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Review

Oceanic Velocity Microstructure Measurements in the 20th Century

Rolf G. Lueck[1]*, Fabian Wolk[2] and Hidekatsu Yamazaki[3]

[1]*School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada*
[2]*System Division, Alec Electronics Co., Ltd., Kobe 651-2242, Japan*
[3]*Department of Ocean Sciences, Tokyo University of Fisheries, Tokyo 108-8477, Japan*

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The science of ocean turbulence was started more than 50 years ago by a small research group using a surplus mine-sweeping paravane to measure the velocity and temperature fluctuations in the ocean. The field has grown considerably and measurements are now conducted by researchers in many countries. A wide variety of sophisticated instrument systems are used to profile horizontally and vertically through the marine environment. Here we review the historical development of velocity microstructure profilers over the past four decades and summarize the basic requirements for successful measurements. We highlight critical technological developments and glance briefly at some of the scientific discoveries made with these instruments.

Keywords:
· Turbulence,
· microstructure,
· profilers,
· mixing,
· dissipation.

1. Introduction

The study of turbulence has two main roots. One developed from the work of Russian scholars, such as Kolmogorov, Obukhov, Monin, Yaglom and others, and is highly theoretical and viewed in terms of spatial structures. The other grew out of the laboratory based program at Cambridge University, conducted by Taylor, Batchelor, Townsend, Stewart and others, and tended to view turbulence in Fourier space. The initial oceanic measurements were motivated by concerns about underwater warfare in the 1950s when a large number of submarines were put into service to "fight" the so-called "Cold-War." Initial attempts to detect the wake of submarines were a complete failure (Stewart and Grant, 1999) and subsequent work, of which little is publicly known, was conducted in secret. The initial military failure was, however, a major scientific success because it validated in Fourier space Kolmogorov's widely respected theory about the spatial structure of turbulent velocity fluctuations. Thus started the field of ocean microstructure measurements.

The first measurements of oceanic turbulence were conducted in the 1950s by a small research group at the Pacific Naval Laboratory near Victoria, British Columbia, Canada under the direction of H. Grant. They instrumented a minesweeping paravane with hot-film anemometers, cold-film thermometers, and other sensors, and towed it in coastal tidal channels where currents were strong and the turbulence was intense. In the open ocean, velocity fluctuations are many factors of ten smaller than in tidal channels and this frustrated the initial attempts at horizontal profiling in the open ocean. There were three technical problems with ship-towed vehicles. One, the velocity measurements had spurious contributions from high frequency vibrations of the towed vehicle. Two, the roll and heave of the ship induced large variations of the speeds and depths of the towed vehicles. Three, because of inadequacies of the early sensors, the velocity signals were very heavily contaminated by environmental fluctuations in temperature.

The early measurements were carried out with horizontal profilers, but by the late 1960s, most work was conducted with vertical free-fall profilers. These instruments were considerably simpler than towed bodies and were completely decoupled from the ship. Propelled by gravity, they moved more smoothly through the water. Three newly available technologies motivated the use of vertical profilers: micro-thermistors, the expendable wire link, and shear probes. The electrical circuitry of a thermistor-based thermometer is much simpler than that used with cold-film probes. Similarly, the circuitry associated with shear probes is trivial compared to that used with

* Corresponding author. E-mail: rlueck@uvic.ca

hot-film probes. Data could be transmitted to the surface via an expendable wire link and logged by tape recorders that, in those days, were far too bulky to fit into a profiler.

Horizontal profiling presents a view of the ocean that is inaccessible with vertical profilers and, hence, this mode of profiling was revived in the 1980s. The problem of contamination of the velocity signal by temperature fluctuations was eliminated by using the shear probe, which is completely insensitive to temperature fluctuations in the microstructure range. New towing techniques greatly decoupled ship induced variations in the tension of the towline and discouraged vibrations of the vehicle. Thus, it was possible to measure velocity microstructure with fidelity comparable to that obtained with vertical profilers.

The development of both vertical and horizontal velocity microstructure profilers has always been motivated by science rather than engineering. These instruments were built to address specific scientific questions and—unlike the autonomous underwater vehicle developed during the last decade—they were never "solutions looking for a problem." Oceanographers worked closely with engineers and technologists, always keeping the instrument's purpose clearly in mind. Frequently, those researchers who engaged in oceanic turbulence measurements were scientists with a strong grasp of engineering who enjoyed exploiting the latest technology for scientific purposes. The development of profilers was expensive. Without the generous support of the US Office of Naval Research, which has a policy of funding novel and high-risk research, many of the early development projects would not have been possible.

The technology has matured considerably during the past 40 years of oceanic turbulence profiling. Many profilers have been developed and their use has revealed numerous unexpected features of oceanic processes. Here we review the technological developments of oceanic turbulence measurements and some of the resulting scientific discoveries. A large number of turbulence instruments have been built over the past four decades and a complete review of all these instruments would exceed the scope of this contribution. Therefore, we restrict this review to instruments that measure oceanic velocity turbulence in the microstructure range, a range that will be formally defined in the next section. We thereby omit many fine instruments judiciously developed for scalar turbulence measurements. "Oceanic" means that we also omit instruments used for fresh water research. Ample references give the reader the opportunity to examine the many details that must be excluded from this presentation for the sake of brevity.

In the next section, we review the very basic requirements of profiling velocity fluctuations in the dissipation range of the wavenumber spectrum. The crucial probes or sensors that are the foundation for oceanic turbulence measurements are described in Section 3. Horizontal profilers take a vast variety of shapes and sizes, ranging from small autonomous vehicles that can be carried by hand to a full-size submarine staffed by a crew of 50. Therefore, horizontal profiling will be reviewed on a vehicle basis (Section 4). Vertical profilers have a great commonality of shape and size, and they will be reviewed on a regional or geographical basis (Section 5). New technologies, which are promising but still in their infancy, will be summarized in Section 6.

2. Basic Requirements

Three elements are required to make oceanic measurements: a sensor or probe that detects the physical parameter of interest, excluding (as much as possible) all other parameters; electronic circuitry that amplifies and filters the signal produced by a probe and records this signal for later analysis; and a platform that moves the probe smoothly through the ocean to produce a space series of the parameter, i.e., a profile. In this section, we present the basic requirements for the platform and the probes. The probes themselves are described in the next section. The electronics are mentioned only briefly.

Oceanic turbulence measurements are mainly made to assess the rate of mixing (water mass modification) and the role of turbulent friction in controlling circulation. A wide variety of analytic and numerical models indicate that the average diffusivity of density is $O(10^{-4}\ \mathrm{m^2 s^{-1}})$ while four decades of observations indicate that most of the ocean has a diffusivity that is ten times smaller. With this hindsight we can estimate the required sensitivity of turbulence instruments. In steady, homogeneous and stably stratified turbulence, turbulent kinetic energy (TKE) is produced from the large-scale shear (usually attributed to internal waves). Most of the TKE is dissipated by viscous friction, ε, while a small fraction, $\Gamma \sim (0.1)$, is used to mix the fluid (raise its center of mass). The relationship between diffusivity and dissipation then is

$$\varepsilon = \frac{KN^2}{\Gamma} \tag{1}$$

where K is the vertical diffusivity of density and

$$N^2 = \frac{\partial \rho}{\partial z} - \frac{g^2}{c^2} \tag{2}$$

is the squared buoyancy frequency, ρ is the density, z is the vertical co-ordinate, g is the acceleration of gravity and c is the speed of sound (Osborn, 1980). The buoyancy frequency squared ranges from $O(10^{-6}\ \mathrm{s^{-2}})$ in deep abyssal waters to $O(10^{-3}\ \mathrm{s}^{-2})$ in the seasonal thermocline. Using Eq. (1), the lowest rate of dissipation that must be detected is then

$$\varepsilon \sim \frac{10^{-5} \cdot 10^{-6}}{0.1} = 10^{-10}\ \mathrm{W\ kg^{-1}}. \tag{3}$$

We now know that oceanic turbulence is very intermittent and the sensitivity of an instrument need not be quite as low as Eq. (1) to get a depth mean estimate equal to the value in Eq. (1).

In isotropic turbulence, the rate of dissipation is related to the turbulent shear and rate of strain by

$$\varepsilon = \frac{15}{2}\nu\overline{\left(\frac{\partial u}{\partial z}\right)^2} = 15\nu\overline{\left(\frac{\partial u}{\partial x}\right)^2} \tag{4}$$

where $\nu \approx 1 \times 10^{-6}\ \mathrm{m^2 s^{-1}}$ is the kinematic molecular viscosity, the over-line indicates a spatial or ensemble average, u is a velocity component, and x and z are co-ordinates parallel and orthogonal to the velocity component, respectively. From Eqs. (3) and (4), the root-mean-square shear that an instrument must detect is $3 \times 10^{-3}\ \mathrm{s^{-1}}$. It remains to determine the bandwidth of oceanic turbulence.

In a turbulent fluid, the velocity and scalar parameters fluctuate in space and slowly evolve in time. At the smaller scales of the velocity fluctuations, the shear and the rate of strain are extremely large and all fluid motions are strongly dampened by the action of viscosity. The scale at which all fluid motion ceases and all residual kinetic energy is dissipated into heat is of the order $(\nu^3/\varepsilon)^{1/4}$.

Observations indicate that 90% of all dissipation occurs at length scales between 1.5 and 70 times $(\nu^3/\varepsilon)^{1/4}$, or between 2.3×10^{-3} and 0.11 times $(\varepsilon/\nu^3)^{1/4}$ when expressed in terms of cyclic wavenumbers (cpm). This is the microstructure range of velocity fluctuations. For the open ocean, the range is approximately 0.23 to 11 cpm in waters with very low rates of dissipation ($\varepsilon \sim 10^{-10}\ \mathrm{W\ kg^{-1}}$) and 2.3 to 110 cpm in active regions ($\varepsilon \sim 10^{-6}\ \mathrm{W\ kg^{-1}}$). In coastal regions, the rate of dissipation can be larger yet by three orders of magnitude, giving a range of 15 to 600 cpm.

The wavenumber range of microstructure sets explicit and implicit requirements for a profiler. Obviously, the probes must have the spatial resolution to cover the microstructure range. The smallest wavelength of interest in the open ocean is 0.01 m and the probes must be small compared to this length in order to provide undiminished measurements. The platform carrying the probes must move smoothly through the water so that the data, which are sampled regularly in time, can be converted to a space-series. All practical velocity sensors measure velocity relative to the platform, and so the platform must not vibrate or have other spurious motions in this range, because such motions will be added to the environmental signals measured by a probe.

The speed of the platform cannot be chosen arbitrarily. Environmental structures with a wavenumber of k will appear to the probe at a frequency $f = Uk$, where U is the speed of the platform relative to the ambient water. The speed of the platform must be chosen so that the apparent frequency of the microstructure range falls within the frequency response of the probe. This usually places an upper limit on the speed. The evolution of the turbulence itself places a lower limit on the speed of a profiler. The time scale of dissipating eddies is $(\nu/\varepsilon)^{1/2}$ and the profiler must traverse over the largest scale of the microstructure range, 70 $(\nu^3/\varepsilon)^{1/4}$, during an interval that is short compared to this time scale. Otherwise, the time series cannot be converted to a space series. These constraints combine to give the inequality

$$U >> \frac{70\left(\nu^3 / \varepsilon\right)^{1/4}}{\left(\nu / \varepsilon\right)^{1/2}} = 70(\nu\varepsilon)^{1/4}. \tag{5}$$

For the open ocean, the right hand side of Eq. (5) is less than $0.07\ \mathrm{m\ s^{-1}}$ and most profilers satisfy this condition by traveling faster than $0.5\ \mathrm{m\ s^{-1}}$.

3. Probes

Two velocity probes have been successfully adapted for use in the ocean; the hot-film anemometer, and the shear probe.

3.1 Hot-film anemometer

A constant temperature anemometer consists of a metallic element that is actively held at a fixed temperature by servo-electronics. The element's temperature is sensed by measuring its electrical resistance and the current flowing through the element is adjusted to maintain it at a constant resistance and, thereby, at a constant temperature. The element is frequently a fine wire but wire anemometers are inappropriate for use in natural waters because they effectively snag plankton and gelatinous material. One alternative approach is to use a metal film that is applied to a glass substrate in the shape of a wedge or cone. The probe is then more rugged and tends to shed plankton. The probe used by Grant *et al.* (1962, 1968a, 1968b), and subsequently by several other researchers, is conical. The film is a narrow (0.1 mm) band of platinum deposited about 1 mm from the probe tip (Fig. 1(a)).

