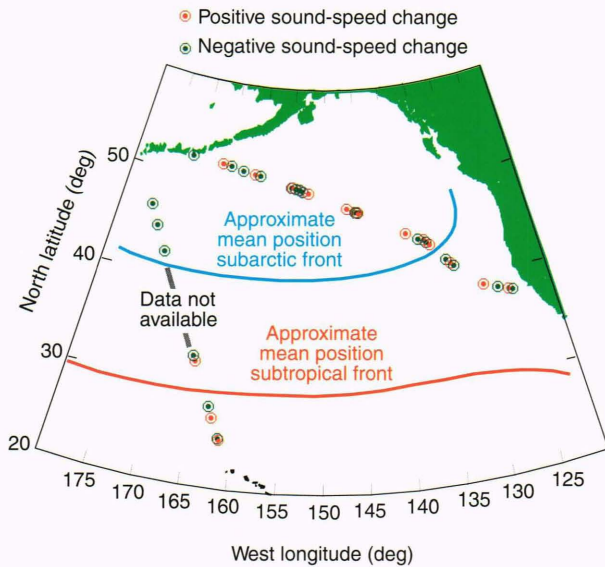
$$\text{Compensated temperature} = T_{obs}(z) - T_{ref}(z)$$

Figure 8. Map of fronts detected by the tactical oceanographic monitoring system (TOMS) during the submarine test exercise transit from Hawaii to the Aleutian Islands and back in March 1991. Fronts were observed not only in the vicinity of the climatological mean frontal zones, but in the coastal and interior regions as well. The expected locations of the climatological mean North Pacific subtropical and subarctic fronts are taken from Reference 9.

Figure 9. Frequency distribution of frontal strengths of the fronts mapped in Figure 8. The distribution excludes features with sound-speed signatures under 3 m/s.

also been used in several coastal training operations to examine characteristics of coastal fronts. In March 1990, the TOMS-equipped USS *Tautog* (SSN 639), operating about 9 km southwest of Barbers Point, Oahu, Hawaii, passed through a sharp coastal front with a sound-speed signature of approximately 5 m/s. The front was also expressed in the measured temperature, conductivity, seawater density, and chlorophyll-a data.

Some of these TOMS-derived data are illustrated in Figure 10. The front is first heralded by the decrease in temperature and ship's speed and the increase in seawater density at time 16:04. The physical data (including some not illustrated here) suggest a cool, less saline water filament extending offshore from Barbers Point. Interest-
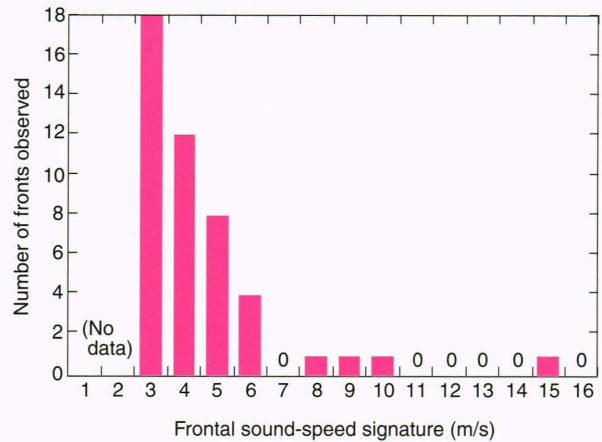
ingly, the ship's speed, taken from the submarine's electromagnetic log, noticeably decreases (approximately 41 cm/s) over a short distance (≈2 km). This offset to the forward motion is attributed to an ocean flow along the frontal feature extending offshore in the lee of the island, since other submarine operations (e.g., an ordered change in ship speed or course; excessive use of the rudder, sail, or stern planes) were eliminated as possible causes of the change in relative speed. The TOMS results are especially valuable, therefore, because coastal-front features such as these are difficult to predict in advance and can affect many submerged ship operations, particularly at slow speeds in shallow water.

