Oceanographic Sensor System Development

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When the Submarine Technology Department (now the National Security Technology Department) was formed in 1977, it launched an evolution, if not a revolution, in the design of oceanographic sensor systems at APL. This drove rapid advances in ocean sensor systems engineering and technology to support a better understanding of upper ocean dynamics. In this article we provide a brief review of engineering efforts for one oceanographic system consisting of a towed sensor array and a launch-and-recovery motion compensation crane. The sensor array instrumentation grew to measure temperature, fluorescence, conductivity, and other parameters, while the crane decoupled the towed sensors from wave-induced ship motion. Development of this system introduced new design techniques, sensors, and innovative devices that have influenced the department's programs over the past 25 years.

INTRODUCTION

The inception of an important family of sensors in the mid-1970s can be traced to the development of a unique towed oceanographic array known as the "thermistor-fluorometer" (TF) chain.[1,2] With the formation of the Submarine Technology Department in 1977, the TF chain took on a central role in oceanographic research. Although other oceanographic systems were built contemporaneously, TF chain–related engineering in particular influenced the development of nearly every nonacoustic sensor system (and some acoustic systems) undertaken over the last 25 years by the department (now the National Security Technology Department). Thermistor chain engineering has formed a natural backbone connecting the development of small, sensitive, accurate, and reliable sensors for the measurement of temperature, conductivity, fluorescence, and optical properties. Design improvements provided increasingly greater sensor densities, larger sensor numbers, and in the unforgiving ocean environment, high reliability.

ANALOG THERMISTOR CHAIN SYSTEMS

Groundwork

From 1974 through 1976 APL ran a series of sea tests to better understand the ocean dynamics of seawater mixing and transport by measuring thermal and salinity gradients. During this period the Laboratory developed a TF chain system consisting of a low-drag tow cable, specialized winch, depressor, and overboarding A-frame (Fig. 1). Each major component in turn comprised a multitude of complex and delicate components.

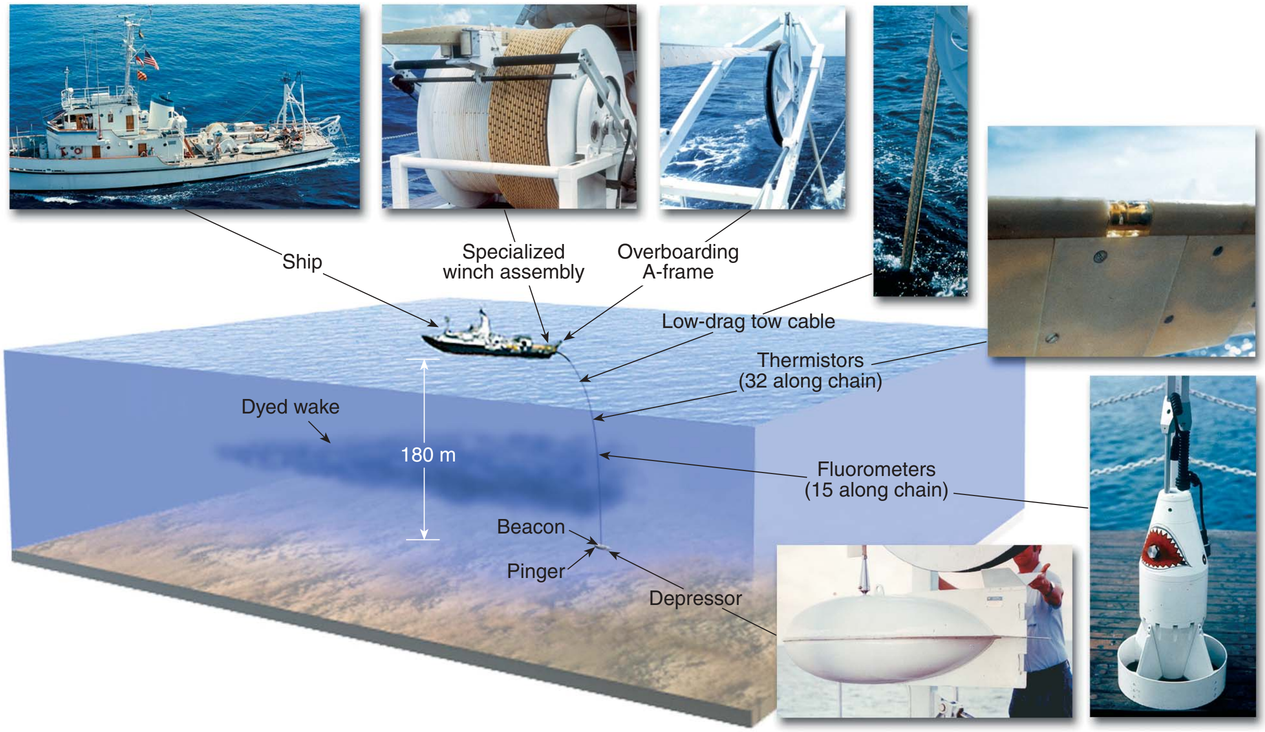

Figure 1. TF chain system components as configured in 1976.

The basic thermistor chain concept consisted of mounting a regularly spaced array (chain) of glass bead thermistors along a low-drag, relatively vertical tow cable. When towed from a ship, the temperature measurements produced a continuous horizontal and vertical profile, a slice, as it were, of the ocean. Additional sensors consisting of depth transducers and fluorometers that detect fluorescent tracers in seawater provided a more complete survey of the environment.

This seemingly simple concept entailed a daunting list of difficult design issues, however. The analog signals connected to the thermistors, fluorometers, and depth sensors required a large number of dedicated wires, and the criteria for insulation and circuit resistance stability precluded the use of electrical connectors. Each circuit required insulation integrity to seawater in excess of 160 MΩ, while the *in situ* oceanographic sensors required direct exposure to the seawater in a manner that left the seawater relatively undisturbed. Conventional oil-filled hoses, which have proven so reliable in acoustic systems, would result in too much disturbance of the seawater for these measurements.

APL engineers worked with Fathom Oceanology, Ltd., of Canada, and Sippican, Corp. in Massachusetts, to construct a low-drag cable system that met the TF chain measurement requirements and reduced system bulk. At the time, Fathom made plastic low-drag cable fairings and Sippican developed sensitive thermistor amplifiers and expendable bathythermograph systems. The Fathom fairings used for the TF chain had a flexible polyurethane nosepiece wrapped around a steel-armored cable with rigid ABS (acrylonitrile-butadiene-styrene) symmetrical plastic tails that interlocked and clamped to the nosepieces. The 10-cm-tall, 2-cm-thick nose and 20-cm-long tail pieces completely enveloped a circular cross-section tow cable to present a streamlined low-drag shape to the water flow. When towed from a ship with a deadweight attached, the faired cable towed fairly vertically.

APL engineers requested some modifications to the fairing design: increase the amount of nosepiece material between the leading edge and the cable to provide enough room to mold in glass bead thermistors, and lengthen the tails to provide space to run wire bundles that connect to the sensors. Some fairing tails were modified at the Laboratory to facilitate attachment of external sensors. APL built towed fluorometers that connected to these modified fairings which trailed behind like large fishing lures. Repackaged Sensotec depth transducers were also distributed along the cable using modified fairings. The choice of tough ETFE (ethylene-tetrafluoro-ethylene) insulated wires provided high insulation integrity.

