Part Three

Techniques of Investigation

14
Ocean Instruments and Experiment Design

D. *James Baker, Jr.*

What wonderful and
manifest conditions of
natural power have
escaped observation.
[*M. Faraday, 1859.*]

We know what gear will
catch but . . . we do not
know what it will not
catch.
[*M. R. Clarke* (*1977*).]

14.1 Observations and the Impact of New Instruments

"I was never able to make a fact my own without seeing it, and the descriptions of the best works altogether failed to convey to my mind such a knowledge of things as to allow myself to form a judgment upon them. It was so with new things." So wrote Michael Faraday in 1860 (quoted in Williams, 1965, p. 27) close to the end of his remarkably productive career as an experimental physicist. Faraday's words convey to us the immediacy of observation—the need to see natural forces at work. W. H. Watson remarked a century later on the philosophy of physics, "How often do experimental discoveries in science impress us with the large areas of *terra incognita* in our pictures of nature! We imagine nothing going on, because we have no clue to suspect it. Our representations have a basic physical innocence, until imagination coupled with technical ingenuity discloses how dull we were" [Watson (1963)]. Faraday recognized the importance of this coupling when he wrote in his laboratory *Diary* (1859; quoted in Williams, 1965, p. 467), "Let the imagination go, guiding it by judgment and principle, but holding it in and directing it by experiment."

In the turbulent, multiscale geophysical systems of interest to oceanographers, the need for observation and experiment is clear. Our aim is to understand the fluid dynamics of these geophysical systems. Although geophysical fluid dynamics is a subject that can be described with relatively few equations of motion and conservation, as Feynman, Leighton, and Sands (1964) stated, "That we have written an equation does not remove from the flow of fluids its charm or mystery or its surprise." In fact, observations and experiments have been crucial to the untangling of the mysteries of fluid processes in the ocean and in the atmosphere.

For example, on the smaller scales, lengths of the order of tens of meters and less, the discovery of the sharp discontinuities in density, temperature, and salinity that was brought to focus by the new profiling instrumentation has given us a whole new picture of mixing in the ocean. On the large scale, a good example is the explanation of the general circulation of the atmosphere in terms of baroclinic instability. The theoretical development was firmly based on the remarkable set of observations of the atmosphere carried out in the 1940s and 1950s. As E. Lorenz (1967, p. 26) noted in his treatise on *The Nature and Theory of the General Circulation of the Atmosphere,* "The study of the circulation owes a great deal to the practice of weather forecasting, for without these observations our understanding could not have approached its present level. Yet certain gaps will continue to exist in our knowledge of the circulation as long as extensive regions without regular observations remain." The emphasis that Lorenz placed on the need for observations before understanding can occur is equally valid for oceanographic studies of the same scale.

One must search long and hard for counterexamples where theory has preceded observation in geophysics. One of the few such examples in oceanography is the prediction and subsequent confirmation by direct measurement of southward flow under the Gulf Stream by the Stommel-Arons theory of abyssal circulation. The theory is discussed elsewhere (e.g., chapters 1 and 5, this volume) so I shall not pursue it further. The point is that observations guide and appear to limit the progress of our science. There is no inherent reason that this should be so. Why is our imagination so limited that, as Watson put it, we are so dull? Perhaps the historian of science can answer the question.

If observations guide the science, then new instruments are the means for guidance. The following two examples show how this has occurred; we consider first the North Atlantic circulation. Most of our ideas about the ocean circulation have been based on the indirect evidence of the temperature and salinity fields and the assumption of geostrophy. With the advent of direct velocity measurements by deep floats and current meters during the 1960s and early 1970s, the necessary data for a consistent picture of ocean circulation, at least in limited areas, began to come in. Worthington's (1976) attempt to put together for the first time such a picture of circulation in the North Atlantic was based on the new direct data.

One of the important pieces of evidence used in the work by Worthington were the data from the neutrally buoyant floats, which show a high transport for the Gulf Stream [see Worthington (1976) for references]. Until the direct measurements, the distribution of the absolute velocity field was ambiguous. With the new data, Worthington was encouraged to put together a complete picture that includes a tight recirculation pattern. However, within the constraints he used, Worthington's attempts at a complete mass and dynamic balance for the entire North Atlantic circulation were not successful. He decided, therefore, to choose a circulation pattern that was not consistent with geostrophy. This provocative work stimulated a number of attempts to look more closely at the circulation system there. Because both scale analysis of the equations of motion and the direct moored measurements of Schmitz (1977, 1980) confirm geostrophy to the leading order, as do the measurements reported by Swallow (1977) and Byrden (1977) in the MODE region of the Sargasso Sea, Worthington's total picture is not correct. The moored data are consistent with the recirculation pattern, but, in addition, reveal a flow with an eastward component immediately south of the Gulf Stream and north of the recirculation. The latter feature is not clearly contained in any existing picture of the North Atlantic circulation.

A second approach was taken by Wunsch (1978a), who used hydrographic data, mass balance, and geostrophy to estimate the absolute velocity field in the North Atlantic. Since the system is basically underdetermined (one requires point measurements to find unique solutions to the relevant fields), an auxiliary criterion is required. Wunsch found a unique solution by minimizing a measure of the energy. This is an example of the geophysical "inverse technique" that provides estimates in underdetermined systems by optimizing auxiliary measures of merit. The circulation pattern found by Wunsch is thereby in general agreement with geostrophy and the recirculation ideas of Worthington and Schmitz, thus lending further support to this idea. Stommel and Schott (1977) have also shown how to use hydrographic data to estimate absolute velocity, by using conservation of potential vorticity.

In sequence, then, we can see that the new observational data from the floats stimulated a new view of the circulation, which in turn led to further observations and data studies that extend and correct the picture.

We note that the inverse techniques are just as much an observational tool as the instruments we use, because they allow us to rearrange data in ways that are not necessarily obvious or easy. The choice of the proper measure of merit was discussed by Davis (1978b). He showed that the Wunsch method is dynamically equivalent to the Stommel and Schott technique; the major differences result from implicit assumptions about the scales of oceanic variability, and different definitions of the smooth field to which the dynamic model pertains. Davis gave an example of an optimization criterion based on a measure of merit related to the process of inferring fields from point measurements.

Schmitz's conclusion on the subject at the time of this writing was that the situation is still unresolved: "the North Atlantic Circulation is inadequately described at the present time, much less understood, and could be very complex both spatially and temporally. This could also be the case in the North Pacific. . . . We are still in the process of exploration, attempting to identify the relevant elements of several hypotheses, and utilizing different techniques for investigating diverse features of the circulation" [Schmitz (1980)].

Our second example of the way that instruments give us a new picture is from the time-dependent circulation. El Niño, the appearance of warm water off the coast of South America every few years, is a large-scale phenomenon of both dynamic and practical importance. One strong contender for the explanation of El Niño is that relaxation in the trade winds in the western Pacific results in the propagation of a warm-water anomaly toward the east. The long-term fluctuations in oceanic circulation on which the model is based have been inferred from direct measurements of sea level at islands in the tropical Pacific (Wyrtki, 1973b, 1979). These measurements, suitably filtered and averaged, appear to be a good indicator for variations in the geostrophic transport of the upper layers. The provocative data and subsequent models have spurred a whole new interest in the dynamics and air-sea interaction in the tropical regions.

Thus the data from new instruments give us a new context for our science; continued innovation is required. As late as 1965, when meterologists were using the simple but elegant radiosondes and beginning to use satellites for remote sensing of atmospheric circulation, Henry Stommel noted the problems of ocean observation:

> When I emphasize the imperfection of observing techniques perhaps I should say that I wrote this chapter during a succession of midnight-to-dawn watches during an attempt to survey the Somali current near Socotra in the heart of the Southwest monsoon. It is rather quixotic to try to get the measure of so large a phenomenon armed only with a 12-knot vessel and some reversing thermometers. Clearly some important phenomena slip through the observational net, and nothing makes one more convinced of the inadequacy of present day observing techniques than the tedious experience of garnering a slender harvest of thermometer readings and water samples from a rather unpleasant little ship at sea. A few good and determined engineers could revolutionize this backwards field. [Stommel (1966).]

It is safe to say that since 1965 there has been an influx of more than a few "good and determined" engineers, and there has been a flood of new instruments and new ideas. Our view of the ocean has changed markedly, especially on the smaller scales, where the old instruments and techniques were essentially blind.

The sections to follow outline some general principles of instrument design and the development of the technology, and then provide some history and working principles in four major areas of instrumentation that have made an important impact on modern oceanography. We turn next to some examples of instruments that have shown promise but have not yet reached their potential, and then to some areas where new instruments are needed, but the technology is not yet available. The chapter concludes with a section on experiment design.

14.2 Instrument Development: Some Principles and History

14.2.1 General Principles

Chapter 10 of *The Oceans* (Sverdrup, Johnson, and Fleming, 1942), "Observations and Collections at Sea," covers techniques and instruments for the study of the physics, chemistry, geology, and biology of the sea. It is not possible for a chapter like the present one to cover the development since then of modern instruments and techniques for all of these disciplines, in fact, not even for one of these disciplines; there is simply too much material. There are some important general aspects of instrument design, however, that are useful to point out, and it is instructive to look at the development since *The Oceans* was written of some of the instrumental techniques that are generally applicable.

The general principle for oceanographic instruments has been to keep them simple and reliable, a principle underlined by the long-successful use of the Nansen bottle and reversing thermometer. The Scandinavian school had another important point: the efficiency of locally operated mid-size vessels. The authors of *The Oceans* noted that the practice during the nineteenth century was to use only government-operated large vessels in oceanographic investigations. In the early twentieth century, Björn Helland-Hansen used the 23-meter *Armauer Hansen,* built to his specifications, to show that smaller vessels could be used effectively. The ship carried out a number of studies in the North Atlantic, and its successful use convinced other laboratories that mid-size vessels, economically and locally operated, were an efficient way to carry out oceanography. The enormous amount of global exploration carried out by the *Atlantis* and *Vema* at the Woods Hole Oceanographic Institution and the Lamont-Doherty Geological Observatory and by the seagoing tugs *Horizon* and *Baird* at the Scripps Institution of Oceanography was an extension of this point into the 1950s and 1960s. A review of oceanographic vessels and their expeditions in the period 1887–1960 is given by Wüst (1964). Today, the oceanographic fleet ranges downward from the large (120-meter) *Glomar Challenger* with its unique deep-sea positioning capabilities used for deep-sea drilling, and the *Melville* and *Knorr* with their cycloidal propulsion that allows remarkable maneuverability, to a variety of ships, platforms, and portable laboratories, each useful for different purposes. For example, FLIP (floating instrument platform) is a 108-meter towable surface craft that can be upended on site to provide a manned spar buoy with a draft of 90 meters and high vertical stability. The mid-size vessels form a large and important part of the data-gathering capability that provides access to the sea for many laboratories.

The need for measurements drives the development of new instruments. But there is sometimes a tendency for instrument development to proceed independently of the scientific needs. For example, Chapter 10 in *The Oceans* describes no fewer than 15 current meters. One wonders if this is not more than the total number of direct current measurements in the open ocean at the time, and whether there would not have been a net gain if more time had been spent in making measurements than in trying to develop new instruments. However, in fairness to the developers, we must point out that most of the effort at that time was aimed at making a useful kind of long-term recording scheme. The recording problem has been solved with the advent of tape-recording techniques (see section 14.2.3) and the focus is now on the problems of sensor designs.

The same point is true of other types of instrument design. In 1968 I surveyed the historical literature on deep-sea pressure gauges [see "The History of the High Seas Tide Gauge" by W. Matthäus (1968) and H. Rauschelbach (1932); English translation by Baker (1969)]. There is no question that at that time there were more designs for deep-sea pressure gauges than there were measurements of deep-sea pressure. This situation happily has changed today: we have seen the direct confirmation of an open-ocean tidal amphidrome (Irish, Munk, and Snodgrass, 1971), and deep-sea pressure gauges are beginning to be included in experimental design of new programs (see section 14.3.5).

Any scientist involved in instrumental design immediately feels the conflict between the need for use and the need for engineering improvements. According to the engineer, the scientist wants to use the equipment before it has been properly tested, and according to the scientist, the engineers want to improve the equipment before it has been used. The proper solution to this problem is close collaboration between scientist and engineer. The development of wave- and tide-measuring devices by W. Munk and F. Snodgrass of Scripps (section 14.3.5) is a good example of a highly successful collaboration between scientist and engineer; another is the work on temperature-pressure recorders by C. Wunsch of MIT and J. Dahlen of the Draper Laboratory (see section 14.3.1).

Whatever collaboration is established, however, it is clear that new equipment must be tested early in the sea. The information gained in actual field tests is crucial to the development of reliable instruments. Moreover, this is the only way that unexpected ocean effects can be found. These unexpected effects include signals of large magnitude (the "Van Allen" effect) and biological phenomena. The latter of these is demonstrated in figure 14.1, where we show a deep-sea pressure gauge brought up from the Drake Passage with an octopus attached to the sensor area. The effect of the octopus's breathing on the long-period variations of pressure measured by the gauge has not yet been determined.

There are two threads that our "good and determined" engineers have followed in order to bring us up to the modern state of ocean instrumental engineering. The first of these is electronics development, which we can trace through the first use of such technology, the advent of solid-state electronics, and finally low-power integrated circuits. The second of these is materials and structure engineering, which includes the development of platforms that can carry the instruments: ships, moorings, and various kinds of floats.

Figure 14.1 Octopus attached to sensor area of University of Washington bottom pressure gauge brought up from 500-m depth, north side of Drake Passage, 1977. (Courtesy of E. Krause.)

In the pages to follow, we shall see that the development of technology in a number of areas in the 1950s and 1960s laid the foundation for a rapid improvement in observing techniques, starting in the mid 1960s. R. H. Heinmiller, Jr., in a personal communication summarizes the history:

> In my opinion, a real change occurred in the area of physical oceanographic technology when everybody realized that it was time to get some engineers to work and stop doing things by string and sealing wax. This was stimulated in part by the increasing need for large-scale experiments with large quantities of instruments which forced the adoption of quality control and engineering planning. In addition, of course, there was

the stimulus of new techniques, products, and materials that had been developed for the space program and the oil industry.

14.2.2 Electronics in Ocean Instruments

A history of the development of ocean instrumentation up to the late 1960s was presented by J. M. Snodgrass (1968). He noted that "until the advent of World War II oceanography proceeded at a rather leisurely pace. The anti-submarine-warfare program during World War II forced the rapid development of underwater acoustics. . . . However, the actual instruments employed to make measurements in the ocean were rather crude, technologically, in contrast to much of the other instrumentation of the day involving electronics." Snodgrass goes on to document the changes and development of instruments in the 1950s and 1960s. The first introduction of electronics instruments into oceanography was not successful. He points out:

> Unfortunately practically without exception, these instruments failed, not necessarily because of faulty electronics or conceptual aspects, but because the instruments engineers did not properly understand the marine environment and the consequent packaging problem. Simple leaks proved to be disastrous. Since research funds were scarce, there was naturally considerable resistance to the introduction of these "newfangled" instruments. In fact, after repeated failures, it was suggested that "the ideal oceanographic instrument should first consist of less than one vacuum tube." As this was in pre-transistor days, it left little latitude for electronics.

Snodgrass comments that the first instrument at Scripps to break the "electronics barrier" was the bottom-sediment temperature-gradient recorder, a simple, by today's standards, but reliable instrument that yielded exciting new results for geophysics. It is a self-contained null-type self-balancing potentiometer that measures temperature gradients in the sediments by using two thermistors about 2 m apart. Snodgrass notes, "The instrument's success on the Scripps MIDPAC expedition in 1950 served to spawn an entire new generation of electronic precision oceanographic measuring instruments." He goes on:

> In view of the skepticism that existed in 1950 when the temperature-gradient recorder was first used, it is perhaps not at all surprising that when temperature gradient values approximately two times greater than those which were anticipated were recorded, there was general disbelief and an unwillingness to accept the values. It was not until over a year later, when another, almost identical, instrument was being used in the same area in the vicinity of the Marshall Islands that an identical high temperature-gradient was recorded and the instrument's earlier results were then credited as being valid.

This skepticism is general, and often accompanies the first use of instruments. The instrument is proved correct often enough, however, to remind us constantly of our "basic physical innocence," as Watson says. Another example is the first use of quartz-crystal bottom-temperature gauges in the Atlantic (Baker, Wearn, and Hill, 1973), which showed large (about 0.1°C) temperature fluctuations at the bottom in the deep Atlantic water. Because the Pacific measurements (see, e.g., Munk, Snodgrass, and Wimbush, 1970) had shown variations at the bottom smaller by factors of 100 to 1000, there was a general reluctance to accept these results until they were later confirmed by other instruments. The fluctuations in the Atlantic are due to intrusions of Antarctic Bottom Water over the Hatteras Abyssal Plain.

One of the most important steps in instrument design was the introduction of the new low-power integrated-circuit solid-state electronics. This goes under the general name of COSMOS (complementary-symmetry metal-oxide semiconductor). Solid-state devices built from these semiconductors can carry out logic operations at very low power because of their use of field-effect technology. The field-effect semiconductor has only one type of current carrier, and limits the current by varying the space charge with the applied voltage. Typical COSMOS integrated circuits have very small quiescent current drains (about 1 nanoampere) and very high input impedances (about 10^6 megohms). For comparison, the older resistor-transistor technology requires quiescent currents of milliamperes. The ocean engineer was greatly limited in what he could do with the transistor technology because the current drains were simply too large. The COSMOS circuits do draw significant currents, but only when changing logic states. Thus the mean current is proportional to the frequency of operation. At frequencies of a few kilohertz the new systems allow a decrease in power consumption by a factor of a million or more. For example, one of the simplest devices, a flip-flop switch, draws only 10 nW (nanowatts) as opposed to the usual 30 to 100 mW (milliwatts) for transistor logic. Moreover, the circuits can be operated from a wide variety of supply voltages [typically 5 to 15 V (volts)] and have excellent thermal characteristics. [See any modern electronics textbook, e.g., Taub and Schilling (1977, p. 38), for further description.] The introduction of COSMOS logic into oceanographic instrumentation in the late 1960s and early 1970s is probably the major change in electronics for oceanographers since ordinary semiconductor logic was introduced.

Many of the instruments discussed in section 14.4 draw heavily on the COSMOS technology. These new integrated circuits permit a number of data processing operations *in situ* that never could have been considered before. For example, the vector-averaging current meter (see section 14.3) computes north and east components of the velocity, and records the speed, compass and vane-follower directions, time, and temperature, as well as the components of velocity over a variable sampling time that can be set to fit the experiment. The total recording time can be longer than 600 days. The use of the COSMOS integrated-circuit technology is crucial to this flexibility.

14.2.3 Batteries and Tape Recorders

Of course, one of the reasons that power becomes less of a problem is the improvement in battery capacity over the past few years. The subject is reviewed in two recent articles by McCartney and Howard (1976) and Jacobsen (1973). The new lithium batteries provide a number of characteristics important for oceanographic use: they have the highest cell voltage, the longest shelf life, the greatest energy density, the best low-temperature performance, and a flatter voltage-discharge curve than any other except mercury cells. The latter characteristic is especially important for use in logic circuits where the system is usually set to run at a given regulated voltage. As long as the battery supplies a higher voltage, the equipment works properly; when the voltage drops below that regulated limit, the equipment will malfunction. Thus a flat voltage-discharge curve is desirable. A useful comparison of battery properties, compiled by R. B. Wearn of the University of Washington, is presented in table 14.1. Here the advantages of the lithium batteries over the carbon-zinc and mercury are evident. The reader is referred to one of the review articles for a summary of the chemical reactions involved: the recent article by Farrington and Bryant (1979) shows future directions for high-density energy storage in rechargeable cells utilizing fast ionic conductors; Murphy and Christian (1979) discuss a new class of electrode material for high-density energy storage.

These batteries and the new high-capacity tape recorders allow us to make measurements in excess of a year of various oceanographic parameters, and to do a certain amount of data processing *in situ*. The major part of the data-collection problem has been solved by the introduction of reliable tape-recording systems now on the market, and it is instructive to outline briefly the development of one of these to show the systems-design problems involved.

In the early 1970s, J. McCullough and R. Koehler of the Woods Hole Oceanographic Institution looked at ways of replacing their existing continuous-loop tape system used in the current meters with a cassette tape recorder. High-quality data cassettes were available, but there was no good reliable tape drive that could run on low power, pack data reliably on the tape, and fit into a 6″ pressure case. There were mechanical problems involved in building a rugged drive that could withstand handling at sea, and that could precisely position and move the cassette tape. There were electronics problems involved in producing an efficient coding scheme, driving the tape, and recording the data, all with little power.

The solution worked out by Winfield Hill of Harvard University and the WHOI engineers was ingenious. A stepping motor was used to drive the tape precisely with electronics designed to provide a near-exact damping of the usual overshoot. A heavy cast body was designed and built with extremely close tolerances. A biphase coding scheme provided self-clocked data. The commercial instrument is shown in figure 14.2.

