CSIRO
Division of Fisheries and Oceanography

REPORT 133

Simple Physical Oceanographic Techniques for Use in Coastal Waters

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1981

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION
DIVISION OF FISHERIES AND OCEANOGRAPHY
P.O. BOX 21, CRONULLA, NSW 2230

National Library of Australia Cataloguing-in-Publication Entry

Pearce, Alan.

Simple physical oceanographic techniques for use
in coastal waters.
Bibliography.

ISBN 0 643 02650 9.

1. Ocean currents—Measurement. I. Commonwealth
Scientific and Industrial Research Organization
(Australia). Division of Fisheries and
Oceanography. II. Title. (Series: Report
(Commonwealth Scientific and Industrial
Research Organization (Australia). Division of
Fisheries and Oceanography); 133).

551.47'01

Printed by CSIRO, Melbourne.

The title of this series is to be changed. The last *CSIRO Division of Fisheries and Oceanography Report* will be number 136. Subsequent Reports will be issued as *CSIRO Marine Laboratories Report*, the first one being number 137.

81.275-800

SIMPLE PHYSICAL OCEANOGRAPHIC TECHNIQUES FOR USE IN COASTAL WATERS

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Aust. CSIRO Div. Fish. Oceanogr. Rep. 133 (1981)

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PREFACE

A knowledge of currents is of great importance in coastal areas for such purposes as effluent disposal, movement of pollutants (e.g. oil slicks), shipping, sediment transport, transport of marine organisms, etc. However, measurement of the currents is by no means easy, bearing in mind the temporal and geographical variability of coastal water movements.

The range of techniques for measuring currents is immense, varying from the most simple methods to highly complex (and expensive) instruments. Part 1 of these notes deals mainly with simple and relatively cheap methods for measuring currents on the continental shelf. Generally, techniques for measuring near-surface currents will be different from those used for near-bottom currents. Two basic approaches have been adopted for direct current measurements:

(a) devices which drift with the water ("Lagrangian" methods), such as drift cards, drogued buoys, ship-drifts, satellite-tracked buoys;

(b) measurements at a fixed point ("Eulerian" methods), such as moored buoys, current meters.

In addition, indirect methods such as calculating the currents from the water density (the "dynamic" method) or remote observations (such as from satellites) can be useful. For a good understanding of the current system it is generally desirable to use both Lagrangian and Eulerian methods.

Part 2 covers a wider range than the sections dealing with current measurements, but is not as detailed. It deals with oceanographic measurements other than currents, and will also concentrate on relatively shallow water, i.e. on the continental shelf. The basic requirements for any instruments to be used in the sea are that they be as simple as possible, cheap, strong, reliable, easy to handle, easy to operate and easy to recover; it is useful to be able to check that they are recording correctly.

It may be emphasised here how important it is to log all relevant information accurately and neatly, and to check it at the time it is written down. A log-book or log-sheets should be used to record all station numbers, times, what exactly has been measured (e.g. XBT number) etc. and it is important that any unusual feature be noted, such as a suspected malfunction of the instrument or any abnormal procedure. It may be impossible to correct faulty observations later, and doubts about the accuracy of a station in any form may cast doubts on the analysis and interpretation of a number of adjacent stations. All station sheets, stripcharts from recorders, and log-sheets of all kinds must be clearly marked with cruise number, date, scales used, times, etc.

These notes were originally prepared for a few lectures given to Asian technicians at a training course in Townsville, so explanations have been kept as simple as possible and advanced/expensive measuring techniques have been avoided.

PART 1: SIMPLE CURRENT MEASUREMENTS

DRIFTERS

Freely-drifting objects have been widely used in the past to give a rough idea of large-scale water movements, although continuously-tracked drifters will of course show up smaller-scale variability as well. A few such drifters are discussed here.

1. *Surface Drift Bottles or Drift Cards*

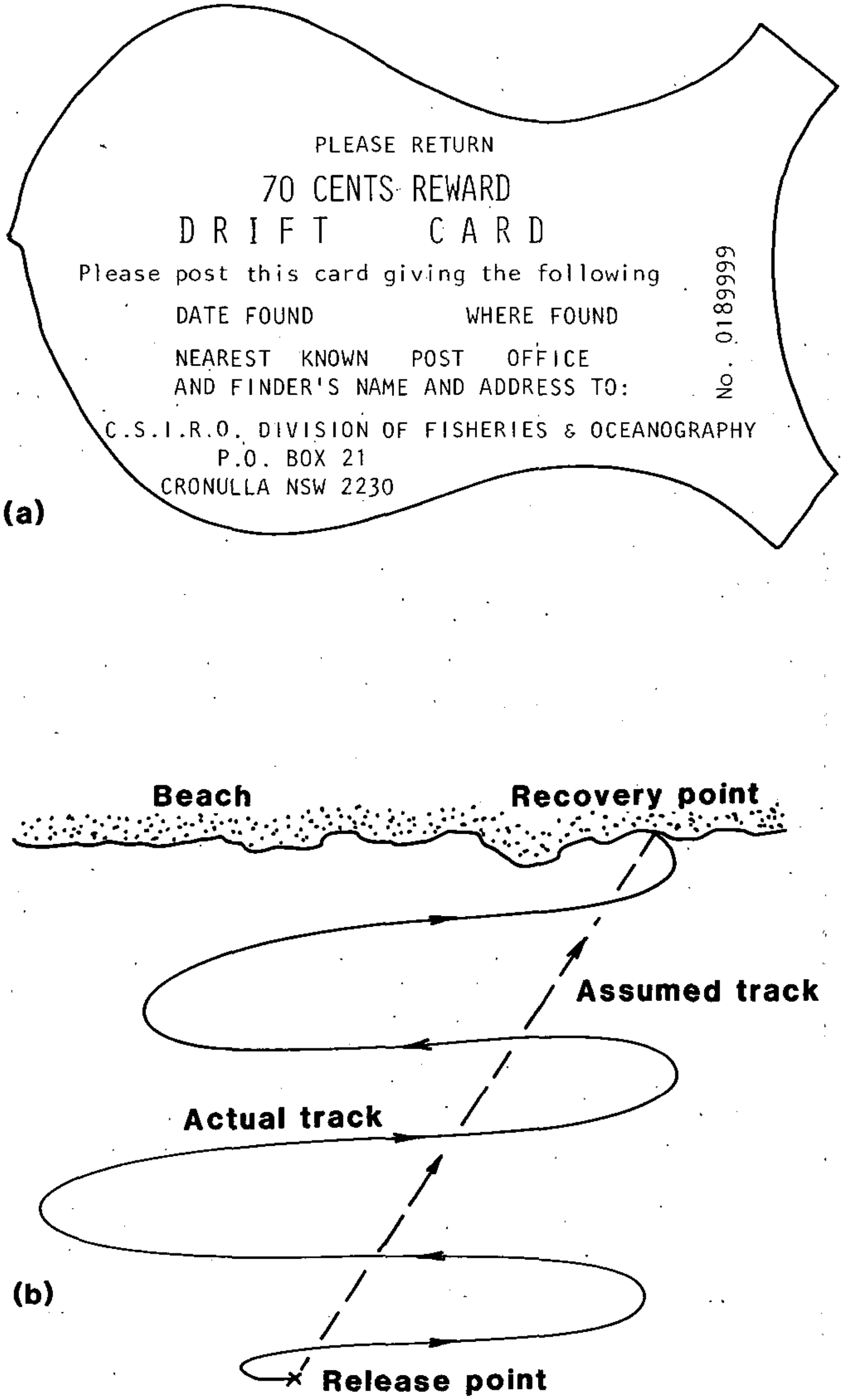
This is probably the cheapest (and oldest) direct method of current measurement, and can give extremely valuable data in situations such as semi-enclosed bays which are well populated. Originally bottles were used, containing a message which requested the finder to send in the location and date of recovery of the bottle to the relevant agency; these bottles sometimes had submerged drogues attached to them so that they would follow the deeper water and be less affected by surface wind. Bottles were superseded by drift cards, i.e. postcards enclosed in transparent plastic envelopes, again requesting the finder to return the card and other information about its recovery. These could be weighted so as to float vertically and thus be less affected by wind in the thin surface film of the sea, but it was found that the envelopes were frequently damaged and might sink, or the card inside become damp and illegible. Most recently, therefore, plastic cards have been used, in a bright red colour to attract attention when they reach the beach, and of such a density as to float in the surface layer. An example is shown in Fig. 1a. The card is numbered (so that its release details are known), the finder must return it with details of its location and date when found, and a small reward with a "thank you" letter is then sent to the finder. Because they are very cheap (they cost about 50¢ to 60¢ each to produce in large quantities) and because normally only 5% to 50% are ever recovered, drift cards are generally released in batches of 10 to 50 at a time, at various sites, and on many different occasions.

One of the main disadvantages of the method is that the actual path of the drifter is not known — it may have oscillated backwards and forwards many times before ending up on the beach, and it may also have been stranded on the beach for many days or weeks before being found (Fig. 1b). The assumed track must then be the straight line from the release point to the recovery point, and the assumed drift time is from release to actual finding — both these errors will result in a lower average current speed than actually existed. However, the recovery point will show the final destination of drifting matter such as oil particles, and the track will also give the *minimum* speed to that point. To summarize, the advantages of drift cards are:
(i) very cheap and easy to produce;
(ii) can be easily released from a small boat or an aircraft in large numbers.