Fathom eliminated connectors in the thermistor wires by placing inside the winch drum what became known as "internal cable winders"—mechanisms that allowed hard-wiring through a rotating winch drum. Each fairing-mounted thermistor had a companion matched calibrated resistor, which together formed a half bridge circuit. Twisted-pair wires connected the fairing circuit half to the topside half (Sippican Corp. precision bridges) located in the ship's instrumentation room.

By 1977, APL had successfully deployed a TF chain. The fairing tailpieces could accommodate up to three wire bundles comprising 111 twisted-pair conductors. This TF chain design had 63 sensors (42 thermistors, 15 fluorometers, and 6 depth transducers) that connected to rack-mounted shipboard electronics. The engineers and scientists that conceived of the APL TF chain left in their wake a flood of brilliant ideas, components for nearly two complete TF chain systems, and many technical challenges to be handled by the newly formed Submarine Technology Department.

Thermistor-Fluorometer Chain

In early 1978, work began on an ambitious plan to complete a series of large upper-ocean hydrodynamic measurement exercises that would run from 1978 through 1981. These exercises required the TF chain to play a central role. Engineers joining the project inherited an impressive design but faced a challenging redesign task. Given the extended at-sea periods planned for the experiments, improvements to nearly all aspects of the TF chain design were called for because of the need for greater sensor sensitivity, improved ease of maintenance, better towing stability and survivability, and better reliability.

At the time, APL had limited in-house test equipment to expose TF chain components to the mechanical stresses of launch, recovery, and towing, as well as the hydrostatic pressures of operating at depth. Empirical solutions were employed when engineering calculations yielded indeterminate solutions or were too protracted. Direct dynamic testing proved useful in improving the operation and reliability of internal cable winders, winch hydraulics, and other mechanical components.

The intensity of sea testing meant that many problems had to be solved in the field. For example, glass bead thermistor seals and ETFE in-line wire splices became problematic when sensor improvements required an increase in electrical insulation from seawater to 1000 MΩ. Remedies designed in house failed, but in the field a reliable epoxy watertight seal was developed during at-sea testing.

APL operated a full-time test facility in Ft. Lauderdale that berthed several research vessels and enabled the conduct of rapid turnaround, full-scale ocean tests. One of the first engineering tests focused on solving a towing instability problem common to hard-faired low-drag cables. Under certain conditions hard-faired cables will tow off to the side. This phenomenon can lift a depressor weighing over 454 kg a vertical distance of 100 m. Figure 2 illustrates this effect, termed "kiting," which occurred when the towing ship simply increased speed while on a constant heading. J. F. Henderson of the University of Bath found a technique to limit kiting angles by placing flat fairing tail extensions on each fairing.[3]

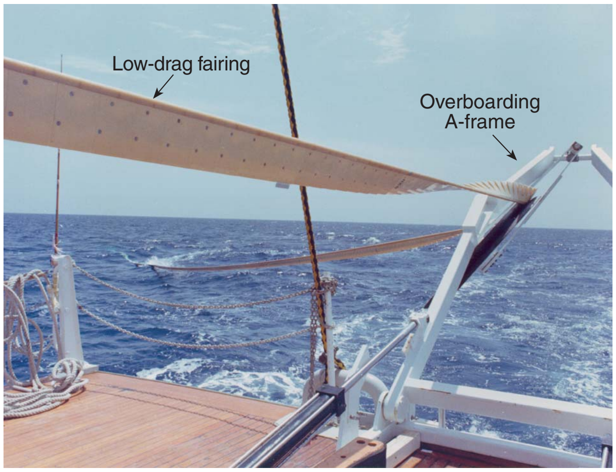

Figure 2. Kiting phenomenon. (Note: the cable normally tows straight down.)

APL engineers elaborated on Henderson's design by modifying the extensions so that they would interlock adjacent fairings while allowing the cable assembly to splay over sheaves and around the winch drum. These staggered extenders kept adjacent fairings in plane and prevented the disruption of tangential flow by exposed fairing edges. Improvements made during this testing eliminated kiting for a wide range of fairing designs, speeds, and depressor types.

Motion Compensation

A well-behaved tow cable does not by itself provide stability for attached underwater sensors, even though the sensors experience a relatively benign underwater environment. Before 1979, the TF chain was towed in a conventional manner from a rigid A-frame or U-frame, as shown in Fig. 2. However, ocean waves induce ship heave (vertical motion) and pitching. These motions couple directly through a rigid tow point to the tow cable modulating the sensor data. Also, in a matter of a few seconds, cable tension can fluctuate from completely slack to very taut. Severe tension extremes can part the tow cable, resulting in the loss of the underwater instrumentation. A means to decouple ship motion from the underwater towed system became an important aspect of the TF chain system development.

Prototype Motion-Compensation Systems

In preparation for a 1979 test, APL built its first motion-compensated towing system.[4] The system reduced sensor motion in the primary ocean wave periods of 1 to 10 s and demonstrated that the basic concept would work reliably and improve safety. However, motion contamination also disrupts the measurements, rendering them useless or misleading. Without motion compensation, it was shown that motion-induced salinity spiking made uncompensated measurements unusable for microstructure studies and of limited use for fine-structure studies.[5]

To eliminate this problem, a second much smaller motion compensator was built specifically to address motion contamination of a relatively lightweight (68 kg) vertically profiling conductivity-temperature-depth (CTD)[6] sensor, which experienced motion contamination as did the TF chain. The CTD motion compensator provided uniform descent rates (Fig. 3), even in rough seas, and maintained near-constant matching of the thermistor frequency response with the spatial response of the conductivity cell.[5] This compensation system provided a model for the next-generation TF chain compensator.

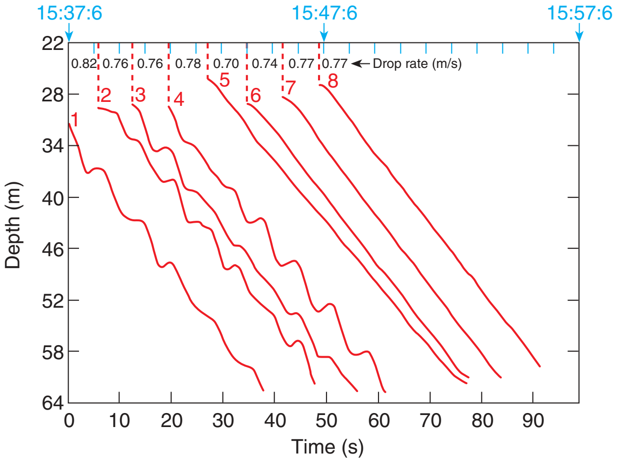

Figure 3. CTD motion compensation system drop rates (1–4, uncompensated; 5–8, compensated). (Reprinted from Ref. 5 by permission. © 1985, American Meteorological Society.)

Launch/Recovery Motion Compensation System

In 1981, a third-generation, fully functional launch/recovery motion compensation system (LRMC) was built for the thermistor-fluorometer-conductivity (TFC) chain, which is discussed in the next section. This system combined compensation characteristics of the CTD motion compensation system with full use of an articulated crane similar to that built in 1979.[7]

The LRMC consisted of a commercial crane reinforced for shipboard use and modified for compensation, high- and low-pressure nitrogen gas storage, a conventional hydraulic power supply, and an air compressor to drive a gas pump for recycling the nitrogen gas used during compensation (Fig. 4). This LRMC version provided compensation over 7 m of vertical stroke while handling up to 1633-kg loads. Articulation and an 8-m extension of the boom allowed the LRMC to reach from the deck to beneath the water on most ships. Saddles attached to the towing sheave capture towed bodies underwater, eliminating the need for personnel dedicated to handling tag lines. LRMC operations typically require a crane operator and a winch operator, half the previously needed crew.