Since 1972 over 1000 of the recorders have been produced commercially by the Sea Data Corporation and used in oceanographic instruments; many of the instruments discussed in section 14.4 use this or a comparable tape recorder. The present Sea Data (1978) model uses less than 4 W h of battery power to record 11×10^6 bits of data. The tape transport can write data as fast as 1200 bits per second or as slow as one record per half-hour (at this rate, with a maximum 396-bit data record, a cassette would take more than a year to fill). To give a comparison, this data capacity is roughly equivalent to 500 feet of 4″-strip chart paper. Other

Table 14.1 Comparison of Battery Properties: D-Cell-Size units at 10-mA Drain

	Initial cell voltage (volts)	Shelf life	Ampere-hours at 10 mA	Energy at 10 mA (joules)	Joules/cm^3	Joules/kg	Joules/$(1979)
Sealed lead-acid	2.1	6 mo @ 21°C	2.5	2.1×10^4	3.7×10^2	1.1×10^5	0.88×10^4
Carbon-zinc	1.5	1-2 yr @ 21°C 1-2 mo @ 55°C	6.2 to 0.9 V	2.7×10^4	5.2×10^2	2.9×10^5	7.7×10^4
Alkaline	1.5	2-3 yr @ 21°C 2 mo @ 55°C	9 to 0.9 V	4.1×10^4	7.8×10^2	3.3×10^5	5.1×10^4
Mercury	1.35	3-4 yr @ 21°C 4 mo @ 55°C	12.4	6.1×10^4	14×10^2	3.6×10^5	1.4×10^4
Lithium-organic	2.9	10 yr @ 21°C 1 yr @ 55°C	10	10.4×10^4	19.5×10^2	12.2×10^5	1.4×10^4
Lithium	3.6	10 yr @ 21°C 1 yr @ 55°C	11	14×10^4	27.4×10^2	14×10^5	1.4×10^4

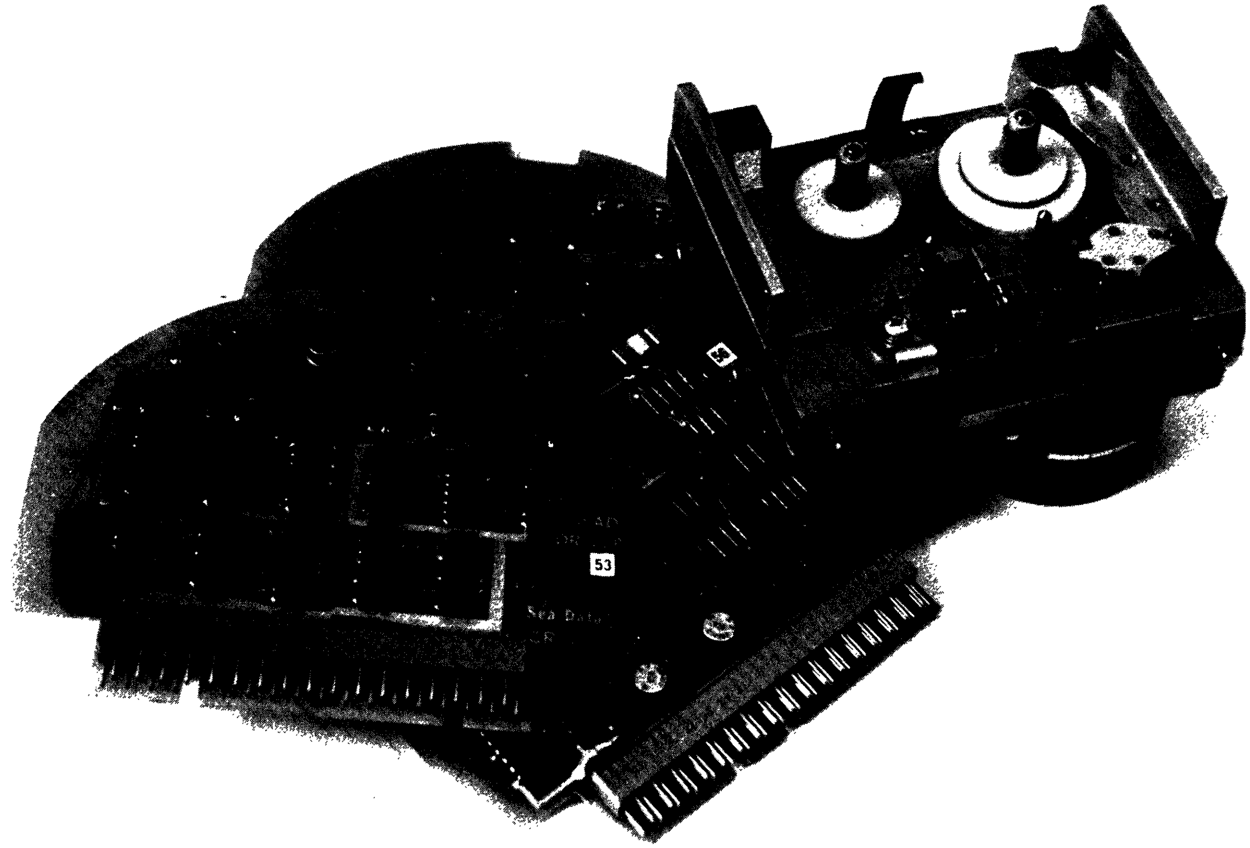


Figure 14.2 Sea Data tape-recorder body (right) and COSMOS circuit cards (left). The cards are rounded in order to fit into a 6"-diameter pressure case. (Courtesy of W. Hill.)

commercial cassette tape recorders are also available now for oceanographic use.

The second thread of engineering design mentioned above is "platform engineering." Since a review has recently been given by Henri Berteaux in his book *Buoy Engineering* (1975), we need not discuss this aspect in detail here. Some aspects of platform engineering are included in the subsections on mooring technology in section 14.3. The reader interested in following current developments (circa 1980) in ocean technology is urged to read *Exposure,* a newsletter produced by R. Mesecar of Oregon State University for discussion of new contributions and problems in instrument design and use in the ocean.

14.3 Examples of Modern Ocean Instruments

Looking over the period since *The Oceans* was written, we can identify four major areas of instrument design that have had an important impact on the development of our ideas of ocean circulation and mixing. These areas are the moored-buoy-current-meter technology, the deep-drifting neutrally buoyant floats, the temperature-salinity profilers (commonly known as the STD and CTD), and the velocity profilers. The first three of these developed essentially simultaneously. The velocity profilers are newer, and, to some extent having built on the technology developed earlier, have not yet had the total impact of the other three groups.

A second set of instruments is in a state of development and has not yet had the extended use or the impact of the four listed above. These include, for example, bottom pressure gauges, surface drifters, and the "inverted echo sounder." We also include in this set the whole suite of remote measurements, e.g., satellite altimetry and laser profiling of the upper layers, and the various acoustic techniques that have been proposed.

Our final discussion in this section covers a set of problems that can not yet be attacked with present technology. New instruments are crucial for understanding and quantitative measurement. Examples are air-sea fluxes in stormy conditions or measurements in strong currents.

Space does not allow me to be comprehensive in any way here, but only selective. The reader is referred to two excellent recent review volumes, *Instruments and Methods in Air-Sea Interaction* (NATO Science Committee, 1978) and the *Proceedings of a Working Conference on Current Measurements,* (Woodward, Mooers, and Jensen, 1978), which cover aspects of many of the instruments to be discussed below. The paper by Rossby (1979) on "The Impact of Technology on Oceanography" contains a number of instructive examples.

Another area of very great impact on ocean measurements is navigation. Advances in both shore-based (LORAN) and satellite-based navigation techniques are responsible for the success of many of the instrumental techniques discussed below from mooring location to velocity determination. The discussion below is limited for reasons of space to instruments themselves.

In thinking about instruments and what they measure, we consider the full equations of motion. The equations include the terms to be measured; ideally, direct measurement of the terms is best, but sometimes it turns out to be more feasible to measure the term indirectly. The terms that appear in the equations involve the velocity, products of velocity, density, pressure, turbulent stresses, and viscosity.

The instruments that we discuss for velocity include those that make direct measurements of currents either at a point or in profile. We have been less successful in measuring turbulent stresses—products of velocity fluctuations—than the meteorologists, primarily because of the lack of a stable platform. However, some useful data have been taken from stations on sea ice and are discussed below.

Density is generally inferred from temperature and salinity; technical difficulties have precluded any useful instrument for measuring density directly. The main problem is finding an instrument that will work *in situ*—in the water column or on board ship. The small variations of density and the large accelerations at sea have prevented much success with direct density measurement. A number of techniques have been developed, however, and some of these will be discussed.

Pressure is generally inferred from the density using the hydrostatic relation. Without some level of pressure reference, however, it is not possible to establish an absolute pressure field in the ocean. Bottom pressure measurements (to be discussed below in section 14.3.5) can monitor pressure fluctuations; sea-surface topography by satellite is a technique currently being developed for measurements of both fluctuations and mean surface field.

14.3.1 Current-Meter and Mooring Technology

There are two parts to the measurement of currents at a point in the ocean. The current meter must be accurate, reliable, and, for most purposes, internally recording. The platform, or mooring, must be robust, deployable, and affordable. Major advances in both of these areas have been made since the 1960s. It is now possible to make long-term (greater than 1 year) measurements of currents at levels below the surface layer with better than 90% data return (e.g., Pillsbury, Bottero, and Still, 1977; Tarbell, Spencer, and Payne, 1978).

The paper of Richardson, Stimson, and Wilkins (1963) is a good starting point because it marks the beginning of the modern age of current-meter and mooring technology. This remarkable paper covers the whole field of mooring and current-meter technology as it was known at that time, and demonstrates the ingenuity of W. S. Richardson and coworkers then at the Woods Hole Oceanographic Institution. The paper documents the early attempts to maintain deep-sea moorings and current meters along a section from Woods Hole to Bermuda across the Gulf Stream. For this purpose, they needed a new current meter that would record for a long time, and a sturdy, reliable mooring for a platform.

Richardson et al. were influenced by Swallow's measurements (1955, 1957) with neutrally buoyant floats, which revealed a variability in the measured currents large compared to the residual drift. They argued that in deep water, where large variability is encountered, the significance of short-term measurements is in serious doubt. They noted that the float tracking could be extended to longer times, but that, as the required measurement time increases, equipment that may be left at sea unattended becomes increasingly attractive. They went on to describe the details of the system that they developed for long-term deep-current measurements, noting, in something of an understatement, that the technique is not an easy one, nor is it a cure-all for the deep-current problem.

However, the system described by Richardson et al. (figure 14.3) has the same basic elements used today. In essence, the system consists of a near-surface or surface float, a line that holds the current meters, and a release that is right above the anchor. We consider first the current meter, and its recent developments, then shall return to the development of the mooring systems.

Current Meters The current meter used by Richardson et al. was the Savonius (1931) rotor-type with a small, freely moving direction vane attached in line with the axis of the instrument. J. M. Snodgrass (1968) discussed some of the aspects of the Savonius rotor. The advantage of the freely moving vane is that its response time is comparable to the response time of the speed sensor. The instrument is cylindrically symmetric and can be used as a link in the mooring system. Two major data-collection design features are also important in this current meter: the photographic recording system and the burst sampling. Richardson et al. recognized that the high-frequency noise in the water coupled with the limited recording capability of the instrument would result in very short records if records were made continuously. Therefore, they used a "burst sampling"

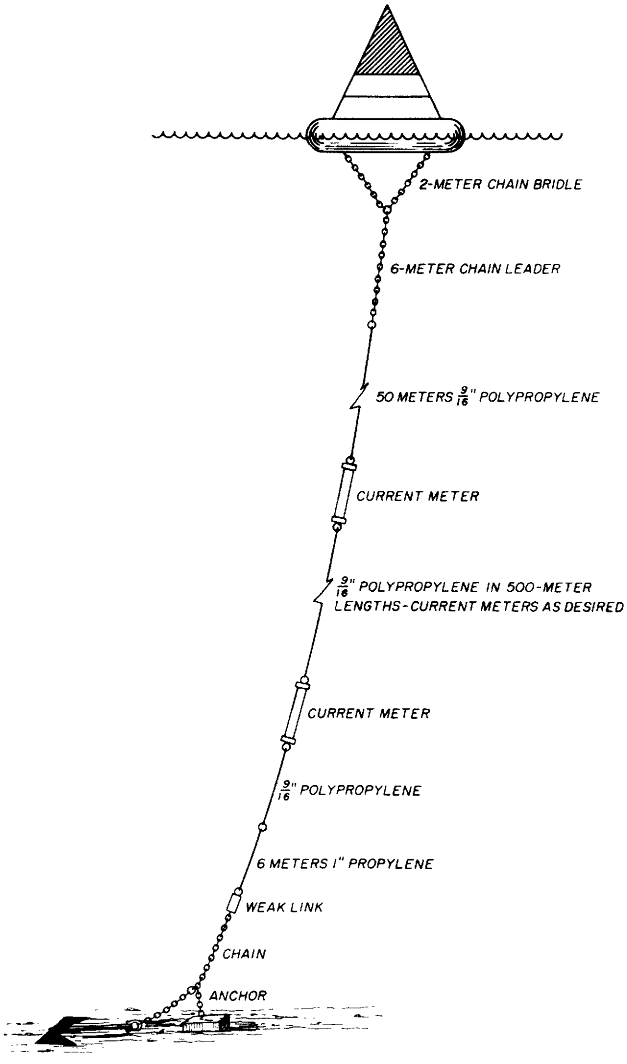


Figure 14.3 Current-meter mooring configuration used by Richardson et al. (1963).

scheme, whereby short samples of densely spaced data are collected, interspersed with longer periods of no data. If enough is known about the spectrum of the system, then such a scheme will provide an adequate estimate of the total energy in the various frequency bands.

The second feature of note is the photographic recording. A clever system of light pipes and coded disks was used to carry data bits from the sensors to a camera with 100 feet of photographic film. In this way a long data set could be collected; 100–200 days were possible, a major increase over the other systems then available. This photographic scheme worked well as long as there were only a few data sets available, but a technique to read the film by computer was never really successful.

The modern commercial version of this current meter is basically similar to the Richardson design. In addition to general improvement of reliability, two major changes have been made: the recording scheme uses a tape recorder (see section 14.2), and the sampling scheme is of the type called *vector averaging.* The vector-averaging current meter, or VACM as it is commonly known (figure 14.4), was developed at Woods Hole by J. McCullough (1975) and R. Koehler.

The use of the new COSMOS integrated-circuit technology is responsible for the increased accuracy of the VACM. The increased data-handling capability allows the instrument to sample the speed and direction approximately eight times per rotor revolution. East and north components are then calculated and stored. The burst-sampling mode is used: typical sampling intervals are 15 min (minutes; at this interval the tape capacity is 530 days). The direct vector-averaging feature allows the instrument to make accurate measurements in wave fields and from surface-following moorings [see McCullough (1978a,b) and Halpern (1978) for further discussion and references on the use of the VACM and comparison with other instruments].

One of the problems with this design is that the response lengths for the Savonius rotor, free-vane system cannot be accurately matched in time-dependent flow because the rotor accelerates about three times faster than it decelerates (Fofonoff and Ercan, 1967). Moreover, the Savonius rotor system does not have a true vertical cosine response (response proportional to the cosine of the angle or attack), and thus its measurements of horizontal velocity are contaminated by the vertical component, which can be large in the wave zone or near a surface-following mooring. Until recently, current meters had not been tested rigorously in unsteady flow conditions in the laboratory to show their performance in the expected environmental conditions. Using a series of such tests, Davis and Weller (1978) [see also Weller (1978) and Weller and Davis (1980)] have developed a two-component propeller current-measuring instrument with an accurate cosine response (rms deviation from cosine of 1.5% of the maximum response). In initial tests the instrument, dubbed the vector-measuring current meter (VMCM), has shown negligible rectification and accurate measurements of mean flow in the presence of unsteady flow. Figure 14.5 shows the arrangement of this system, also in-line like the VACM.

Propellor-type systems have also been successfully used by Eriksen (1978) for measurement of internal waves, and by J. D. Smith (1978) for studies of turbulent currents, both near bottom in estuaries and near the sea ice in the Arctic. Smith documented the need for improving symmetry of the propellers, and ducting at high angles of attack, and he showed the utility of such techniques in high-accuracy, short-duration measurements. He reported studies of the turbulent structure under the Arctic ice, which reveal a high intensity of turbulence in the upper layers (Smith, 1974).

There are a number of other current-meter systems on the market today, and these are reviewed in the volumes mentioned above. It is of interest to discuss one of the other Savonius rotor-type instruments in major use, the one invented by Ivar Aanderaa (1964) of Norway under sponsorship of the North Atlantic Treaty Organization (NATO), because it has also had a major impact on current measurements. The goal of the Aanderaa design was to provide a relatively inexpensive, reliable instrument that could be used by laboratories with only simple electronics capabilities (another example of the Scandinavian notion of distributing equipment as broadly as possible, as Helland-Hansen suggested for ships). (See also Dahl, 1969.)

The Aanderaa instrument is pictured in figure 14.6. It uses a Savonius rotor in combination with a large vane. The entire instrument must move in response to changes in direction. The data are recorded on a fairly simple tape recorder, and the electronics is fully potted to avoid tampering. The instrument is inserted in a mooring line in such a way that it is free to pivot in a horizontal plane, and the large vertical tail fin orients the meter in the direction of the current flow. As with the instruments discussed above, a magnetic compass is fixed within the instrument to give its orientation in the earth's magnetic field and thus the direction of flow. Aside from the two deficiencies noted below, the instrument has proved to be a very reliable device, relatively simple to use, and it has thus served its purpose well. It is one of the most popular of current meters.

Because of the large integral vane, the Aanderaa instruments are not suitable for near-surface moored measurements in waves (Halpern and Pillsbury, 1976; McCullough, 1978a,b; Halpern, 1978). Saunders (1976) shows that while the mean current directions are usually correct, the vane response in waves causes speeds to be too large by a factor of between 1 and 10, with a

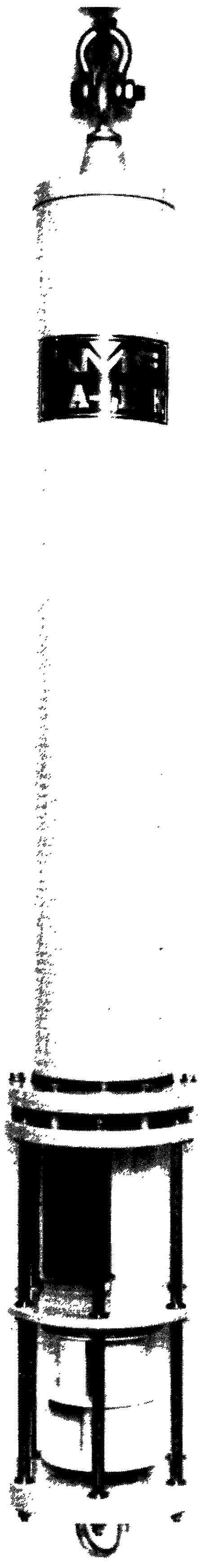


Figure 14.4 Vector-averaging current meter manufactured by Sea-Link. (Courtesy of W. Coburn.)

typical value of about 2. This occurs because the Savonius rotor accelerates to 63% of a new flow speed in 30 cm of water flow past the sensor (Fofonoff and Ercan, 1967), but the vane of the Aanderaa current meter requires 6 m of flow to realign itself after a 180° change in flow direction (Appell, Boyd, and Woodward, 1974).

It is important to note that in all instruments that measure speed and direction separately, the angular conversion required to extract velocity components spreads error due to poor frequency response over all frequencies. Cartesian-component sensors do not introduce such error (Weller and Davis, 1980).

The Aanderaa gauge has been subject to another interesting difficulty. Hendry and Hartling (1979) describe a pressure-induced error in direction found in the earlier models that used a nickel-plated copper pressure case. They found that instruments used in the field at pressures greater than 4000 db (decibars) began to show nearly constant directions over many months, indicating sticking compasses. On return to the laboratory, the instruments showed no problems. This suggested that an environmentally caused, instrument-related magnetic field was competing with the earth's field and affecting the compasses. A series of laboratory tests showed that this was indeed the case. Serious direction errors were found in the nickel-coated current meters used at pressures greater than 2000 db. The errors are caused by the magnetization of the nickel coating by the field of the compass magnets themselves, after the magnetic properties of the nickel are modified by the stresses induced in the pressure case as the external pressure is increased. At 2800 db, errors in direction of up to 10° were seen, and at pressures of greater than 4200 db actual sticking of the compasses was observed. The nickel coating has been eliminated in later models.

Acoustic and electromagnetic current meters show promise for direct fast-response measurement of currents in waves and turbulent zones. The present status of these instruments is discussed in the two volumes mentioned above.

Our final example is not a current meter, but it is an important part of the moored-instrumentation suite. This is the moored temperature and pressure recorder developed at MIT and the Draper Laboratory (Wunsch and Dahlen, 1974). The instrument was designed for long-duration measurement of temperature in the deep ocean. Temperature is sensed with a thermistor of accuracy 0.01°C and a time constant of 3 min. In terms of pressure, instruments destined for 2000 m depth have an absolute error of the order of 1 m and a short-term pressure change measurement error of less than 0.2 m. The instruments, called TP recorders, have proved very successful, yielding a high data return (better than 90%) for mapping temperature fields and monitoring mooring motion. For example, in the MODE-1

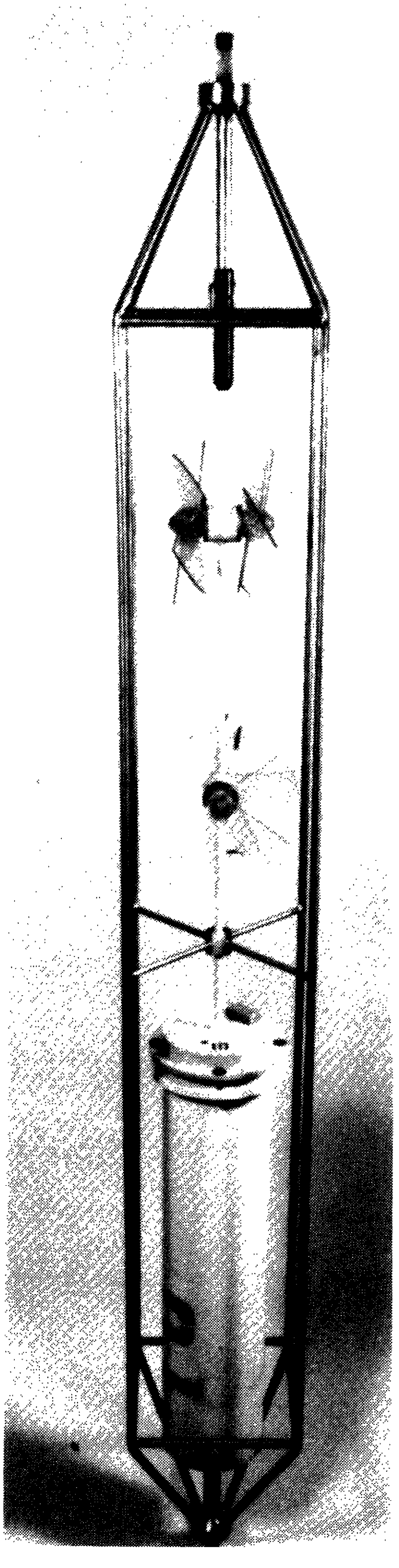


Figure 14.5 Vector-measuring current meter with dual propellers and titanium cage. (Weller, 1978.)