The disadvantages are: (i) may be affected by the wind to a large extent; (ii) actual track and therefore velocity to the beach not known; (iii) under some conditions, such as offshore winds or currents, recoveries may be small.

2. *Near-surface Tracked Float-drogues*

The problem of not knowing the actual path of a drift card can be overcome by tracking it continuously, but it is then usual to construct a bigger float to make it more visible. However this increases the problem of surface wind effects, and a subsurface drogue must be attached to the float so that it will follow the water movements better.



PLEASE RETURN

70 CENTS REWARD

DRIFT CARD

Please post this card giving the following

DATE FOUND WHERE FOUND

NEAREST KNOWN POST OFFICE
AND FINDER'S NAME AND ADDRESS TO:

No. 0189999

C.S.I.R.O. DIVISION OF FISHERIES & OCEANOGRAPHY
P.O. BOX 21
CRONULLA NSW 2230

Fig. 1. Driftcards.

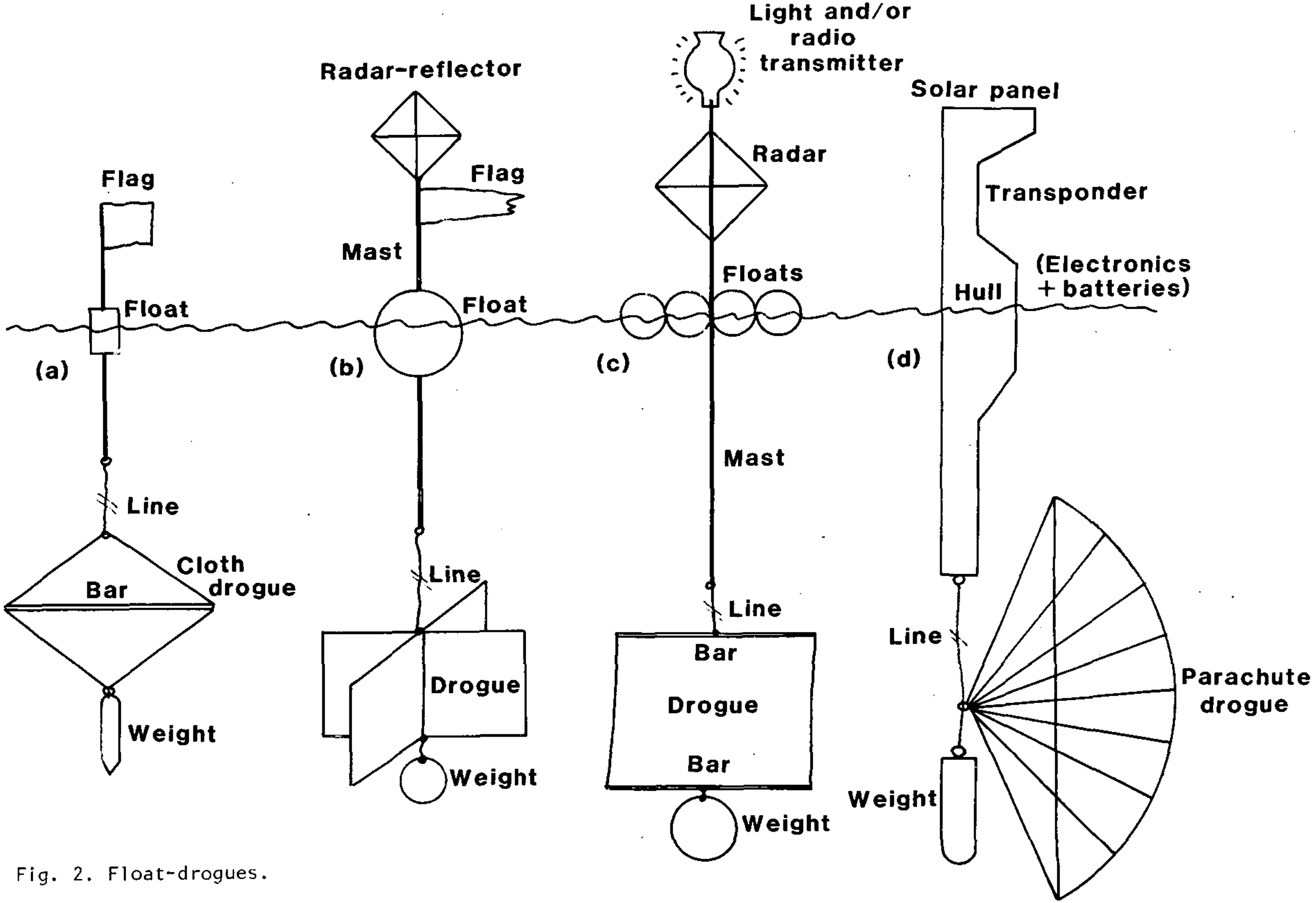


Fig. 2. Float-drogues.

Such float-drogue systems can be fairly simple and cheap (Fig. 2a), rather more substantial (Fig. 2b), or very expensive and elaborate (Fig. 2c,d).). They all have in common: (i) a float, to support the drogue as well as a flag, radar reflector, etc; (ii) a drogue of some kind to lock it to the water; (iii) a means of identifying and tracking the float.

Floats

Small floats can be made from tin cans or blocks of plastic foam; for larger floats, a number of plastic floats can be used, and in the biggest floats (such as for satellite-tracked buoys) the float is a strong hull some two metres long and containing expensive electronic gear and batteries — these buoys are designed to be tracked for many months, whereas the smaller floats are usually followed for a few hours only.

Cheap floats of the type shown in Fig. 2a can be produced in large quantities and tracked for a few hours; they need not be recovered. By rolling them up and wrapping them in newspaper held loosely with glue, they can be dropped from a low-flying aircraft and tracked from shore (small dye-bags attached to the floats assist in finding where they first hit the sea), out to a few kilometres from the coast. It is useful to paint a number on each float, so that if any are washed ashore it will be known where and when they were released.

To minimize the effect of wind and surface currents, the float should be as small as possible and project above the surface as little as possible, and yet be large enough to support the mast and the drogue.

Drogues

There are many drogue designs, all claimed to have some particular merit, but the basic necessity is that they should be as large as possible, and at least many times larger than the surface float — this is important if the float-drogue is to follow the current at the drogue depth rather than the wind or surface current.

For the cheapest drogues, a simple square of cloth can be used, with a cross-bar to hold it open and a weight at the bottom to keep the float and pole vertical. These "window-blind" drogues work surprisingly well despite their simplicity.

More elaborate drogues include rigid crosses made from aluminium or plywood, although these can be folded for storage; cloth in a metal frame can also be used. Again they should be as large as possible, and because of the extra cost they are often recovered after tracking.

For the largest floats, such as the satellite-tracked buoys, parachute drogues are suitable. Some form of spreader to ensure that the parachute does not collapse when the current is very small may be desirable, and there may also be some difficulty in getting the parachute to fully open initially.

Tracking Techniques

Once again, these vary from extremely simple visual techniques to expensive radio or satellite tracking.

(a) For current measurements within a few kilometres of the coast, simple visual methods will suffice in good weather conditions. Small floats with brightly coloured flags (red or orange are most suitable) can be tracked from the shore either by an optical rangefinder or by a pair of theodolites (Fig. 3a). A 3m base rangefinder at a height of say 30 to 50m has been used to track floats over a few hours at distances of up to 5 km in sunlight and fairly calm winds. The rangefinder enables the range and bearing (i.e.distance and