Historical data showed compensated towed sensor motion falling between 2 and 6 cm root-mean-square (RMS) in conditions through sea-state 5 while remaining relatively independent of the type of towing ship. Figure 5 shows the motion compensator's effectiveness relative to the ship's deck motion when operating from the 36-m R/V *Cape*, at a tow speed of 6 kt, with several gas spring stiffness conditions. Analysis of these power spectral density data showed about a 4-cm RMS motion at the sensors, with deck motion of 0.3 m, in the dominant wave period of 3 to 12 s.

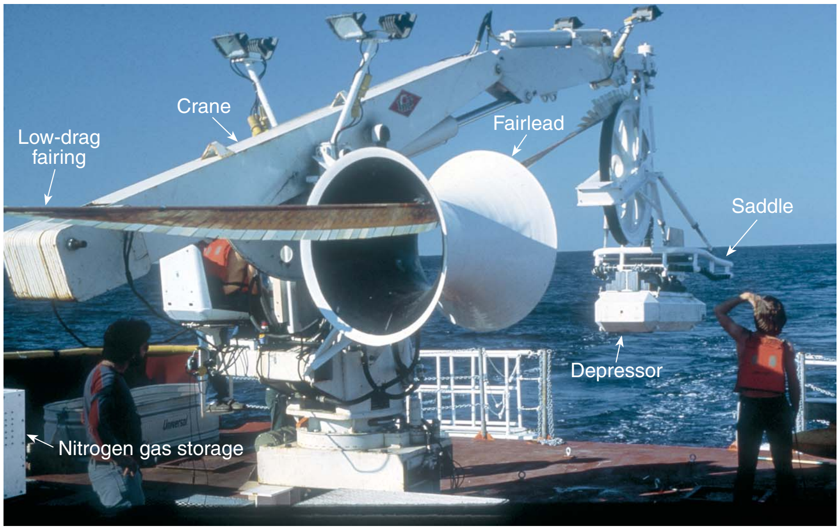

Figure 4. Launch/recovery motion compensation system.

The effectiveness of the LRMC meant that towing operations could proceed safely and continuously over many days while providing a stable platform for high-quality data collection. Reduced motion also meant reduced stress on the TF chain components, which opened up the opportunity to develop more complex and sensitive towed instrumentation.

Thermistor-Fluorometer-Conductivity Chain

Scientific demands for more capability progressed along with engineering improvements in reliability. By the end of 1979, APL had two TF chains fielded simultaneously, and by 1980 conductivity sensors, attached like the fluorometers, were incorporated into the chain design. The 1981 TFC chain consisted of 41 thermistors, 27 fluorometers, 10 conductivity sensors, 5 pressure

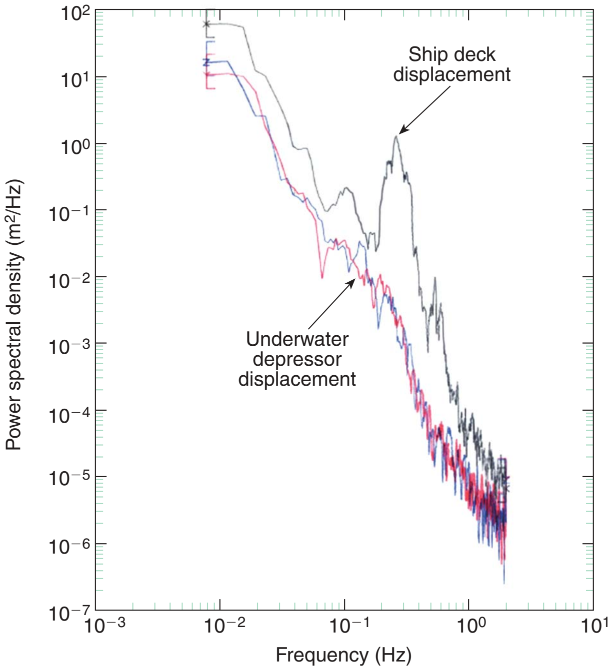

Figure 5. Displacement power spectral density between ship deck and towed depressor.

sensors, and a 3-axis velocimeter, each on dedicated wires that carried power and analog signals. By the end of 1981, cable handling issues were well understood, faired cable preparation used production line tools, the winch had remote-controlled hydraulics, the internal cable winders operated flawlessly, and the system had stable towing characteristics. In addition, measurement activities had moved from protected near-shore waters to open ocean, and the LRMC system allowed for extended towing operations in high sea states.

The scientific demand for greater numbers of more sensitive sensors came upon the need to meet the physical space limitations of the fairings. The chain's fairings could not support any more wires dedicated to individual analog sensors, and although towing operations had became sea-state independent, the procedure for attaching bulky fluorometers and conductivity sensors to the chain (Fig. 6) was not. Meanwhile, another evolution in sensors had already begun. Newly designed depth sensors and miniature roll and pitch sensors each fit within a fairing. It became clear in early 1982 that all the sensor electronics needed to shrink to fit within the fairings. To accomplish this the chain went digital.

DIGITAL CHAIN SYSTEMS

Between 1982 and 1984, the TFC chain went through a dramatic redesign. It would have over 200 thermistors, with a corresponding increase in fluorometers and conductivity sensors. Thermistor, conductivity sensor, and fluorometer signals would be digitized and multiplexed locally, in the faired cable.

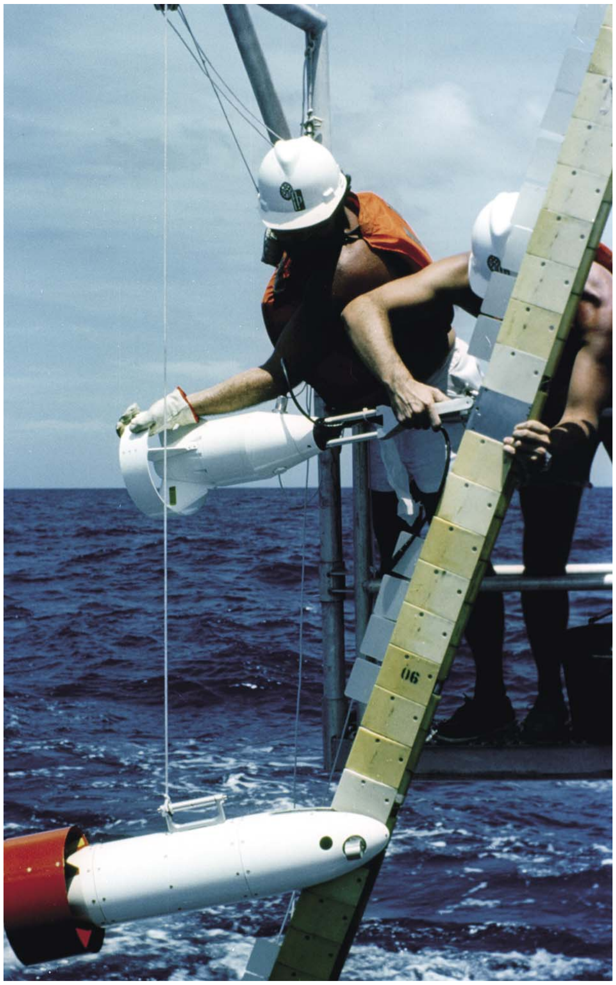

Figure 6. Fluorometers and conductivity sensors attached to the TFC chain.