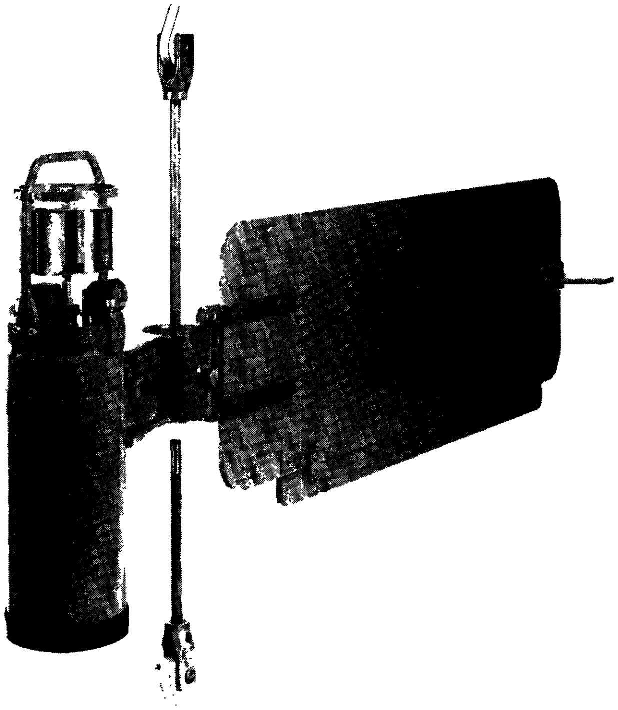


Figure 14.6 Aanderaa Model RCM-4 current meter. The instrument swivels about the vertical rod between the electronics case (left) with Savonius rotor and other sensors on top and the large direction vane (right). (Courtesy of Aanderaa Instruments.)

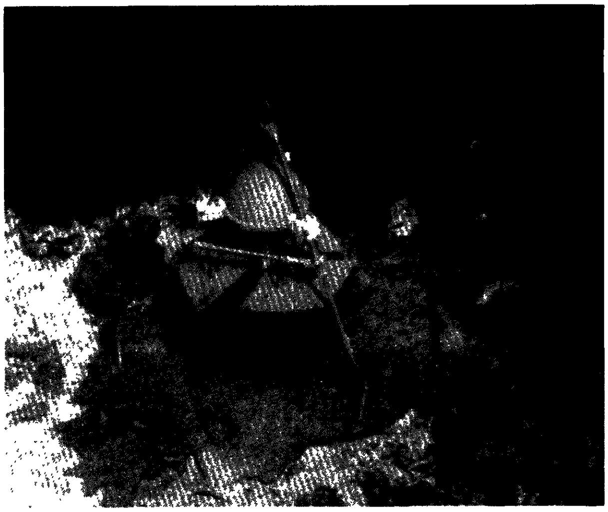


Figure 14.7 Draper Laboratory temperature-pressure recorder moored in 10 m of water off the Seychelles Islands. (Courtesy of J. Dahlen.)

experiment, the TP recorders allowed the mapping of two levels in the array in addition to the levels occupied by the current meters. The additional maps proved important to the description of the eddies observed in the experiment (Bryden, 1977; Richman, Wunsch, and Hogg, 1977). The TP recorders have been used subsequently in many different arrays and are considered an important adjunct to array design. Figure 14.7 shows a TP recorder being used as a tide gauge at a depth of 10 m in the waters near the Seychelles Islands in the Indian Ocean.

Mooring Systems As mentioned above, the first large-scale attempt at current-meter measurements from moorings was tried by Richardson et al. (1963). In all, from May 1961 to December 1962, they report that 106 buoy stations were put out. About half of the shallow stations, about 30% of the stations in the Gulf Stream region, and about 30% of the short-term stations outside the Gulf Stream region were recovered. The average recovery rate of all instruments set out in these first 2 years was about 50 to 60% (Heinmiller, 1976a).

A large amount of engineering effort has succeeded in improving the recovery rate of instruments and moorings. For the period 1968 to 1974 the recovery rate moved up to 95% for all instruments on WHOI moorings. It is instructive to look at the specific engineering changes that led to this remarkable improvement. The engineering specifics and the detailed statistics are presented by Heinmiller in a very complete technical report (1976a). The material discussed below is largely drawn from this report and from several conversations that I have had with him on this subject.

Mooring failures can occur at each point: on launch, on recovery, and on station. On station, mooring failures have occurred in about every imaginable way. Numerous early polypropylene-surface mooring lines failed due to fish attack (Stimson, 1965). Wire failure due to corrosion or kink is common, and surface floats have been swept under and crushed in high currents (Heinmiller and Moller, 1974). Surface moorings were soon shown to be less reliable than the subsurface moorings, mainly because in the latter case the flotation is not subject to the stresses in the wave zone.

The acoustic release became a key item as soon as it was confirmed that the subsurface moorings were significantly more reliable. The timed releases and weak links used earlier were adequate as long as mooring durations were short; but with longer and longer mooring durations being dictated by programs studying lower-frequency variations, the timers became unworkable. Heinmiller (private communication) notes that "we lost some moorings off Bermuda in 1964 when the timers released them during a hurricane and we couldn't recover them. We never actually lost a moor-

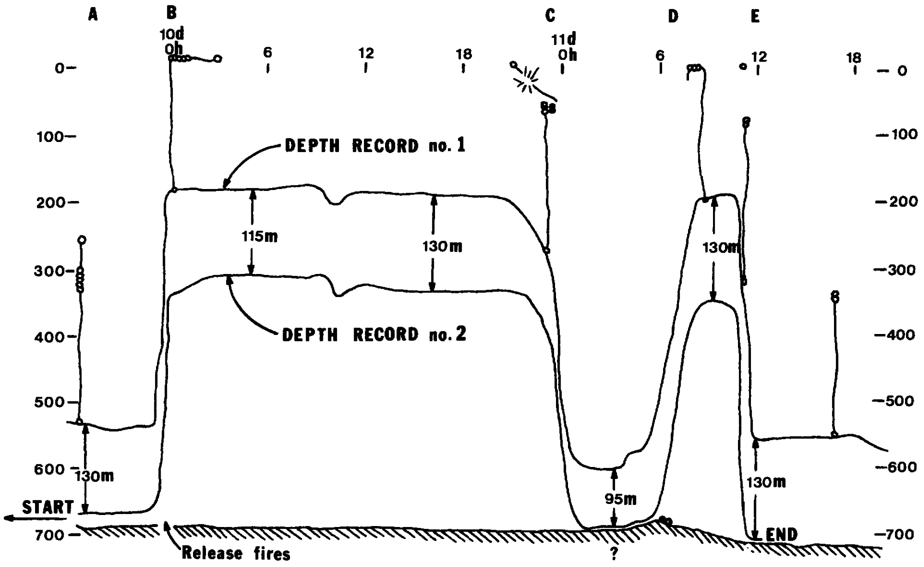


Figure 14.8 Record from two depth recorders on mooring 230 set by Woods Hole Oceanographic Institution in the Denmark Straits, March, 1967. (Heinmiller, 1968.)

ing because of a change of ship schedule, but certainly there was a lot of scrambling for charter vessels at times."

By 1964 it was realized that a device was needed that could be released by command from the recovery vessel. A number of different commercial releases were tested according to the criteria of reliability, security, and information transmittal (e.g., has the instrument released?). For example, the system must be secure from premature tripping of the release mechanism by ambient noise. The strange journey of mooring number 230 set in 705 m of water in the Denmark Straits in March of 1967 is shown in figure 14.8 (Heinmiller, 1968). This mooring refused to come up on command and was later recovered by dragging. Its depth was monitored by a pressure recorder. At A the mooring is supported by six steel ball floats. At B the release apparently tripped letting the buoyancy section surface. At C, one day later, the lower recorder dropped to the bottom. It is supposed that at this point one ball broke loose and two flooded. At D the mooring surfaced again, apparently after the flooded balls broke off. At E one more ball broke loose and the gear sank. The gear when recovered had only two balls on it, both badly battered. Pack ice in the area accounted for the loss of the balls. Ice noise has been suggested as a possible source of sound that actuated the release. The coding system used on the release for this mooring was clearly not secure enough.

As a result of the test program, the WHOI Buoy Group settled on the AMF Sea-Link Model 200 release system (now manufactured by EG&G) (Heinmiller, 1968). As of 1974, the reliability of this release was better than 95%. The AMF system uses a pulsed, amplitude-modulated double-sideband suppressed-carrier frequency, with coding provided by pulse width, pulse-repetition frequency, and time duration. This system has proved to be secure enough against ordinary noise, yet not so secure that it cannot be released when desired. In terms of communication, the AMF device actually monitors the retraction of the piston in the release mechanisms, providing confirmation that the first mechanical step has been taken in the release process. The release is pictured in figure 14.9. An acoustic release system developed and used successfully at Scripps Institution of Oceanography is described by F. E. Snodgrass (1968).

Another important element of the mooring system is wire. Heinmiller notes that two factors were important here. First, the Buoy Group decided that standard torque-balanced wires were not adequate for moorings. The basic industrial torque-balanced wire is designed not to twist when hung from a crane at a height of about 30 m. Since the amount of twist is proportional to length, this wire is not useful over the 4-to-5-km depth of a deep mooring. US Steel finally came to the rescue with a specially torque-balanced oceanographic wire rope.

Related problems included terminations and corrosion resistance. It became clear very early that the wire should be jacketed in order to impede free flow of dissolved oxygen past the wire. The WHOI Buoy Group found that the combination of galvanized steel and standardized terminals with sufficient water barriers was the key to ending corrosion problems.

The fishbite problem was solved simply by using wire in the fishbite zone. Originally this was defined as above 1500 m. Later the group found fishbites at about 1800 m, and extended the zone to 2000 m.

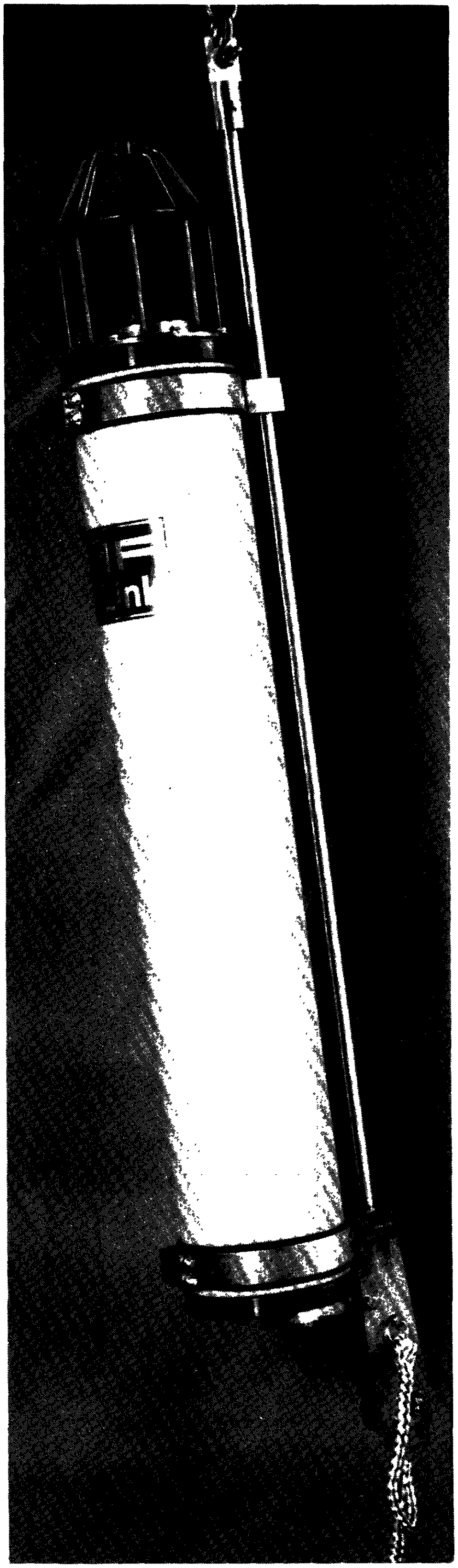


Figure 14.9 Acoustic release system manufactured by Sea-Link. Acoustic transponder is at top, release mechanism at bottom. (Courtesy of W. Coburn.)

Glass balls proved to be the best solution for deep flotation. The first problem with these was quality control; it was solved by working directly with the manufacturers. The second problem was how to get hold of the balls in order to attach them to the mooring line. The group first used nets with quick-fastening hooks, then nets with shackles, eventually going to hard plastic containers (hardhats) of various configurations, bolted to chain. The hardhats also eliminate the need to test spheres because the mooring will not be endangered if a sphere implodes on the chain, when the spheres are far apart enough to avoid sympathetic implosion triggered by the shock wave.

Finally, there is the backup-recovery system, which is made up of a second set of glass balls near the release at the bottom. In case of failure of the upper flotation, the lower balls will bring the mooring up. The advantages are twofold: the system enabled the group to recover equipment that would otherwise have been lost, and it provided engineering data on failed moorings that would have been lost, given the tendency of the top halves of the broken moorings to disappear. Of course, backup recovery involves hauling the mooring aboard upside down. Since tangling is inevitable as the mooring falls to the bottom, the typical situation is as pictured in figure 14.10.

The overall mooring statistics that reflect the engineering improvements discussed above are graphed in

Figure 14.10 Wire tangle resulting from recovery of mooring with backup system. (Heinmiller, 1976b.)

figure 14.11, from Heinmiller (1976a). He noted that in 1967 it was recognized that a major engineering effort was needed for improvement of recovery rates. The improvement in mooring reliability after 1967 is clear; it is due to better acoustic releases, better mooring wire, and improved procedures and quality control (Berteaux and Walden, 1968, 1969; Morey, 1973). During the period 1960 to 1974, 544 moorings were set.

Moorings as currently used by the WHOI Buoy Project are of three types (Heinmiller, 1976b): the intermediate mooring, the surface mooring, and the bottom mooring. The intermediate mooring, shown in figure 14.12, has buoyancy sections at several depths. The lowest buoyancy section provides backup recovery in the event of mooring failure. The depth of the top of the mooring can vary to within 200 m of the surface or less.

The surface mooring for deep-sea use is shown in figure 14.13. The weight of the anchor varies with the expected current profile. A backup-recovery section is included. Surface-wave noise limits the usefulness of this configuration. The bottom-mooring package is shown in figure 14.14. These moorings have no backup-recovery section and typically carry only one or two instruments.

The above description has concentrated on the developments at the Woods Hole Oceanographic Institution because the major engineering effort has been carried out there. It should be noted that a number of other institutions have developed reliable mooring techniques as well; the basic principles we have discussed above are present in all of these designs. In addition, we note a comparison test of different deep-sea mooring configurations that was designed to validate the dynamic computer programs for mooring design (Walden et al., 1977).

The study of current-meter and mooring combinations has been recently an active field. Mooring motion limits our ability to make good near-surface measurements; such motion is particularly large in surface moorings. It is to be expected that acoustic tracking of mooring motion will be more common in future attempts to determine the effect of the motion on the accuracy of the measurements made from the mooring.

14.3.2 Neutrally Buoyant Floats

Measurement of deep motions by the use of *in situ* moving floats requires some method of tracking. The great strides made in acoustics during World War II yielded the necessary technology for acoustic tracking of instruments in the ocean. A significant contribution was the surplus acoustics gear that the oceanographers could scavenge for building and tracking their own equipment.

Interest in developing deep floats was high on both sides of the Atlantic in the mid-1950s. In 1954, Henry

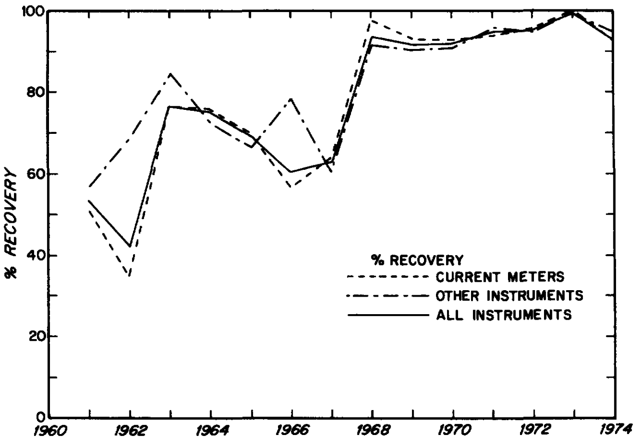


Figure 14.11 Instrument recovery rates as a function of time, Woods Hole Oceanographic Institution Buoy Group. (Heinmiller, 1976a.)

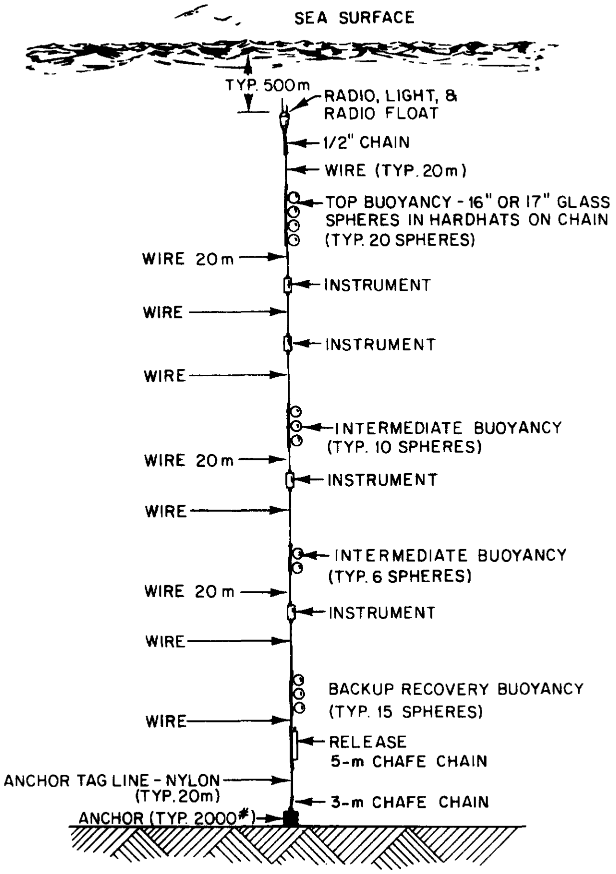


Figure 14.12 Intermediate mooring configuration used by the Woods Hole Oceanographic Institution Buoy Group. (Heinmiller, 1976b.)

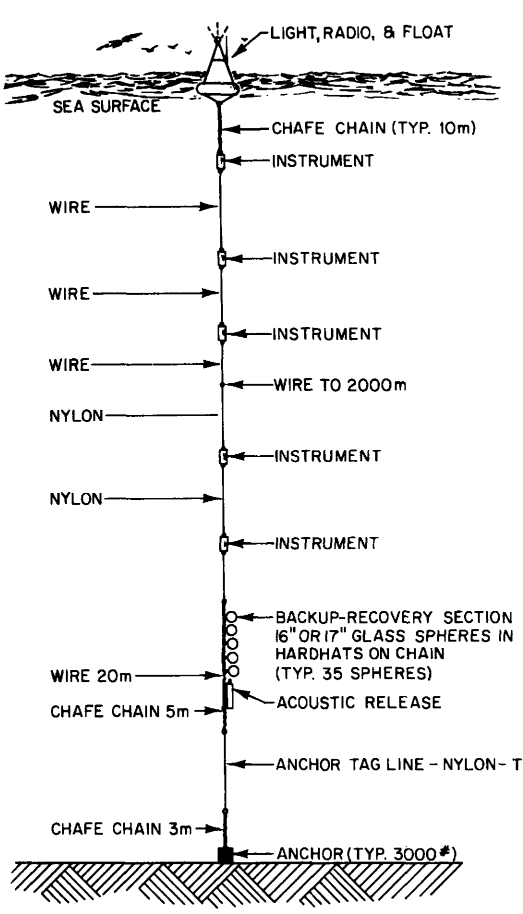


Figure 14.13 Surface mooring configuration used by the Woods Hole Oceanographic Institution Buoy Group. (Heinmiller, 1976b.)