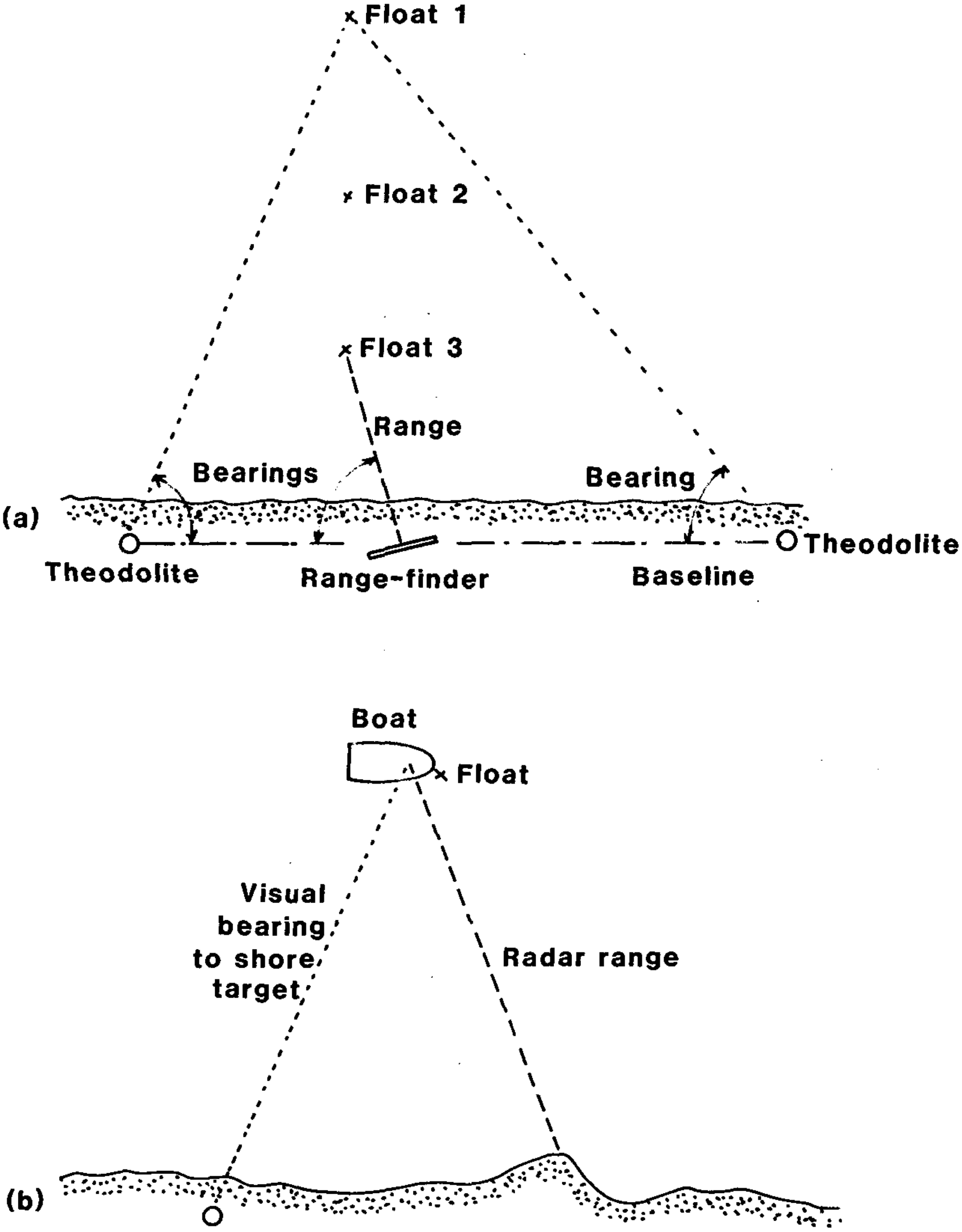


Fig. 3. Free-drifting float tracking near the coast.

(a) Position-fixing by theodolite or rangefinder.
(b) Position-fixing from vessel.

angle) to be found from a single observation point. A pair of theodolites about 3 km apart can be used to give two accurate bearings to the float; the two operators must be in radio contact to ensure that they make simultaneous observations, and the positions of the theodolites on the coast need to be known accurately.

The procedure for this work would generally be as follows: (i) Set up rangefinder or theodolite stations, as early in the day as possible. (ii) Release the floats either from a ship or aircraft, telling the shore station(s) by radio or a signal each time; (iii) Get an initial fix immediately — the position of the boat, which is readily visible, is a great help, but floats dropped from an aircraft should be observed through binoculars as they hit the sea, and a bright dye patch is an added help. (iv) Fix the float positions at regular intervals — follow them closely for the first half-hour and plot their positions accurately on a plotting sheet, so that their initial speed and direction of travel are known. This helps in finding them again for later fixes. (v) Depending on sun and sea conditions, track the floats every half-hour or so until they move out of range. Plot each fix immediately to check for errors in readings. (vi) Estimate the current speed and direction from the plotted tracks, either as say hourly vectors between fixes and/or an average velocity for the entire track.

It is useful (if not essential) to have another person copying down the fixes and plotting them continuously. The advantages of using this method are: (i) The floats are cheap and easily constructed. (ii) A number can be released from either a small boat or an aircraft. (iii) Tracking from the shore is relatively simple (although the rangefinder or theodolites may be expensive). (iv) Plotting of the data is simple, errors can be checked immediately, and the current velocities are easy to calculate. Disadvantages include: (i) The weather must be good — if the sky is heavily overcast, or the sun is reflecting off the sea into the observers' eyes, or if wind causes rough seas and white caps, the floats may be difficult to see and to fix accurately. (ii) If dropped from an aircraft a few floats may fail. (iii) Tracking is restricted to daylight hours and ranges of a few kilometres from shore. (iv) Setting up permanent rangefinder stations can be laborious, as they are large and heavy, and must be protected against vandals. Theodolites can be easily set up but need constant communication between the two bases to ensure simultaneous fixes, which becomes difficult when weather conditions are marginal.

(b) There are several variations on this basic method. (i) The floats can be tracked from a small boat (Fig. 3b), which regularly comes alongside each float and fixes its position by normal position-fixing methods (discussed later). If the floats are moving quickly or separating, and if the sea is rough, it may be very difficult to keep track of all the floats. Once again, it is important to plot all fixes immediately onto a plotting chart. Each float must be individually identifiable by number or colour to avoid confusion between floats. (ii) Fitting a strong light to the mast (Fig. 2c) enables a float to be tracked at night. It may prove rather difficult to focus on the light using a rangefinder, whereas theodolites can still get accurate bearings. The extra weight of the light and the batteries will necessitate both a stronger mast and a larger float, and a correspondingly larger drogue and heavier weight at the bottom. The net result is a larger, more expensive float which is more difficult to handle and which may no longer be viewed as expendable. (iii) As the next step, a radar reflector can be fitted to the mast (Fig. 2c). This must be large enough and high enough above the sea surface to register on a radar screen either aboard ship or ashore, and therefore requiring a much larger and heavier float than the simple version described earlier. Radar will enable buoys to be tracked over greater ranges during both day and night, but in a choppy sea wave clutter can obscure the signal; strong winds will have a relatively large influence on the radar reflector and hence affect the float track. (iv) A radio transmitter can be installed on the float, and tracked using radio direction-finders. Although these direction finders may not give very accurate bearings (especially cheap versions), the floats can be followed for ranges up to 100 km or more and over long periods, regardless of day or night, fog, rough sea, etc. The method has great promise, one of the main difficulties being obtaining permission from radio communication authorities to operate the transmitters.

(c) Probably the most sophisticated technique involves the tracking of buoys by satellite (Fig. 2d). Because of the complexity, the method is only briefly mentioned here. The buoys are large (2 to 5 m long) and heavy, and contain batteries to power a transmitting unit. Each time the satellite passes overhead, the position of the buoy is fixed by the satellite, which then relays its position to the receiving station. CSIRO buoys are fitted with solar panels to recharge the batteries, and in this way ocean currents have been tracked for a period of years.

(d) At the other extreme of complexity, dye patches can be tracked by aerial photography. If small bags containing a dye such as fluorescein or rhodamine are dropped from an aircraft, a succession of aerial colour photographs will show the water movements in the near surface layer. It is necessary to include some reference points in the photographs, such as the coastline, islands, reefs, or anchored marker buoys, and it may be necessary to drop more dye into the dye patches after say 2 hours as they diffuse and grow weaker. Disadvantages of this method are the expense of an aircraft flight of a few hours, possible difficulties in estimating the true positions of the patches (particularly if the photographs were not taken vertically downwards), difficulty in estimating the true centre of the dye patch (especially when the patch is greatly distorted by turbulent and shear processes, or when the sea is very silty), and the need for good visibility.

3. *Deep and Bottom Drifter Tracking*

On the continental shelf, seabed drifters (which are used in exactly the same way as driftcards) can be used to give a rough indication of bottom currents. These are shaped like umbrellas, are made of buoyant plastic so that they will just float, and a small metal sleeve is attached to the base of the stem to make them sink (Fig. 4). They therefore stand on the seabed and drift with the bottom currents. They are released in batches, and may be recovered on beaches or occasionally trawled up by fishermen. When the card is returned to the research institute, the finder is sent a small reward. As in the case of drift cards, the actual track between the release and recovery points is not known, but in semi-enclosed bays or regions where onshore bottom currents dominate, these drifters give a fair indication of bottom water movements. Generally, recovery rates are lower than those for driftcards.