Incorporating sensors and electronics into the fairings markedly changed the TFC chain system design concept. To make this practical, the sensors needed a complete redesign to improve reliability and to shrink to the size of a fairing. The increased sensor density and associated sensor electronic pressure vessels required fairing redesign to mechanically support the localized weight and withstand dynamic loads. Improvements were needed in deck handling equipment, cable fairleads, and motion compensation automation. Also, cameras were required to provide continuous monitoring of all deck equipment from the safety of the ship's interior. Each of these improvements led to a system that provided better quality data and could remain safely at sea for long periods with little maintenance and minimal personnel.

Sensors

Thermistor Improvements

The reliability of the thermistor moldings was the primary electrical insulation problem remaining by the end of 1981. With just 41 thermistors, repair and replacement at sea seemed manageable because a thermistor fairing could be easily replaced during recovery operations. However, a chain composed of several hundred sensors made it impractical to perform at-sea repairs and to carry sufficient spares.

Eliminating failures due to leaks required a new molding technique. Within 6 months, the problem was solved with construction of over 500 molded thermistors,[8] most of which are still available for use today. During extended sea tests, losses ran at an acceptable rate of 2%, mostly from glass breakage, eliminating the dominant need for at-sea repairs. Developing reliable thermistor molds led to procedures and material choices that subsequently transformed the way the department designed and fabricated sensors, specified and built cables, and selected materials for oceanographic systems.

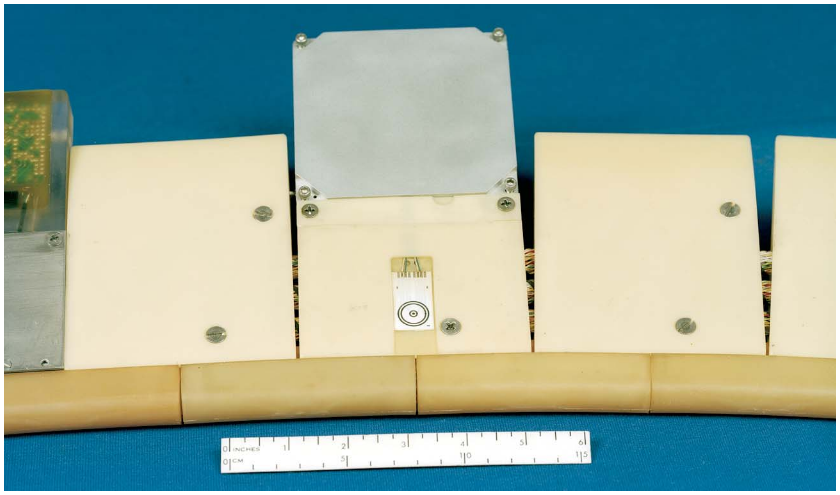

Figure 7. Cell and electronics package mounted on the towed array.

In-Fairing Conductivity Sensors

In-fairing conductivity sensors were developed at APL for the TFC chain.[9] The rationale for this effort was to provide a stable and accurate measurement of oceanic electrical conductivity in a 2 × 10 × 10 cm package which would replace the tail of a fairing. Small size was critical to creating an extremely dense vertical array of sensors for the measurement and characterization of vertical oceanic conductivity microstructure. High-frequency response (≈100 Hz) was also desired to detect the minute fluctuations of oceanic conductivity at centimeter scales.

To meet these requirements, a "bulls-eye target" type cell (Fig. 7; contrast with Fig. 6) was used that contained a center dot electrode and three ring electrodes. The electrodes were constructed of a platinum-gold alloy embedded in a ceramic substrate. A bipolar square-wave current signal was impressed upon the first and second rings, with the center dot and outer ring providing the conductivity "sense" electrodes.

The voltage measured by the sense electrodes equals the current drive amplitude multiplied by the resistance of the volume of seawater "seen" by the sense electrodes. A servo control loop (Fig. 8) varied the current to the drive electrodes to maintain a constant voltage across the sense electrodes. A zero-mean alternating-current signal was used to prevent electrolytic corrosion of all the electrode surfaces, and a full-wave rectifier converted the zero-mean amplified signal to a DC value. This was then subtracted from a reference voltage before being fed into an integrator circuit. The integrator output fed a pre-emphasizer circuit, which amplified and "emphasized" the small, high-frequency signal fluctuations from the detector/amplifier that were indicative of oceanic conductivity microstructure.

To optimize sensitivity, the electrodes made direct contact with the seawater, requiring the sensor's electronics to be isolated from the ship and other conductivity sensors in the TFC chain. Otherwise, stray ground-loop currents through seawater would create errors in the measurements. Isolation was achieved by transformers in the power-conditioning circuitry, a digital optical isolator for the square-wave drive, and an analog optical isolator for transmitting the pre-emphasized output to the data acquisition system.

Successful development and deployment of these conductivity sensors demonstrated an order of magnitude improvement in sensor miniaturization, as well as the ability to produce a sensitive, fieldable, open-faced, direct-contact conductivity sensor devoid of biofouling and corrosion. This sensor was the first known to provide microstructure measuring performance in a miniature package.

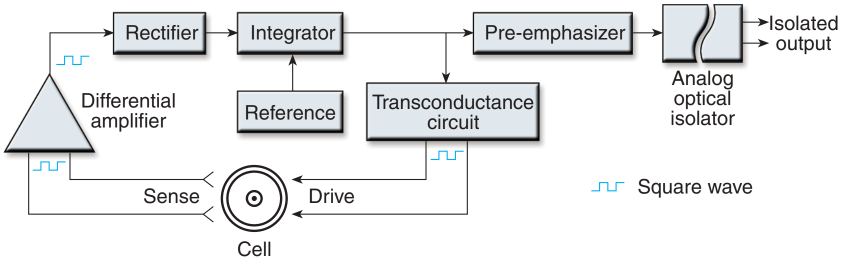

Figure 8. Block diagram of a conductivity circuit.

In-Fairing Fluorometers

In-fairing fluorometers[10] were also developed at APL for the TFC chain to measure fluorescence. Dimensions of the basic fluorometer were similar to those of the conductivity sensor, except the fluorometer had an elongated plastic cowling attached to the end of the electronics can (Fig. 9). The cowling channeled a continuous flow of water through the sample volume as the fluorometer was being towed. The cowling shape also protected the sample volume from stray external light.

Referring to Fig. 10, blue light is emitted as a series of "chopped" half-sinusoid pulses from a small incandescent lamp source through a window in the pressure vessel. The light illuminates a sample volume located inside the cowling and, if illuminated, certain particulates or dyes dispersed in the water can be excited to return a fluorescence. The chopped fluorescence return light is detected with a photodiode/filter combination highly tuned to the fluorescence wavelength. A reference photodiode continuously monitors the output of the incandescent lamp, so the source level is known.

Amplitude/clock information from this photodiode output is used first to normalize the detected signal with the reference amplitude, and then to synchronously detect the normalized signal with both frequency and phase information from the reference "clock" (i.e., the recovered clock signal from the modulated lamp). This synchronous detection technique significantly reduces both internal broadband electrical noise from the signal photodiode circuitry and external optical noise from sunlight leaking into the sample volume. Output from the synchronous detector is low-pass filtered before final output to external data acquisition circuitry.