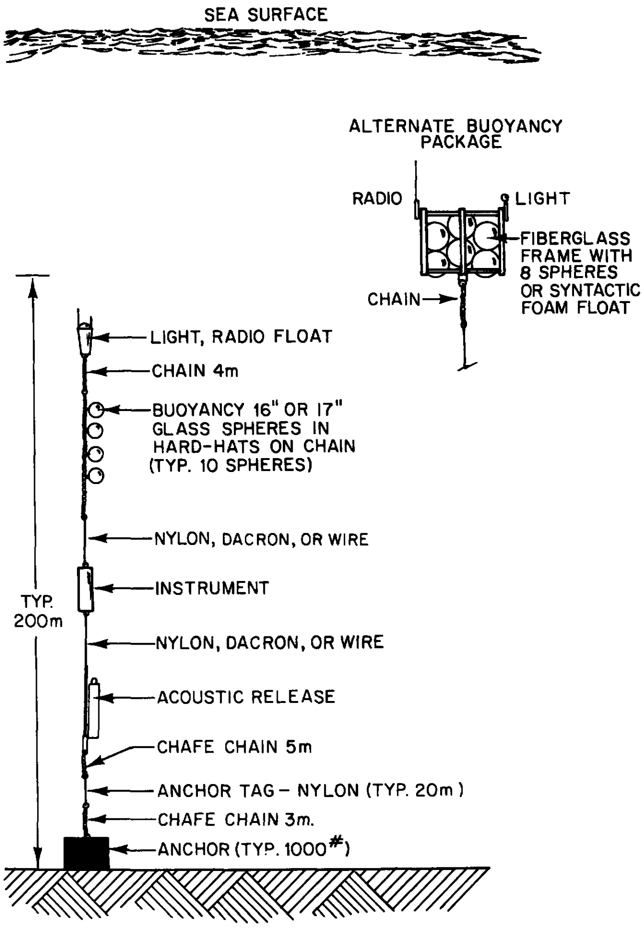


Figure 14.14 Bottom mooring configuration used by the Woods Hole Oceanographic Institution Buoy Group. (Heinmiller, 1976b.)

Stommel mentioned in an address to an oceanographic convocation at Woods Hole, "Were it possible to design cheap neutrally buoyant floats which could signal their position by means of a SOFAR network, then we could start immediately to study the deep water circulation of the sea" [Stommel (1955)]. In England, John Swallow of the Institute of Oceanographic Sciences was a key figure in this development; in fact, the floats have been commonly known as "Swallow floats." Perhaps the early story is best told in his own words (Swallow, personal communication):

> In the summer of 1954 James Crease, Tom Tucker, and others tried to measure the vertical profile of currents in deep water by tracking a slowly sinking sound source relative to three anchored sono-radio buoys. That was only partially successful, and I got involved in trying to improve it when I joined the NIO (National Institute of Oceanography—now the Institute of Oceanographic Sciences) in October 1954. Looking at the scattered results from those profiling attempts, it was a fairly obvious improvement to think of trying to track a sound source at a constant level.

Apparently Swallow came by this idea independently of Stommel; he notes that "Dr. Deacon (Director of NIO) had attended that Convocation in Woods Hole and must have heard Henry; moreover, Willem Malkus (then of WHOI) was working at Imperial College that winter (1954-5) and occasionally visited the Institute. I don't recall that either of them told me about Henry's idea, though."

Swallow goes on:

> Stabilizing the float by heating a petrol-filled container seemed likely to need too much power, besides the possible danger. The next idea was to stabilize the float by making it less compressible than water. That, too, seemed a fairly obvious thing to try, especially to someone familiar with the velocities of elastic waves in water, rocks, and other substances. To anyone doing seismic refraction shooting at sea, water is a highly compressible, low velocity medium. For most metals, the compressibility would be many times less, and clearly a piece of metal could be hollowed out to some extent and still be less compressible than water. Moreover, one could see immediately that one would not be dealing with very small effects: for water, the velocity of sound is about 1.5 km/s, so that the bulk modulus is about 2×10^{10} cgs units, i.e., the relative change in volume is 5×10^{-11} per dyne/cm^2 or 5×10^{-3} per km of depth. So, if we made a float with a compressibility half that of water, it would gain buoyancy at the rate of about $2\frac{1}{2}$ grams per kilogram displacement per kilometer of depth. The critical questions were, would a

hollow piece of metal of suitable compressibility have any useful buoyancy in water, and could it withstand the pressure at useful oceanic depths without collapsing?

It was possible to build such floats, and Swallow's 1955 paper details the construction and first use of the aluminum tube floats. He says:

> The first batch of floats were made from old lengths of scaffolding. I picked out a dozen lengths from a stack that was leaning against the wall somewhere. They were too thick-walled, much lower compressibility than was really needed, and hardly any buoyancy. Not straight enough to be machined, and that would have been too expensive anyway. So I got a wooden trough made, and filled it with caustic soda solution, and dissolved off the outsides of the tubes until they were down to a suitable weight. That first batch of tubes cost about £17 each (not counting my own time). We got the transducers for nothing—they were rejected from a Navy project.

Figure 14.15 (Swallow, 1955) shows the float, consisting of two tubes, the end plugs, and the acoustic transmitter. Swallow notes that "it seemed very much a matter of luck that any of the early floats worked at all. The sound source had been designed for the earlier profiling experiment and the only trouble with it was the packaging. The simple cheap lead-through plug was something I invented myself."

O-rings played an important role in sealing the end plugs, since the flat gaskets and packed glands normally used for pressure vessels leaked at less than 1000 m depth. Accurate navigation techniques were crucial in establishing ship position for triangulating on the floats.

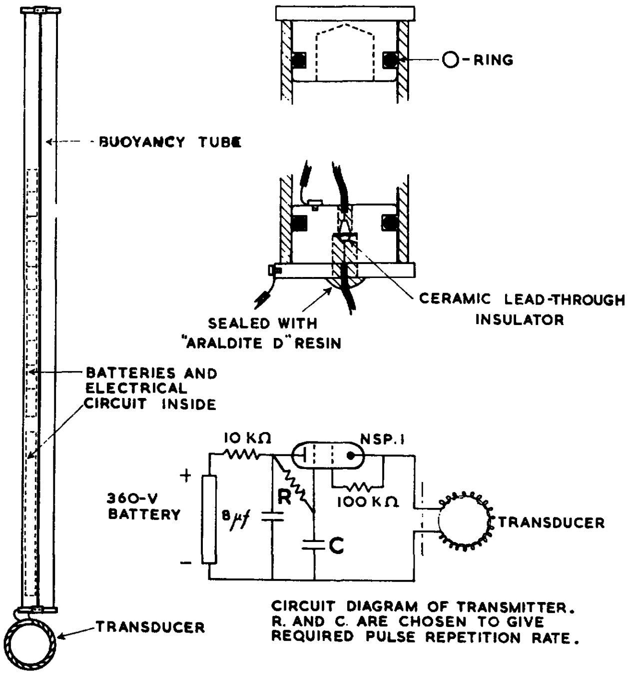


Figure 14.15 Early neutrally buoyant float; sketch of float and end plugs, and circuit diagram of acoustic transmitter. (Swallow, 1955.)

According to Douglas C. Webb of the Woods Hole Oceanographic Institution, no major changes in the float design from Swallow's initial ideas took place until the middle 1960s. At that time three major advances were achieved. G. Volkmann and Webb provided a synchronized time base so that the floats could be heard with an echo sounder, and several signals could then be averaged to give a more accurate position indication. The second change was to increase the range to 20–25 km over the 5–6 km obtained by Swallow by lowering the frequency to 4–5 kHz from 10–12 kHz, and the third was to use glass spheres for small, cheap floats. It also became possible to position the ship directly above a float at a prescribed time, thus eliminating the need for continuous navigation information. This allowed float tracking in the open ocean beyond the range of shore-based navigation systems when satellite navigation became available.

Lowering the sound frequency was an important advance. Since the absorption of sound is proportional to frequency squared, increased range requires lower frequency. Lower frequencies are harder to transmit and receive, however, and there is more ambient noise. An optimum is reached below 1000 Hz, and the longest range floats now operate at about 250 Hz. Low-frequency transmitters for the ocean are not simple: Webb points out that he had to take time out to become a "loudspeaker" designer in order to get the low frequencies necessary for long range.

The long-range floats ride in the SOFAR (sound fixing and ranging) channel, an acoustic waveguide (Ewing and Worzel, 1948). The channel is produced in many parts of the ocean by the combination of pressure and temperature effects on the speed of sound, which decreases with depth from the surface to about 1000 to 1500 m owing to the decrease of temperature, and increases with depth below this owing to the increase of pressure. In the SOFAR channel a few watts of sound can be heard about 2000 km away (Rossby, 1979).

The first big SOFAR floats were placed out in a triangle of listening stations at Eleuthera, Puerto Rico, and Bermuda. The range of listening was about 700 km, and the floats were successfully tracked (Rossby and Webb, 1971). This success generated enough interest so that a large program could be funded as part of the MODE-1 experiment (see section 14.4). A medium-range float program, clusters of floats listened to from a set of hydrophones lowered from a ship, was also used in MODE-1 by Swallow (1977). A 70-km range was achieved with this technique.

The long-range float used in MODE-1 is pictured in figure 14.16. It is housed in an aluminum tube, the

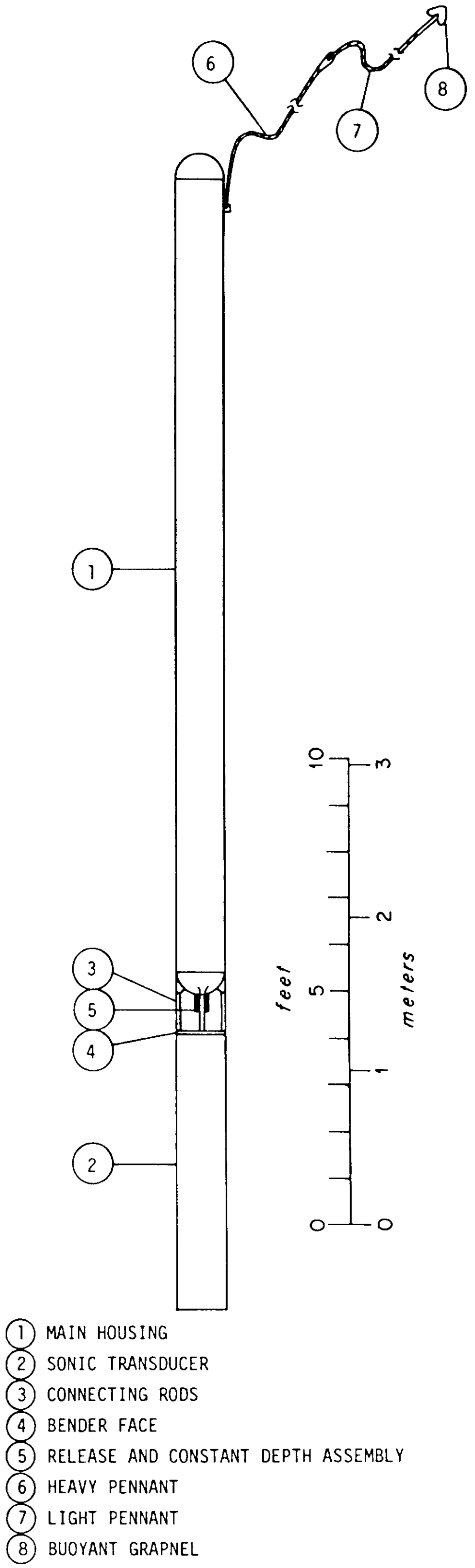


Figure 14.16 Long-range SOFAR float. (Courtesy of T. Rossby.)

cheapest structure for the amount of buoyancy required here. It contains (Rossby, 1979; see also Webb, 1977) a pressure-temperature telemetery system, whereby a 48-h (hour) average of pressure and temperature is transmitted on alternate days. Platinum resistance thermometers and titanium strain gauges are used for stability. Since compressional creep of the aluminum tube causes the instrument to sink about 0.5 m per day, a mechanism is needed to reduce its weight at the same rate. The floats thus have active ballasting: the weight is reduced electrochemically using a sacrificial anode controlled electronically by the pressure measurements. Consideration is being given at WHOI to the use of polymer concrete spheres that could alleviate some of these problems.

In order to relax the geographical constraints imposed by existing shore-based receivers, A. Bradley of Woods Hole Oceanographic Institution, in collaboration with Rossby and Webb, has developed autonomous listening stations for deployment on subsurface moorings. These have a vertical array of hydrophones, a COSMOS microprocessor-controlled signal-detection system, and the high-density cassette recorder discussed above. Rossby (1979) pointed out that when these listening stations become operational in sufficient quantities, it will be possible to conduct experiments in any ocean basin where the sound channel is sufficiently stable for long-range transmission.

A second major development in the float family is the vertical current meter. The measurement of the vertical component of velocity in the ocean is a major problem for oceanographers because it is so hard to find a reference platform. In shallow waters, rigid platforms on the sea floor could be used, but in deep water this is not possible. In 1965 Webb and Worthington at Woods Hole discussed the possibility of using a neutrally buoyant float as a platform for measurement of the vertical velocity. Webb's idea was to mount fins on the cylindrical float, at an angle, so that water movement past the float would cause it to rotate. The rotation could be used as measured relative to a compass, and then stored and transmitted to the surface. The instrument was successful in its first use, the measurement of vertical water movement in the Cayman Basin (Webb and Worthington, 1968). A spectacular result was found in the Mediterranean Sea where large vertical velocities were found confined to relatively small horizontal areas (Stommel, Voorhis, and Webb, 1971). The direct measurement of the vertical velocity here has had an important effect on our thinking about the spatial scales of the processes of bottom water formation in the ocean in general.

An interesting extension of the idea of the neutrally buoyant float is the self-propelled and guided float. One example of such an instrument has been built successfully at the Applied Physics Laboratory of the University of Washington. Called SPURV (self-propelled underwater research vehicle), it can maneuver underwater on command with acoustic signals to produce horizontal and vertical profiles of temperature, salinity, and other parameters. One important use of SPURV is the collection of horizontal temperature data on internal waves—data that were used by Garrett and Munk (1972b) in their modeling of internal wave spectra. A second use has been the delineation of horizontal and vertical plumes from chemical outfalls.

14.3.3 Temperature and Salinity Profilers

With profiling instruments in general, the quote by M. R. Clarke at the beginning of this chapter is apt: we know what the discrete sampling instruments can catch, but we do not know what lies within the sampling intervals. Hence the interest in continuous-profiling instruments. Gregg (1976b) has presented a useful history of the development of many of these instruments.

Temperature profilers were developed first; then, with the advent of reliable conductivity sensors, salinity profilers were added. Thus this section is logically divided into two parts: the development of the bathythermograph (BT) and its successor, the expendable bathythermograph (XBT), both used for the upper ocean; and the development of the salinity (as measured by conductivity), temperature, and depth-recording (STD, CTD) systems, which measure right down to the ocean floor.

The BT operates with a pressure-driven bellows that moves a metal- or smoke-coated glass slide under a stylus driven by a liquid-filled bourdon tube sensitive to temperature. The XBT, on the other hand, uses a thermistor to sense the temperature, and depends on a known fall rate to determine the depth. The XBT therefore requires a shipboard electrical system to record the data.

The BT is mentioned in *The Oceans* as having "the great advantage that it can be operated at frequent intervals while underway, and thus a very detailed picture of the temperature distribution in the upper 150 m can be rapidly obtained." Since the BT is entirely mechanical in operation, it is extremely reliable, and as J. M. Snodgrass (1968) says, "The bathythermograph over the years has perhaps been more extensively used than any other single oceanographic instrument." Since the engineering details and the development of the BT and an extensive discussion of the development of the XBT are covered in his article, we shall not repeat that material. It is useful to note, however, some of the developments in the expendable field since then.

As of 1978, the Sippican Corporation, suppliers of the XBT, had produced more than two million of the probes. It is likely that the number of records obtained from XBTs will soon surpass that of the BT, if that point has not been reached already; according to D. Webb, the scientific community alone uses approximately 65,000 XBTs annually. One of the major achievements of Sippican was the development of an insulated hard-wire link between the sensor and the ship. The present system consists of wires with four coats each of nylon and epoxy, jointed together by heat mating into bifilar pairs. The wire link is a 0.008"-diameter pin hold-free two-conductor cable. The cable is wound on two spools in a configuration similar to the spinning reel used by fishermen. The cable is unreeled from the outside of each spool in a direction parallel to the spool's axis. In this way the cable unreels simultaneously but independently from a vessel or aircraft and from the deployed sensor package (Sippican, 1973). This double-reel system is the heart of the expendable system. In use at sea, the dual-spooling technique permits the probe to free-fall from the point of sea-surface entry, without being affected by the speed or direction of the ship.

Current expendable products include the wire link itself, temperature sensors usable to depths of 200 to 1830 m, a fine-structure probe, a probe that can be launched from submarines while under water, and probes that can be launched from aircraft. To show the sensitivity of these probes, we note that the slower sink rate of the fine structure probe enables the thermistor, which has a time constant of 100 ms (milliseconds), to respond to a change of temperature in a layer of water of thickness 18 cm versus 65 cm when mounted in the standard XBT probes. The accuracy of the probes is ±0.1°C, and ±2% of depth.

A sound velocity probe is also available. It will measure sound velocity to an accuracy of $\pm 0.25\ \mathrm{m\,s^{-1}}$ to depths of 850 m. The sensor measures directly the time it takes for an acoustic pulse to traverse a total path of 52 mm. The effects of temperature, salinity, and pressure are thus accounted for directly in the measurement (Sippican, 1978). A salinity sensor is under development that uses the sound velocity and temperature probes together to compute salinity. Figure 14.17 shows the expendable configuration.

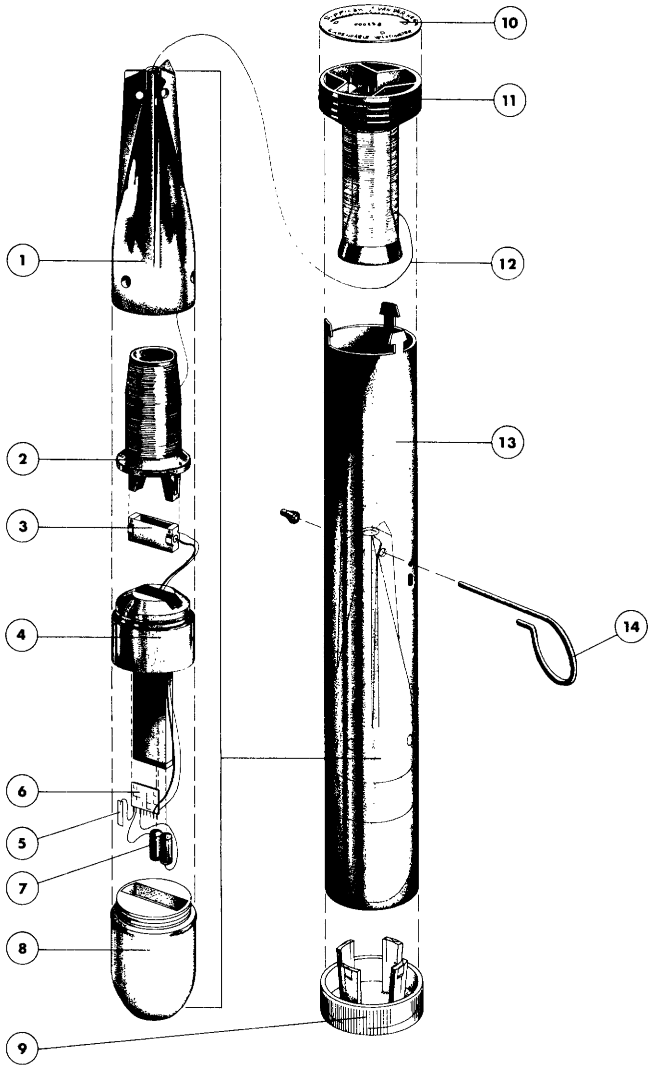
The XBTs are an invaluable tool for ocean monitoring. Merchant ships equipped with XBTs have yielded extensive sets of data for the study of the variability of the thermal structure of the upper ocean in both the North Pacific and the North Atlantic (Bernstein and White, 1977). Their widespread use has also stimulated further research into the systematic errors (e.g., depth) that exist in the system (McDowell, 1977).

The STD and CTD systems have also improved the oceanographer's hydrographic techniques and given us a new view of the small-scale distributions of temperature and salinity. Before this continuously recording system became available, the standard technique was that presented in *The Oceans*: the use of reversing thermometers and collection of water samples for later determination of salinity by laboratory titration or conductivity measurements. Hamon and Brown (1958) listed some of the problems of this technique: the measurements are made at preset depths so that important detail may be missed; the salinity information is not available quickly enough to guide the progress of a cruise; and sampling and analysis are time consuming and expensive. On the other hand, the technique is straightforward and reliable, virtues not to be overlooked in work at sea.

Apparently the first reference to the use of conductivity for measurement of salinity of sea water is in Nansen's report (1902, p. 197) of the Norwegian Polar expedition 1893-1896 (this reference, not in *The Oceans,* was pointed out to me by B. Hamon and H. Mosby). Nansen states, "Considering it very important to determine the specific gravity or salinity of the water of the North Polar Sea with the highest degree of accuracy, I asked Mr. Hercules Tornøe to help me in the matter, which he did in a most friendly manner. He constructed for the expedition an apparatus for the determination of the salinity of sea water by its power of electrical conductivity, which he has himself described in 'Nyt Magazin for Naturvidenskaberne,' Christiania, 1893." The system was used on deck, and gave some useful results while exhibiting problems we still find today with electrode drift.

A continuous recording system for both conductivity and temperature was described in 1948 by Jacobsen (1948). This system was designed for a maximum depth of 400 m, and separate supporting and electrical cables were used. The system was crude, but pointed the way to the development by Hamon and Neil Brown then of the Division of Fisheries and Oceanography of the Commonwealth Scientific and Industrial Research Organization of Australia of the forerunner of the currently used system. Hamon points out, "Neil Brown and I both started working on an STD instrument as the result of a suggestion from David Rochford. He had seen the 1948 paper by Jacobsen, and wondered if we could do anything along similar lines. The instrument that we developed at that time is described in Hamon (1955) and Hamon and Brown (1958). First sea trials were carried out on 29 April 1955."