In deep water, subsurface currents can be studied using "Swallow floats", which are designed to float at specified depths and are therefore

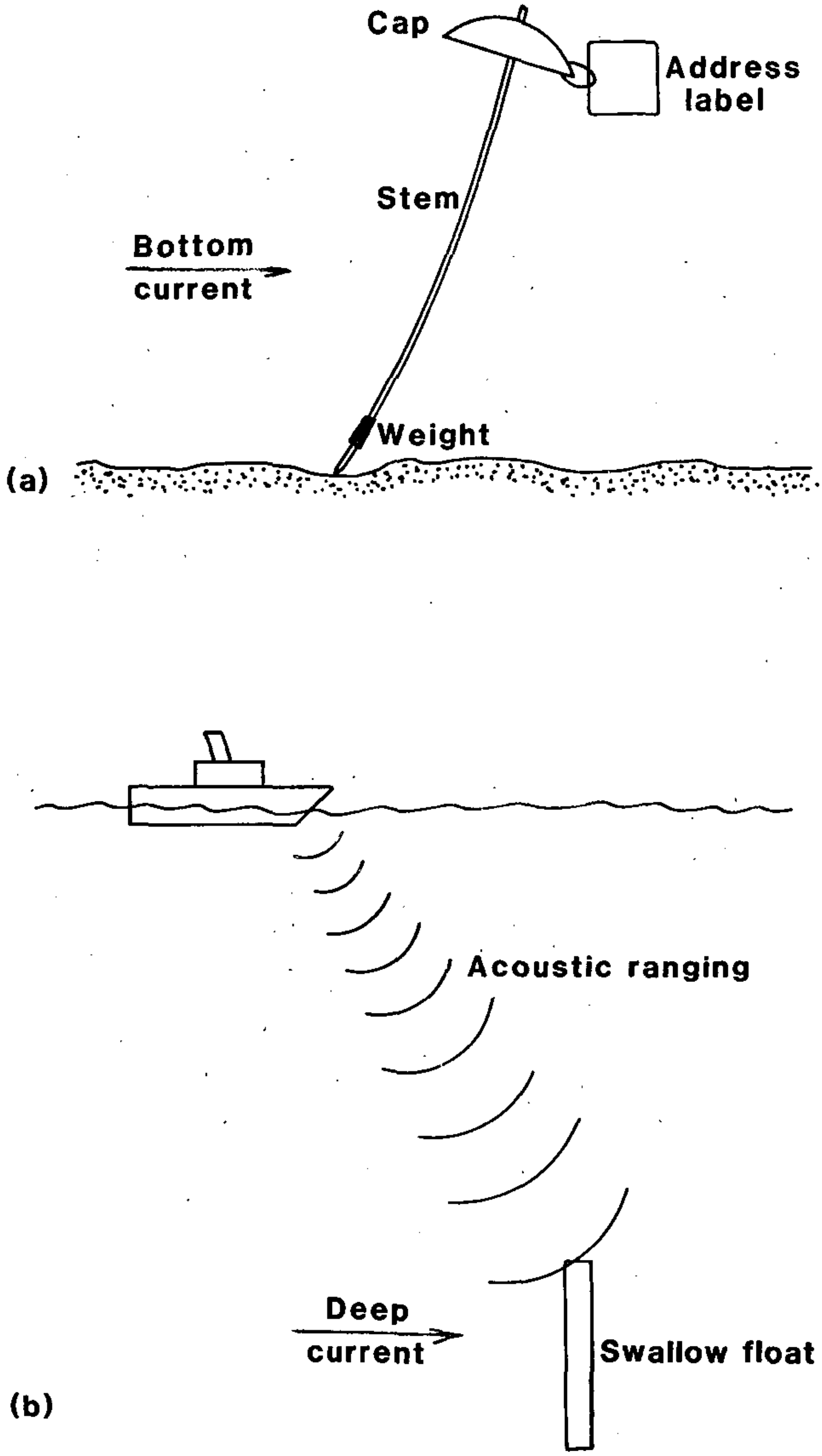


Fig. 4. (a) Seabed drifter for bottom currents.
(b) Swallow float (neutrally buoyant float) for deep current tracking.

transported by the currents at those depths (Fig. 4b). They are tracked by acoustic means from a surface vessel, and have shown up some interesting deep current patterns.

MOORED INSTRUMENTS

While the drifters described above will show the path taken by a water body, instruments at a fixed point will indicate the variability of the currents at that point. There is a tendency for increasing complexity and cost in current meters, but some quite simple techniques are available to give an overall impression of water movements near the coast.

1. *Tethered Floats*

The system illustrated in Fig. 5 has been found to be most useful in measuring nearshore surface currents. It consists basically of three floats (or buoys) of different colours. One float is anchored to the seabed and acts as a reference point. The centre float is tethered to the reference float by a buoyant line of say 10m length. The end float has a drogue attached to it, and is tethered to the centre float by a weighted 10m line.

The principle of operation is thus: when a current is flowing, it creates a drag on the floats and lines them up with the flow. It also imposes a drag on the drogue and outer float which are therefore pulled away from the centre float by an amount proportional to the current speed. However, the distance between the reference and centre floats is constant. The relative distances between the outer and centre floats and the centre and reference floats gives a rough estimate of the current speed, and the current direction is obtained from the direction of the buoys as a whole.

In practice, the spacing between the buoys is found either using a telescope (or binoculars) of appropriate power, with a grid engraved in the eyepiece, or using a theodolite. The current speed must be read from a calibration curve, while the direction can be calculated from the float spacing or (for convenience) read from a graph. It is an advantage if the observation site is as high as possible, as this enables greater ranges to be used (i.e. floats can be moored further offshore) and the floats can be seen more easily. These tethered float systems have been used at distances of up to 3 km offshore in water depths of a few tens of metres.

Their advantages are: (i) Cheap and simple to construct and lay. (ii) Robust. (iii) Show up changes in alongshore currents well. (iv) Easy to calculate the current speed. (v) Can be observed by unskilled operators.

The disadvantages of tethered floats include: (i) Not very accurate, especially for onshore-offshore components. (ii) May be affected by strong winds. (iii) Limited to fairly shallow water near the coast. (iv) Very low or very high current speeds may not be easily measured. (v) Only usable in daylight and good visibility. (vi) Only measures near-surface currents (i.e. at drogue depth).

2. *Recording Current Meters*

Nowadays most current measurements at sea are made using expensive current meters which record the velocity at regular intervals over a long period. These instruments, which are available in a wide variety of designs and prices, are moored at a fixed point in some way. Because of the number of models available, many of which are expensive and require advanced data processing techniques, only the

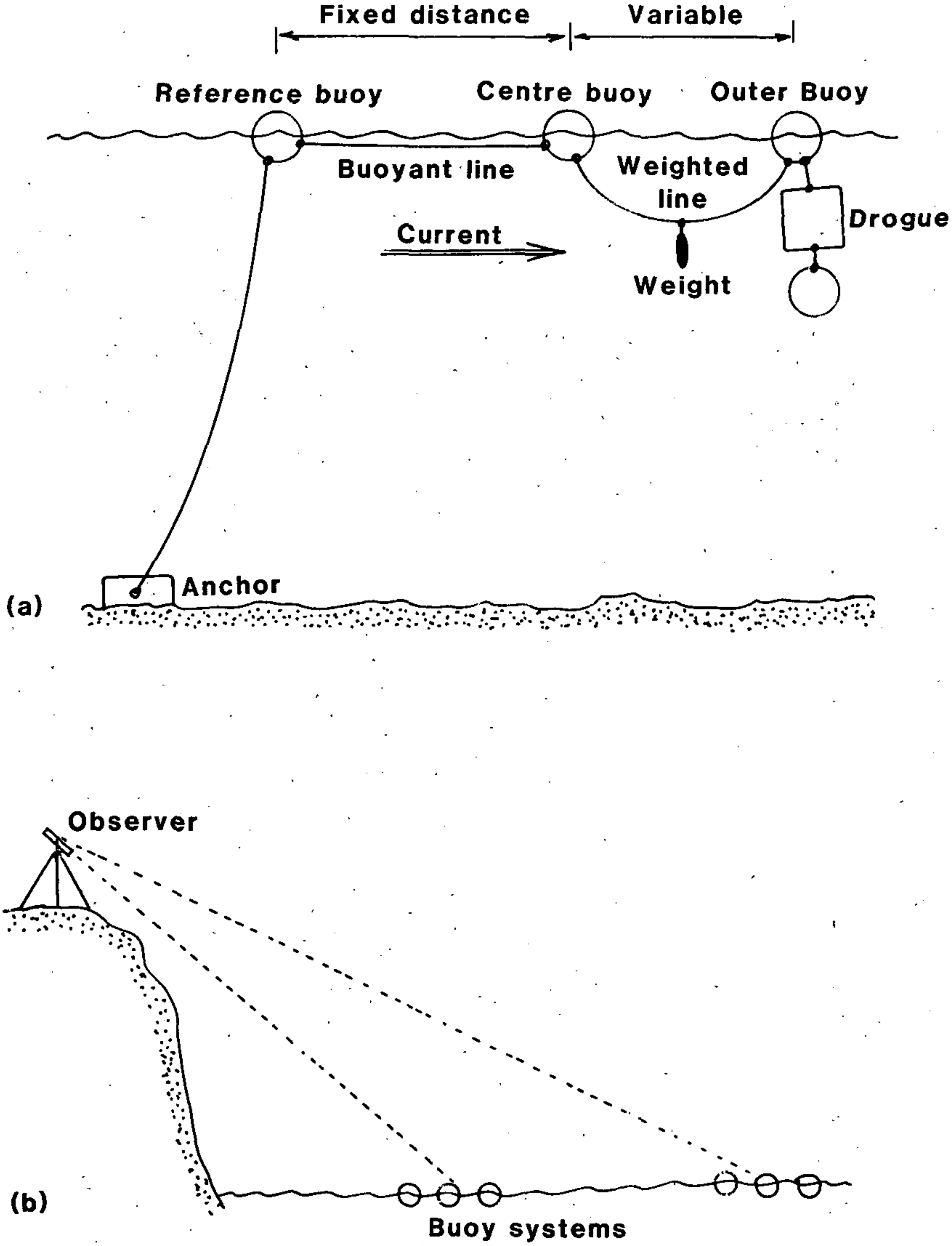


Fig. 5. Tethered buoy current measurements.

popular Aanderaa RCM-4 current meter and a simple mooring type will be described here.