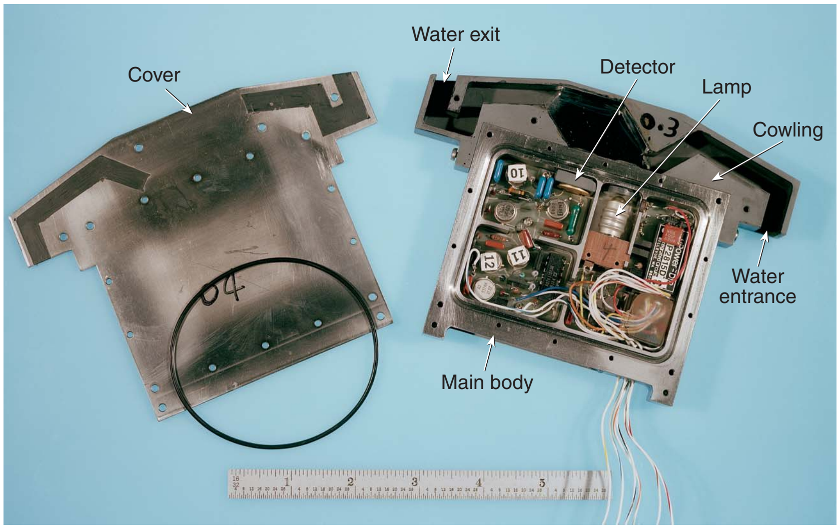

Figure 9. In-fairing fluorometer sensor.

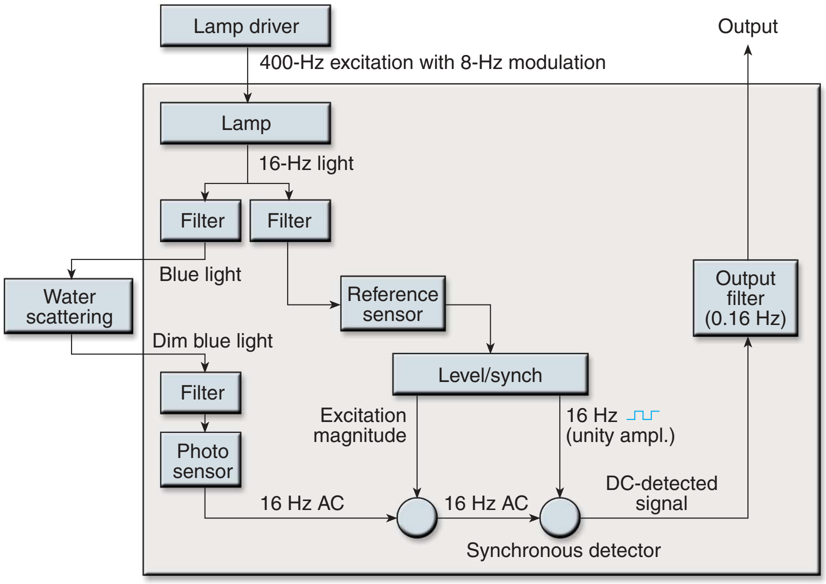

Figure 10. Block diagram of the fluorometer.

Successful in-field deployment of the fluorometers demonstrated substantial miniaturization over previously deployed fluorometer designs. Of even greater significance was that this ocean optical sensor employed a synchronous detection technique (also known as a "lock-in amplifier") that was applied to later APL ocean optical instrument designs. Lock-in amplifiers had been widely used in the optics field, but the designers believe this was the first known use within the oceanographic community.

Many sensors evolved from the first miniature fluorometer, including future incarnations of APL fluorometers and backscatterometers. Backscatterometers measure dispersed particulate matter and employ the same synchronous detection electronics design technique as the fluorometer. However, instead of using an enclosed sample volume, the backscatterometer emits a cone-shaped beam of light into the surrounding water volume. Particulate matter is measured from light backscattered in the volume defined by the intersection of the emitted cone and the detector's field of view.

Multiplexing Electronics

Thermal Gradiometer

A prototype electronics package built in 1982 digitized and multiplexed 10 thermistors and incorporated a depth transducer within the electronics. The electronics fit in a lightweight pressure-compensated metal frame. Tubes welded to the sides of the frame protected the thermistor wires and mechanically coupled adjacent fairings (Fig. 11).

Since all of the components were pressure insensitive (could withstand the hydrostatic loading), a soft re-enterable polyurethane gel, 3M 2112, filled the metal frame/mold and encapsulated the circuit board. This eliminated the need for a complicated pressure vessel to protect the circuits from seawater. The amber-tinted transparent gel simplified circuit debugging because one could insert a probe through the gel to reach various test points. Twenty digitizer packages went out on the prototype system engineering test, with time series displays as shown in Fig. 12.[11]

The thermal gradiometer digital chain provided a platform to test new ideas and demonstrated a mechanically mature system, but demands for greater sensor sensitivity exceeded the capabilities of these first-generation digitizing electronics. These demands led to development of a densely instrumented towed sensor (DITS) chain that met the accuracy, resolution, and noise requirements. Although mechanically more complex, the multiplexed DITS system provided exceptional data quality.

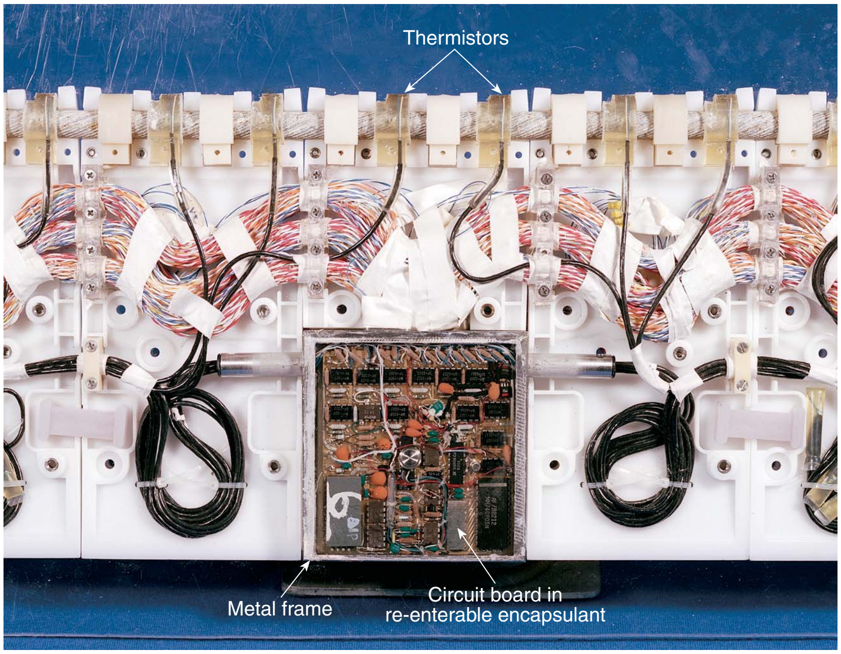

Figure 11. Thermal gradiometer chain fairing assembly.

Densely Instrumented Towed Sensor System

The DITS system built for the TFC chain[12] gathered analog signals from thermistors, conductivity sensors, and other adjacent sensors, and digitized and multiplexed them in 32-channel underwater acquisition modules (UAMs). The suite of UAMs formed a programmable, distributed data acquisition system, i.e., a specialized high-speed underwater data network. Multiple, nested, sensor-sampling rates supported the different sensor bandwidths used to detect minute fluctuations at centimeter and longer oceanic scales.

A primary objective for the design of the UAM was the accurate measurement of a variety of low-level electronics signals in a package that could fit into the space occupied by no more than two adjacent $2 \times 10 \times 20$ cm fairings of the TFC chain, as shown in Fig. 13. Small size was again important to facilitate creating a dense vertical towed array of sensors. Often a dozen or more of these UAMs would be networked together in a dual-bus redundant configuration spread out over 100 m of vertical aperture supporting several hundred chain sensors.