This first instrument was designed to operate in the upper 1000 m and had a range of 0-30°C with an accuracy of ±0.15°C, and a salinity range of about 13 ppt (parts per thousand) with an accuracy of ±0.05 ppt. A conductivity cell with platinum electrodes was used. One of the novel features of the Hamon and Brown design was the use of a single-cored armored cable as the only connection between the underwater unit and the ship. The cable carried power from the ship down



XSV EXPLODED VIEW

① AFTERBODY
② PROBE SPOOL
③ SOUND-VELOCITY SENSOR
④ ELECTRONICS HOUSING
⑤ STARTING CONTACT
⑥ INTEGRATED CIRCUIT
⑦ BATTERIES
⑧ ZINC NOSE
⑨ SHIPPING CAP
⑩ LABEL
⑪ SHIPBOARD SPOOL
⑫ SIGNAL WIRE
⑬ CANISTER
⑭ RETAINING PIN

Figure 14.17 Schematic diagram of expendable probe used for measurement of sound velocity. (Courtesy of Sippican Corporation.)

to the underwater unit, brought up the measuring signals, and also supported the full weight of the underwater unit. The feature greatly simplified the handling of the equipment at sea, and has been used on all of the STD and CTD systems since then. In essence, the measuring elements were all variable resistors with values depending on conductivity, temperature, or depth. These elements were connected in turn to an oscillator whose frequency was a function of resistance. In this way the measured variables were converted into audio frequencies that were fed to the central core of the cable, the outer steel sheath acting as the return conductor.

While the original STD was being developed, Hamon had the idea of making a portable bridge instrument for use in estuaries, at least partly to gain experience with the application of conductivity cells to marine work. The instrument described by Hamon (1956) was the result, and with minor modifications it has been in production up to the present. Hamon notes that work on the STD and to a lesser extent the portable bridge led to the first measurements of the effect of pressure on electrical conductivity (Hamon, 1958) [see Bradshaw and Schleicher (1965) for later work on this subject]. Hamon's instrument used a small glass-enclosed thermistor immersed in the sample and yielded an accuracy equivalent to the Knudsen titration.

About this time, Brown used the idea of the inductive coupling principle (which avoids the use of metal electrodes) to build a portable salinometer. The advantage is that the windings themselves can be insulated from the corrosive effects of sea water. Brown was able to avoid the use of a thermostat by using a thermistor to give temperature compensation. His design resulted in a portable instrument with an accuracy of approximately 0.003 ppt. The concept of using an induction technique was already known (e.g., Gupta and Hills, 1956) but Brown's contribution was to produce a workable unit. The instrument is described by Brown and Hamon (1961) (figure 14.18). Cox (1963) reviews the field of shipboard salinometers and their development.

It was a logical step to add the inductive sensor to the continuously profiling system, and Brown did just that. The new instrument, called the STD, was designed and sold in the early 1960s by the Bissett-Berman corporation and quickly became an important part of the oceanographer's set of tools (Brown, 1968) (figure 14.19). As Brown (1974) says, "The routine use of continuous profiling instruments such as the STD introduced a decade ago showed very clearly that the ocean structure was very much more complex than the classical Nansen bottle data would suggest."

When the STD was designed, computers, their peripherals, and software were too expensive and unreliable for routine use at sea. As a consequence, the STD required the use of analog computation of salinity from the *in situ* temperature measurements. One of the problems that continually arose was the mismatch in time response of the temperature and conductivity sensors. Since conductivity is a strong function of temperature, salinity is a small residual left over from the temperature correction. If the correction was applied too rapidly, as it inevitably tended to be in the STD, spikes appeared in the salinity trace. Moreover, the conductivity sensor did not give as high a resolution as desired and its inherent sensitivity was not as good as the electrode design. Finally, the oscillatory stability was not high enough to yield good accuracy at high data rates.

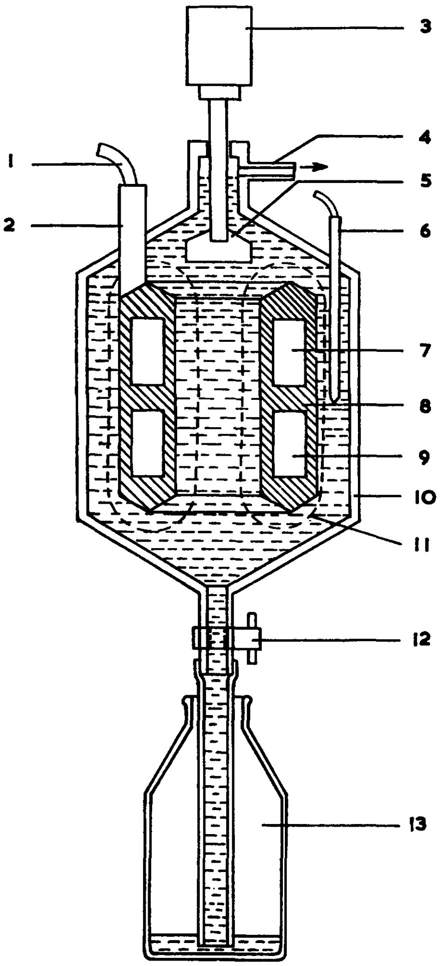


Figure 14.18 Simplified diagram of the measuring head for the laboratory inductive salinometer: 1, leads from toroid assembly; 2, support stem for toroid assembly; 3, stirring motor; 4, connection to aspirator; 5, stirrer; 6, thermistor; 7, toroidal core of voltage transformer; 8, toroid assembly; 9, toroidal core of current transformer; 10, clear plastic housing; 11, path of electrical current in the water sample; 12, stopcock; 13, sample container. (Brown and Hamon, 1961.)

Brown's later designs were able to overcome most of these problems. With the rapid improvement and cost reduction in computer systems, the development of a

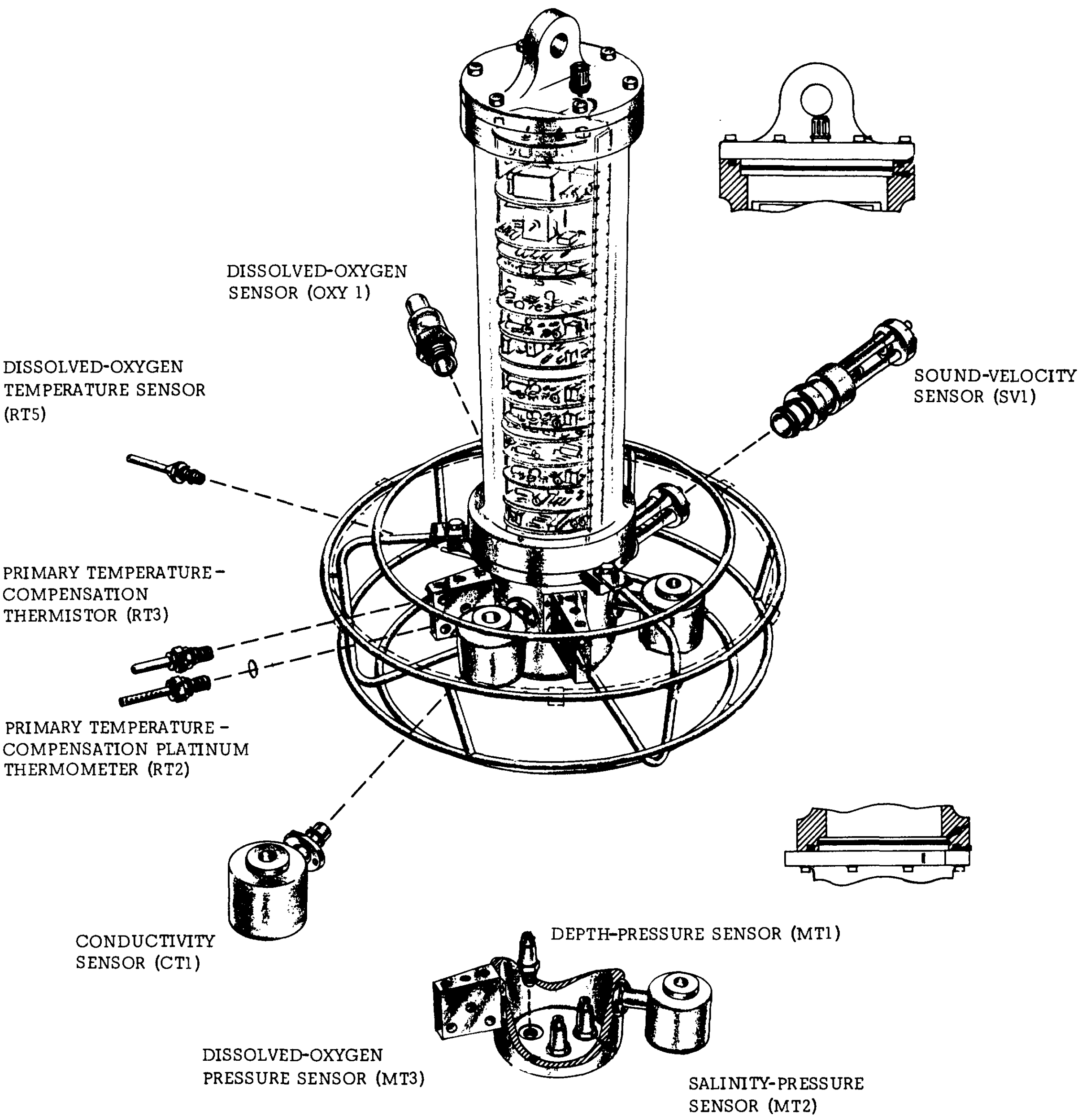


Figure 14.19 Schematic of STD showing available sensors. (Courtesy of Grundy Environmental Systems, Inc.)

relatively drift-free electrode system, and the use of 10-kHz sinusoidal sensor excitation with an ac digitizer, he produced the new CTD. The slightly different name is used to distinguish the new system, which makes precise, fine-scale measurements at a high data rate, from the earlier STD. The details of the new system are given by Brown (1974). Thus we have seen a cycle, from the electrodes to the inductive cell and back to the electrodes. The inductive system is still being used for those applications where the highest resolution is not required. We should note, however, that the system does not replace the use of bottles. Oceanographers have found that water samples are necessary in order to maintain the salinity calibration, and most chemical measurements require samples. Salinity calibration is usually done with a rosette sampler; a small model is illustrated in figure 14.20.

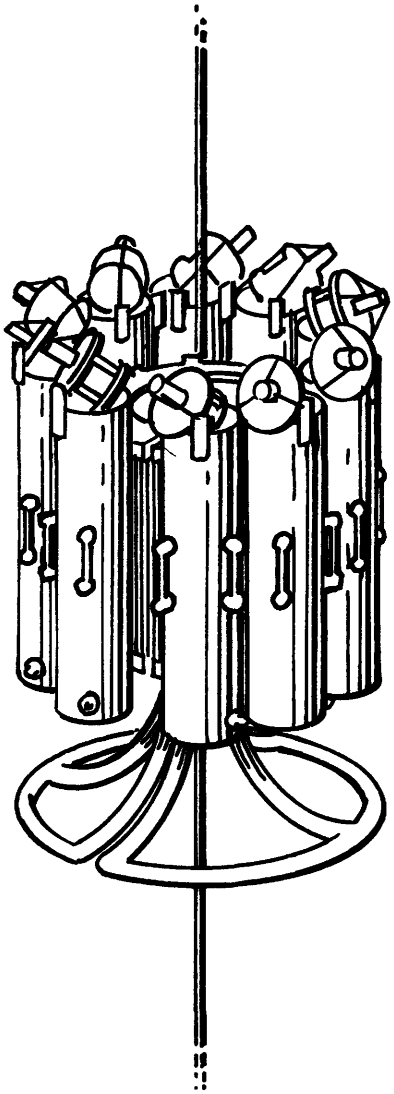


Figure 14.20 Rosette multibottle array. (Courtesy of General Oceanics, Inc.)

The latest version of the CTD is manufactured by Neil Brown Instrument Systems and a schematic is shown in figure 14.21. The conductivity sensor is a miniature four-electrode cell with platinum electrodes, and the temperature sensor is a combination of a miniature fast-response thermistor and a platinum-resistance thermometer. The four-electrode cell eliminates errors due to polarization at the electrode–sea water interface, and the temperature outputs are processed to achieve both the accuracy of the platinum and the speed of the thermistor. The pressure sensor is a strain gauge, compensated to minimize temperature effects.

The current system has a precision of better than 0.001°C over a range of −3 to +32°C, and a conductivity precision of the order of one part per million. The instrument will also accept an oxygen sensor. In summary, the use of the new instruments has shown the effectiveness of the equipment for fine-scale work and high-accuracy deep-ocean survey studies.

The success of the conductivity measurement for salinity has produced a new practical salinity scale (Lewis and Fofonoff, 1979). The new salinity scale, defined by conductivity ratio, has been found to be a better route to density than a "chlorinity" scale since conductivity will respond to changes in any ion, whereas chlorinity is ion specific. Lewis and Fofonoff pointed out that it has been demonstrated conclusively that in the hands of average observers conductivity-ratio measurements allow density to be predicted with a precision nearly one order of magnitude greater than that allowed by chlorinity measurements.

The instruments above provide a vertical resolution of temperature and conductivity to about 1 m, defined as the *fine-structure* regime. To go to the *microstructure* regime, defined as approximately 1 m to 1 cm, new instruments are required. A number of groups have developed free-fall instruments for studying both fine and microstructure of temperature and salinity.

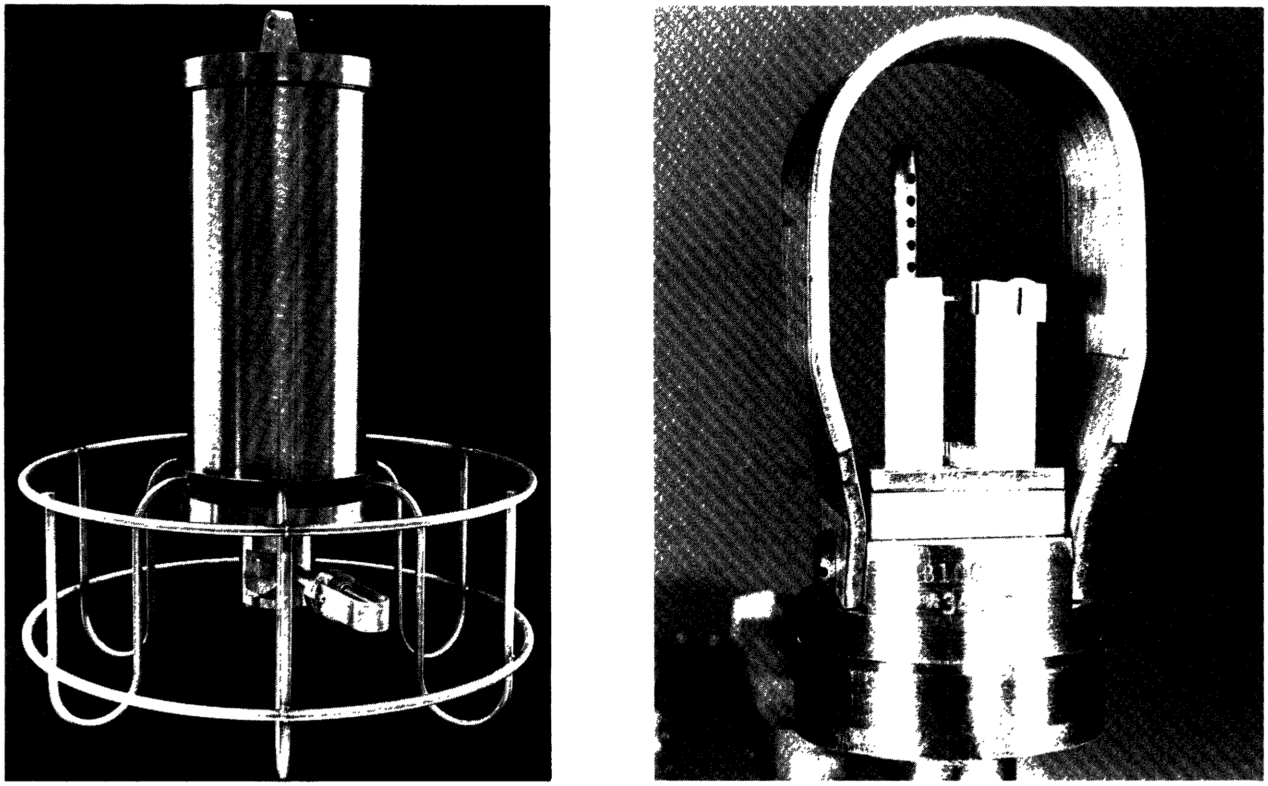


Figure 14.21 CTD (Mark IIIb) underwater unit (left) and sensor head (right). The conductivity cell is to the right of the temperature sensor. (Courtesy of Neil Brown Instrument Systems, Inc.)

The early development in the field was due mainly to C. S. Cox and his collaborators at Scripps (Osborn and Cox, 1972; Gregg and Cox, 1971). The extended wings of the microstructure recorder (MSR) developed by this group permit rapid descent (greater than 1 m s^{-1}) to the preset depth, then slow descent (10 cm s^{-1} or less) through the area of interest; the motion is similar to that of a falling maple seed or helicopter in autorotation (figure 14.22). Due to the slow fall rate and accurate thermistors (Gregg, Meagher, Pederson, and Aagaard, 1978), this instrument has a noise level of 2–3 microdegrees and takes a data point every 1.5 mm. It has proved capable of resolving most structures in the upper 4 km, and can obtain direct measurements of internal-wave velocities (Desaubies and Gregg, 1978). Caldwell, Wilcox, and Matsler (1975) have developed a relatively simple freely falling probe for study of microstructure. Other groups have developed instruments that include velocity profiling as well; these will be discussed in the next section of the chapter.

Cairns and Williams (1976) (see also Williams, 1976) have used a freely drifting, mid-water float equipped with a buoyancy controller to make repeated profiles of thermal microstructure of a 20-m segment of the water column. These measurements augment the free-fall instrument data.

An optical imager for studying small-scale features in the ocean has been developed by A. J. Williams (1975). The device, a self-contained imaging microprofiler (SCIMP), uses a shadowgraph technique to record optical inhomogeneities in an *in situ* sample of sea water. Features of the order of millimeters can be observed—in particular, the detection of fields of "salt fingers" becomes possible. The salt-finger problem has an interesting history [Williams, (1974b) and chapter 8]. In 1956, Stommel, Arons, and Blanchard published a paper on the "perpetual salt fountain," which described the convective process since called salt fingering. Stern (1960a) pointed out that the different diffusivities of salt and heat meant that the process could be a significant mechanism for the vertical transport of salt and heat in the ocean. Laboratory experiments showed fingers or convective cells between interfaces of warm, salty water and cold, fresher water. Later, ocean measurements with the STD in the late 1960s demonstrated the existence of layers and sheets: thin interfaces which separated mixed layers. The question was whether this layering structure in the ocean was associated with salt fingers.

In late 1972, Williams tested the first version of his instrument, designed after the suggestions of Stern (1970), which combined an optical imager (a shadowgraph system that records density inhomogeneities) with a conductivity-temperature-depth microprofiler. A sketch of the instrument is shown in figure

14.23. The instrument is mounted on an autonomous vehicle, in acoustic communication with the ship, which sinks slowly through microstructure features in the ocean. The shadowgraphs are produced by a 5-cm-diameter laser beam that is reflected through a horizontal path, 160 cm long, and recorded on film. In 1973, Williams obtained photographs of shadowgraph images of fields of salt fingers in the Mediterranean outflow. The images matched with those he had made using the same instrument in laboratory-produced fields of salt fingers, and the agreement with theoretical calculations on the size of the fingers was good (Williams, 1975). Since the observed fingers occurred at an interface between mixed layers, as expected, Williams was able to conclude that "thus 17 years has brought salt fingers from an oceanographical curiosity to an observed ocean process." The latest of the SCIMP instruments utilizes a Cassegrain telescope to expand the viewing aperture yet decrease the size of the pressure housing, and a simpler free vehicle is used. In addition, a shear meter provides velocity fine-structure data for Richardson-number calculations.

14.3.4 Velocity Profilers

Free-Fall Profilers The profile of velocity is an important part of our picture of the ocean. Since moored current meters can give us only a time series at a few points, and the moorings are not yet adequate for strong currents, features such as narrow jets may not be seen. Thus there has been interest for a long time in techniques for the measurement of currents as a function of depth or horizontal position.

We can divide these instruments into three classes. The simplest, in principle, is the analog of the meteorological balloon—the sinking float. The float is tracked acoustically as it sinks, and the horizontal path is differentiated with respect to time to yield velocity as a function of depth. A subset of this class is the transport float, whose position before and after a trip to the bottom is shown by dye patches at the surface. The second class is the free-fall device that has a current sensor on it, including the electromagnetic and the airfoil lift probes. Finally we have the class of instruments consisting of a current meter that goes up and down a line attached to a ship, mooring, or drifting buoy.