Aanderaa RCM-4

The Aanderaa current meter (Figs 6-8) has a Savonius rotor to measure current speed, a large vane to align the instrument with the current so that an internal compass can give the direction, a temperature and a salinity sensor, and a pressure gauge for depth measurements (not all these sensors need be fitted). The recording interval can be adjusted over a wide range from about 30 seconds to 3 hours, and at the end of each interval all measurements are recorded onto standard magnetic tape. With the usual 10 or 15 minute sampling interval, about 2 months data can be logged. The instrument can be used to depths of 2000m (a deeper version is also available) and in currents with speeds of 3-250 cm/s. Aanderaas have been widely used all over the world for many years, and although new kinds of current meters have been developed which overcome some of the limitations of the Aanderaas, they remain popular because of their reliability and relative cheapness (about $A4500).

It is important when laying any self-recording current meter in the sea to note carefully the time it is switched on and off, its position, the particular sensors used (as the calibration can vary for different individual sensors), etc. After recovering the instrument, the magnetic tape must be read by a tape reader (this can be done as a service by the Aanderaa Company in Bergen, Norway for a small fee) and subsequent processing of the data follows normal time-series analysis techniques, such as current vector plots, alongshore and cross-shelf current component plots, current roses, histograms, progressive vector diagrams, spectral analysis, etc. (e.g. Fig. 9, 10).

One of the major disadvantages of any current meter with a Savonius rotor (which turns in only one direction regardless of the current direction) is that in fairly shallow water, say less than 30m below the surface, orbital velocities of waves can badly affect the current speed and direction measurements — Aanderaas should therefore not be used at any depth where wave action can be a problem.

Moorings

For shallow water on the continental shelf, the simplest mooring is a U-type mooring (Fig. 11a). It is important that the subsurface float above the current meter is below the depth of severe wave action as this can result in erroneous current readings. To lay such a system, which requires a boat with a winch and frame strong enough to hold the 200 kg (or more) concrete anchors, the subsurface float and current meter (with the small marker buoy) are floated away from the boat; the first anchor is then lowered to the seabed, followed by the groundline and the second anchor as the boat moves slowly forward, and the main buoy and light (if used) are finally dropped over.

In the ideal situation, the recovery is the reverse of above, i.e. retrieve the entire mooring by hauling on the main buoy line. However, it frequently occurs that the main buoy is missing for various possible reasons, in which case the ground line (whose length should be about four times the water depth) can be hooked by a grapnel from the ship using the small marker buoy as a guide for positioning the ship. In case both surface floats are missing, it is a good idea to lay one or two completely separate marker moorings, which can be recovered if so desired or else left for further current meter moorings at the site. All surface floats should be numbered and carefully plotted on a chart, so that

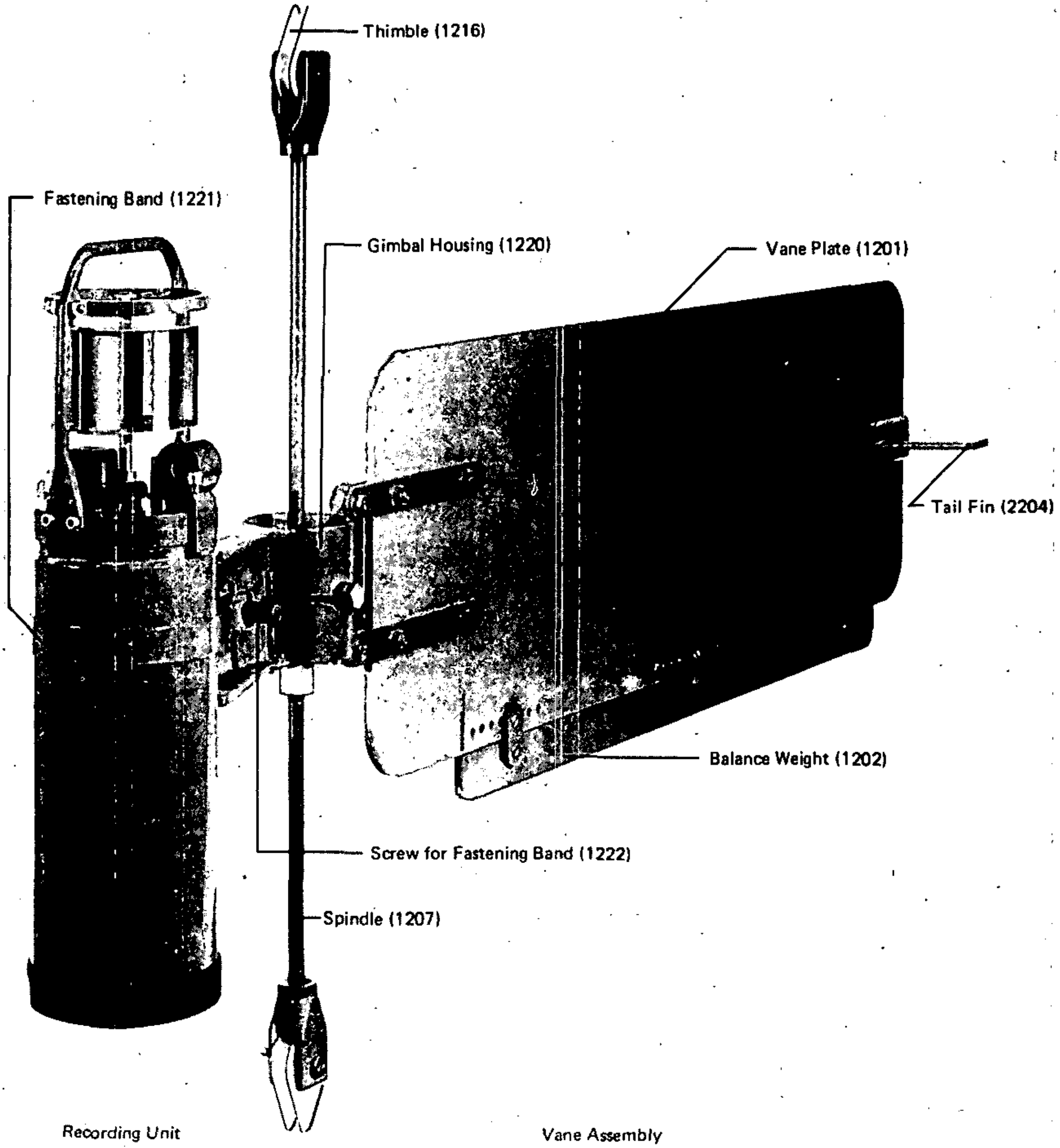


Fig. 6. Assembled Aanderaa current meter.