The heat flow Q from the film to the ambient fluid is, to first order, proportional to the temperature difference, ΔT, between the film and the ambient fluid and the square root of the fluid speed, U, that is

$$Q = \frac{E^2}{R} \propto \Delta T U^{1/2}, \quad (6)$$

where E is the probe voltage and R is its constant resistance (Lueck, 1980). The fluctuation in voltage, δE, in response to changes in speed, $u = \delta U$ is

$$\delta E \propto \frac{1}{4}(\Delta T)^{1/2} U^{-3/4} u, \quad (7)$$

while the response to fluctuations of the ambient temperature, δT, is

$$\delta E \propto \frac{1}{2}(\Delta T)^{-1/2} U^{1/4} \delta T. \quad (8)$$

This means that heated anemometers also act as thermometers. It is not immune to environmental fluctuations of temperature and this has limited its application to the open ocean where temperature fluctuations are relatively large. The probe senses fluctuations of the flow component directed along the axis of the probe. The along-path gradient of these fluctuations are interpreted as the rate of strain. The sensitivity to velocity fluctuations decreases with increasing profiling speed, as shown by Eq. (7). The rate of dissipation is estimated using Eq. (4). The frequency response of the heated-film probe is outstanding. Grant *et al*. (1962) calibrated the response to 1000 Hz by vibrating the probe longitudinally in a water tunnel. At typical towing speeds of 1.25 m s^{-1}, this corresponds to 800 cpm and is more than adequate for microstructure measurements.

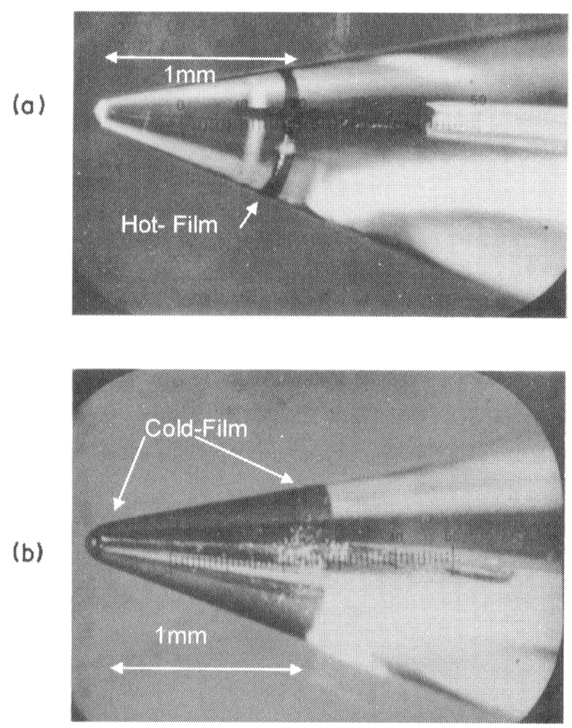

Fig. 1. The platinum hot-film anemometer (a) and the platinum cold-film thermometer (b) used by Grant *et al*. (1962, 1968a, 1968b). [Courtesy of P. Nasmyth.]

3.2 Shear probe

The most commonly used and best-suited sensor for measuring microstructure velocity fluctuations is the airfoil (shear) probe. This probe was initially conceived by H. S. Ribner and T. Siddon at the University of Toronto and developed for atmospheric and wind tunnel velocity measurements (Siddon, 1965; Siddon and Ribner, 1965). The probe was subsequently modified for use in water (Siddon, 1971), and in 1972 T. Osborn successfully deployed the shear probe on a microstructure profiler in a fjord near Vancouver, Canada (Osborn, 1974).

Osborn and Crawford (1980) describe the theory of operation and calibration of the shear probe. The sensing element is a piezo-ceramic bimorph beam which generates an electrical charge in response to cross-axial forces (Fig. 2). The resistance of the beam must exceed 10^{10} Ω for it to function properly at the low frequencies of microstructure signals. Heat-shrink tubing is frequently used to block seawater (Oakey, personal communication) but it is only effective for several hours of immersion. A Teflon sheath is more effective (Moum *et al*., 1995) and our tests indicate that it blocks seawater for at least 3 months which makes long-term deployment possible. An outer jacket of silicon rubber gives the probe its axially symmetric "bullet" shape. The shear probe is insensitive to environmental temperature fluctuations in the microstructure range.

Several variants of the shear probe are being used. They are geometrically very similar but differ in size. The probe developed by T. Osborn is 9 mm long (distance from fulcrum to probe tip) and 5 mm wide (maximum diameter). Our probe has the same dimensions but its

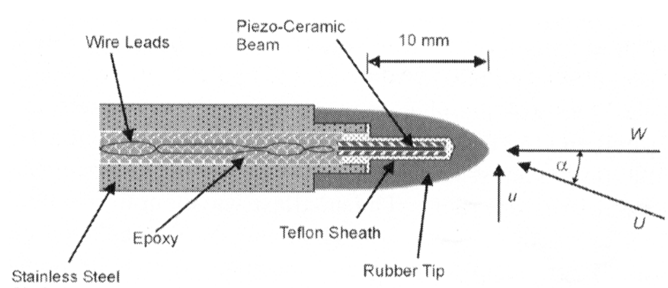

Fig. 2. The air-foil shear probe made at the University of Victoria.

cross-sectional area increases linearly from the tip (cf. Fig. 2). The probe developed by N. Oakey at the Bedford Institute of Oceanography and also used by M. Gregg at the University of Washington has corresponding dimensions of 14 and 5 mm. The probe developed by M. Moum at Oregon State University is 25 mm long and 6 mm wide (see Moum *et al*., 1995, figures A2 and B2 for both probes).

The wavenumber response function of the shear probe is still an unsettled issue. Ninnis (1984) compared the shear probe signal against a laser Doppler anemometer in laboratory grid turbulence. He concluded that the half-power wavenumber of the Osborn and Oakey type probes is 70 cpm and 56 cpm, respectively. However, the agreement between measured and modeled response was poor and recent work indicates that the Osborn probe attenuates the environmental variance by a factor of 2 at only 50 cpm (Wolk *et al*., 2001; Macoun and Lueck, 2002). Thus, the signals from shear probes need some correction when used in very intense oceanic turbulence. Vibrations test indicate that the shear probe resonates near 3000 Hz and that, for frequencies much smaller than this, the response is strictly spatial in nature.

An alternative design of the shear probe was developed by H. Prandke (Prandke, 1994). This probe measures velocity from the deflection of a small, airfoil-shaped bead protruding from a conical shroud. The cross-axial force is transmitted to the piezo-ceramic bimorph by a cantilever, which is potted together with the piezo-ceramic beam into a flexible rubber mount. The advantage of the Prandke probe is that its sensitivity is increased by the cantilever and its shroud offers some protection against excessive side forces that may otherwise break the ceramic beam. However, the cantilever lowers the resonance frequency of this probe to only about 200 Hz which places constraints upon the maximum speed of profiling.

When the shear probe travels at speed W, then the voltage E_p produced by the probe in response to a cross-axis velocity u is

$$E_p = \hat{s}Wu, \tag{9}$$

where the constant of proportionality $\hat{s}$ is the sensitivity of the probe and must be determined by calibration. Contrary to the behavior of the heated anemometer Eq. (7), the sensitivity of the shear probe increases with increasing profiler speed. The probe voltage is usually differentiated and interpreted as shear, i.e.

$$\frac{\partial u}{\partial z} = \frac{1}{W}\frac{\partial u}{\partial t} = \frac{1}{\hat{s}W^2}\frac{dE_p}{dt}, \tag{10}$$

and Eq. (4) is used to estimate the rate of dissipation. When the probe is used on a vertical profiler it can be oriented to sense either of two horizontal velocity components. When mounted on a horizontal profiler it detects either $\partial w/\partial x$ or $\partial v/\partial x$, where w and v are the vertical and lateral horizontal velocity components and x is the horizontal co-ordinate.

3.3 Thermometers

The original sensor for measuring oceanic temperature fluctuations in the microstructure range is the platinum cold-film thermometer. Cold-film thermometers are tiny cones or wedges of glass covered by a thin film of metal (Fig. 1(b)). The film is insulated from seawater with a thin layer of glass. The frequency response of these thermometers was investigated by Fabula (1968) who found that they were fast enough to resolve the microstructure range at speeds of up to 1 m s^{-1}. However, the temperature coefficient of electrical resistance of platinum is quite small and the probe resistance is in the 5 to 100 Ω range. Both characteristics present design problems.

Thermistors are the most popular probe for measuring temperature fluctuations in the microstructure range. They are commercially available in a wide range of shapes, sizes, and base resistances. The temperature coefficient of resistance is ten times larger than that for cold-film probes. A frequently used thermistor is the FP07* which consists of a metal-oxide bead of about 0.2 mm diameter. The bead is mounted to the front of a 2 mm glass bulb, which is attached to the end of a 15 mm long glass rod. The frequency response of this thermometer is about 25 Hz which is not fast enough to resolve the microstructure range unless the sensor is used on very slowly moving platforms.

Thermocouples have a very poor sensitivity to temperature but they are extremely small. Nash *et al*. (1999) have demonstrated that their frequency response exceeds 100 Hz, which may render them useful for microstructure measurements and regions of strong temperature fluctuations.

4. Horizontal Profilers

4.1 Towed bodies

4.1.1 Grant, Stewart, Moilliet, and Vogel

Ocean microstructure measurements were started by a research group, lead by H. Grant, at the Pacific Naval Laboratory (PNL) of the Defense Research Board of Canada in the early 1950s. Initial attempts to use hot-wire anemometers were a complete failure. By 1958, the team developed a heated platinum-film anemometer and

*Thermometrics Inc., 808 US Highway 1, Edison, New Jersey 08817, U.S.A.

an unheated thermometer (Fig. 1) specifically for use in seawater and measurements were taken in tidal channels along the coast of British Columbia. The work was motivated by the Kolmogorov (1941) theory of isotropic turbulence which applies to Reynolds numbers higher than those attainable in wind tunnels. The most frequently cited measurements (Grant *et al.*, 1962, 1968a) were conducted in Seymour Narrows where currents typically reach 12 knots and the Reynolds number based on the channel depth (the smallest dimension) is 3×10^8.

The PNL team converted an old minesweeping paravane (Fig. 3) to carry their instrumentation. It was hydro-dynamically depressed by an inverted wing and used a drag tail to provide both static and dynamic stability. The electro-mechanical tow line was nearly vertical and, therefore, under great tension at the typical towing speeds of 1.25 m s^{-1} relative to the ambient water.

The sensors and their electronics presented numerous challenges, because integrated circuit and digital electronics were not available in those days. Stewart and Grant (1999) provide a lucid description of these trials and tribulations. Their work is a splendid example of the value of thorough planning and preparation. The electrical resistance of thin films is notoriously unstable. Moilliet (personal communication) annealed the thermometers and anemometers by cycling them between room temperature and 1000°C. The survivors of this torture test had stable temperature coefficients of resistance and most of them worked for another twenty years. The team at PNL developed an AC bridges for their anemometers and thermometers which were far superior to commercially available DC bridges. The work was conducted in winter when plankton populations are at their minimum and the water tends to be isothermal. This minimized the data lost to collisions with plankton and the contamination of the velocity signals by temperature fluctuations. The plankton that was inevitably captured by the probes was cleared by periodically washing the probes with a high-speed jet of water directed upstream from behind the probes.

The one-dimensional spectrum, $\Phi(\hat{k})$, of along-stream velocity, u, and its rate of strain, $\hat{k}^2\Phi(\hat{k})$, show that in Seymour Narrows there is at least one decade of wavenumbers where the contribution of both spectra is small (Fig. 4). Such a separation of the energy containing scales from the viscous scales is required to test the theory of Kolmogorov. The velocity spectrum has 3 decades of –5/3 slope (inertial sub-range) before viscous effects dampen the fluctuations, as predicted by Kolmogorov (Fig. 5). Another theory, that for temperature fluctuations of Batchelor (1959), was also confirmed. The spectrum of temperature fluctuations has a –5/3 slope in the inertial subrange, takes a –1 slope in the viscous diffusive region, and drops rapidly with increasing wavenumber in the diffusive region (Fig. 5).