The idea of tracking a sinking float for velocity profiles came out of the World War II acoustic developments—recall that Swallow mentions that Crease and Tucker were working on it in 1954. In 1969 Rossby reported measurements that he had made in 1968 with a slowly sinking pinger tracked from a set of hydrophones at the ocean bottom. The measurement was

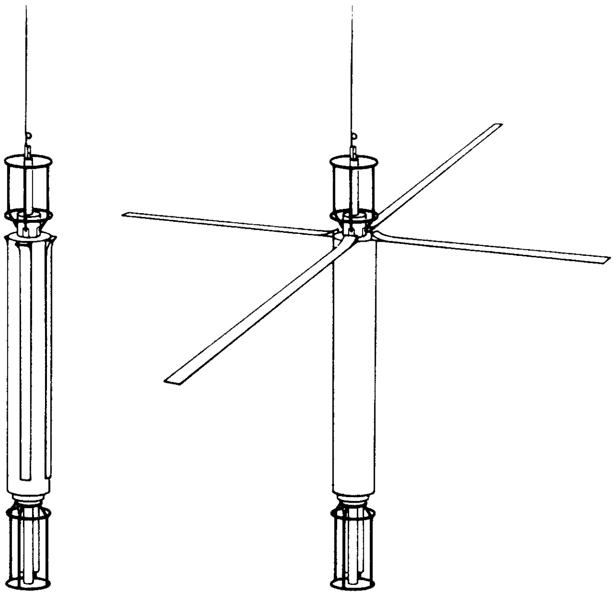


Figure 14.22 The microstructure recorder configuration: (left) during rapid descent; (right) during the data cycle, when the wings are extended. The rotation induced by the pitch of the wings generates sufficient lift to slow the fall rate to 0.08 m s^{-1}. (Desaubies and Gregg, 1978.)

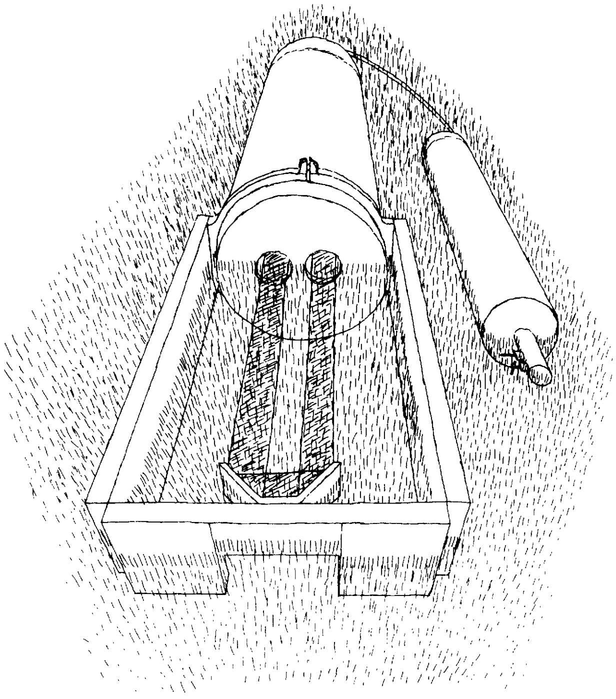


Figure 14.23 Self-contained imaging microprofiler of Williams (1974b). The optical instrument and the CTD simultaneously measure an undisturbed microstructure feature, here a salt-finger interface. Refraction by optical inhomogeneities along the path produces a shadowgraph, which is photographed within the housing.

made near the Plantagenet Bank 25 nautical miles southwest of Bermuda in order to take advantage of an existing set of hydrophones. Substantial velocity variations over small vertical scales (10-m thickness or less) were observed. Rossby noted that the resolution is limited by the timing accuracy, and that the hyperbolic geometry for distance differences to two points can amplify the timing errors. But the Rossby experiment showed the feasibility of the technique.

In 1970, Pochapsky and Malone (1972) carried out a similar experiment in the Gulf Stream southeast of Cape Lookout, North Carolina. They used an instrumented float with temperature and pressure sensors that sank slowly over three disposable bottom-anchored transponders. The float was designed to drop a weight at the bottom and then make a return set of measurements. In this case, as the float sank to the bottom, it not only transmitted its transit times to each of the transponders, but also reported its own temperature and pressure to the ship. The velocities obtained agreed with the results of Swallow and Worthington (1961) mentioned earlier, and the structure seen in the profile is consistent with the later more detailed results of the electromagnetic profilers. The important step here was the move to portable transponders [Rossby later (1974) extended this technique to use moored hydrophones]. One of the attractive features of the Pochapsky-Malone device is its small size. The floats can be launched over the side of a ship by hand, with no winch or crane requirements whatever, making the technique usable from smaller vessels, although ship acoustic noise can be a problem. It was successfully used in MODE-1 (Pochapsky, 1976).

It was a straightforward step to add temperature and salinity profiling to the sinking floats. One of the successful developments is the White Horse, developed at the Woods Hole Oceanographic Institution by W. J. Schmitz, Jr., R. Koehler, and A. Voorhis. The device (figure 14.24) is about 2 m long and has an outer structure of white plastic (hence the name). It is basically an acoustic dropsonde with a CTD microprofiler (Brown, 1974). It utilizes a pulsed acoustic navigation system with bottom-moored transponders (Luyten and Swallow, 1976). The White Horse has a positional accuracy of better than 1 m corresponding to $\pm 1.5 \text{ cm s}^{-1}$ error in horizontal velocity when estimated over 100-m increments in the vertical. Luyten and Swallow (1976) used the instrument to show the existence of an equatorially trapped, jetlike structure in the Indian Ocean. Since geostrophy fails at the equator, such a direct-measuring instrument is essential.

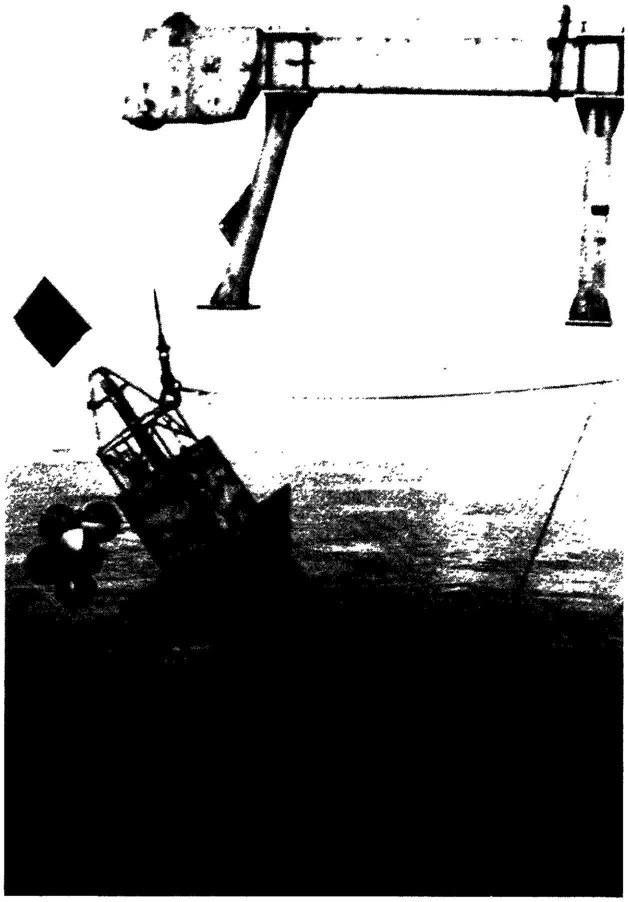


Figure 14.24 The White Horse (velocity-, temperature-, and conductivity-profiling instrument) developed at the Woods Hole Oceanographic Institution. (Courtesy of J. Luyten.)

One of the simplest uses of the sinking float is in the transport measurements of Richardson and Schmitz (1965). In its shipborne use, the technique involves marking the position of a float as it leaves the surface of the ocean heading for the bottom. At the bottom, the float releases weights and becomes positively buoyant, and rises to the surface. The position at the surface is noted, and the total horizontal distance traveled is then proportional to the vertically averaged velocity. The technique requires accurate navigation (local Hi-Fix was used) and some estimate of surface currents so that the position of arrival at the surface can be properly estimated. A number of studies of transport of the Gulf Stream in the Florida Straits has been carried out with this technique (Niiler and Richardson, 1973). Velocities for different depth intervals can be estimated by allowing the weights to drop off at shallower levels.

The extension of this idea to floats dropped from aircraft (Richardson, White, and Nemeth, 1972) is clever, but has not yet worked reliably. This technique does not require the precision navigation of the shipborne equipment. Here a three-probe system is used. An expendable probe is ejected from the aircraft and on striking the water a surface marker separates and dispenses fluorescein dye. The remainder of the probe carries two buoyant streamlined floats to the bottom. At a preset time (longer than the time required for the probe to reach bottom) the first float is released, and later the second float is released. Each releases dye when it reaches the surface. Photographs of the three dye streaks provide enough information for the average velocity to be determined. The instruments were used in MODE-1 but there were many difficulties in observing the dye patches. The simplicity of such techniques suggests that further development would be profitable.

An ingenious velocity profiler based on electromagnetic techniques was developed by T. Sanford and R. Drever [see Drever and Sanford (1970) and Sanford, Drever, and Dunlap, (1978) for the latest version]. This instrument yields the variations of horizontal velocity by measuring the electrical currents generated by the motion of the sea water through the earth's magnetic field. The instrument is especially interesting because by producing a profile it eliminates part of the ambiguity inherent in electromagnetic measurements at one level only, e.g., those with the geomagnetic electrokinetograph (towed electrodes at the surface—the GEK).

In short, the principle is the following: an instrument that drifts with the local velocity does not see any electromotive force due to its own motion, since there is no relative velocity between the water and the instrument. The drifting instrument sees only the voltage drop due to the electrical currents that have been generated in the water. These have two sources: the local electromotive force, which varies with depth, and the electrical field in the water. Because the current systems are broad compared to their depth, the electrical field in the water is essentially independent of depth. It is proportional to a conductivity-weighted, vertically averaged velocity except where the sea is shallow or the bottom is unusually conductive. The net electrical current at each level is the difference between the currents generated by the electromotive force at each level and the currents generated by this depth-independent electrical field.

The instrument designed by Sanford and Drever consists of a pair of electrodes attached to a cylinder that drifts with the local velocity as it sinks to the bottom. It measures the voltage drops due to the local electrical currents, which as we have just seen are caused by the difference between the local velocity and the average velocity. A velocity profile relative to the unknown conductivity-weighted averaged velocity is thus obtained. The GEK, because it gives only a surface measurement, requires some assumption about the depth-independent velocity to be made before a number for surface velocity can be obtained, and is thus ambiguous. The profile of velocity from the Sanford-Drever instrument is ambiguous in the same absolute sense, but the profile structure is not ambiguous.

The second important design point was to solve the problem of detecting the small signals in the presence of large noise. Given the size of the instrument, the expected voltages are about 1-100 μV. However, the electrode offset voltage is much larger, about 0.1-5 mV. Adding rotation fins to the instrument allowed the dc signal to be modulated into an ac signal with frequency of the rate of rotation. Bandpass filters selectively amplify the signal at that frequency, thus bringing it up above the noise that is spread over all frequencies. In addition, because the sensors rotate, the electrical field is sensed along many orientations, thus providing the required components for construction of a relative velocity vector.

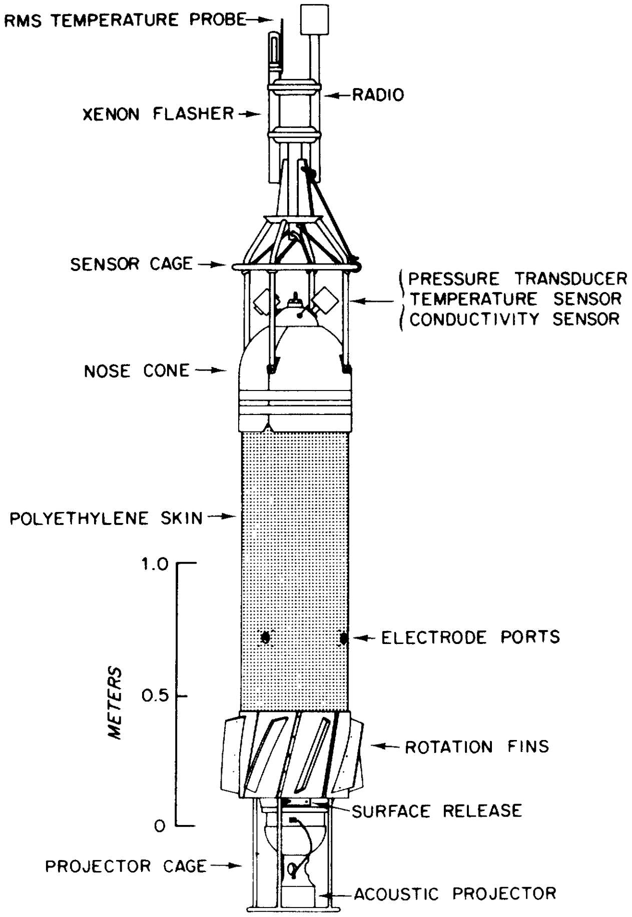


Figure 14.25 Electromagnetic velocity profiler. (Sanford, Drever, and Dunlap, 1978.)

Absolute velocity can be determined by tracking the instrument acoustically or by using some other technique of direct velocity measurement. In the present instrument (see figure 14.25), the reference velocity is determined by acoustic Doppler measurements of the absolute velocity of the instrument as it nears the sea floor. Overall, the electromagnetic method yields velocity determinations every 5-10 m with an uncertainty of about ±1 cm s^{-1}. A round trip in 6000 m of water lasts about 3 h. The instrument has been used in the MODE-1 experiment, to study internal waves, and in the Gulf Stream. An expendable version of this instrument is now in the testing stage.

In 1971 a series of experiments was carried out to compare the electromagnetic profiler with the acoustic tracking method of Rossby (Rossby and Sanford, 1976). Density measurements for geostrophic comparisons were also made. The two free-fall profile methods agree within 1 cm s^{-1} averaged over depth intervals in which the observations were separated in time by less than 10 min. A steady component was averaged from a time series of 4 days; it agreed within ±2 cm s^{-1} with the geostrophic profile computed every 200 m. For comparison, we note that the acoustic method appears to be more suitable for time-series measurements at one location, whereas the electromagnetic technique may be better for surveys of density and relative current profiles over large geographical areas since it is not tied to a mooring. Moreover, the resolution of the electromagnetic technique can be made small enough for studies of microstructure.

In order to measure finer scales of velocity fluctuation, it is necessary to design smaller sensors. Woods (1969) showed from dye measurements that shears of 1 cm s^{-1} in intervals of 10 cm could occur. To address these smaller scales, Simpson (1972) designed a freely falling probe that could measure small velocity changes by use of a neutrally buoyant vane. The instrument was successfully used in Loch Ness and had a resolvable shear of about $2 \times 10^{-3} s^{-1}$ averaged over 30 cm.

Osborn and Crawford (1978) report on the successful use of an airfoil-type probe. The probe is a pointed body of revolution in which the lift force on the axisymmetric nose is sensed with a piezoelectric sensor. The probe measures the horizontal velocity. The instrument used has the airfoil probe, a thermistor, and a salinometer head mounted at the lower end of the body (figure 14.26). It has been used in several open-ocean experiments. A resolution of about 1 cm in vertical resolution of velocity fluctuations is estimated for the instrument. The probe can be used to estimate the local rate of energy dissipation by use of the velocity-shear data.

Attached Profilers The idea of either raising or lowering a current meter from a ship is straightforward, as is the extension to a current meter moving up and down a fixed line, either attached to a ship or a mooring. We shall not attempt to trace the history of these devices here, but simply report on some examples of current design and use.

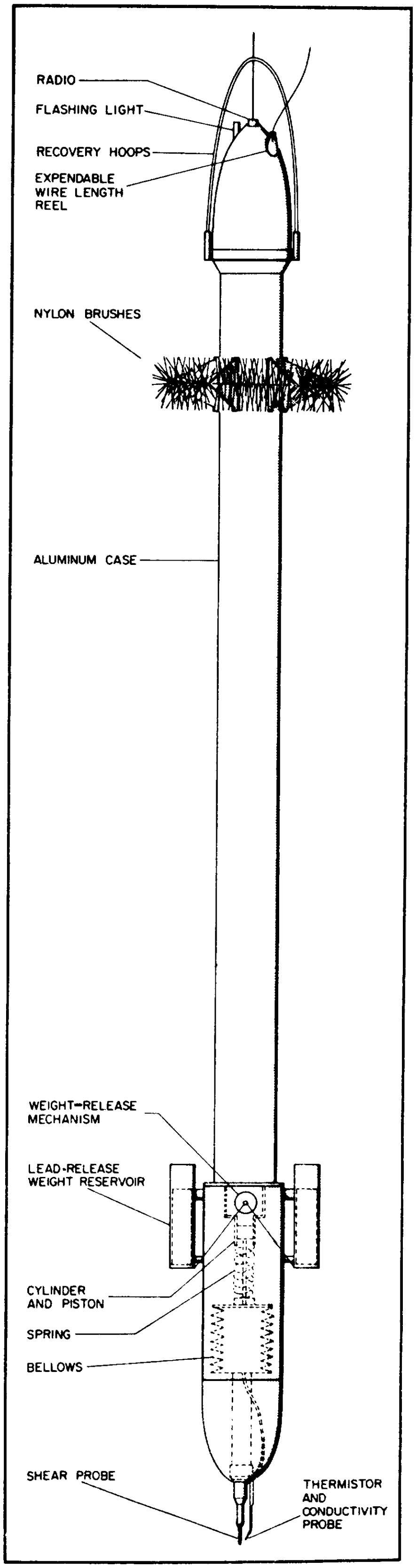


Figure 14.26 Velocity profiler with airfoil-type probe, temperature, and conductivity probes. (Osborn and Crawford, 1978.)

One of the successful profiling current meters has been discussed by Düing and Johnson (1972) (figure 14.27). The most recent version of this instrument consists of three major parts. A roller block couples the front of the instrument to a hydrowrire, in order to decouple the ship motion from that of the instrument. The second part is the hull, which makes the overall system nearly neutrally buoyant. The hull also serves as a direction vane. The final component is a speed, temperature, and depth recorder made by Aanderaa inserted in the bottom of the hull. The complete instrument is ballasted to be slightly heavier than sea water so that it sinks down the hydrowire. If the wire is kept relatively vertical, the descent rate is about 10–15 cm s^{-1}. This corresponds to a 3-5-m vertical resolution for the resulting profile data. This device has been used successfully in such regions of strong currents as the Gulf Stream, the North Equatorial Current, and the Somali Current.

The Cyclesonde is a good example of an instrument designed for continuous unattended use (van Leer et al., 1974) in the upper layers. It is a logical continuation of the development of profiling current meters described by Düing and Johnson (1972) above. The Cyclesonde consists of a buoyancy-driven platform with a recording package containing sensors for pressure, temperature, current speed, and current direction. It makes repeated automatic round trips up and down a taut-wire, subsurface mooring, while scanning these four parameters. The instrument can work for several weeks, depending on the water depth profiled and the frequency of profiling.

The cyclic vertical motion of the Cyclesonde is controlled by changing the mean density of the instrument package by a few percentage points with an inflatable bladder. The present instrument can be used to a depth of 500 m (figure 14.28). It has been used in experiments in coastal waters and in the deep water in the GATE experiment to study the surface layers.

A second example of a profiling current meter for the upper layers is the type being developed at the Draper Laboratory. This instrument (Dahlen et al., 1977) utilizes a piston-driven changing volume to sustain cyclic vertical motion for long periods, an electromagnetic current sensor to achieve accurate results even in a wave zone, and a microprocessor-centered, programmable electronic system for control of operational functions.

14.3.5 Instruments in Development

We turn next to some examples of instruments that have been designed to address specific interests in physical oceanography, but that have not yet achieved the widespread use of many of the instruments discussed above. I shall briefly outline the principles and potential in four areas: bottom instruments, surface instruments, remote measurements, and acoustic-averaging techniques.

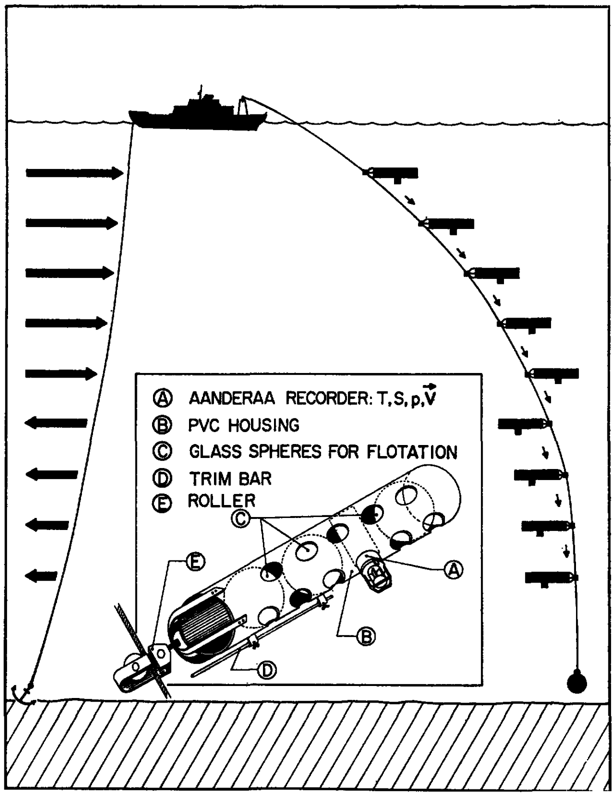


Figure 14.27 Profiling current meter designed to operate from a fixed line. (Düing and Johnson, 1972.)

Probably the best example of a bottom-dwelling instrument is the pressure gauge, which for accurate measurements must rest on a stable bottom. Pressure gauges can be used to monitor mooring motion, as in the TP recorders, but the noise generated by the mooring (decibars) is usually much larger than the dynamic pressure signals (millibars) of interest. The bottom pressure gauges are a link between the previous section and this one, because in one respect they have been very successful, and in another respect are still developmental.

