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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

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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.

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.)

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.

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 MID-PAC 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 com-

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ponents 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/cm³	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 @ 1–2 mo @	21°C 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 @ 2 mo @	21°C 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 @ 4 mo @	21°C 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 @ 1 yr @	21°C 55°C	10	10.4×10^4	19.5×10^2	12.2×10^5	1.4×10^4
Lithium	3.6	10 yr @ 1 yr @	21°C 55°C	11	14×10^4	27.4×10^2	14×10^5	1.4×10^4
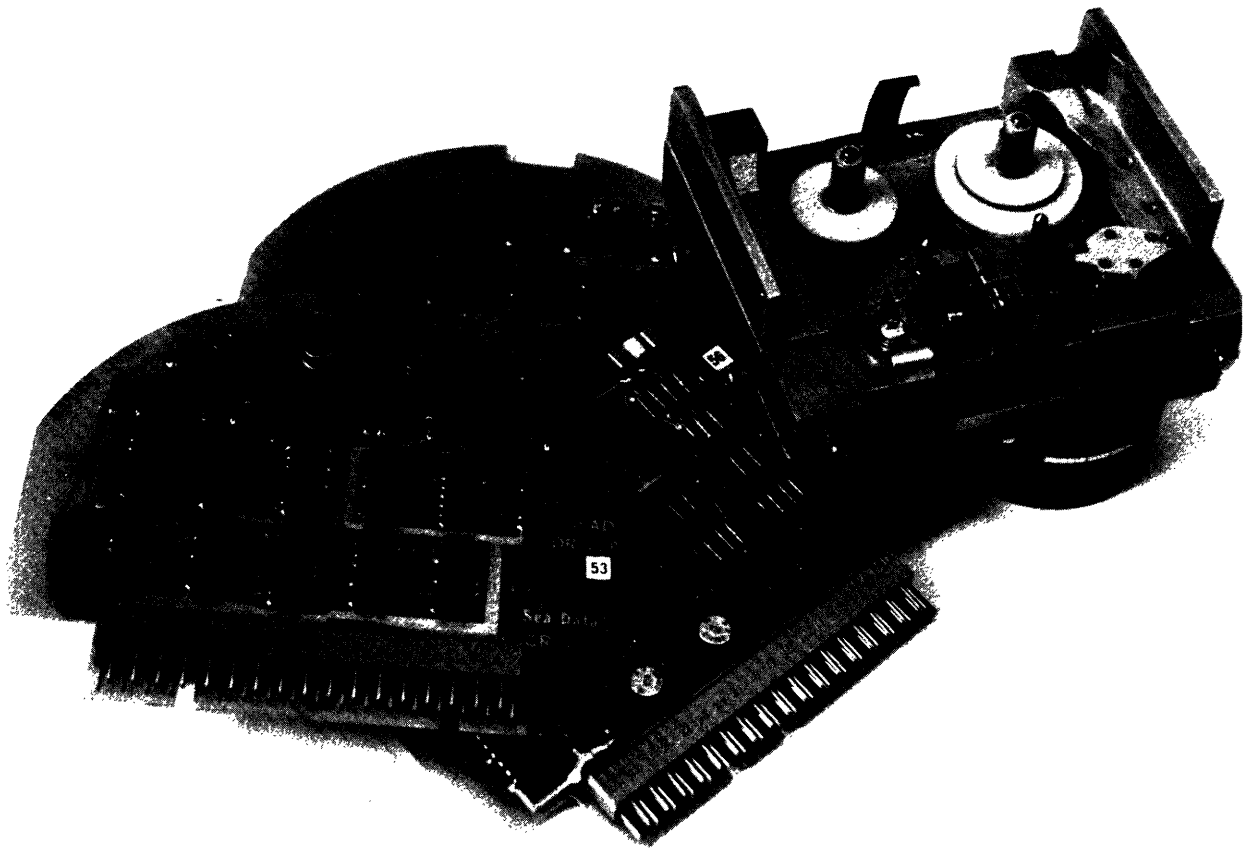
Figure 14.2 Sea Data tape-recorder body (right) and COSMOS circuit cards (left). The cards are rounded in order to fit into a 6"-diameter pressure case. (Courtesy of W. Hill.)

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,

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