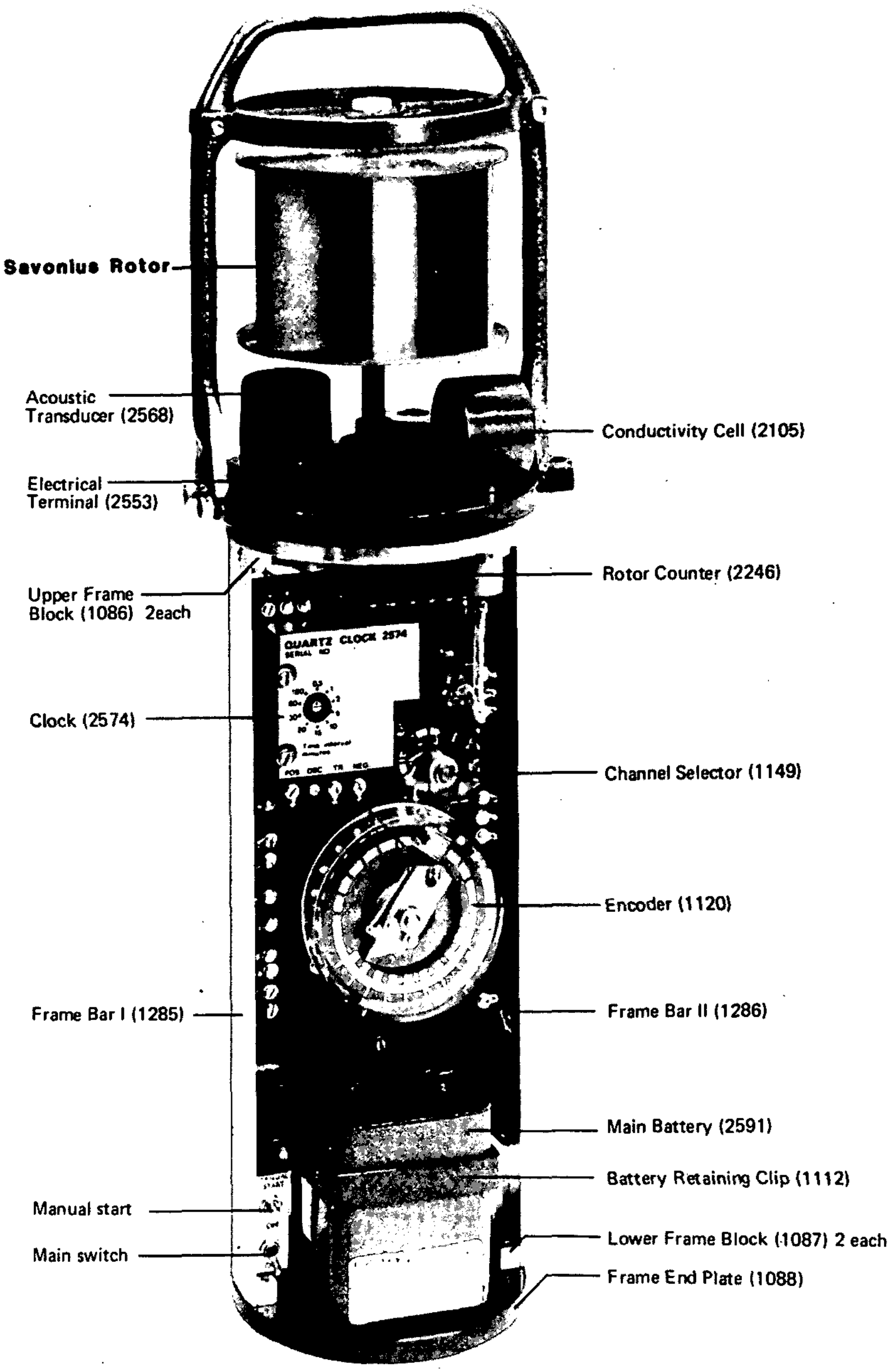


Fig. 7. Aanderaa current meter, encoding unit.

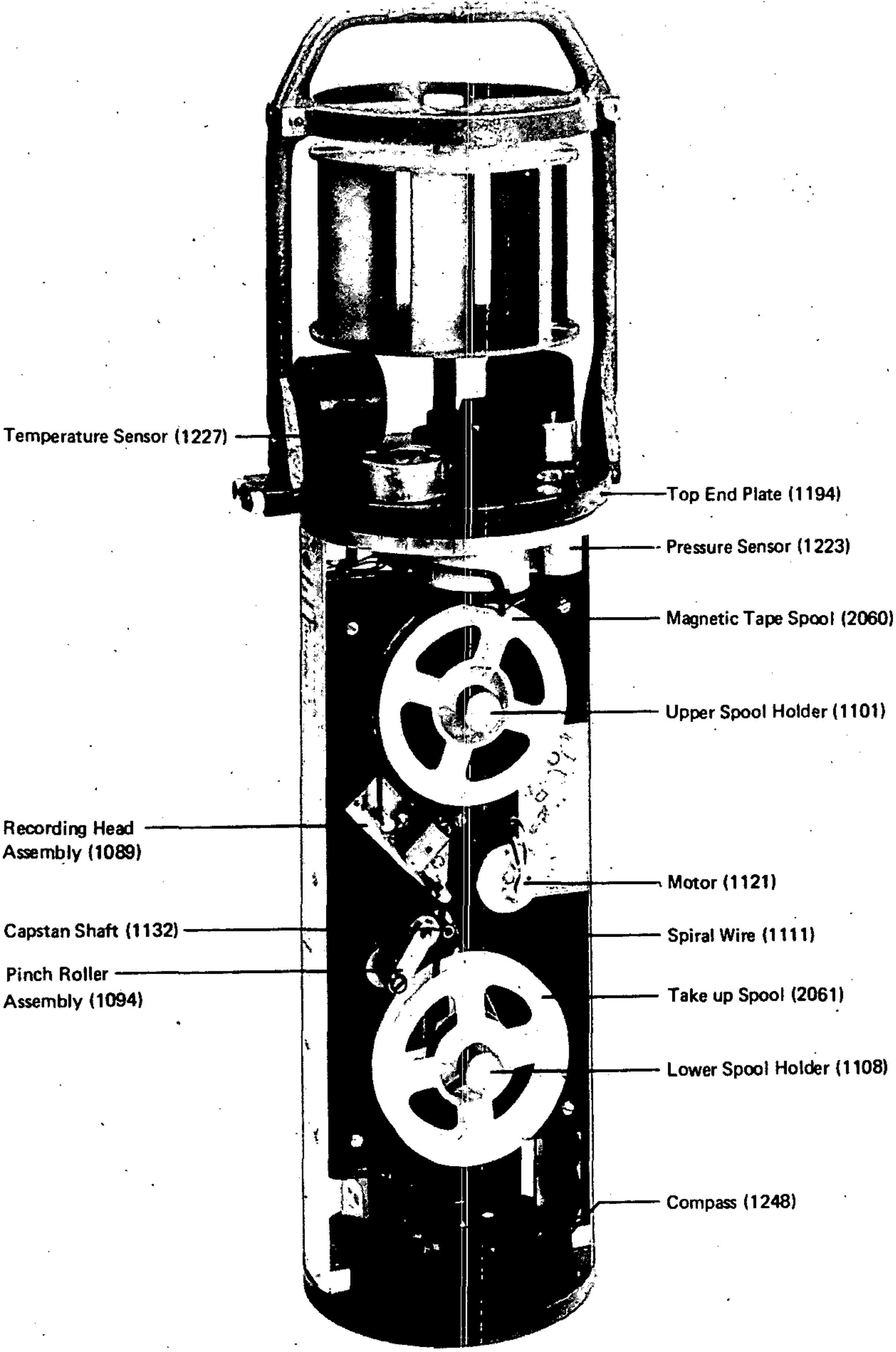


Fig. 8. Aanderaa current meter, tape recording unit.

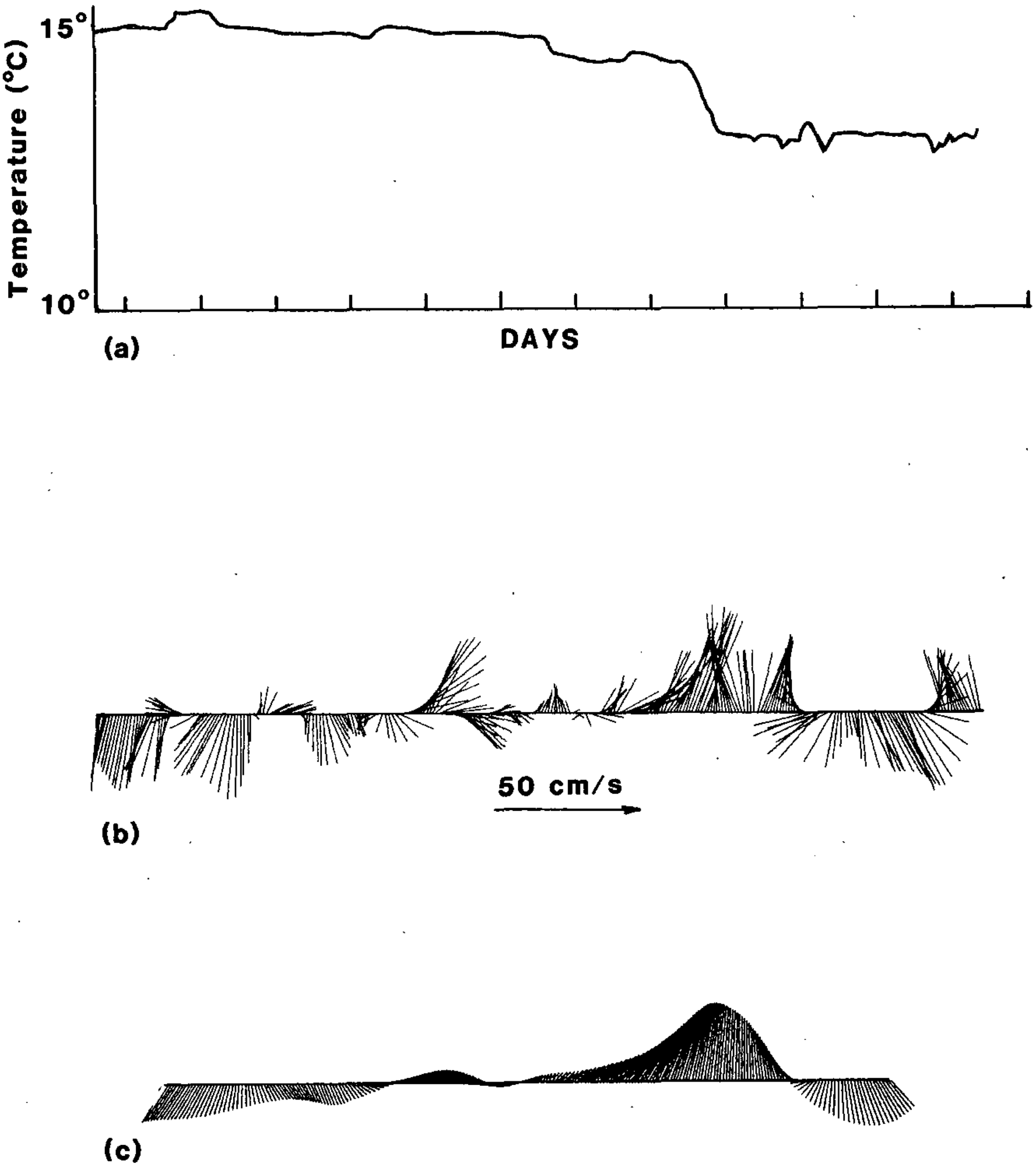
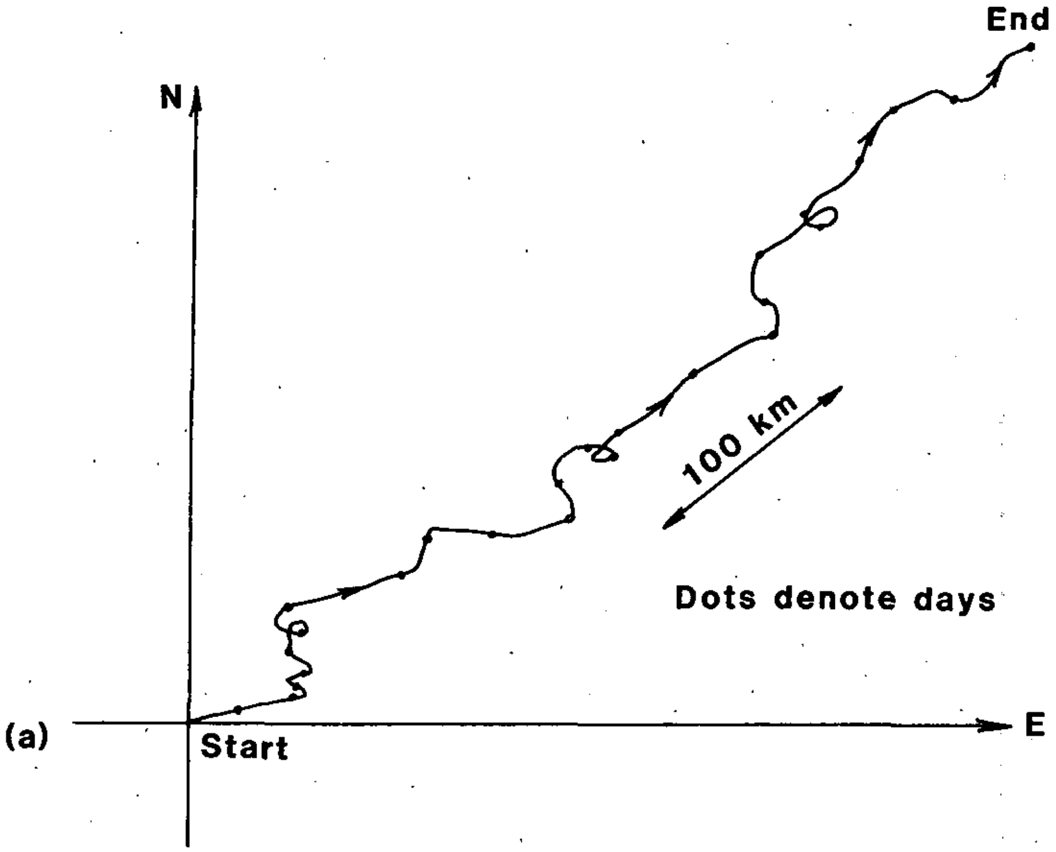