For tides and higher-frequency phenomena, bottom pressure gauges have had an important impact on the field. Hendershott, in chapter 10, reviews some of the aspects of tidal instrumentation, so we need discuss the subject only briefly. Cartwright (1977) gives a recent review of the general subject (see also Baker, 1969; Matthäus, 1968; Rauschelbach, 1932). Gauges connected by cable to the shore have been used for a long time to measure tides and waves (e.g., Nowroozi, Sutton, and Ault, 1966); the first deep-sea tide measurements from a self-contained arrangement were made by Eyriès (1968). In 1967 Filloux made measurements of the tides off California with a bourdon-tube-type gauge (Filloux, 1970), and Munk, Snodgrass, and Wimbush (1970) report on a series of measurements of tides off California through the transition zone between coastal and deep-sea waters using a newly developed deep-sea capsule that measures pressure, temperature, and current. The capsule and its sensors are discussed by F. E. Snodgrass (1968) and Caldwell, Snodgrass, and Wimbush (1969). The instruments have worked well for such measurements; Irish, Munk, and Snodgrass, (1971) showed the existence of an open-ocean tidal amphidrome in the Pacific, and Irish and Snodgrass (1972) presented the first measurements of the open-ocean tides in the Southern Ocean south of Australia. A review of techniques for such measurements is presented by Wimbush (1972) and an intercomparison experiment is discussed by SCOR Working Group 27 on Tides of the Open Sea (UNESCO, 1975). It is safe to say that the deep-sea tides can be monitored now at any location in the ocean.

If one looks at deep-sea pressure from the point of view of inferring geostrophic currents, then the problems are more difficult. As in the case of meteorology, pressure gradients along the bottom should yield geostrophic currents above the bottom boundary layer. However, the strongest signals in the ocean are near the surface; bottom pressure measurements in the ocean correspond more closely to stratospheric pressure measurements in the atmosphere. There are two other major problems in taking over the atmospheric analogy to the ocean. The first is that the ocean bottom cannot be surveyed well enough to determine the depth of the instruments as accurately as required. Thus measuring absolute pressure gradients is not possible; one can look only at time variability. Second, the signals are small compared to the instrumental noise in the frequency range appropriate to geostrophic currents (periods longer than a few days). A comparison with the atmosphere is instructive: typical signals there for high- and low-pressure systems range from 10 to 100 mb out of a total of 1000 mb, a ratio of 1% to 10% over a few days. In the ocean, the signals are of the order of 1 to 50 mb out of a total of 4×10^5 mb, and occur over time periods of days to months. The instrumental requirements are consequently much more severe, and most of the existing deep-sea pressure instruments have shown long-term drifts too large to allow accurate measurements of these signals.

The absolute gauges (e.g., Filloux, 1970; F. E. Snodgrass, 1968) balance the total bottom pressure against a mechanical property, e.g., diaphragm or heavy bourdon tube; the drift of that element generally shows up in the measured pressure signal. The differential gauges (e.g., Eyriès, 1968; Baker, Wearn, and Hill, 1973) balance the total bottom pressure against a fixed volume of high-pressure gas. Drifts in the gas pressure affect the long-term signals, and the temperature sensitivity is high at high total pressure. Work is continuing on both these fronts. A promising device that has been used successfully for long-term measurements at depths up to 500 m is a combination of the Paroscientific quartz sensor with one of the new data loggers (Wimbush, 1977; Hayes, 1979b; Baker, 1979). The sensor is a quartz-crystal oscillating beam whose resonant frequency varies with applied loads (figure 14.29). Yearlong time series from depths of 500 m in the Drake Passage with drifts less than a few centimeters per year have been obtained with this instrument (Wearn and Baker, 1980). A deep-sea version is currently under test.

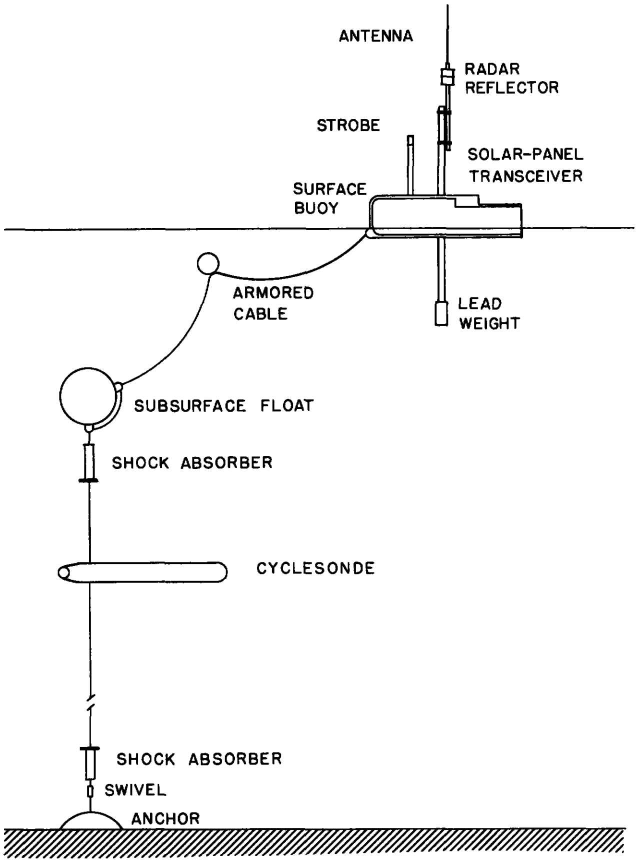
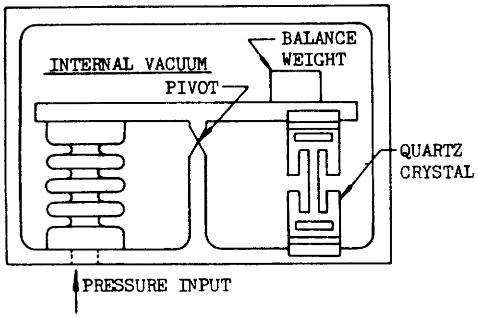
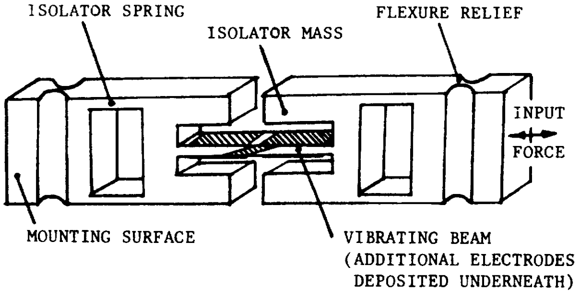


Figure 14.28 The Cyclesonde, an automatic repeating profiling current meter with provision for measurements of pressure and temperature. (Courtesy of J. van Leer.)

Other bottom-mounted measurements include the electromagnetic devices for monitoring current. Measurements of horizontal and vertical electrical field can yield estimates of averaged velocity (horizontal or vertical, depending on electrode configuration) from Faraday's law and the electrical and magnetic properties of the earth below. The measurements appear promising, but the ambiguities present in the removal of the electrical-conductivity effects of the bottom sediments



Absolute-pressure transducer



Quartz crystal resonator

Figure 14.29 Schematic of absolute-pressure transducer and quartz-crystal resonator used in the Digiquartz pressure transducer of Paroscientific, Inc. (Paros, 1976.)

and in the effects due to magnetic storms remain a problem (see Filloux, 1973b, 1974).

At the surface of the ocean, measurements are also difficult, for other reasons, primarily because one is in the wave zone. For example, wind waves and swell have periods of a few seconds. A 6-s-period wave will subject a surface platform to almost one million flexure cycles every month. It is not surprising that reliability and longevity are prime problems. The areas of interest for surface measurements are large, including surface waves, currents, salinity and temperature, humidity and carbon dioxide, wind, pressure, air temperature, radiation, and precipitation. We do not have space here to cover all the instrumental problems; the NATO Science Committee (1978) volume covers these items in some depth. It is of interest to single out the subject of satellite-tracked drifting buoys for special attention, however, because of the potential of this technique for large-scale measurements.

It is clear now that maintaining enough moorings to monitor large-scale ocean circulation is too expensive, for both equipment and logistics. One must look to satellite-based systems, together with a modest number of moorings and hydrographic observations. The surface drifters will certainly play a major role in any new global observation system, providing surface measurements for calibration of satellite data, giving a direct measurement of surface currents for use with hydrographic data, and providing an interpolation between moorings.

There are problems with drifters, however, which were most recently addressed at a recent Woods Hole Drifting Buoy Conference (Vachon, 1978). In addition to the problems of reliability, which are slowly being solved, there is the difficulty of interpretation. This has two aspects, the first of which is slippage. The effect of wind on the buoys can be reduced by keeping the amount of buoy volume above the water as small as possible, but true windage effects are not yet known (see Kirwan, McNally, Pazan, and Wert, 1979). Typical results show that the slippage can be as high as 1% of the wind speed (Nath, 1977) when wave effects are included. Measurements are needed to show how well buoys with and without drogues drift relative to the water under different conditions. The second problem is the quantitative interpretation of Lagrangian measurements. In strong currents the interpretation is easier than in the mid-ocean, where mean flow may be weaker than the time-dependent flow. For statistical interpretations, large samples are required. Molinari and Kirwan (1975) show how to construct differential kinematic properties from Lagrangian observations, and show the need for larger numbers of buoys to make significant statements. In spite of these difficulties, the potential of the techniques is large, the entire field of drifter technology and interpretation is active, and one may expect major advances in the next few years. Examples of different kinds of drifters are shown in figures 14.30 and 14.31.

Remote sensing of the ocean surface by aircraft and by satellite is gaining increasing importance. This is also an active field; government agencies especially are interested in a number of its practical aspects. I shall discuss here two areas that illustrate the activity in the field; the reader is referred to Apel (1976) for a more comprehensive review [see also McClain (1977) and Twitchell (1979)]. The article by Born, Dunne, and Lame (1979), and those following in the same issue of *Science*, give an overview of preliminary Seasat results.

R. Legeckis of NOAA/NESS has shown (1977a, 1977b, 1979) how high-resolution thermal-infrared data from the polar-orbiting satellites can be used to track wave features in currents. Variations in the polar front in the Drake Passage (1977a), long equatorial waves in the Pacific Ocean (1977b), and the time variations in the flow of the Gulf Stream between Florida and Cape Hatteras (1979) are evident in the data. Each of these observations has some independent evidence, but perhaps the best corroborated are the Pacific measurements. In that case, the satellite pictures were confirmed by both drifting buoys and sea-level

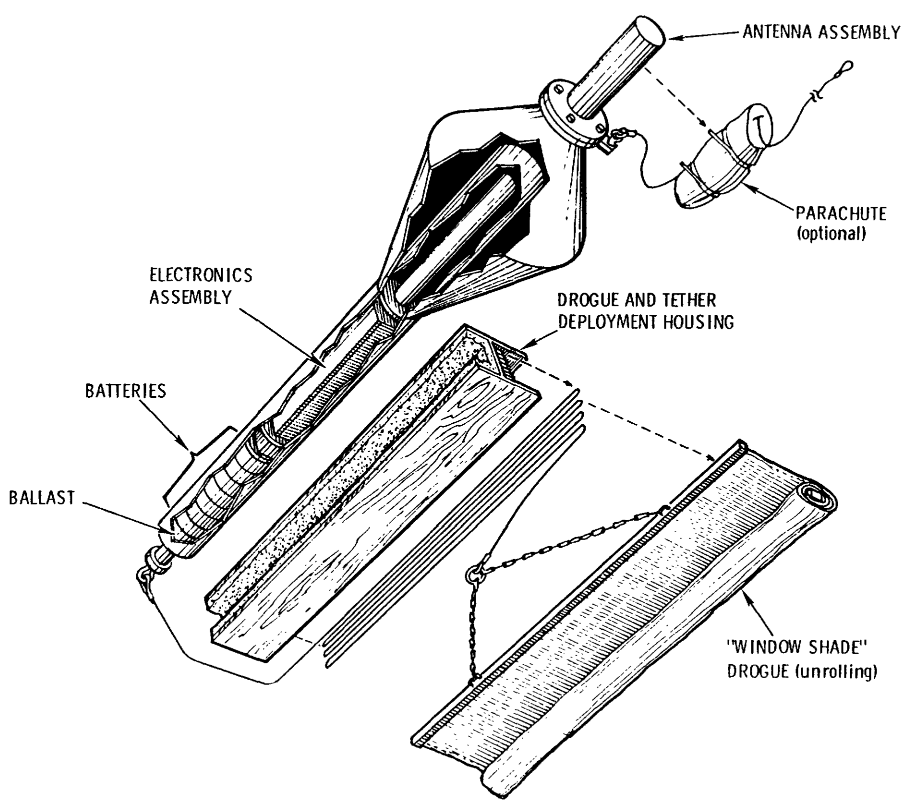


Figure 14.30 Drifting buoy system developed by the Polar Research Laboratory, Inc. The buoy hull is made of aluminum; lifetime is approximately 6 months. The electronics package transmits a signal to the NIMBUS 6 satellite random access measurement system (RAMS). Positions are calculated to an accuracy of ±5 km. (Courtesy of J. O. Anderson.)

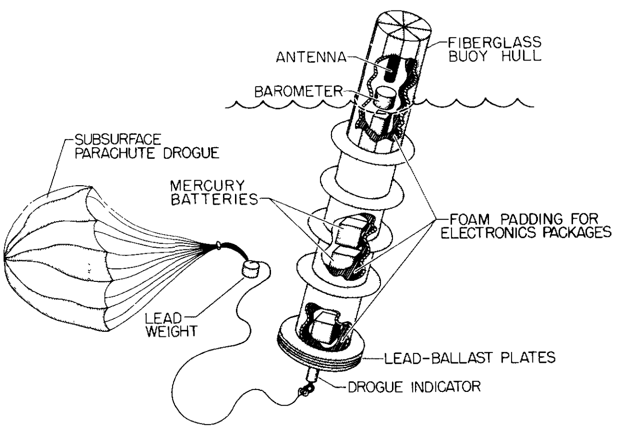


Figure 14.31 Drifting buoy system developed for NORPAX at the Scripps Institution of Oceanography. This system also uses the RAMS information for tracking; see Kirwan, McNally, Pazan, and Wert, 1979. (Courtesy of G. McNally.)

measurements (Wyrtki, 1978). Wyrtki used the drifters to establish a mean flow from which he could calculate a Doppler shift for the satellite and sea-level data. A wave period of about 34 days was inferred. Another good example of evidence from several sources was presented by Bernstein, Breaker, and Whritner (1977) in a study of the California current.

Over most of the ocean, the present satellite-based sea-surface temperature measurements show large errors (Barnett, Patzert, Webb, and Bean, 1979) because of the influence of water vapor and clouds in the atmosphere above the ocean. It is expected that the use of multichannel radiometers will improve these data by allowing a more accurate determination of the water in the atmosphere (Lipes et al., 1979).

A second satellite technique is the measurement of the surface topography. Because the distance from the satellite to the sea surface can be measured with great accuracy by radar altimeters (to better than 10 cm), one needs only to combine such a measurement with an accurate knowledge of the geoid in order to get the surface pressure field. Accuracy in three elements is required: the satellite orbit, the altimeter measurement, and the geoid itself. Aspects of these problems are discussed in the National Academy report on "Requirements for a Dedicated Gravitational Satellite"

(Committee on Geodesy, 1979). The uncertainties in the three areas are rapidly decreasing, and thus this technique may be one of the most promising for a synoptic view of surface circulation (Tapley et al., 1979; Wunsch and Gaposchkin, 1980; see figure 11.16).

Another important idea is the technique of remote sensing of subsurface temperature of Leonard, Caputo, Johnson, and Hoge (1977), who use a laser Raman backscattering technique. The Raman scattering is a function of the amounts of monomer and dimer forms of liquid water; the relative concentration of these is a function of temperature. A pulsed laser is used so that the round-trip time for a pulse determines the depth that it reached. Data to 10 m below the surface have been collected with an accuracy of ±2°C. It is expected that the system will work to at least a depth of 60 m with an accuracy of ±1°C. With such accuracy and depth, the system may be very useful for airborne surveys of the upper layer of the ocean.

Finally we consider examples of acoustic techniques. The inverted echo sounder, designed to study the temperature structure of the water column from an instrument on the sea floor, combines an acoustic transmitter and receiver to monitor the time it takes for a pulse of sound to travel from the sea floor to the surface back to the sea floor. Fluctuations in this time interval are due primarily to changes in the average temperature of the water over the gauge; the movement of the thermocline as a function of time can be inferred. The instrument works remarkably well; variations in travel time can be measured with an accuracy equivalent to a displacement of the 10°C isotherm of ±4 m (Watts and Rossby, 1977). For the MODE-1 experiment, a comparison with the CTD stations showed that the inverted echo sounder was indeed capable of producing records representative of the motions of the main thermocline. It appears that the instrument could replace the shipborne use of CTDs for special types of long-term monitoring (Gould, 1976).

A Doppler sonar system for measurement of upper-ocean current velocity has been developed by Pinkel (1979). The sonar transmits a narrow beam that scatters off drifting plankton and other organisms in the upper ocean. From the Doppler shift of the back-scattered sound, the component of water velocity parallel to the beam can be determined to a range of 1400 m from the transmitter with a precision of 1 cm s^{-1}. The instrument has been used successfuly from FLIP.

An acoustic technique of great promise has been proposed by Munk and Wunsch (1979). Called "ocean acoustic tomography," after the medical procedure of producing a two-dimensional display of interior structure from exterior X rays, the technique monitors acoustic travel time with a number of moorings. Because the number of pieces of information is the product of the number of sources, receivers, and resolvable multipath arrivals, the economics of the system is enhanced over the usual spot measurements. The necessary precision does not appear to be a difficulty, and the main limitation at high acoustic frequencies is imposed by the effects of variable ocean fine structure (limiting horizontal scales to 1000 km). Using the geophysical inverse techniques discussed at the beginning of this chapter, Munk and Wunsch are able to show that it should be possible to invert the system for interior changes in sound speed and, by inference, changes in geostrophic velocity associated with density variations. They conclude that such a system is achievable now and that it has potential for cost-effective large-scale monitoring of the ocean. Initial tests of the technique have begun.

It is conceivable that a global monitoring system for the ocean circulation could consist of a combination of several of the elements discussed above: (1) satellite observations of the surface temperature and surface pressure fields; (2) direct measurements of the surface current and temperature by drifters and a modest number of moorings; and (3) deep-ocean monitoring by a combination of acoustic tomography, shipborne hydrography, and moorings. All of the elements are present now or are being tested; we could have such a system in the next ten years (SCOR, 1977).

14.3.6 New Techniques Required

Some of the major problems have already been discussed above and need not be reviewed here. In summary, we need techniques for measurement of currents in regions of strong currents: drifters yield surface currents, but moorings are not strong enough to withstand the forces. We need techniques for measuring ocean currents and mixing in the surface layer under storms; meteorologists have these techniques, being able to fly instrumented aircraft through stormy weather. We still do not have an unattended platform from which we can make observations during severe storms, yet the transfer of heat, mass, and momentum is probably largest then. Better current meters for the wave zone are needed; perhaps the acoustic or electromagnetic techniques now being developed will solve this problem.

We need techniques for long-term monitoring of the profiles of currents; these are of interest both for ocean dynamics and for the engineering of deep-sea drilling rigs that will sit on station for several months with the drill pipe subject to the variable currents. Synoptic measurement of deep currents over large areas is not yet within reach. As has been suggested, a deep neutrally buoyant float that periodically pops up or reports in some acoustic mode to the surface and to a satellite would yield a kind of global coverage, as would acoustic tomography.

In the end, however, we can expect that a mix of instruments and techniques will yield the most knowledge about the ocean, and that there will be no simple solution. Stommel's comments (1965)—referring to current fluctuations—are apt:

> It takes years of expensive observations to produce even a very crude description of (fluctuations in ocean currents). There is . . . a persistent though erroneous notion that all worthwhile problems will eventually be solved by some simple, ingenious idea or clever gadget. A well-planned long-term survey designed to reveal fluctuations in ocean currents would be expensive and time-consuming. It might even fail, because of inadequacies of the tools we have at hand. But until this burdensome and not immediately rewarding task is undertaken, our information about the fluctuations of ocean currents will always be fragmentary.

14.4 Ocean Experiment Design

The controlled experiment for test of hypotheses is the cutting tool of the physical scientist. It is easy to document advances in laboratory physics through the route of discovery, models, controlled laboratory experiments, models, revised experiments, and so on. The earth scientist does not have this capability, at least as far as controlling the system. Lorenz (1967, p. 25) pointed out that "the meteorologist who wishes to observe the circulation of the atmosphere cannot follow the customary procedures of the laboratory scientist. He cannot design his own experiment in such a manner as to isolate the effects of specific influences, and thereby perhaps disprove certain hypotheses and lend support to others. He can only accept the circulation as it exists. Moreover, since the circulation is global in extent, he cannot even make his measurements singlehandedly, but must rely for the most part upon those which have been made by other persons, in most instances for different purposes." The general difficulty has been pinpointed by V. Suomi (1976): "It is possible for the secrets of nature to be hidden in a flood of data as well as in nature. Clearly, we need information more than we need data." These points are equally valid for oceanography. There is a basic difference, however, in the availability of data from the ocean, because oceanographers do not have a global synoptic weather network, accumulating data routinely, upon which they can draw (see US POLYMODE Organizing Committee, 1976, p. i). Selected representative data and properly designed ocean experiments are required.

14.4.1 Varieties of Oceanographic Experience

Thus we are led to the question of the design of oceanographic experiments for testing hypotheses. Stommel (1963) addressed the problem in the context of the historical evolution of the design of oceanographic expeditions in his paper on "Varieties of Oceanographic Experience." He noted that in the early days uniformly spaced, broad surveys were required: little was known, and large areas had to be covered. Planning followed the *Challenger* model: multidisciplinary, multiregion, multiyear studies combined in a single expedition. These geographical surveys yielded atlases of the distribution of properties in the sea from which dynamic processes and climatological properties could be inferred. Stommel's point in 1963 was that enough was known at that time about the inherent high-frequency, small-scale energy in the system (diurnal tides contaminating seasonal sea level, etc.) that we could not improve the statistical significance of the data much more with this kind of broad geographical measurement design.