4.1.2 Nasmyth

The towed profiling program at PNL was terminated in the late 1960 and the equipment was transferred to the newly founded Institute of Ocean Sciences near Victoria, British Columbia, Canada. P. Nasmyth extended the work of Grant *et al.* to the open ocean using a new and more streamlined towed vehicle. Between 1967 and 1969, Nasmyth (1970) conducted two series of tows off the west coast of Vancouver Island in the depth range of 0 to 300 m. A motion compensating winch and cable fairing were used to reduce depth variations induced by ship motions

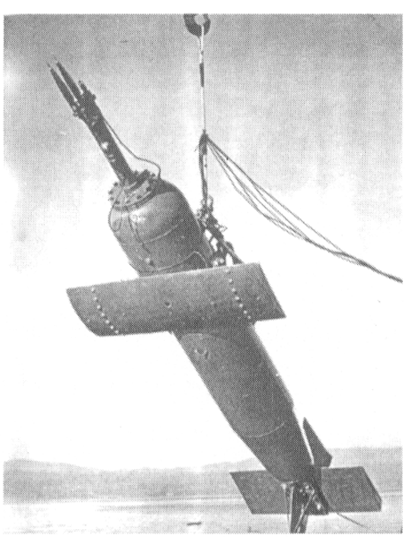

Fig. 3. The towed body (a converted mine-sweeping paravane) used by Grant *et al.* at the PNL around 1960. The hot- and cold-film probes are at the very front. Note the inverted wing. [Courtesy of P. Nasmyth.]

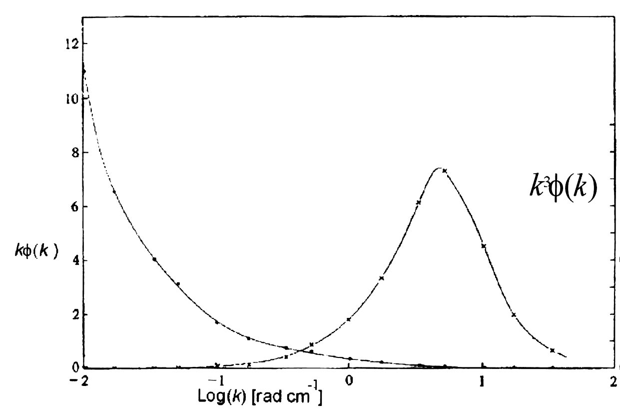

Fig. 4. The one-dimensional spectrum, $\Phi(\hat{k})$, of along-stream velocity, u, (left scale) and its rate of strain, $\hat{k}^2\Phi(\hat{k})$, (right scale) measured with the PNL tow body in Seymour Narrows. [After Grant *et al.* (1962).]

to less than 0.3 m. The winch controller was also used to produce saw-tooth profiles to provide a quasi-two-dimensional view. The towed vehicle carried the same high-frequency velocity and temperature probes used previously by Grant *et al*. Additional sensors included a vertical array of three thermistors, a conductivity probe, and a propeller anemometer (Fig. 6).

These tows provided considerable insight into the spatial distribution of turbulence in the oceanic thermocline. For example, Nasmyth found that turbulence was intermittently distributed with vertical scales of 0.3 to 20 m and horizontal scales from several tens of meters to the full 10 km span of his tows. We now refer to this commonly found spatial feature of turbulence as "pancakes" and patches.

Nasmyth provided the first microstructure observations of a sub-surface front (Fig. 7). On one side of this front, the turbulence was weak for at least 3 km (the left side leading into Fig. 7). There, the fluctuations of velocity and temperature are very small. The front was contacted about one-quarter of the way "into" Fig. 11. The front is sloped because the lowest thermistor (T_3) makes the first report of cooler water, which is followed by the middle (T_2) and then the upper thermistor (T_1), respectively. The water temperature at a fixed depth is progressively cooler towards the "right" side. All three thermometers are immersed the cooler water during all depth excursions of the towed vehicle in the left third of Fig. 7. The turbulence is most intense right at the interface between the two water types.

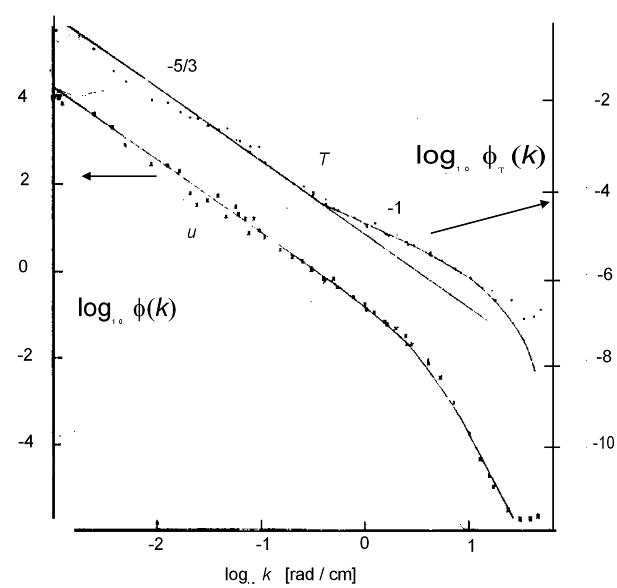

Fig. 5. The spectrum of velocity fluctuations (right scale) and temperature fluctuations (left scale) measured with the PNL tow body in Seymour Narrows. [After Grant *et al*. (1962).]

Finally, Nasmyth identified three segments of data collected in in-shore waters where the velocity fluctuations were large *and* the temperature fluctuations were very small. These segments, one of 95 seconds and two of 175 seconds duration, provided the cleanest spectra available and were used to construct the non-dimensional velocity spectrum now commonly called the "Nasmyth Spectrum." The values have been tabulated by Oakey (1982) along with the non-dimensional rate of strain spectrum and the non-dimesnsional shear spectrum derived under the assumption of isotropy. A good fit to the shear spectrum (Wolk *et al*., 2002) is provided by

$$G_2 = \frac{8.05x^{1/3}}{1+(20x)^{3.7}}, \tag{11}$$

Fig. 6. The towed body used by P. Nasmyth around 1970, hanging in its launch/recovery cradle over the stern of the ship. [Courtesy of P. Nasmyth.]

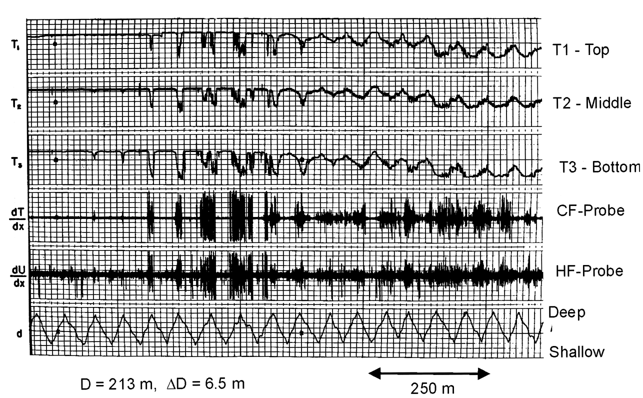

Fig. 7. A time series of temperature (upper three traces) and the microstructure of temperature gradient and strain rate (next two traces), and the depth of the towed vehicle (lowest trace) taken in a front 213 m below the surface. The depth scale is inverted. [Courtesy of P. Nasmyth.]

where $x = k/k_v$, k is the wavenumber (cycles per meter) and $k_v = (\varepsilon/\nu^3)^{1/4}$.

4.1.3 Gargett

A. Gargett continued the towed profiling program at the Institute of Ocean Sciences and conducted numerous horizontal profiles in the North Pacific of temperature and velocity microstructure during the 1970s with the vehicle and probes previously used by Nasmyth.

Gargett's measurements provided, among other things, the first compelling evidence that salt-fingers and turbulence have different horizontal gradients of temperature. In regions favorable for salt-fingers, the temperature fluctuations have uniform amplitude, whereas in turbulent regions, the amplitude fluctuates considerably (Gargett and Schmitt, 1982). The spectra from salt-finger favorable regions were band limited with a Q (ratio of bandwidth-to-center wavenumber) of unity, whereas turbulent regions have much broader spectra. Gargett found a tendency for stronger temperature microstructure in regions favorable to the growth of salt-fingers (Gargett, 1978).

Although no instrumentation problems per se were encountered with the heated velocity measurements, Gargett (1978) suspected that more than 95% of her velocity measurements were afflicted with temperature contaminations. No further towed microstructure measurements were conducted by researchers at the Institute of Ocean Sciences.

4.1.4 Soviet measurements

The reports from researchers in the Soviet Union are sparse in the English language literature, owing in part to the politically motivated restrictions placed upon these researchers until 1990. Balyaev *et al.* (1975) used a towed vehicle equipped with a "hydro-resistance anemometers" but few details are given about the instrumentation and the location of the measurements. Judging from the hydrographic profiles, it appears that the measurements were taken in the Atlantic equatorial region. The principle of operation of the hydro-resistance anemometer is similar to that of a heated anemometer (C. Gibson, personal communication) and, consequently, this sensor is plagued by temperature signal contamination to at least the same extent as the hot-film anemometer. There is clear evidence for such contamination. Dissipation rates reported by Balyaev *et al.* are very high (comparable to values found in Seymour Narrows by Grant *et al.*), nearly independent of depth from the surface to below the core of the undercurrent, and about 1000 times larger than the rates measured by Crawford and Osborn (Crawford and Osborn, 1980; Crawford, 1982) using shear probes mounted on a free-fall vertical profiler.

4.1.5 Osborn and Lueck

The art of using towed vehicles to measure turbulent velocity fluctuations in the dissipation range was revived

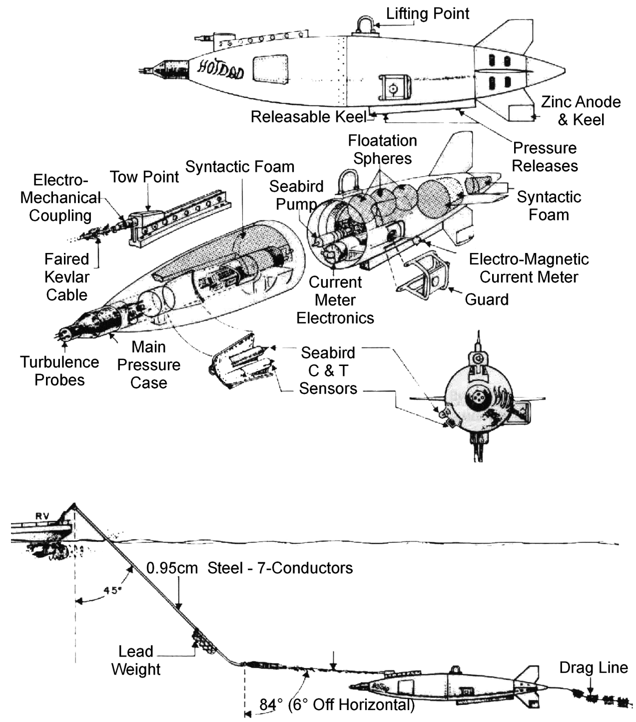

Fig. 8. (Upper half) Diagrammatic views of the towed vehicle HOTDAD showing the placement of sensors, buoyancy and weight. (Lower half) The hybrid long-line towing technique. Cable lengths are not shown to scale.

in the 1980s by T. Osborn and R. Lueck. Two major problems revealed by previous work were solved. The temperature contamination of the velocity measurements was eliminated by using shear probes. The large mechanical vibrations, induced by highly tensioned and nearly vertical tow lines, was greatly reduced by using the technique of long-line towing promoted by E. Katz of the Lamont-Doherty Observatory, New York.

If the vehicle is only slightly denser than water, then the tow-line will be nearly horizontal and at right angles to the directions of ship heave and roll which, through geometry alone, reduces the variations of line tension from these sources of ship motion. The flow over the line is mainly tangential which reduces the drag on the cable and the pulsation by eddies shed from the cable. These concepts were demonstrated with a small prototype towed vehicle which had a resolution of $\varepsilon = 2 \times 10^{-9}$ W kg^{-1} (Osborn and Lueck, 1985b).