Fig. 9. (a) Temperature time series (each mark is a day) from an Aanderaa current meter.
(b) Current vector time series ("stick diagram"); each line is an hourly current vector indicating strength and direction. The speed scale is as shown.
(c) Filtered vector time series, to eliminate short-term variations. Same scale as for (b).



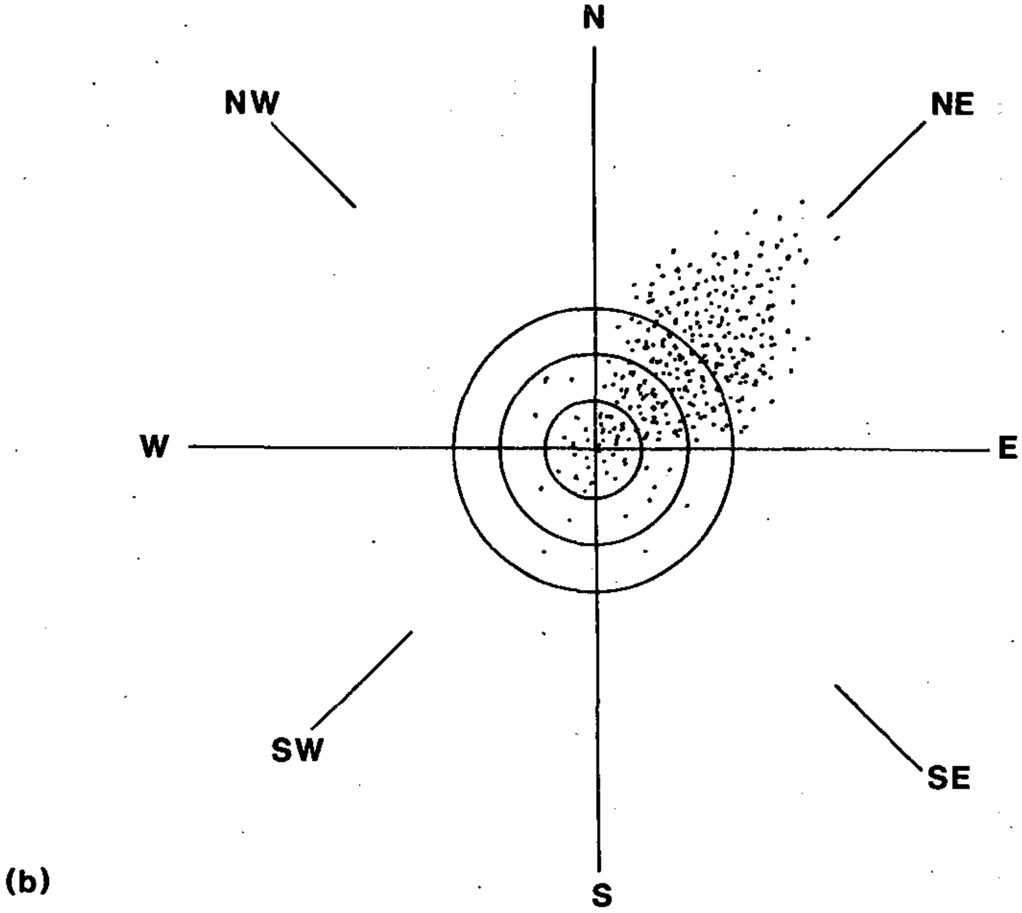


Fig. 10. (a) Progressive vector diagram (i.e. individual hourly vectors plotted nose-to-tail).

(b) Current rose.