In order to improve significantly the results from the geographical studies, specific experiments designed to obtain statistically significant results are required. Observational programs in the ocean, Stommel argued, must be designed on the basis of what is known about the dynamics and spectral distribution in time and space of the phenomenon of interest. Thus studies of western boundary currents, mid-ocean eddies, or the formation of bottom water will have different experimental designs. He noted that "one may well say that where so much is unknown, such detailed planning is impracticable—unexpected complications may arise. I reply that where so much is unknown we dare not proceed blindly—the risk of obtaining insignificant results is too great."

Three examples from the paper are particularly instructive. The first is from a study of the equatorial undercurrent in the Indian Ocean in 1962–1963. The design of the study was based on knowledge of the Pacific Equatorial Undercurrent, which appeared from measurements of Knauss (1960) to be relatively steady with a long east–west scale, almost the entire Pacific basin, and a short north–south scale, extending about 2° across the equator. The Indian Ocean undercurrent was expected to have similar space scales with a time variation that depended on the monsoons. Since the monsoons reverse every 6 months, the current was expected to have its major time variability on that scale. The schematic diagram of velocity spectra presented in figure 14.32 shows three important points: the two peaks associated with the Pacific undercurrent; the two annual peaks that the expedition expected to find and that it planned to map; and the probable actual peak for velocity that was revealed but could not be mapped by the procedures employed in the expedition for mapping the two annual peaks. Thus the original design of the expedition could not show the annual component because of contamination, and could not map the shorter-period irregularities. Later studies in the Indian Ocean, based on these studies, have begun to describe the complex features of the monsoon-driven circulation (see, e.g., Luyten, 1980).

A second example involves the Gulf Stream and its variability. Stommel noted that during the 1930s, C.

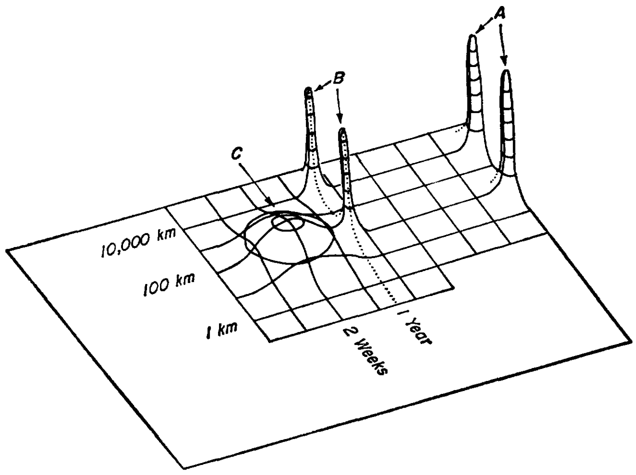


Figure 14.32 Schematic diagram of velocity spectra as function of time and space for equatorial undercurrents. A, Pacific undercurrent; B, peaks expected by *Argo* expedition; C, probable actual peak for velocity that was revealed by *Argo* expedition. (Stommel, 1963.)

Iselin of WHOI had encountered certain problems in trying to establish the Gulf Stream transport. By making hydrographic sections across the stream at 3-month intervals, Iselin had hoped to determine the annual variation of transport. What he actually obtained was a random sampling of irregular meanders. The Fuglister measurements of the 1960s show that the annual part of the spectral distribution of velocity is so close to a high-energy meander peak in the spectral diagram that to resolve it would require observations several orders of magnitude greater than Iselin had planned to make.

The use of neutrally buoyant floats, discussed earlier, leads to the third example. In the mid-1950s J. Swallow and J. Crease from the National Institute of Oceanography in England planned to make extended observations of deep-water currents near Bermuda as representative of the open Atlantic Ocean. They expected to see weak eddies, but hoped that by averaging over many of them, perhaps as long as a year, the long-period mean would be revealed. Stommel noted that "the amplitudes of motion were, surprisingly, ten times greater than expected; the original strategy of operation had to be abandoned, and it was not possible to develop as sharp a picture of the spectral distribution of these motions as had been hoped with the minimal ship facilities that were mustered." The results of these measurements were later described by Swallow (1971) at a meeting to discuss the need for an open-ocean experiment to explore eddies. Stommel went on to ask, "Can we design an observational program that can be reasonably expected to yield statistically significant information on this question?" He noted the need for new instrumentation, heavier moorings, longer-range floats, etc., and the need for cooperation among the oceanographic institutions to carry out a large coordinated study.

In fact, instrument development did proceed to a point where a mid-ocean experiment was possible, and several oceanographic institutions did cooperate in carrying out the Mid-Ocean Dynamics Experiment (MODE-1; MODE Group, 1978) and a cooperative effort called POLYMODE, which developed from MODE-1 and the Soviet project POLYGON (IDOE, 1976; cf. chapter 11).

Thinking in terms of ocean experiments instead of ocean surveys for the study of dynamic phenomena has become so pervasive in the last few years that sometimes one forgets the change in thinking that has taken place in the field. Yet this change is fundamental because it means that we are beginning to treat oceanography as an experimental, as opposed to a geographical, science. The points noted by Stommel have been confirmed again and again with new measurements that look at smaller scales and in different regions of the ocean. One need only to point to the emergence of eddies as a worldwide phenomenon (Swallow, 1976; Wyrtki, Magaard, and Hager, 1976; and see chapter 11) and the recent discovery of a complex equatorial jet structure (e.g., Luyten and Swallow, 1976; see chapter 6).

14.4.2 MODE-1 and ISOS

How have these ideas been translated into real experiments? It is instructive to look at the design of two recent studies to see how, for example, the sampling problems are handled when the aims of the studies are different. We consider the MODE-1 experiment, which is an attempt to look at eddies in the Sargasso Sea, and the International Southern Ocean Studies (ISOS), which is an attempt to look at the variability of the Antarctic Circumpolar Current in the Drake Passage. To a large extent, both of these studies depended on the existence of new, reliable technology.

Three unpublished documents present in detail the principles of the design of MODE-1. The first, "The Design of MODE-1" (MODE-1, 1972a), by a committee of experimentalists, focuses on observations and intercomparisons. The second, "Dynamics and the Design of MODE-1" (MODE-1, 1972b), was the result of a theoretical workshop to summarize dynamical modeling and observational needs. The two documents are in basic agreement over the design of the experiment. The third, "Dynamics and the Analysis of MODE-1" (MODE-1, 1975), written after the experiment, summarizes the statistical techniques used and initiates an analysis of the experiment in dynamical terms.

Underlying the design of the MODE-1 experiment was the need to test the hypothesis that eddies play an important role in the general circulation. The design of an eddy experiment, given the existing theoretical knowledge and the resources and equipment available, involved several points that are highlighted in the documents.

The first point was that MODE-1, because it was a 4-month study to focus on deep, mesoscale low-frequency variability, was a nonstatistical, kinematic experiment. The time periods expected, and confirmed by experiment, were too long to sample over many periods. The MODE-1 organizers recognized very early this time limitation. For this reason, a number of moorings and floats were maintained in the same area for up to 2 years after the main experiment.

The second point was that an intercomparison of instruments was required. This was one of the major aims of MODE-1, and one of the major achievements (MODE-1, 1974; Gould, 1976; MODE Group, 1978). Examples of the intercomparisons were discussed earlier.

The third point concerned sampling statistics. The report on "Dynamics and the Analysis of MODE-1" gives an excellent summary of the statistical methods used in the analysis and design of the experiment by R. Davis. Davis pointed out that statistical methods have been used in the experiment for two essentially different purposes. One of these, largely an adaptation of the method of objective analysis (Gandin, 1965), is the improvement of signal-to-noise ratios through use of analysis techniques that account for both instrumental noise and sampling noise resulting from unresolved small-scale variability (the problem discussed by Stommel in his 1963 paper). Some results of the application of objective analysis have been discussed by Bretherton, Davis and Fandry (1976). The technique allows an estimate of interpolation error and statistical uncertainty to be made for each data set based on the statistics of the fields involved.

The second purpose of the statistical methods is compression of numerous observations into concise statements that can be useful in describing the data even if statistically unreliable. Such statements are particularly useful in comparing theory and experiment.

Using the objective technique and given the correlations of the velocity field and the estimated errors of instruments and noise, the MODE scientists were able to compute the rms errors in area-averaged velocity measurements over an array. The working hypothesis for the MODE-1 array design was that the transverse velocity correlation function had a zero crossing at 100 km. The scales observed from the spatially averaged temperature field over the actual array ranged from 140 km at 500 m, to 70 km at 1500 m, to 55 km at 4000 m (figure 14.33) (Richman, 1976), thus validating the original array design.

The fourth point concerned array size. Without knowledge of all of the scales of motion, it was difficult to choose an optimal scale for the array. Thus the concepts of "pattern recognition" and "pattern definition" were used. The first of these was chosen on the

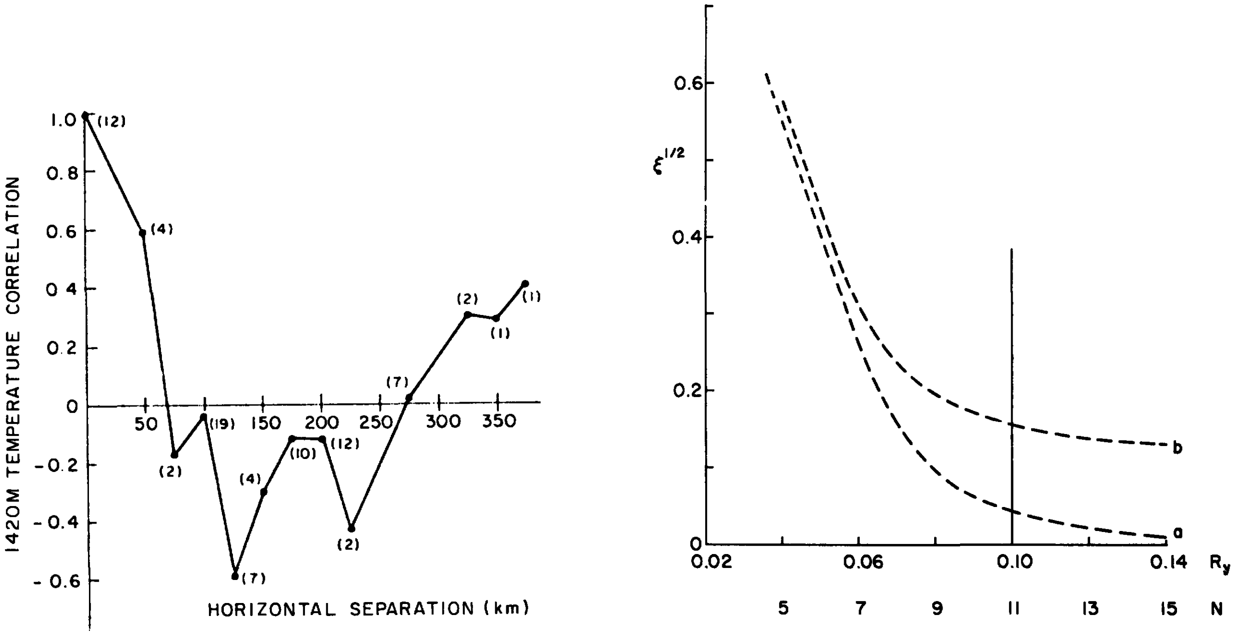


Figure 14.33 (Left) Correlation function of the spatially averaged temperature field over the MODE-1 array at 1420-m depth. Note zero crossing at about 70 m. (Richman, 1976.) (Right) Error in transport ($\xi^{1/2}$) as a function of cross-passage correlation function R_y in Drake Passage (scaled by width of passage, 620 km). Since the cross-passage correlation function has a zero near 60 km in the Drake Passage, the actual R_y is near 0.1 (solid vertical line). Error is also plotted as a function of number of independent horizontal measurements or moorings N: case a, zero random noise; case b, random noise-signal ratio of 0.1 Thus we expect that 11 moorings across the passage will yield an error of about 20% in the transport. (Fandry and Pillsbury, 1979.)

basis that it is more important to be able to define the spatial extent of the motion observed than to describe in detail only a fraction of the pattern. The planning groups noted that both of the earlier experiments looking for eddy scales had been too small in horizontal extent to allow confident determination of the eddy diameters. The final array was designed to satisfy the needs of the intercomparison, with an inner array in a central region of radius about 100 km. The outer array was about 200 km in radius, a pattern recognition area. Figure 14.34 shows the moored-current-meter and density-survey pattern; only intermediate-depth moorings were used.

The design proved to be adequate for the description of eddy dynamics over the relatively short period of the experiment (MODE Group, 1978). Suffice it to say that agreement between different types of instruments measuring the same thing was generally good, e.g., between the different velocity profilers, between the temperature-pressure recorders and the CTD sections, and between the floats and current meters. The paper points out that the field of mesoscale variability is a good deal more complicated than might have been expected.

The concepts involved in using correlation functions of temperature and velocity to design the array were carried over directly into the ISOS experimental design. Here the interest is not in eddies per se, but in measuring the variability of the Antarctic Circumpolar Current (ACC) transport and its variability. But the eddies exist, and must be accounted for in array design. One of the special problems in the ACC is that the coherence lengths are small, about 60 km. Limited funds required an alternating series of arrays in the Passage. The first study, in 1975, used an incoherent array to establish energy levels across the Passage. In alternate years linear and cluster arrays were used to estimate the transport and to collect data for correlation scales (Fandry and Pillsbury, 1979).

Calculations similar to the MODE work were carried out based on the transverse correlation functions in order to design the final ISOS array, a combination of linear and cluster experiments (ISOS, 1978). A significant difference was found between the cross-stream and downstream directions, the downstream scales being longer than the cross-stream scales. The final multipurpose array is shown in figure 14.35. The array was designed to monitor the transport of the current with minimum error (figure 14.33), to allow a comparison between current meters and bottom pressure gauges, and to define the features that exist and are advected through the region by the current.

These examples show us that the principles of experiment design are an integral part of observational oceanography. Clearly, the modern experimental oceanographer needs a working knowledge of statistical experiment design as well as a basic understanding of the ocean and ocean instruments. The appropriate point was made by Leonardo da Vinci in his *Hydrodynamica* (see Le Méhauté, 1976): "Remember, when discoursing about water, to induce first experience, then reason."

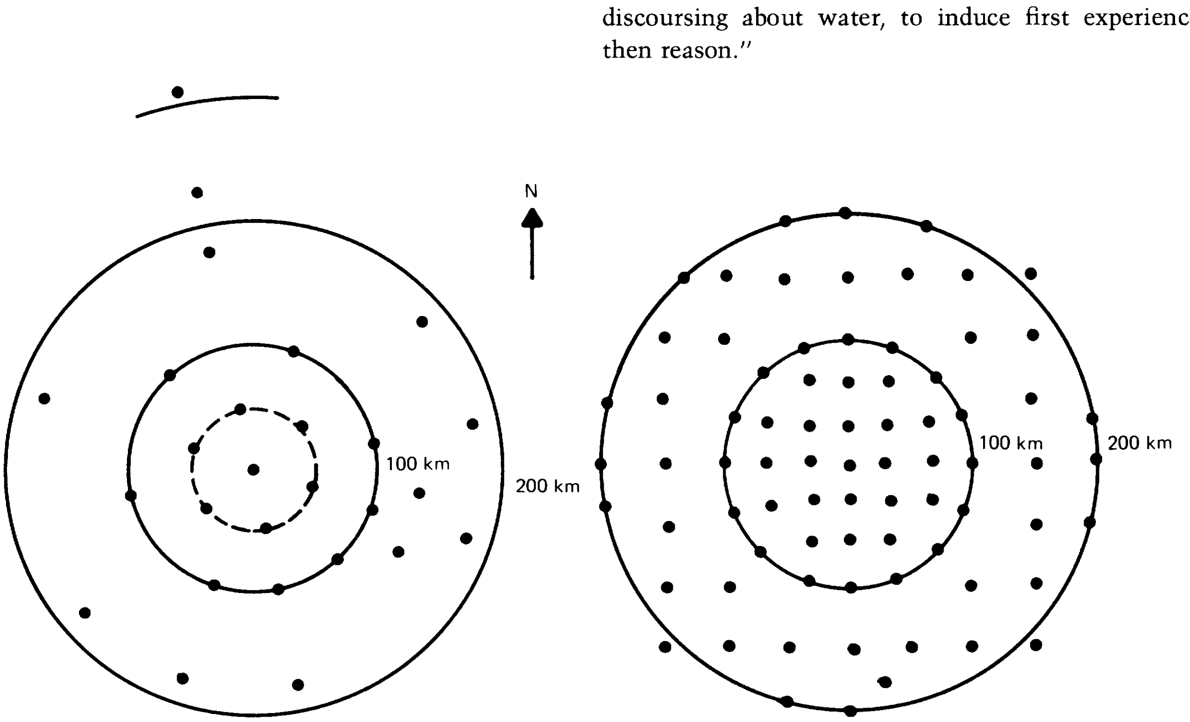


Figure 14.34 Moored current meter (left) and density survey (right) arrays for MODE-1. The inner 100-km circle represents an "accurate mapping" area, the outer circle a "pattern recognition" area. (Gould, 1976.)

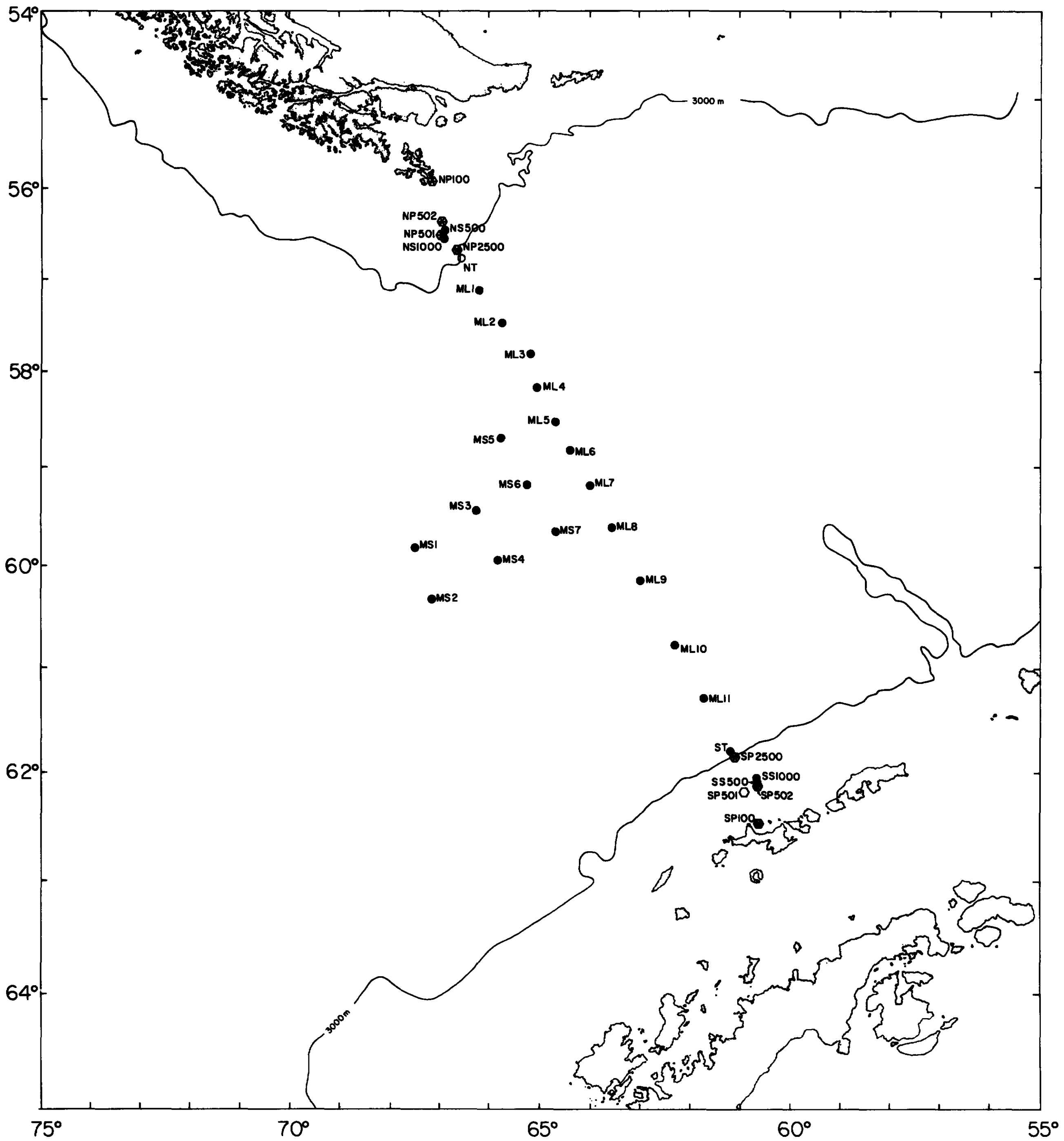


Figure 14.35 Plan view of the ISOS Drake 79 array in the Drake Passage. The moorings marked ML are the main line for transport measurement; the ones marked MS are for mapping and statistics of polar frontal features; NP and SP are the north and south pressure-gauge moorings; NT and ST are the north and south density-measuring moorings for transport monitoring; NS and SS are the north and south slope moorings. Numbers of 100 and greater are the water depth in meters. (Courtesy of W. D. Nowlin Jr. and R. D. Pillsbury.)