4.1.6 Lueck

R. Lueck developed the follow-on vehicle, HOTDAD (Horizontal Ocean Turbulence Data Acquisition Device). The vehicle was 3.8 m long and 0.6 m wide at its midpoint. It carried four shear probes, two FP07 thermistors, a platinum cold-film thermometer, a Sea Bird thermometer and conductivity sensor, three orthogonal acceleròm-

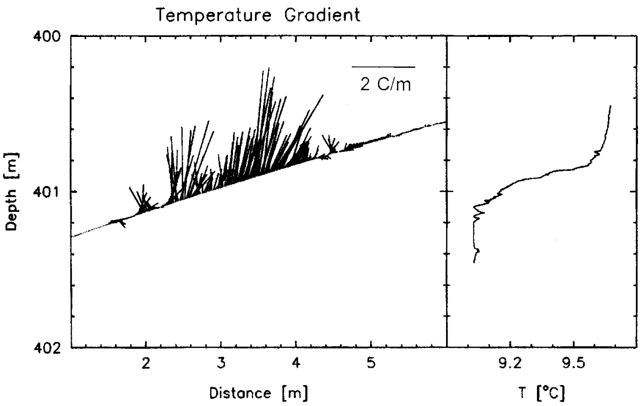

Fig. 9. Stick diagram of temperature gradient along the path of HOTDAD through a very thin (0.25 m) salt-finger interface in the tropical North Atlantic. Note the predominance of vertical gradients over horizontal gradients.

eters, an electromagnetic current meter and a pressure transducer (Fig. 8).

Two changes were made to reduce the dissipation noise level and to increase the practicality of using the towed vehicle. The dissipation noise level was reduced by increasing the mass (real plus entrained) of the towed body to 1000 kg while keeping its weight in water at about 150 N (newtons). The length of the tow-line was reduced by using a hybrid long-line technique. The first 200 m of line ahead of the body was made of Kevlar to reduce its weight and provided a tow angle of about 6° (Fig. 8). The Kevlar line connected to a more conventional steel cable. A streamlined weight of 1000 N was attached to the bottom end of this steel line which forced the steel line to an angle of about 45°. The mass of the weight also acted as a nodal point to block vibrations in the steel line from coupling into the Kevlar line attached to the towed vehicle. The noise level of the dissipation measurements was 2×10^{-10} W kg^{-1} which was comparable to the best vertical profilers available at that time. In moderate seas of 2 m significant wave height, the vertical motions of HOTDAD (for fixed line length) was less than 0.07 m. Pitching motions were less than 2° and roll was smaller than 1°.

HOTDAD was used to examine the temperature and velocity microstructure in salt-finger layers (Lueck, 1987; Fleury and Lueck, 1992), the fluxes of heat and salt by double diffusion (Fleury and Lueck, 1991) and the covariance of vertical velocity and temperature (Fleury and Lueck, 1994). One novelty of HOTDAD was that it carried two FP07 thermistors aligned vertically and separated by 35 mm. By using the along-path temperature measurements to derive the horizontal gradient (which is common practice) and the vertical temperature difference to derive the vertical gradient, it was possible to map the

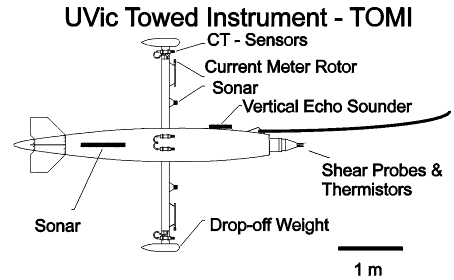

Fig. 10. Schematic of the towed vehicle TOMI as outfitted around 1995. Note the vertical (sail-boat) mast with CTDs and the 150 N keel for roll and pitch stability.

two-dimensional temperature gradient along the path of the vehicle. The temperature gradient in oceanic salt-finger interfaces is predominantly vertical and its variance is relatively small (Fig. 9).

A major difficulty with horizontal profiling is that variations in the ocean are predominantly vertical. It is often difficult to determine if changes measured along the path of the vehicle are due to changes of depth within a mean vertical background gradient or due to horizontal structures, such as fronts. The second generation of towed vehicle developed by R. Lueck is TOMI (Towed Ocean Microstructure Instrument). It has two masts that project above and below the main body (Fig. 10). Two pairs of SeaBird conductivity and temperature sensors near the top and bottom of the upper and lower masts, respectively, and one at mid-body provide the local gradients of temperature, salinity and density as well as the buoyancy frequency. A 750 N weight attached to the bottom of the lower mast increases the rolling and pitching stability for work in highly turbulent environments. The vehicle is 5.7 m long and has a diameter of 0.6 m at mid body. It is 30% more massive than its predecessor but also only weights on 150 N in water. Wolk and Lueck (2001) used TOMI to examine the vertical flux of heat by measuring the covariance of temperature (FP07 thermistor) and vertical velocity (shear probe). They found that the ratio of mixing to dissipation is fairly high ($\Gamma \approx 0.4$) and that the co-spectrum peaks at about half the buoyancy wavenumber, $(N^3\varepsilon^{-1})^{1/2}$.

4.1.7 Moum

The latest towed vehicle is MARLIN, developed by J. Moum at Oregon State University, which also exploits the concept of long-line towing. It is towed at approximately 35 m below a stream-lined depressor weight by a 200 m Kevlar cable. The depressor weight is attached to a 9000 m long, 17 mm diameter steel cable. MARLIN is 5 m long and has a diameter of 0.8 m at mid body. It weighs 4000 N in air and a mere 150 N in water. This vehicle is the most heavily instrumented towed body ever used to probe the ocean (Fig. 11). It carries three shear

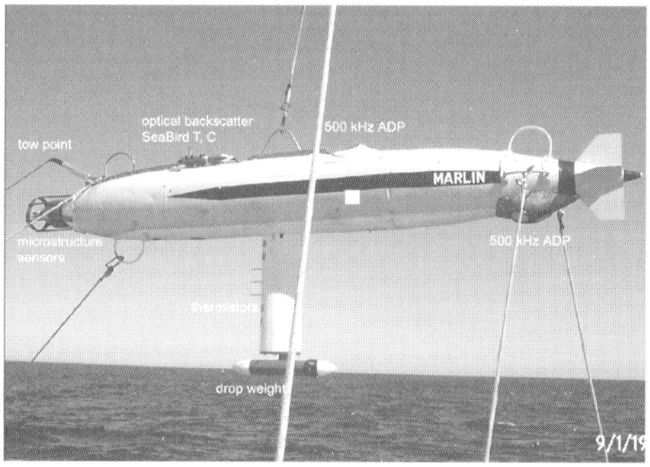

Fig. 11. The towed vehicle MARLIN during recovery around 2000. [Courtesy of J. Moum.]

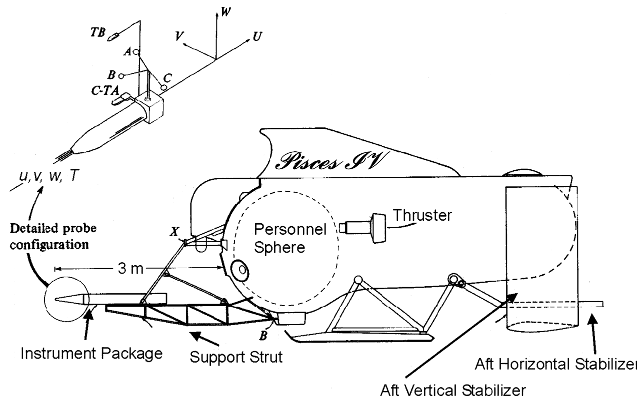

Fig. 12. Schematic of the manned submersible PISCES IV as used by A. Gargett around 1984. The turbulence sensors were project 3 m forward from the main hull using framing. [Courtesy of A. Gargett.]

probes to detect the velocity fluctuations orthogonal to the tow path and a Pitot tube to measure the along-path velocity fluctuations. A cluster of five fast thermistors on the keel is used to measure the vertical structure of temperature and there are slower and redundant sensors for temperature, conductivity, optical properties and depth. Two 500-kHz acoustic Doppler current profilers are mounted aft of the keel, one directed upwards and the other downwards. The real-time display from an altimeter enables the operators to tow the vehicle within 50 m above the bottom.

During moderate seas, the vehicle rolls less than 0.1° and pitches about 0.3°. Vehicular vibrations are small and the shear probes can resolve dissipation rates as low as 5×10^{-10} W kg^{-1}. MARLIN has recently been used to examine mixing induced by the M_2 internal tide over the continental margins where the slope is critical (Moum *et al.*, 2001). Nepheloid layers (resuspended sediments) generated by bottom mixing and subsequent separation were found with horizontal extents of 100 m to 10 km.

4.2 Submersibles

The first and so far only adaptation of a manned submersible to turbulent velocity measurements is by Gargett *et al.* (1984) who used the vessel PISCES IV (Fig. 12) to examine the lee-wave generated by an internal hydraulic jump around the sill in Knight Inlet, British Columbia. The vehicle initially suffered from a pitching instability that easily grew to 15° amplitude and precluded measurements of any sort. The instability was very effectively dampened by the addition of wings to the tail section. The PISCES was not well stream lined and it was necessary to make extensive use of framing to project the sensors well ahead of the vessel and avoid flow disturbances. However, it is difficult to adequately brace long structures on a small vehicle. The instrumentation carried by PISCES IV included; two shear probes to measure the vertical and horizontal cross-stream components and one hot-film anemometer to sense the down-stream component of velocity fluctuations (a probe previously used by Grant *et al.*); a three-component propeller anemometer array for low-frequency velocity; a pair of vertically spaced thermistors to measure the local temperature gradient; a CTD; sundry items such as pressure transducers, accelerometers, etc.

PISCES IV was the first system that could measure all three components of velocity fluctuations and Gargett *et al.* exploited this feature to examine the effect of stratification on isotropy. The intensity of turbulence in the lee-wave diminishes with distance from the sill as this wave propagates down stream. The data were classified according to their value of

$$I = \frac{k_\nu}{k_O} = \frac{\left(\varepsilon / \nu^3\right)^{1/4}}{\left(N^3 / \varepsilon\right)^{1/2}} = \left(\frac{\varepsilon}{\nu N^2}\right)^{3/4},$$

where k_ν is the Kolmogorov wavenumber, and k_O is the buoyancy wavenumber. Thus, this ratio represents the separation between the small scales at which the fluctuations are erased by viscosity from the large scales at which they are damped by buoyancy. For $I > 75$, the spectra of all three velocity components are consistent with isotropy in the dissipation range of wavenumbers, which implies that the rate of dissipation estimated from the variance of shear or strain rate should be correct. For $I > 1000$, the spectra are also consistent with isotropy in the inertial subrange implying that the level of the velocity spectrum may be used to estimate the rate of dissipation.

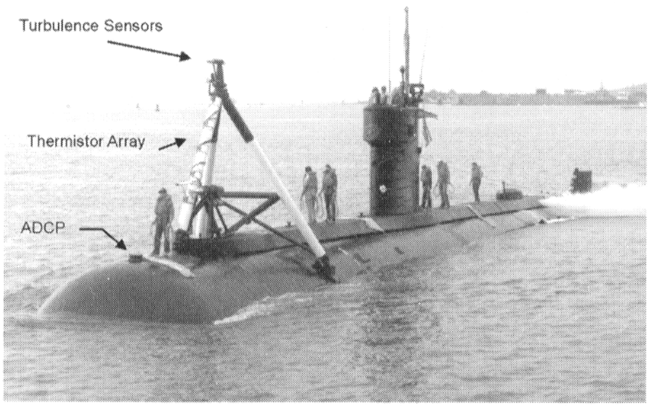

Fig. 13. The USS Dolphin research submarine on its transit out of San Diego harbor around 1984. The large tripod on the ship's bow carries the sensor array.