INVESTIGATIONS TO IMPROVE OCEAN–FRONT ALERTING

The complex pattern of upper ocean and coastal fronts observed during the TOMS trials reinforces the need for improving front alerting procedures for automated monitoring systems. The TOMS prototype includes various data processing procedures for deriving early indications
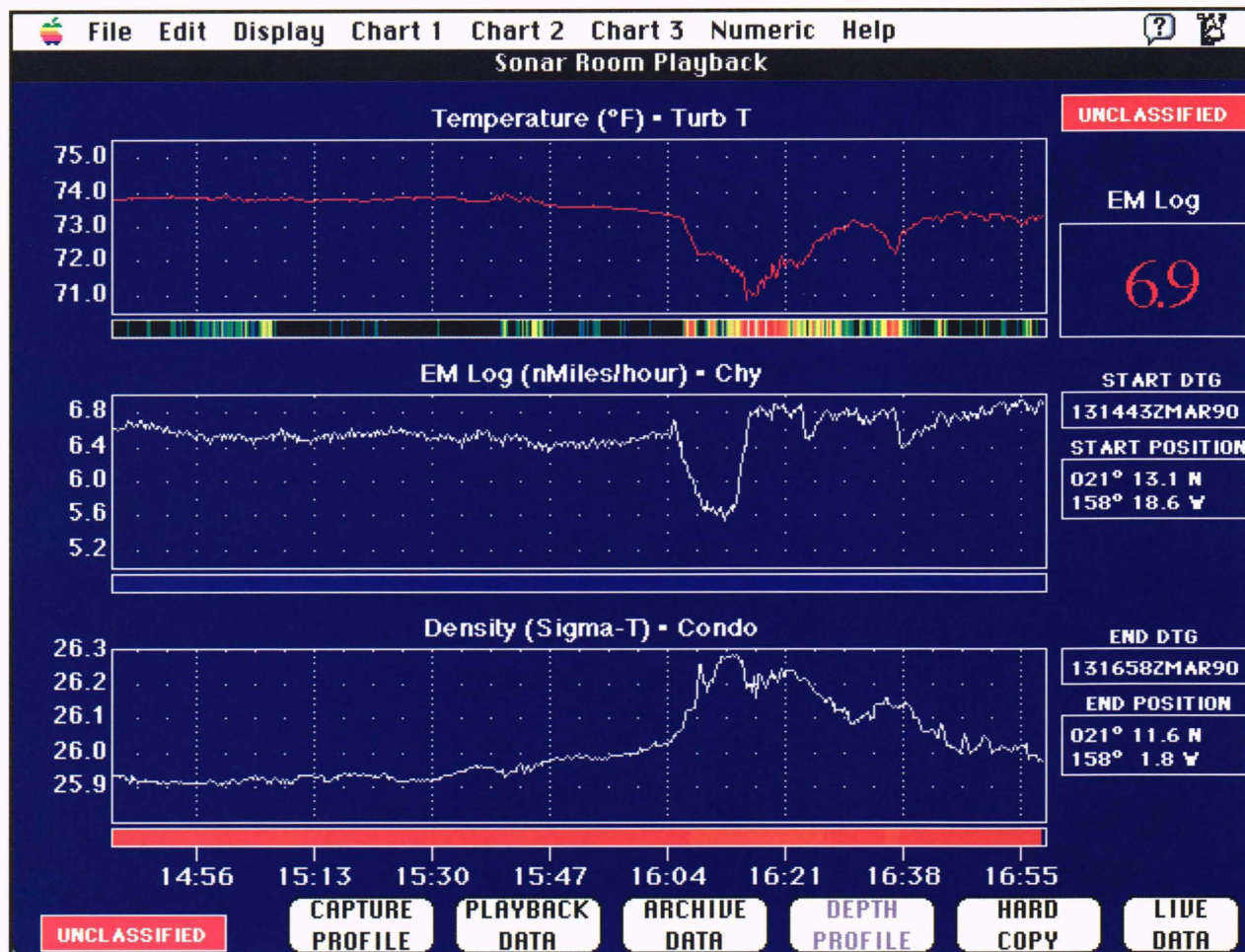
Figure 10. Coastal front detected by the tactical oceanographic monitoring system (TOMS) 9 km off Barbers Point in the lee of the island of Oahu, Hawaii, in March 1990 at 16:04. It is identified by (top to bottom) the decrease in temperature and ship's relative speed and the increase in seawater density. The data are consistent with a filament of near-surface, cool, moderately less saline water extending offshore.

of ocean fronts and displays of measured and calculated parameters known to be indicative of ocean fronts.

The TOMS also incorporates another approach for alerting to fronts: exploitation of the cross-frontal turbulent signature of temperature and conductivity associated with near-frontal mixing processes. In exploratory measurements in the subtropical North Atlantic, Zenk and Katz observed that energy levels of spectra for small-scale horizontal temperature fluctuations were significantly higher within and near ocean fronts than in the surrounding, more quiescent water mass.[10] Dugan et al. later suggested that oceanic temperature and conductivity variability over horizontal distances of less than 25 m fluctuates markedly and is associated with small-scale mixing patches in the ocean.[11] Ocean fronts are rich sources of such patches.[1] Consequently, increases in the variance of the temperature fluctuation can be used as an indicator of horizontal mixing across the front. Since this mixing can extend into the surrounding waters from a few hundred meters for weak fronts to tens of kilometers for strong fronts,[1] it potentially offers an additional ocean-front detection signature as the ship approaches the front.

The TOMS automatically estimates and color maps the bandpassed small-scale temperature variances as a small bar strip chart immediately below the temperature strip chart, as shown in Figure 10. The higher-magnitude temperature fluctuation variances are yellow and red, and are strongly correlated with the location of the frontal feature.