The electromechanical subsystems that made up each UAM were assembled in a pressure vessel that included several innovative features. The internal walls served as electromagnetic interference shields and supported the lid. Glass insulator hermetic feed-throughs passed dozens of electrical signals and sealed the pressure wall. An integral junction box served as a wire strain-relief, as a mold for the gel re-enterable encapsulant, and as protection for a small depth transducer. Elongated slots permitted the housing to float on pins as the towed chain's fairings splayed to pass around a sheave or winch drum while being held firm for normal towing.

The data acquisition front-end also had some unique features. A single, common voltage reference was used throughout so that everything behaved ratiometrically. Using this technique reduced and even eliminated a number of common-mode noise, temperature stability, and absolute accuracy problems.

The most sensitive circuitry (that supporting the thermistors) was placed on ceramic daughterboards to increase the effective thermal mass of critical components for temperature stability near DC. The thermistor circuit's gain and offset were adjustable. Additional temperature resolution was obtained by using a multiplying digital-to-analog converter (MDAC) to subtract the bulk of the DC component

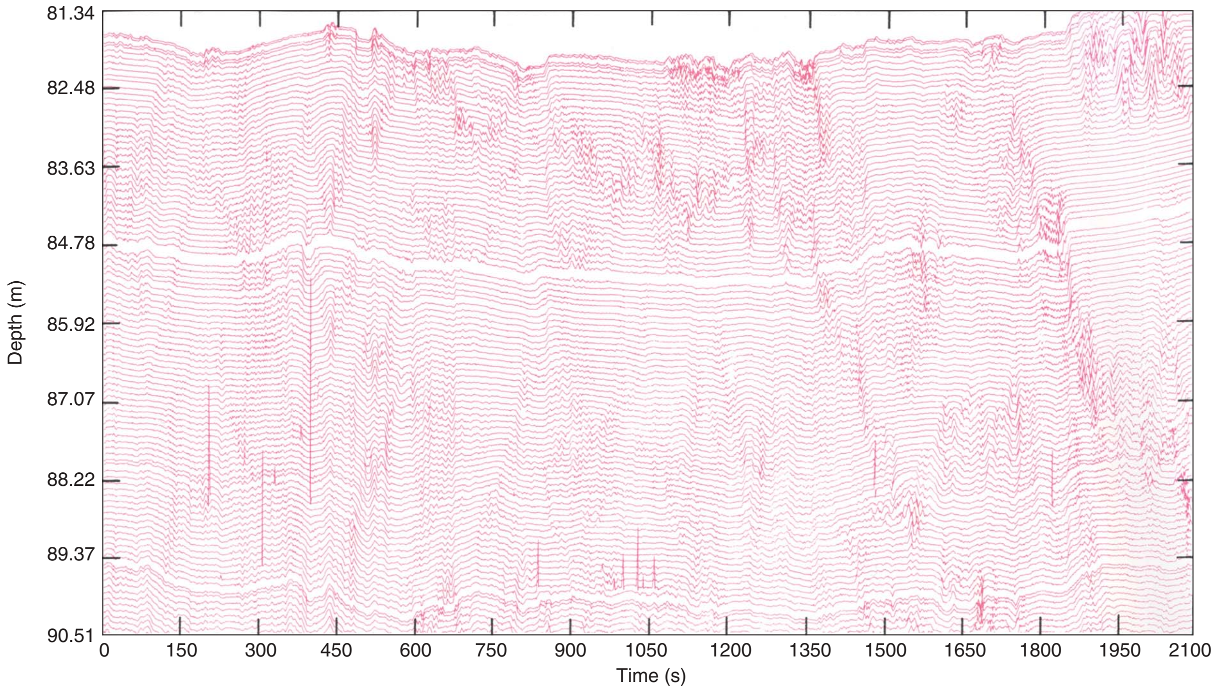

Figure 12. Display of thermistor data. Every second thermistor is plotted for a total of 100 sensors. The vertical scale indicates the depth of each temperature sensor, and subsequent temperatures are relative to the first point using a scale of 0.5°C per vertical division.

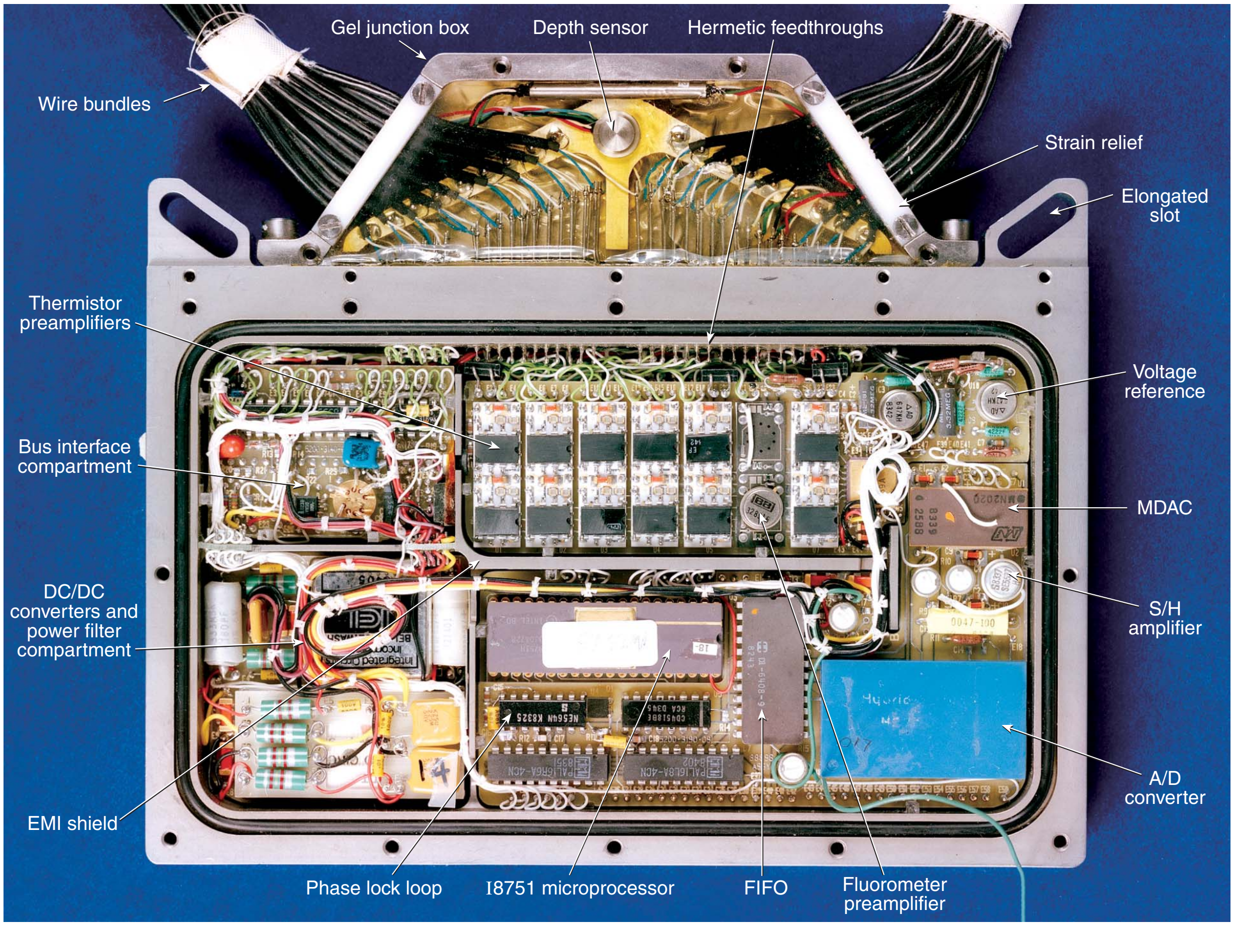

Figure 13. The 32-channel underwater acquisition module.

of thermistor signals. The fluctuating part of the signals would then be centered near zero volts and could then be amplified further using higher programmable gain settings. Since most of the ocean is horizontally stratified over very long length scales, the MDAC required adjustment only when encountering an oceanic front. Software in a shipboard deck unit continually monitored each UAM's output to ensure that no thermistor ever clipped.