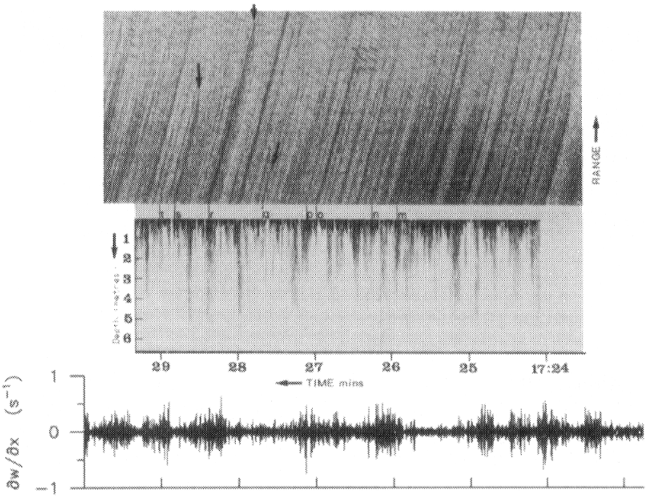

Fig. 14. An example of the simultaneous measurement acoustic backscatter from a forward directed sonar (upper rectangle), a vertical echo sounder (middle rectangle) and microstructure shear (lower rectangle) taken with the Dolphin off the coast of southern California. Individual bubble clouds ahead of the boat can be tracked right to the location of the shear probes but the patches of turbulence are broader than the clouds. [Courtesy of T. Osborn.]

4.3 Submarines

The instrumentation developed by Grant *et al.* was also used on a submarine, the HMCS Grilse. The sensors were extended out of a forward torpedo tube. With the muzzle door open, the depth limitation of the submarine was 90 m, but this was deep enough to reach into the thermocline where Grant *et al.* (1968b) were surprised to observe patches of turbulence. These patches extending hundreds of meters horizontally but only a few meters vertically. Turbulence within the thermocline was then still a complete mystery. Owing to the limited availability of the submarine, the project was terminated and there are no other reports from those early days.

Osborn revived submarine-based measurements in the 1980s through his extensive use of the USS Dolphin which is a diesel-electric boat, 55 m long and specifically designed for research. Its length, mass and strong structure allows the attachment rigid frames. Osborn used a tri-pod constructed from 0.3 m diameter steel pipes to hold a turbulence measuring package at 4.5 m above deck (Fig. 13). The pipes were pressurized with gas. This reduced the mass of the tri-pod which raised the frequencies of vibration and brought most of the modes above the frequency of interest for microstructure measurements. The gas was also needed for operational safety, because it precluded implosions at the maximum operating depth of the boat. The instrumentation carried on the Dolphin included; two shear probes; an FP07 thermistor; two three-axis acoustic velocity sensors; a CTD; an array of 10 FP07 thermistors mounted along the front leg of the tri-pod; a 1200 kHz upward looking acoustic Doppler current profiler mounted into the deck ahead of the front leg of the tri-pod; accelerometers, pressure transducers, and sundry items. The velocity microstructure instrumentation was located above the deck rather than ahead of the bow for several reasons; maintenance (e.g., probe changes) was possible without using divers; for equal distance from the hull, flow distortions are smaller above the deck than ahead of the bow; it is possible to make measurements right through the air-sea interface.

A full-size submarine provides several advantages for turbulence measurements. It has a very large ratio of inertia to drag forces which promotes low levels of vibration and smooth motion. The boat is about 100 times longer than the scale of dissipative eddies which gives it the stability needed for measurements at energy-containing and flux-supporting scales. Yamazaki and Osborn (1993) took advantage of this feature to measure the vertical flux of heat, $\overline{w'T'}$, directly from the co-variance of vertical velocity and temperature fluctuations. The noise level of the dissipation estimates obtained with the Dolphin submarine were less than 3×10^{-10} W kg^{-1} which matched the best free-fall vertical profilers then in operation and bettered the contemporary towed bodies by a factor of 100.

The Dolphin profiles revealed numerous features of oceanic turbulence. Transects through salt-stabilized intrusions revealed, for the first time, *both* the temperature and the velocity signature of oceanic salt-fingers (Osborn and Lueck, 1985a). The amplitude of the temperature gradient was fairly uniform in layers conducive to double diffusion and its spectrum was narrow banded. In turbulent layers the amplitudes were highly irregular and the spectrum was broad. The velocity fluctuations were quite detectable in the turbulent layer but remained below the noise level of the shear probes in the salt-fingers. An analysis of many patches of salt-fingers and "layered" double diffusion indicates that the buoyancy flux by these processes is negligible compared to the flux by turbulence (Osborn, 1988).

With the addition of forward and athwartship direct side-scan sonars and an upward looking echo sounder, the Dolphin submarine was used to map the distribution of bubble clouds and to measure the rate of dissipation of kinetic energy within these clouds (Osborn *et al*., 1992). The dissipation rate was slightly intermittent but the length scale of the patches of turbulence greatly exceeded the ten-meter horizontal scale of the bubble plumes observed by the sonars (Fig. 14). This work also provided the first oceanic evidence that the rate of dissipation below breaking waves significantly exceeds the rate predicted by the classical "law of the wall" scaling.

4.4 Autonomous vehicles

In the 1990s, autonomous underwater vehicles (AUVs) were put into service for environmental measurements. These vehicles come in a variety of shapes and sizes but all bear a strong resemblance to a torpedo. They are self propelled and controlled by an on-board computer. The trajectory of an AUV can be as simple as a straight-line track and as complicated as an entangled-string pattern with transitions to multiple depths.

A major concern for turbulence measurements is mechanical vibrations produced by the AUV's motor and fin actuators. These are typically in the 10 to 200 Hz range and are likely to disturb the microstructure velocity measurements. A second concern is vehicular stability because many AUVs are not much longer than the largest eddies in the dissipation range of velocity fluctuations ($\approx$1 m).

The first velocity turbulence measurements were taken in January 1996 with a large diameter (0.66 m) vehicle that is 7.6 m long and has a mass exceeding 2000 kg (Levine and Lueck, 1999). The measurement package was attached to the nose of this AUV and consisted of two shear probes, one FP07 thermistor, and three orthogonal accelerometers. The vehicle traveled at 3.4 m s^{-1} with respect to the water. Pitching and rolling motions were typically less than 0.3° for time scales shorter than 10 seconds. Strong and narrow banded vibrations, which completely obscured the oceanic velocity signals, were found at 18, 44, and 88 Hz in both the shear probe and accelerometer records. These frequencies are associated with the drive motor and fin actuators. The coherency between acceleration and shear probes signals was used to remove the noise both in the time and in the frequency domain. The lowest level of dissipation rate observed by Levine and Lueck was 1×10^{-8} W kg^{-1}.

The above work was soon followed by Dhanak and Holappa (1999) who showed that a much smaller vehicle such as the Ocean Explorer (Fig. 15), which is only 2.4 m long and 0.53 m in diameter, could also be used to make velocity turbulence measurements. The Ocean Explorer does not have the advantage of a large mass to dampen vibrations induced by the propulsion and steering devices. However, Dhanak and Holappa used rubber mounts for both the drive motor and the turbulence package which greatly reduced the vibration of their velocity probes. After coherent noise removal, dissipation rates as small as 0.3×10^{-8} W kg^{-1} were resolved from shear probes measurements.

Recently, the small diameter (0.18 m) AUV REMUS (Fig. 16) has been outfitted with shear probes, FP-07 thermistors, a pair of vertically spaced CTDs, a three-dimensional acoustic velocity sensor and a pair of up and downward looking ADCPs by E. Levine of the Naval

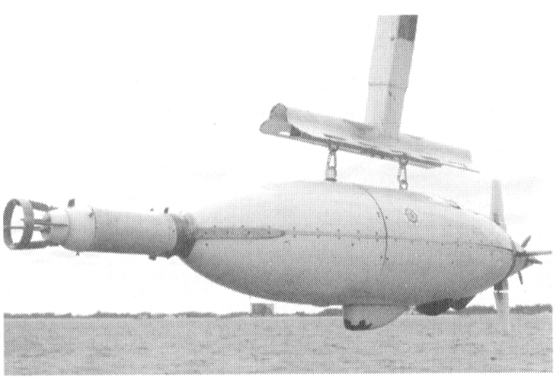

Fig. 15. The AUV Ocean Explorer hanging from its launch/recovery cradle. The turbulence package is mounted on the front and cushioned by open-cell foam. The probes are protected by a guard ring. [Courtesy of M. Dhanak.]

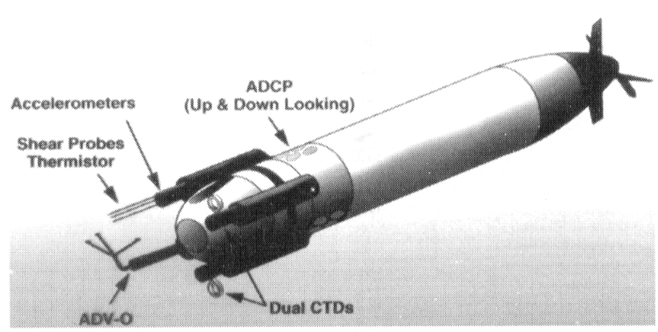

Fig. 16. Sketch of the AUV REMUS around 2001. Because the nose is used for navigation and homing, the turbulence and other sensors are strapped in a harness around the periphery of the vehicle.

Undersea Warfare Centre (Newport) for coastal studies (Levine *et al*., 2001). The very large AUV Autosub (Fig. 17), which is operated by the Institute of Ocean Sciences in Southampton UK, was outfitted by T. Osborn with a turbulence package and by S. Thorpe with an acoustic backscatter system to study the relationship between turbulence and bubble clouds in Langmuir cells (Thorpe *et al*., 2002). For these measurements, Autosub operated autonomously for up to 4 days in a Scottish Fjord. A unique feature is a retractable guard to protect the shear probes during launch and recovery (Fig. 17, inset).

4.5 *Moored instruments*

The viability of long-term and autonomous measurement of turbulence was demonstrated by the moored instrument TAMI (Lueck *et al*., 1997). Although this instrument looks like a towed vehicle, it is moored to the bottom and relies on the ambient current to advect the turbulence past its sensors. The instrument is swiveled so that it continually directs itself into the current. Data are processed and recorded internally and the noise level is 1×10^{-9} W kg^{-1}. TAMI erased a long-held misconception about shear probes, namely, that they must be exposed to a considerable mean flow, $O(1\ \mathrm{m\ s^{-1}})$ to function properly. This notion is rooted in the fact that the sensitivity of shear probes is proportional to the mean flow Eq. (9). However, the noise that limits almost all shear probe measurements comes from mechanical vibrations of the platform rather than the electronics used to amplify the probe signals (Moum and Lueck, 1985). In weak ambient currents, the hydrodynamic forces that induce vibrations are very small which compensates for the reduced sensitivity of the shear probes. Spectra of velocity microstructure shear have been resolved with TAMI in currents as weak as 0.05 m s^{-1} and remain in close agreement with the empirical spectrum of Nasmyth. This moored instrument has also been used in a swift tidal channel were it had sufficient stability to measure turbulent velocity fluctuations in the inertial subrange of very intense turbulence (Lueck and Huang, 1999).

4.6 *Tethered glider*

Greenan and Oakey (1999) converted the vertical profiler EPSONDE (Subsection 5.1) into a tethered quasi-horizontal glider (Fig. 18). With the addition of a main wing for lift and a rear elevator attached to one side of the former vertical profiler and a ballast weight mounted to the other side, this new vehicle glides through the water at an angle of 14° below horizontal. A micro-controller aboard the EPSONDE-Glider controls the pitch of the vehicle by adjusting the angle of the rear elevator and it controls the roll by adjusting the main-wing ailerons. After the glider is put into the water, it quickly adjusts its control surfaces and flies with a speed of 0.55 m s^{-1}. The instrument drags a four-conductor Kevlar cable to communicate the turbulence and flight-control data to the ship. The roll angle varies by less than 2° and short-term pitch variations are less than 1°. The pitch slowly increases to 18° at the maximum range (300 m) from the ship. At the end of the flight, lead ballast is released, the glider ascends to the surface, and is retrieved with its tether line. The vehicle is suitable for studies of the surface mixing layer and other processes shallower than 50 m. The glider carries 2 shear probes, an FP07 thermistor, a platinum cold-film thermometer, and a micro-conductivity sensor. The vehicle has two narrow vibrations in the 20 to 30 Hz range and a much weaker oscillation near 10 Hz. With some correction for these spectral disturbances, the glider is able to resolve dissipation rates smaller than 9×10^{-10} W kg^{-1}.

