

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"

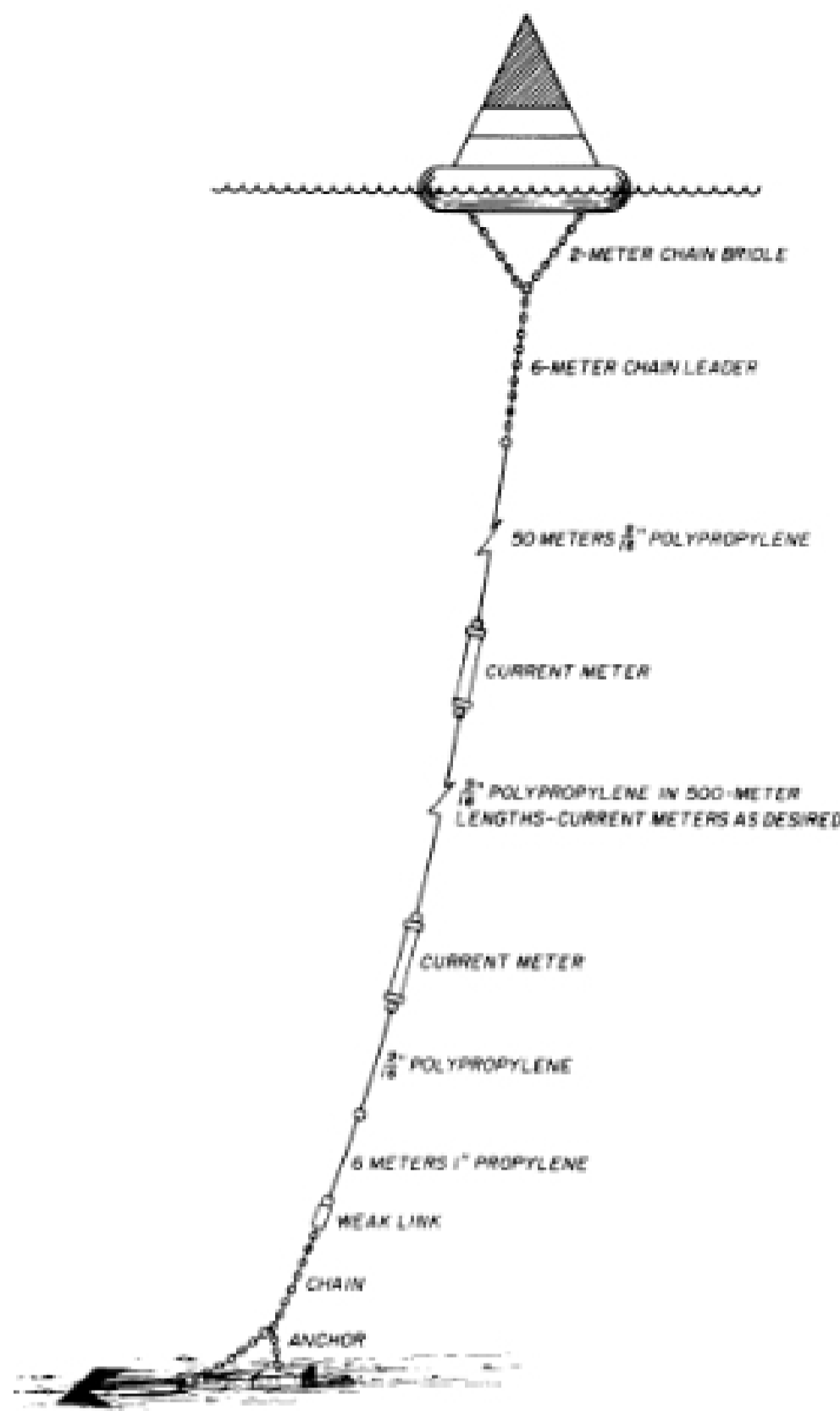


Figure 14.3 Current-meter mooring configuration used by Richardson et al. (1963).

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 re-