In later designs the MDAC approach was replaced by a pre-emphasis circuit that took advantage of the red spectrum normally found in the ocean. This circuit allowed DC to pass straight through, but would increase gain linearly with frequency above a designated corner frequency. Using these two innovative techniques realized an equivalent of roughly 20 bits of resolution out of the system's 16-bit analog-to-digital (A/D) converter.

A major performance breakthrough involved both innovative techniques and careful attention to detail to realize the A/D converter subsystem's full potential. Sixteen-bit A/D converters do not work to specification in the presence of digital noise coupled onto power rails and grounds. Eliminating these noise sources by a combination of filtering, synchronous clocking, and "quiet" code improved system performance tremendously. All clocks in the system were either phase locked or derived from an integer multiple of the sampling rates, thus eliminating precessing cross talk. The A/D was tightly coupled with the microprocessor so that no external memory or input/output instruction calls were made when the A/D was making a conversion, in effect, the quiet code. (This technique also ensured that each UAM stayed "in sync" with the other UAMs in the distributed system to within 1 μs.) At the highest programmable gain, it was possible to watch a thermistor, placed in a calibration bath with the stirrer turned off, count down by single A/D counts as the bath cooled slowly. Each count would hold value for a period of say 30 s with no least-significant-bit toggling or jitter.

Digitized sensor data associated with each sample rate were buffered by the microcontroller and sent topside in a novel fashion. The highest rate or oldest sample's data would be loaded into a first-in first-out (FIFO) buffer after entering the relative address of the data sample (where the sample was to be stored in memory topside), in essence creating a self-addressed data packet. Very fast interrupt service routines were written using direct-memory access. This was done so that the relatively slow computers of the time could keep up with multiple streams of high-speed data and spend the bulk of their time performing real-time analysis instead of just data acquisition. Data were routed through multibuffered shared-memory pools for access by various analysis and data quality monitoring routines. D/A converters and sample-and-hold (S/H) amplifiers strobed by content-addressable memories drove multichannel strip charts showing selected sensors of interest in earlier deployments. Computer-driven raster plotters mapped out isotherms, isopycnals, or internal wave displacements in later systems.

Also developed were a bus repeater module top and bus terminator module bottom. These were used to bracket and localize tri-state signals to the vicinity of the UAMs and recondition them for the long haul topside (much like network repeaters are used today between buildings or campuses). The "network's" bus system was based on RS-422 and RS-485 differential line driver/receiver standards (new at the time). It consisted of a system clock (960 kHz); a frame clock (4 Hz); asynchronous serial protocol downlink and party-line uplink communication lines for commands and status; a high-speed (960 kbits/s) Manchester encoded uplink for data; and daisy-chained, positional-priority, request-and-grant lines that were employed to obtain access to the high-speed data uplink. Using differential digital signals over twisted-pair wires had the benefit of preventing cross talk to low-level analog signals, often sharing the same wire bundle, as well as minimizing susceptibility to high-level signals like shipboard radio transmissions.

The first UAM prototype and deck unit, connected to a DEC PDP-11/34, was conceived, designed, assembled, and fielded over a 3-month period in 1982. It produced data quality better than any previously obtained. The following year was dedicated to making the design more robust and developing a mini production line for the chain instrumentation in preparation for upcoming major sea tests.

CONTINUED SYSTEM DEVELOPMENT

Thermistor-Fluorometer-Conductivity Chain

The "production" DITS design—deployed repeatedly in various TFC chain configurations between 1983 and 1988—addressed a number of hydrodynamic research issues and supplied ground truth for several overflight and satellite ocean-air/sea interface experiments. During 1989 and 1990, the UAM was redesigned for delivery to the Naval Ocean Research and Development Activity, later absorbed into the Naval Research Laboratory. This expanded and ruggedized version was taken to a number of sites each year to track seasonal changes in oceanic regions of tactical interest. One deployment followed the Persian Gulf War to assess the pollution damage caused by all the burning oil wells and oil slicks.

The TFC chain is fielded every few years, most recently in 2002. Only in the past few deployments has technology capable of supplanting DITS capabilities and specifications become available. TFC chain designs now exploit fast microprocessors, greatly miniaturized integrated circuit designs, and virtual instrumentation software. Replacements for the UAMs have physically shrunk from spanning two fairings to one. Mechanically, TFC chains today resemble an updated version of the gradiometer chain with extensive use of high-strength plastics instead of metal housings, and the electronics and data quality meet or exceed those of the DITS.

Launch/Recovery Motion Compensation

The success of the LRMC and continued use with the TFC chain brought demand for support of other projects. The LRMC became the primary deployment system for nearly all oceanographic sensor systems since its use meant that sea conditions would rarely delay or otherwise interfere with test operations and that wave-induced ship motion would not degrade data quality.

To simplify installation, the crane base was modified to easily bolt or weld to decks of ships of opportunity. Improvements included ceramic coatings on hydraulic actuators that eliminated corrosion and extended service life from several years to several decades. In most cases the LRMC's value justified the removal of large, existing ship A-frames and U-frames. Since installation of these improvements, the LRMC has needed only one major overhaul (in 2002) to support a TFC chain sea test.

For an electromagnetics project, the LRMC supported the capture cage used for launch and recovery of a towed superconducting gradiometer system (TSGS) tow body (Fig. 14). After deploying the tow body, the crane would release the cage and pick up the sheave for deployment of a thermistor chain. The tether for the TSGS tow body would then be connected to an attachment block on the thermistor chain.

Responsiveness of the LRMC to small tension changes allowed for rapid comparison of adjacent TFC sensors. On one TFC chain test, control flaps added to a wing depressor allowed cyclic variation of the depressor lift. When acting through the motion-compensation system, this induced vertical motion of the chain with sinusoidal amplitudes of several meters, which provided real-time intercalibration checks of the closely spaced thermistors.