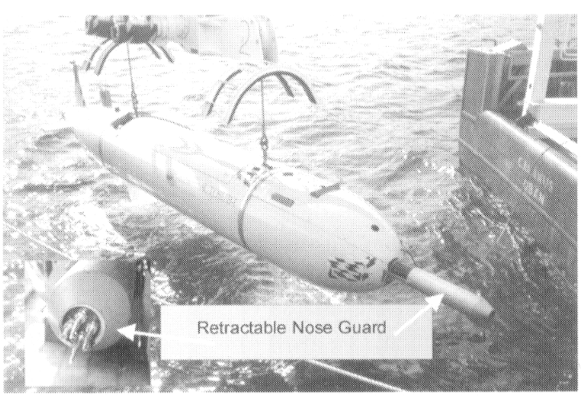

Fig. 17. The AUV Autosub hanging from its launch/recovery cradle around 1999. A retractable sheath protects the shear probes and thermistor during handling (inset).

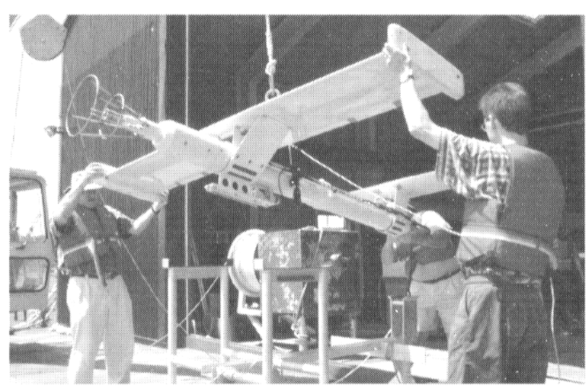

Fig. 18. The tethered glider EPSONDE-Glider being readied for test around 1995. A guard ring protects the sensors and the recovery winch is visible in the background. [Courtesy of B. Greenan.]

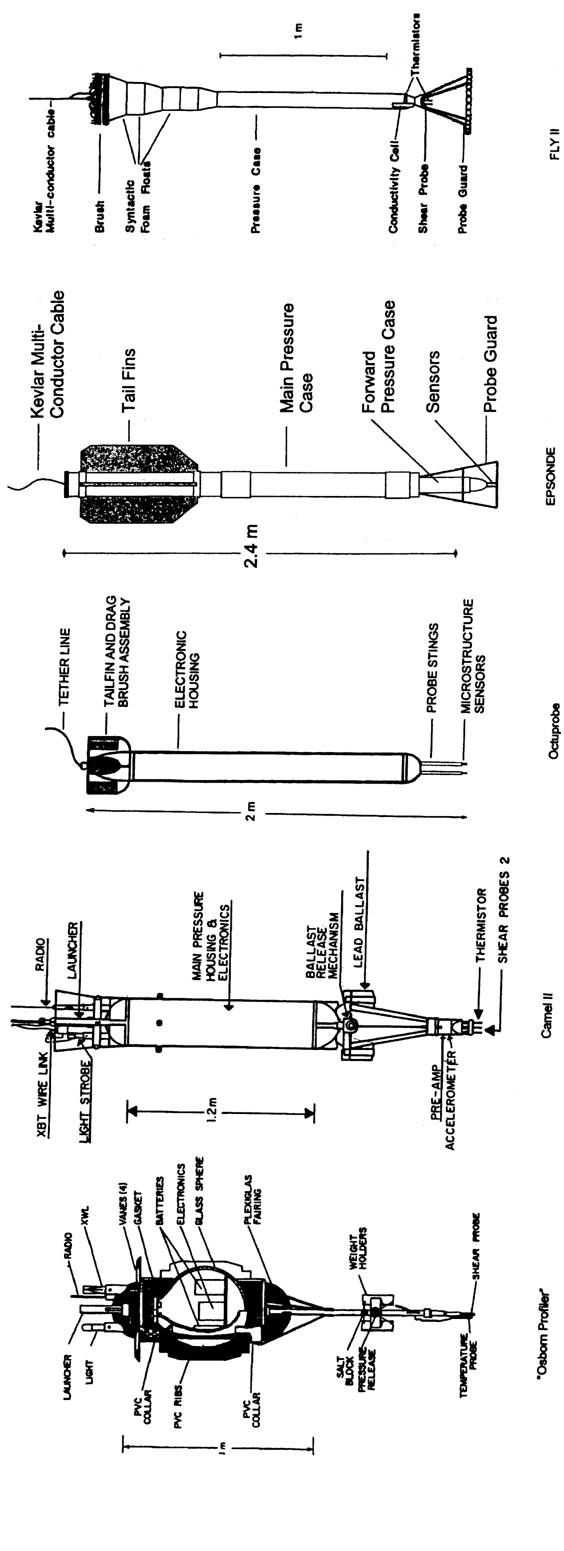

Fig. 19. Sketches of some of the vertical microstructure profilers developed in Canada between 1972 and 1985. Drawings and relative sizes of the instruments are not to scale. [Courtesy of T. Osborn, N. Oakey, and R. Dewey.]

5. Vertical Profilers

Instruments for profiling the vertical microstructure of velocity generally are long and cylindrical and descend axially through the water column. The sensors are mounted on forward pointing stings, which places them in the undisturbed water ahead of the pressure case. Vibrations of the profiler add spurious signals to the measured velocity, and so these instruments usually have smooth outside surfaces with few protrusions to minimize the generation of eddies. Vertical profilers are deployed in a free falling or quasi-free falling fashion, so that their descent is completely decoupled from the motion of the deployment platform, usually a ship. True free falling profilers have no link to the surface. They descend to a predetermined depth, where they release ballast and return to the surface by their own buoyancy. The ascent back to the surface is generally slow and recovery of the instrument may take a long time in areas of strong subsurface currents, even with the aid of strobe lights and radio beacons. Consequently, the time between consecutive profiles may be several hours. In contrast, quasi-free profilers are loosely tethered to the surface vessel by a thin line, which is used to haul the instrument back to surface after it reaches its terminal depth. During the descent, the tether line is paid out fast enough to maintain a slack line at the surface. On some profilers, the recovery line is also used to telemeter data to the surface for real-time monitoring and recording.

The development of velocity microstructure profilers began in the early 1970s at the University of British Columbia, Canada under the leadership of T. Osborn. The first vertical turbulence profiler carrying airfoil shear probes was deployed in 1972 (Osborn, 1974). Throughout the 1970s and the 1980s, other research groups around the globe developed a great variety of vertical profilers, often with unique designs that were geared towards a specific scientific purpose. In the following, we describe some of the milestone developments of vertical microstructure profilers in four geographical regions: Canada, United States, Europe and Japan.

5.1 Canada

A series of vertical microstructure velocity profilers were developed by T. Osborn at the University of British Columbia (UBC) starting in the early 1970s. The first profiler (Fig. 19) was built by Osborn in 1972 (Osborn, 1974). The instrument was not distinguished by a catchy-sounding name, so we will refer to it as the "Osborn profiler." This profiler carried two shear probes to measure both components of the horizontal velocity fluctuations, a thermistor to measure temperature and the rate of change of temperature, a pressure transducer and a flux-gate compass to gauge the instrument's rotation about its vertical axis. A 46-cm-diameter glass sphere housed the signal conditioning and telemetry electronics. This sphere was mounted between two 36-cm-diameter PVC pipe sections, giving the entire assembly a close to cylindrical shape. An approximately one-meter long straight metal rod protruding from the lower end of the profiler held the sensor assembly and ballast weights. The instrument descended at a nominal rate of 0.25 m s^{-1} and rotated once around its center axis every 5 meters. The measured signals were multiplexed using frequency modulation (FM) and transmitted to the surface via a two conductor expendable wire link like the ones used on expendable bathy-thermographs. The wire link was incapable of transmitting any ship motions to the profiler because its breaking strength was only 2 N and it was very flexible. At the surface, the FM modulated signals were amplified and logged on audio tape recorder. The signals were also demodulated and displayed on a chart recorder. At a predefined depth, a stretched pin release dropped the two ballast weights and the instrument floated back to the surface.

Osborn's 1974 report from two cruises to Howe Sound, a fjord near Vancouver, shows that the velocity spectrum suffered from some low-frequency pendulum motions at frequencies below 0.2 Hz which is below the microstructure range. Vibration noise is evident in shear spectra above 100 cpm (20 Hz) but this is above the band of interest for dissipation rates smaller than 10^{-7} W kg^{-1}. Typical rates of dissipation measured were 3×10^{-9} W kg^{-1}. Osborn concluded "the airfoil probe combined with a free-fall instrument housing is ideal for studying the vertical current shear in the ocean."

The profiler's shortcomings in terms of handling, stability, and vibration were overcome with the second-generation profilers called the "Camel." This name was chosen because many people contributed to the development of the instrument; a "camel" is a colloquial expression for "a horse designed by a committee." The first Camel (Fig. 19) was constructed from a slender aluminum tube approximately 4 m long and provided the first measurements of dissipation rate in the Equatorial Undercurrent (Crawford and Osborn, 1980; Crawford, 1982). A set of chimney flue brushes was used to adjust the fall rate to 0.7 m s^{-1} and to provide a righting moment. For easier handling, Camel II and III (Fig. 19) were only 2 m long and 0.3 m in diameter. Camel II (Lueck and Osborn, 1982; Lueck *et al.*, 1983) was rated to 1000 m depth and, like Camel I and the Osborn profiler, it used an expendable wire link to transmit data to the ship. Camel III (Moum and Osborn, 1986) was externally very similar but was rated to 2000 m and recorded its data internally on a modified audio-cassette recorder. The Camel series carried two shear probes, one thermistor, one pressure transducer and a pair of orthogonal horizontal accelerometers. The dissipation noise level of Camel II and III was 3×10^{-10} W kg^{-1} and stemmed mainly from mechanical vibrations of the profiler which added a spurious signal to the environmental signal reported by the shear probes (Moum and Lueck, 1985).

In 1972, a research group surrounding N. Oakey at the Bedford Institute of Oceanography (BIO), in Nova Scotia, Canada, began the construction of a series of vertical microstructure profilers called Octuprobe (Oakey, 1977). Three incarnations of Octuprobe (Fig. 19) were produced (Octuprobe I, II, and III), all of which had an approximately 2 m long cylindrical pressure case as a main housing. The first model of Octuprobe was attached to the ship via a heavy, armored multi-conductor cable and, apparently, this tether caused strong vibrations that rendered the instrument incapable of measuring velocity microstructure. The second and third models of Octuprobe were tethered by a thin (6 mm) nylon line and fell at a speed of 0.5 m s^{-1} to a maximum depth of 500 m. Data were recorded internally on an audio tape recorder. Octuprobe carried two orthogonal Oakey-style shear probes, a four-terminal micro-conductivity probe with a spatial resolution of approximately 60 mm, a cold-film thermometer, a pressure transducer, and three orthogonal accelerometers.

The follow-up instrument to the Octuprobe was the EPSONDE (Oakey, 1988), which was developed at BIO around 1985 and copies of it are still in use today (Fig. 19). The main pressure case is 2.4 m long, which increased the instrument's righting moment and stability. EPSONDE carried essentially the same sensor suite as the Octuprobe. One FP07 thermistor augmented the cold-film thermometer and the custom-built micro-conductivity probe was replaced with a Neil-Brown conductivity sensor. In terms of data acquisition, the EPSONDE was radically different from all other instruments before it. The analog signals were digitized internally into 14-bit words and telemetered as a serial bit stream to the surface using a four-conductor Kevlar cable. The noise level of EPSONDE was approximately 3×10^{-10} W kg^{-1}, similar to the Camel series.

The FLY (Fast Light Yo-yo, Fig. 19) series of vertical profilers was started at the Institute of Ocean Sciences (IOS), British Columbia, in the early 1980's and borrowed heavily from the technology used in the EPSONDE profilers. Its major novelty was the ability to profile within centimeters of the bottom thanks to a probe guard attached to the lower end of FLY (Dewey *et al.*, 1987). The FLY series was extensively used to study benthic boundary layers and coastal regions and versions are still being used by researchers at IOS, the Dutch Institute of Oceanography (NIOZ) and the University of Bangor in Wales. With the probe guard attached, the noise level of the dissipation estimates was 3×10^{-9} W kg^{-1} which was satisfactory for near bottom measurements. With the guard removed, the noise level was almost ten times lower.