To verify that the frontal features depicted in Figure 10 expressed a detectable mixing signature that correlated with the ship's observed frontal position, we used these and other frontal data to determine the distribution of temperature fluctuation variances. Specifically, we estimated the time-dependent temperature variance density (in $°C^2/cycle·m^{-1}$) by applying a speed-normalized 64-point digital fast Fourier transform to the measured temperature-time series. In the Figure 10 example, this procedure produced a sample spectral estimate approximately every 12 m along the ship's track through the front. We then summed the wave number spectral estimates over the 1.0- to 0.1-cycle/m wave numbers (1- to 10-m horizontal length scales) to generate the total temperature variance in the 1- to 10-m waveband (horizontal scales
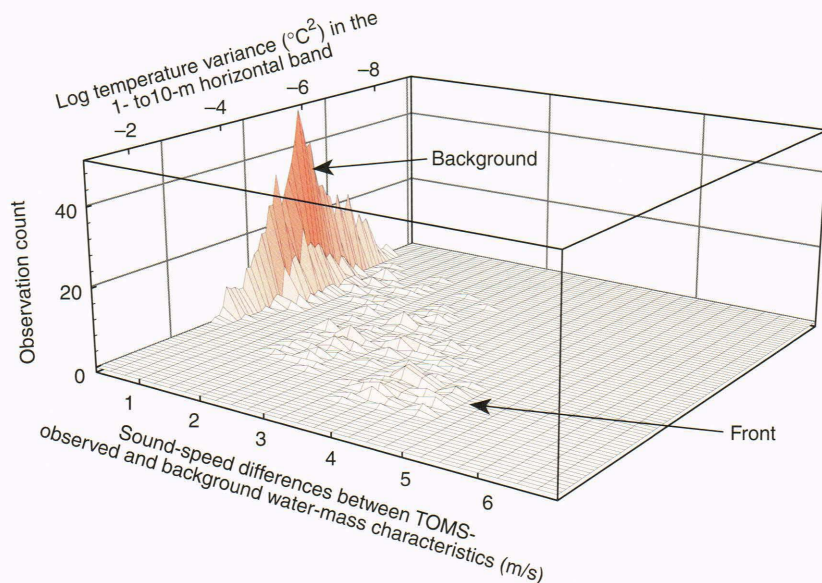
Figure 11. Joint frequency distribution of the short horizontal spatial scale (1–10 m) temperature variance and sound-speed anomalies observed during a 2-h, 15-min transit through the coastal front off Barbers Point, Hawaii, in March 1990. The ocean background (non-frontal) conditions comprise the most frequently observed temperature variance and sound-speed changes, and are shown here as the large observation count near zero sound-speed difference and 10^{-5} to 10^{-6} $^{\circ}C^2$ temperature variance. The front appears as a separate population distribution with temperature variances of 10^{-2} to 10^{-5} $^{\circ}C^2$ and sound-speed differences of 0.5 to 4.75 m/s.

within the oceanic mixing band).[11] Finally, we compared these horizontal wave-number–bandpassed variance estimates with the contemporaneously measured sound-speed differences across the front.

Figure 11 provides a detailed post-trial summary of the joint frequency distribution of the frontal sound-speed characteristics and temperature fluctuation variances for the data shown in Figure 10. The background (non-frontal) water-mass statistics accumulate in an approximately log-normal frequency distribution along the near-zero sound-speed difference and with a mean temperature fluctuation variance of about $10^{-5}°C^2$. The distribution associated with the correlated front data is distinct from that of the background, exhibiting both a higher mean variance level ($\sim 10^{-2}$) and a positive correlation with the front's sound-speed anomaly. These preliminary results suggest that fine-scale measurements by an automated monitoring system can provide additional evidence of ocean fronts, thereby reducing the number of potential false alerts to an operator. Investigations are under way to determine the reliability of this approach in other oceanic regions, both deepwater and coastal, for which TOMS data exist.

PROSPECTS FOR REAL-TIME OPERATIONAL TACTICAL OCEANOGRAPHY

The initial prototype TOMS test has demonstrated the utility of real-time environmental data in a wide range of tactical operations. The data reveal the complexity of the open and coastal ocean environment, especially the property variations that are too small to be measurable by conventionally equipped Navy ships but large enough to potentially affect the performance of the ship's tactical sensing systems. On the basis of our operational experience during the test period, we are planning with the Navy to establish a permanent testbed system. This permanent
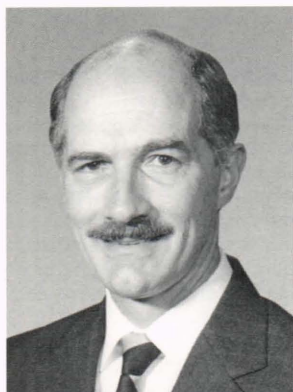
installation will support the continuing assessment of new sensor technologies and the development of accompanying tactical doctrine for future system use.

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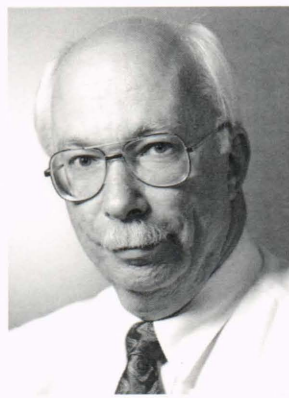
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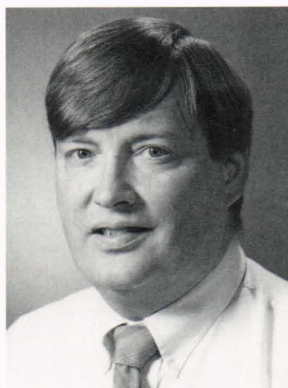
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