Modifications to the towing sheave assembly adapted the LRMC for use with a towed vertical profiling vehicle[13] and a station-keeping vertical profiler, two systems that incorporated sensor technology derived from the TFC chain. Since the LRMC nearly always went to sea to deploy a variety of sensor suites,[14] special capture saddles and sheaves were made to accommodate many instruments, as shown in Fig. 15, including the motion-compensated crane, a vertical-profiling towed

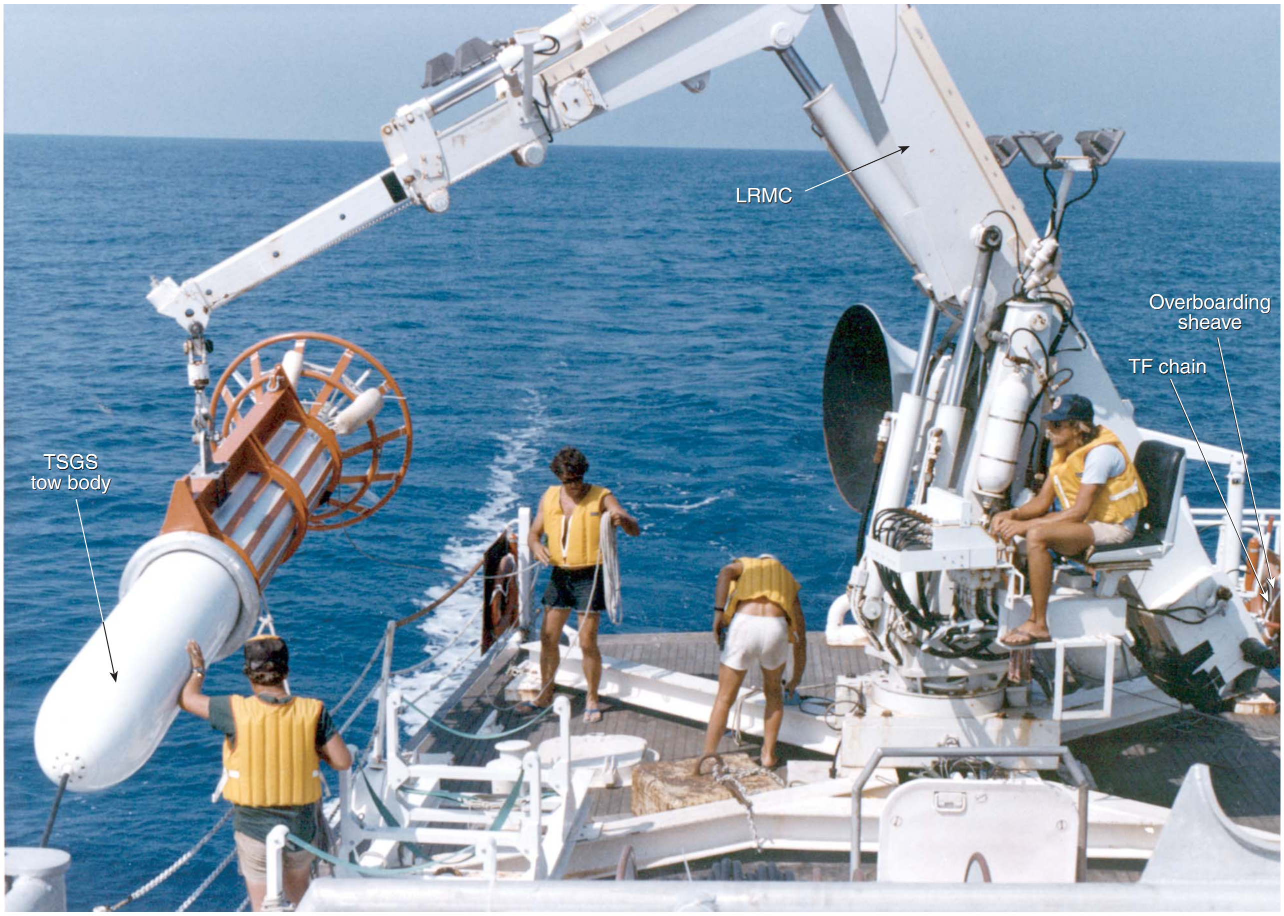

Figure 14. Towed superconducting gradiometer system launch.

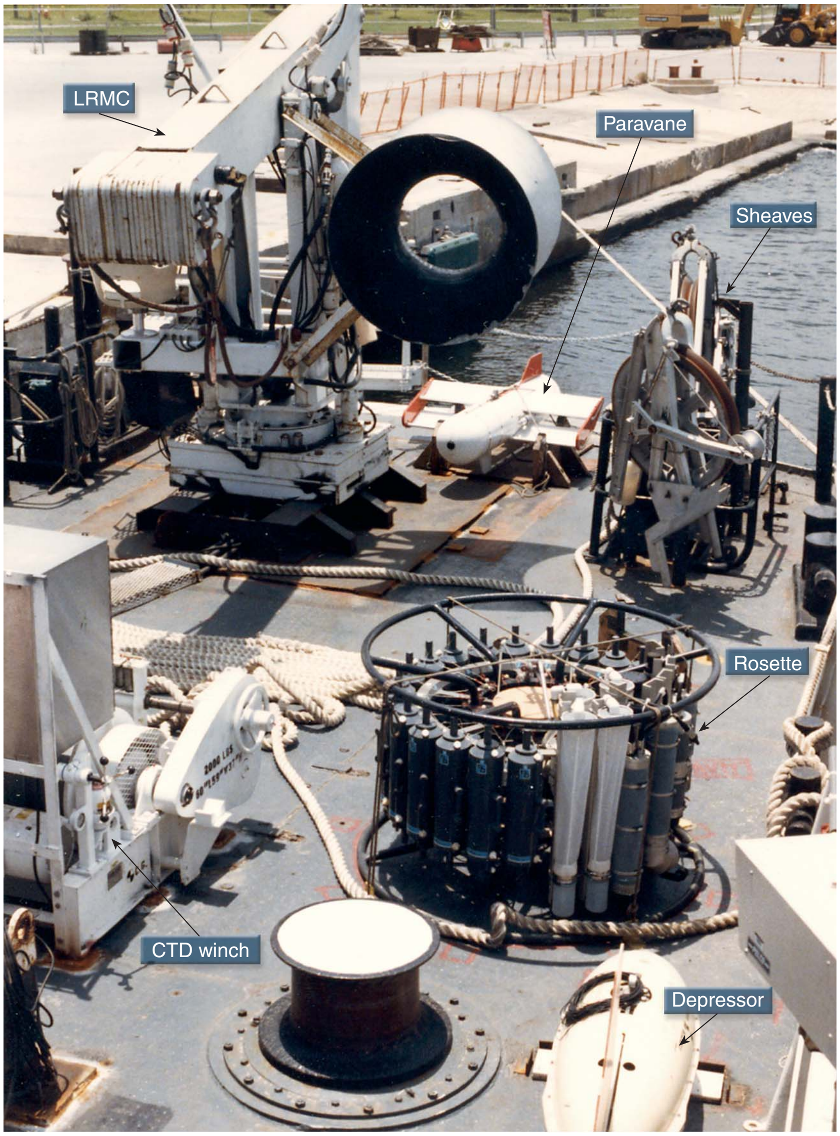

Figure 15. Deck of a research vessel.

paravane, several overboarding sheaves and saddles, a water sampling rosette, a deadweight depressor, and a CTD winch.

CONCLUSION

The TFC chain oceanographic sensor system program has produced a range of sensors to precisely measure temperature, fluorescence, conductivity, and other physical and biological parameters of interest to the study of ocean phenomena. Development of this system by the National Security Technology Department over the past 25 years introduced new and innovative sensors, design techniques, material applications, and devices as well as novel data collection, processing, and networking approaches. Although not covered in this article, many other sensors and sensor systems built by the department have benefited from this technology base. The data collected and technology developed continue to influence the department's programs.

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ACKNOWLEDGMENTS: The authors would like to emphasize that many people contributed to the development of these sensor systems and to acknowledge the Navy, DARPA, and other organizations that sponsored the oceanographic sensor systems development. Engineers and scientists responsible for the development of the TFC chain systems owe much to the highly skilled engineering assistants and technicians and to those who laid the technical groundwork from which these systems have grown.

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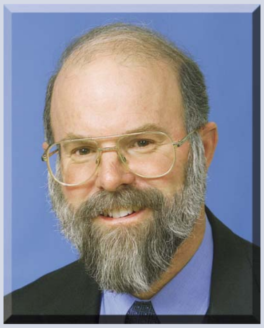

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