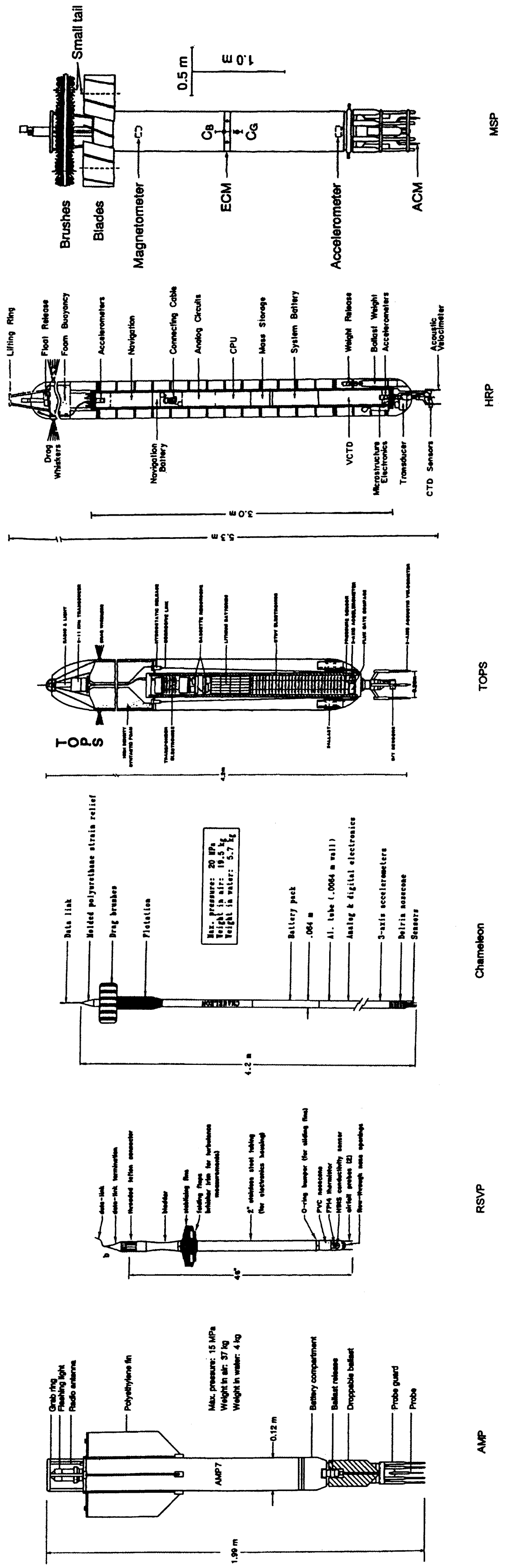

Fig. 20. Sketches of some of the vertical microstructure profilers developed in the US in the 1980s. Drawings and relative sizes of the instruments are not to scale. [Courtesy of D. Caldwell, J. Moum, R. Schmitt, and M. Gregg.]

5.2 US

M. Gregg at the Applied Physics Laboratory on the campus of the University of Washington (APL-UW) developed the first American profiler of velocity microstructure, the Advanced Microstructure Profiler AMP (Fig. 20). The general design of the AMP is based on the Canadian Octuprobe profiler, and it carries the Oakey-style shear probes. The AMP is the first profiler with a fiber-optic data link to the shipboard data acquisition computer, transmitting the measured data at a rate of 100,000 bits per second (Gregg *et al.*, 1982). The usual sensor suite comprises two shear probes, fast and slow response thermistors, a conductivity cell, a pressure transducer, and two horizontal accelerometers. The first models of AMP suffered from noise contamination which was identified by Miller *et al.* (1989) as the first bending mode of the pressure tube. This mode is excited by protruding instrument parts such as fins, probe guards, recovery cage, etc. The amplitude of these vibrations increases strongly with increasing decent rates. Using finite element analysis, Miller *et al.* (1989) re-designed the pressure case, making it slightly wider and shorter. This shifted the bending mode to 166 Hz and out of the band of interest. Because most microstructure profilers have a cylindrical, slender pressure case, the results of Miller *et al.* are of general interest for designers of microstructure profilers, and stipulate that these instruments should have short, stout pressure cases rather than long and slender ones. Unfortunately, this often conflicts with the need for stability and righting moment which is most easily achieved by lengthening the instrument. The AMP series of instruments have continually improved and several continue to serve the research work at APL-UW.

The Rapid-Sampling Vertical Profiler (RSVP; Caldwell *et al.*, 1985) was developed at the College of Oceanography, Oregon State University (OSU) by D. Caldwell (Fig. 20). The instrument was designed to be deployed from the stern of a ship steaming as fast as six knots, which permits rapid (near-synoptic) profiling along a section. The first prototype of RSVP was tested in 1982, and an improved version was deployed in 1983. Shear probes, however, were only retrofitted in 1984. The decent rate of the RSVP can be adjusted between 0.5 and 2 m s^{-1} by adding or removing ballast. The main body of the instrument is 1.14 m long and only 0.05 m in diameter, and is filled with oil. A membrane at the top of the body provides a pressure compensation, which eliminates the need for high-pressure seals. To suppress fishtailing motions during recovery when the profiler is hauled in behind the fast moving ship, the RSVP has a movable fin-assembly that freely slides along the body. Data from the airfoil probes, high-resolution thermistor, pressure sensor, and conductivity probe are transmitted via a Kevlar-reinforced cable to a shipboard recorder. Shear spectra measured with the RSVP (Caldwell *et al*., 1985, figure 14) are severely affected by vibration noise between 15 and 20 Hz, most likely due to strumming of the tether wire or contortions of the pressure case. Below 2 Hz, the shear spectra rise sharply due to slow pendulum motions of the profiler. The shear noise is about 5×10^{-9} W kg^{-1}.

Around 1988, J. Moum and D. Caldwell at OSU developed another profiler called "Chameleon" (Moum *et al*., 1995) (Fig. 20). Seven iterations of Chameleon with different sensor and body configurations were built. Currently, OSU has five working Chameleon profilers, which are in active use. This instrument descends at a nominal rate of 0.8 m s^{-1}, carries the usual suite of sensors, and transmits data in real-time to the ship. The instrument body is usually 2 m long and 64 mm in diameter, but can be extended to a total length of 4 m by adding tubes to the middle of the body. Even though Chameleon has a large ratio of length to diameter, vibrations (at 15 Hz and its harmonics) are small and this instrument resolves dissipations down to 2×10^{-10} W kg^{-1}.

The size and weight of most microstructure profilers and the fragility of their sensors sometimes precludes the deployment of these instruments during severe weather and in shallow seas. The Expendable Dissipation Profiler (XDP) was conceived by T. Osborn and developed in the mid 1980s by T. Osborn and R. Lueck to study turbulent layers separating from the side walls of Monterey Canyon (Lueck and Osborn, 1985). The XDP produces profiles right to the very bottom of the sea floor, where the shear probe is frequently destroyed upon impact. The XDP is 0.05 m wide and 0.6 m long, weighs less than 30 N and carries one shear probe and one thermistor. It descends at 2.7 m s^{-1} and its depth is determined from time of flight. The data are transmitted as FM signals through a fine wire link. The original version had a maximum depth of 500 m and a 1000 m version was used to study the Mediterranean outflow (Johnson *et al*., 1994).

A special breed of turbulence profilers that emerged in the early 1980s are the so-called multi-scale profilers. These instruments are designed to measure turbulent and non-turbulent velocity and velocity shear over all vertical scales, from the microstructure range to the full depth of the ocean. These instruments are long (order 5 m) so that they have the stability to measure velocity with vertical scales of several meters. To reduce vibrations, they have considerable inertia from their own mass and that of entrained water. Typical sensor configurations consist of passive electromagnetic current meters, acoustic current meters, shear probes, and a CTD. The horizontal current and its vertical shear on scales between 20 m and the full depth are usually inferred by ranging to carefully surveyed bottom-mounted acoustic transponders. The time derivative of the position of the profiler then gives the large-scale horizontal velocity field (Luyten *et al*., 1982). Velocities with shorter vertical wavelength are measured directly with an onboard acoustic current meter. The microscale of velocity is measured with shear probes. The model of Hayes *et al*. (1984) is usually applied to determine the velocity of the vehicle for vertical scales comparable to the length of the profiler.

The first multi-scale profiler (MSP; Winkel *et al*., 1996; Fig. 20) was developed by M. Gregg and T. Sanford at the APL-UW in 1980. MSP carries a geo-electromagnetic current meter that senses the voltage induced by horizontal currents due to their motion through the earth's magnetic field. These measurements are unaffected by horizontal motion of the instrument and are used to correct the fine-scale velocity data collected with the instrument's acoustic current meters. A set of shear probes completes the sensor array. The MSP is 4.3 m long and has a diameter of 0.4 m. A pressure case that houses the electronics package is at the core of the main body, and the space between the pressure case and the outer shell is flooded with water to increase the instrument's inertia. The effective mass is approximately 400 kg. MSP is a true free falling vehicle that records data internally.

The Absolute Velocity Profiler (AVP) is an old fine-scale velocity profiler that was recently upgraded by T. Sanford with shear probes to convert it into a multi-scale profiler. The AVP was used to measure velocity and turbulence in the North Atlantic Deep Western Boundary Current at the Blake Outer Ridge (Stahr and Sanford, 1999). Although this instrument was never intended for microstructure velocity measurements, careful cushioning of the shear probes allows the instrument to resolve dissipation rates as small as 3×10^{-9} W kg^{-1}.

In the mid 1980s, R. Schmitt and J. Toole of the Woods Hole Oceanographic Institution developed the High Resolution Profiler (HRP; Schmitt *et al*., 1988; Fig. 20), which is also a multi-scale profiler capable of reaching full ocean depth. It is 5.3 m long and has an outside diameter of 0.38 meter (including flooding cells). Like the MSP and AVP, HRP is a true free-fall profiler without a tether. The sensor suite routinely comprises CTD probes, microstructure sensors (shear, fast temperature, and high resolution conductivity), as well as an acoustic current meter for fine-scale velocity measurements. HRP tracks its position by ranging to an array of bottom-mounted transponders. The instrument can carry an optical shadowgraph system described by Converse *et al*. (1986) to take images of the microstructure of temperature and salinity. Data are recorded internally. Velocity spectra and velocity shear spectra measured by both MSP and HRP exhibit anomalous features on scales corresponding to the length of the instruments (about 5 m), but these "kinks" in the spectra are removed by applying the dynamic response model of Hayes *et al*. (1984). Spectra of microstructure shear are free of spurious vibration components and the noise level of the dissipation estimates made with HRP are the lowest obtained with any instrument to date. Owing to its large inertia and extremely smooth exterior, HRP routinely reports rates of only 3×10^{-11} W kg^{-1} in deep abyssal waters far from boundaries.

5.3 Europe

Velocity microstructure measurements in Europe began in 1970 with the development of the free-fall profiler PROTAS (Probe Recording Ocean Temperature and Shear; Fig. 21). The instrument was developed by J. Simpson at the University College of North Wales, Bangor, UK (Simpson, 1972). It was used on several cruises in mid 1970s. PROTAS seems to be the first profiler judiciously designed with a slender, cylindrical pressure tube as its main structure. The large aspect ratio of the instrument reduced its pitching motions in response to large-scale vertical shear. This construction later inspired modifications of the initial Osborn profiler (Osborn, 1974), leading to the design of Camel. PROTAS sensed shear by measuring the motion of a neutrally buoyant vane that was attached by a universal joint to a frame protruding forward from the main pressure case. During the descent, changes in the horizontal velocity encountered by the probe caused a displacement of the vane. The position of the vane was determined from the electrical resistance between a pick-up electrode mounted on the vane and two pairs of fixed electrodes rigidly attached to the frame. The vertical spatial resolution of this velocity sensor was of the order of 0.3 m and was determined, in essence, by the length of the vane.

Until the late 1980s, reports on microstructure research in Eastern Europe were sparse, and the few reports that did appear in the open literature were mostly in German or Russian. In the former German Democratic Republic ("East Germany"), microstructure research was carried out by a group surrounding H. Prandke at the Institute for Marine Research, Warnemünde. Microstructure measurements began with the MSS profiler (Mikrostruktursonde; Prandke *et al.*, 1985), which was developed for investigations of the pycnocline structure in the Baltic Sea. The MSS descended along a pair of guide wires that were heavily ballasted and suspended from a ship. This setup prevented any lateral drift of the instrument relative to the ship. It was possible to attach a horizontal boom carrying fast-response thermistors separated by any distance between 0.001 and 2 m. This provided two simultaneous profiles of high-resolution temperature (Prandke and Stips, 1985, 1992). A subsequently modified version of the MSS86 did not have the guide wire and was deployed using an elaborate, computer-controlled winch system. From 1990, MSS86 also carried airfoil probes. The MSS86 was used until 1992.

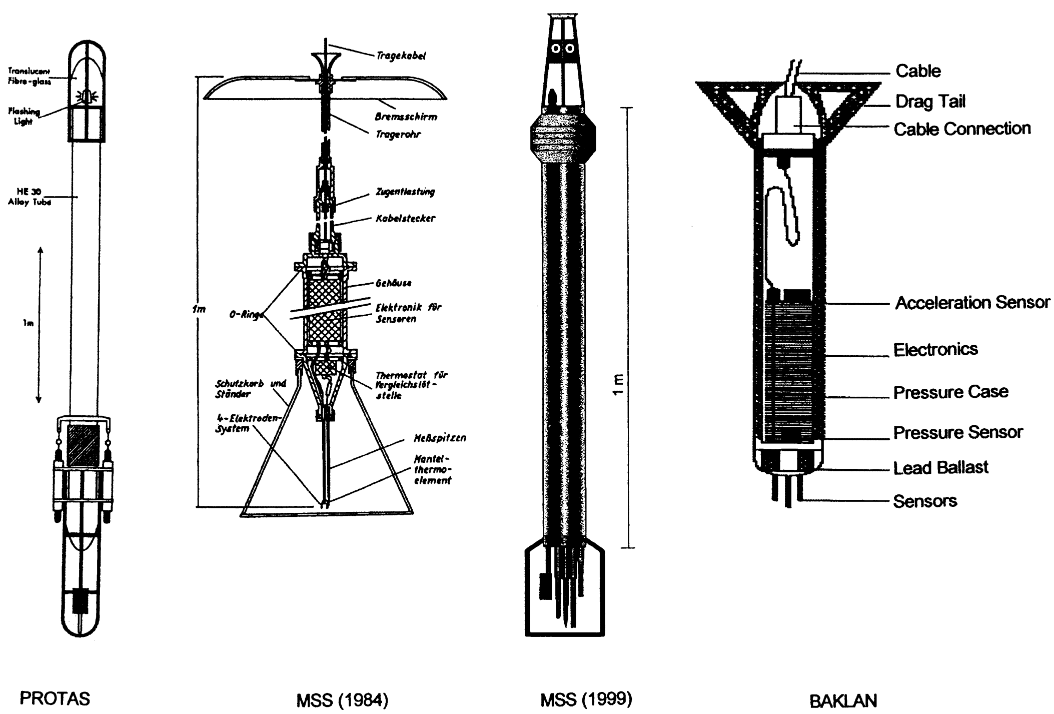

Fig. 21. Sketches of some of the vertical microstructure profilers developed in Europe between 1974 and 1999. Drawings and relative sizes of the instruments are not to scale. [Courtesy of J. Simpson, H. Prandke, and V. Paka.]

The formal development of a “European” microstructure profiler began in the early 1990’s at the European Commission’s Joint Research Centre in Ispra, Italy (Prandke *et al.*, 2000). The so-called MST (Microstructure Turbulence) Profiler was based on the MSS86 (Fig. 21) profiler and many of the technical experts formerly with the Institute in Warnemünde were engaged in this project. The latest profiler was again named MSS (Fig. 21). Unlike most North American microstructure instruments, it is quite short, with an overall length of approximately 1.4 m. The instrument is equipped with CTD sensors, Prandke-style airfoil probes, and fast-response thermistors. Data are transmitted to a shipboard computer via a loose Kevlar tether. The instrument can be deployed in a freely sinking or uprising fashion, which facilitates turbulence measurements near the air-sea interface. In uprising mode, the profiler is trimmed to be positively buoyant and operated with an underwater winch or pulley system.

The P. P. Shirshov Institute of Oceanology in Kaliningrad produced a vertical microstructure profiler called BAKLAN (Arvan *et al.*, 1985; Paka *et al.*, 1999; Fig. 21), which was deployed extensively in the Atlantic and Pacific Oceans and the Mediterranean and Black Seas between 1985 and 1991, when it suffered the “seaman’s death” in the Atlantic. When integrated into a tow body, the profiler could also be used for horizontal measurements. The overall design of the instrument is similar to the Octuprobe (Oakey, 1977). The main body was a cylindrical pressure case with a maximum diameter of 0.15 m and an overall length of approximately 2.6 m. The sensor set could be modified depending on the scientific objectives, and usually consisted of two orthogonally oriented shear probes, CTD probes, and a microstructure conductivity sensor with a spatial resolution of approximately 12 mm. A vertically oriented accelerometer reported the tilt of the instrument. All sensor output signals were digitized with a 15-bit A/D converter and transmitted to a shipboard computer.

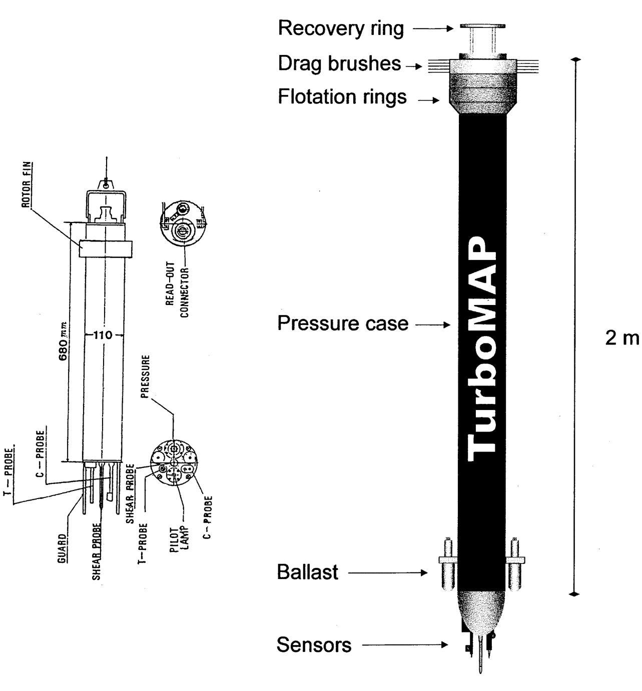

Fig. 22. Sketches of two Japanese vertical microstructure profilers developed in the 1990s. Drawings and relative sizes of the instruments are not to scale. [Courtesy of S. Kanari.]

5.4 *Japan*

In Japan, microstructure measurements were initiated around 1988 by S. Kanari at the Hokkaido University, where he developed the Micro-Scale Profiler (MSP; Kanari, 1991). The original MSP (Fig. 22) was a small and light instrument, measuring only 0.8 m in length. The signal conditioning and data acquisition electronics and battery were housed in a 0.1-m-diameter PVC pressure tube. Data from the shear and CTD sensors were recorded at a rate of 100 Hz and stored internally in a solid-state memory package. The memory package could record the data for a single cast. The shear probe used on MSP was slightly longer and wider than the Osborn-probe but had a similar shape. However, it used a silicon strain gauge to sense the cross-stream force which gives this probe a much poorer sensitivity than a piezo-ceramic probe. An uprising version was also developed by Kanari and has been used by Y. Takasugi of the Chugoku Industrial Research Institute in Hiroshima to take measurements in shallow coastal waters (Hashimoto and Takasugi, 1998).

In 1996, H. Yamazaki at the Tokyo University of Fisheries initiated the development of a new microstructure profiler, TurboMAP (Turbulence Ocean Microstructure Profiler; Fig. 22). This instrument is tethered by a 5 mm Kevlar cable. It is 2.1 m long, 0.15 m in diameter and weighs 350 N in air and 30 N in water. Its nominal rate of descent of 0.5 m s^{-1} can be adjusted by adding or removing buoyancy elements. TurboMAP samples each sensor at a rate of 256 Hz and either records the data internally in a 200 MB array of non-volatile RAM or transmits them up the tether. TurboMAP carries the standard microstructure sensors (shear probe and FP07 thermistor), CTD sensors, and internally mounted accelerometers. In addition, it also carries a unique high-resolution bio-optical sensor. This backscatter-type sensor simultaneously measures in-situ chlorophyll and turbidity and resolves scales as small as 0.02 m (Wolk *et al.*, 2001). The high spatial resolution of the optical probe matches that of the shear probe and FP07 and, thus, makes it possible to study the effect of turbulent velocity fluctuations upon biological constituents in the ocean. Shear and acceleration spectra reveal some vibrational noise spikes at 60 Hz and 80 Hz. The latter has been identified as the first bending mode of the pressure case (Miller *et al*., 1989). The frequencies and the amplitudes of the noise spikes do not affect the measured shear spectra (Wolk *et al*., 2002) and the dissipation noise is 3×10^{-10} W kg^{-1}.

6. New Approaches

A limitation of conventional microstructure measurements is that they only provide a profile along one coordinate. Thanks to rapidly improving computer and optical technology, it is now possible to image two velocity components in a plane using a Particle Imaging Velocimeter (PIV). The PIV system described by Bertuccioli *et al*. (1999) uses a digital camera with a resolution of 1024×1024 pixels to image a square with 0.2 m sides. This square is illuminated twice and in rapid succession by a sheet of laser light, which captures the change of position of particles within the field of view. The cross-correlation between two images is used to estimate the change in position of the particles in each 4×4 sub-domain in the image. This change in position, when divided by the time between successive illuminations, gives (by definition) the two-dimensional velocity field from which one can derive the two-dimensional spectrum of both shear and the rate of strain. The resolution is sufficient to provide wavenumber spectra in the microstructure range. Images collected in the ocean benthic boundary layer by Doron *et al*. (2001) at heights of 0.1 to 1.4 m above the bottom provide very interesting, yet somewhat disturbing, results. The ratios of the spectra of strain and shear are not consistent with isotropy in the microstructure range and the strain spectra depart significantly from the Nasmyth spectrum. Nimmo-Smith *et al*. (2001) improved the PIV system reported by Bertuccioli *et al*. (1999) by increasing the sides of the image square to 0.5 m and the image resolution to 2048×2048 pixels.

An instrument that images the three-dimensional motion of passive and actively swimming plankton was demonstrated by Gallager *et al*. (2002). The instrument uses a two-axis video system mounted on a two by two meter frame. The frame itself is attached to the front of the ROV Jason. The system can be positioned at various depths, and control signals and data are passed to the ship through a fiber-optic tether. The field of view is 6.1 by 5.2 by 7.3 cm (width, height, depth). The Lagrangian velocity power spectra obtained with this method have k^{-2} slope in the inertial subrange, demonstrating that the spectral features of swimming planktonic organisms are different from those of passive particles.

7. Summary

The in-situ measurement of velocity fluctuations in the microstructure range requires a stable platform that moves smoothly through the water in this range, sensors that can resolve (temporally and spatially) the fluctuations in this range and a signal conditioning and sampling system. When Grant and his colleagues attempted the first oceanic turbulence measurements in the late 1950s, their instrumentation was cutting-edge technology. Nevertheless, vast technical improvements have been made and our understanding of ocean turbulence has grown in step with these changes. Major improvements include the development of stable hot-film anemometers, the shear probe, fast thermistors, hybrid long-line towing, and large-scale velocity sensors (acoustic and geo-electromagnetic). The size of platforms ranges from the tiny XDP weighing less than 30 N to full-size submarines and this enormous range of scale reflects the effort that has been devoted to microstructure profiling. The recent deployment of PIV systems and related instruments promises a multi-dimensional view of oceanic turbulence that will surely challenge many of our current notions and reveal the effect of turbulence on micro-biological activity.

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