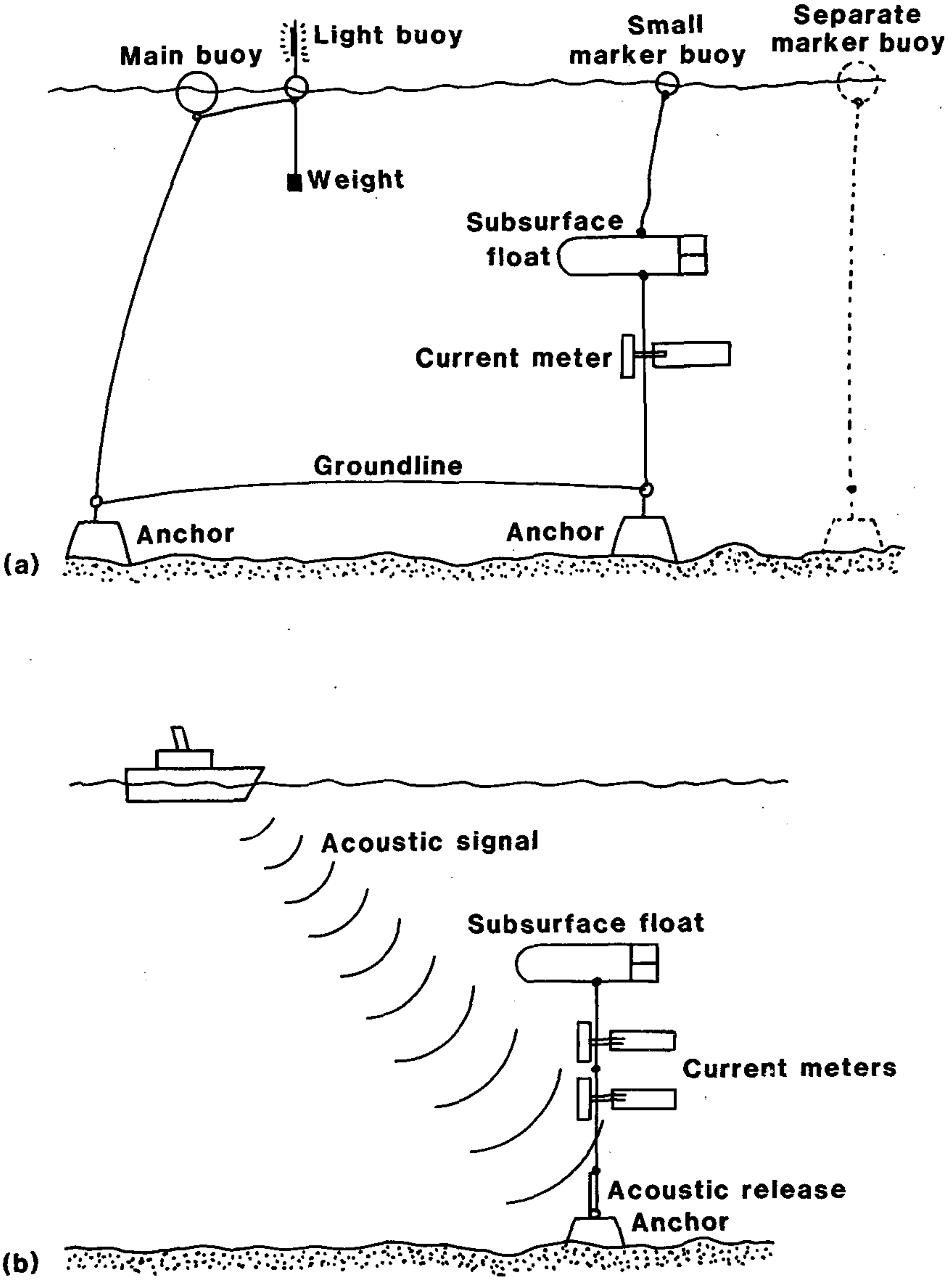


Fig. 11. Current meter moorings.

(a) U-mooring with surface buoy and groundline; separate marker buoy is recommended.

(b) Acoustic release mooring.

if any are missing it will be known. Local maritime authorities, as well as fishing companies, should be notified of the positions of all moored equipment.

In deeper water where it is not practicable to use the above type of mooring, acoustic releases can be used. As can be seen in Fig. 11b, the mooring is much simpler, with a single subsurface float and anchor. The mooring is laid either "float-first" or "anchor-first". For recovery, a series of acoustic commands is relayed to the mooring from the ship; the acoustic release replies, and then (if all is well) releases the mooring from the anchor and the float brings the whole mooring except the anchor to the surface. Acoustic releases are not completely reliable, and if they fail to release properly there is little likelihood of subsequent recovery of the equipment.

It is wise when planning current meter moorings to select areas where the seabed is flat and sandy (to avoid snagging any ropes on rocks etc.) and where shipping and fishing activities are limited. The position of the mooring should be fixed as accurately as possible, using electronic methods (described later) if available.

Advantages of using moored self-recording current meters include: (i) A large amount of data is obtained at a fixed point, without a ship being in attendance. (ii) Use of a number of moorings enables detailed studies of the currents and their relationship to wind, tide, etc. to be made.

Disadvantages may be: (i) Relatively high cost of the system. (ii) Need for a moderate-size ship for the moorings. (iii) Computer processing of the data is usually required. (iv) If the instrument is faulty (which is not always obvious at the time of installation) no data will be obtained.

CURRENT MEASUREMENTS FROM SHIPS

1. *Ship-drifts*

The amount by which a ship is offset from its steered course is a measure of the surface current plus wind effect. The very earliest ideas of current patterns along shipping routes were obtained this way, and data centres now contain many millions of such current estimates. Although the method is relatively crude and possible errors are many, routine logs from ships can be very useful in building up a picture of the major currents operating in a particular area; this is especially true if modern navigational aids are used for accurate position-fixing.

The method is illustrated in Fig. 12a, and is very simple. The ship's position at any time (where a fix is obtained) is plotted on a chart, and at the end of a certain period its intended position can be estimated from the speed and course steered, i.e. by dead-reckoning. However, after this period, its actual position is found to be different from the intended position, and the vector joining the two positions is the offset due to the current and wind. The current speed can then be estimated. Wind effects can be important if the current is weak and the wind is strong, and it is not easy to distinguish between the two. Normally, wind effects are ignored. Use of a 2-component log, which gives a measure of the sideways push of the wind on the ship, can be used to correct for wind effects.

It is clear that the accuracy of the method is limited by the accuracy of the ship's log and compass, and the positional accuracy of the fixes. The current estimates are of course averages over the interval between the fixes, so small-scale current variability cannot be found. Some workers subtract say 3% of the wind speed from the current to try and allow for wind effects.

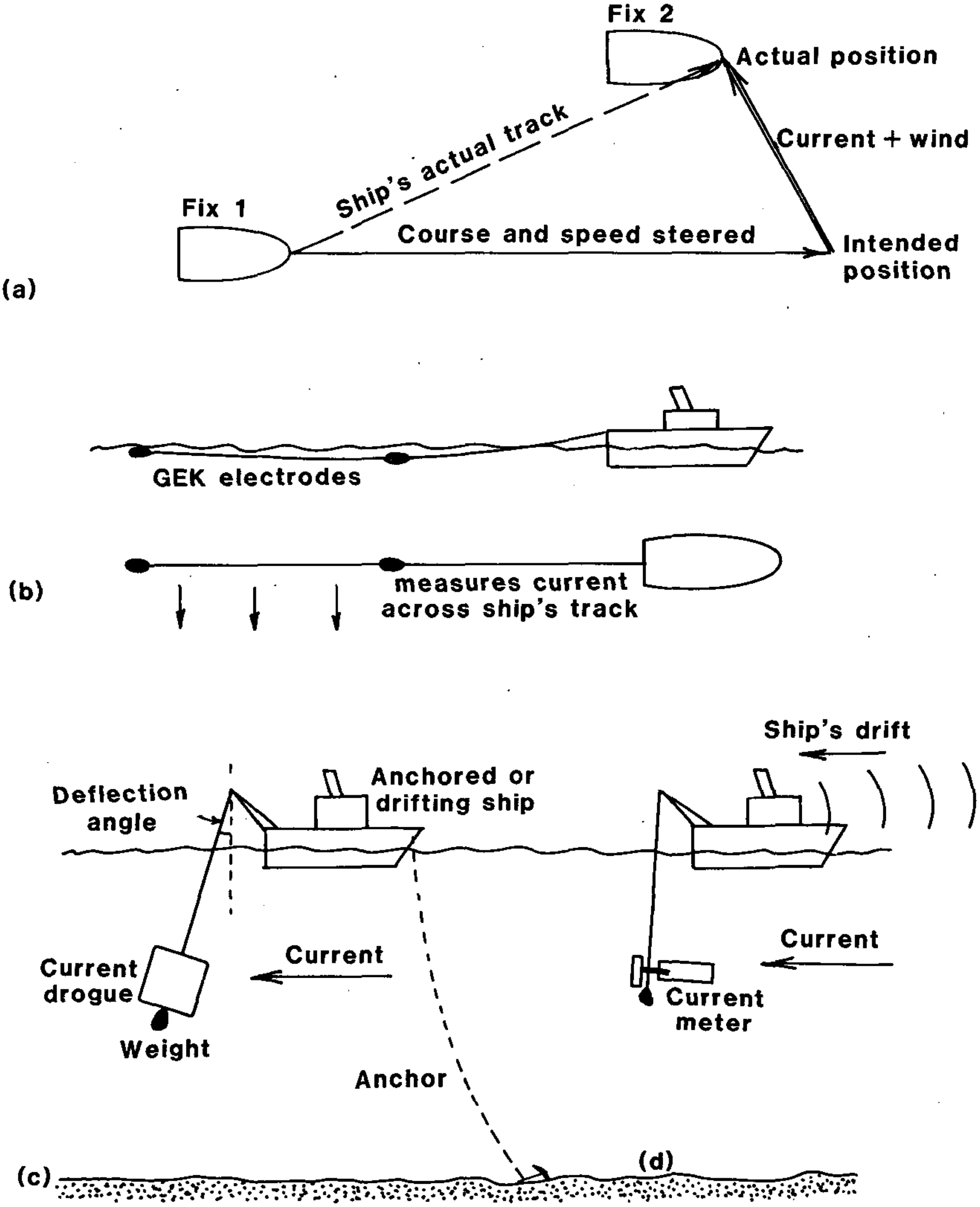


Fig. 12. Current measurements from a ship.

(a) Underway ship-drift method, by dead-reckoning.
(b) Geomagnetic Electro Kinetograph (towed electrodes).
(c) Suspended current drogue from drifting or anchored ship.
(d) Current meter suspended from drifting ship.

The advantage of the ship-drift method is that: (i) In regular shipping lanes, a large amount of data can be easily obtained at little cost, using normal navigational procedures.

Disadvantages include: (i) Reliance on the interest of the ships' officers to log all the required observations accurately. (ii) Errors due to inaccuracies in the ship's log or compass, or in position-fixing, may be serious enough to invalidate the current estimates. (iii) Wind effects may be severe on some ships. (iv) For a proper large-scale program, the amount of data obtained can be tremendous and require a major data processing effort to check for errors, calculate the currents, and store the data.

2. *GEK*

The Geomagnetic Electro-Kinetograph (GEK) works on the principle that when seawater flows through the earth's magnetic field, an electric potential gradient is set up which is proportional to the current speed. Therefore by measuring the potential between two electrodes in the water, the current flowing perpendicular to the line joining them can be estimated.

In practice, two electrodes are towed behind the ship, the first electrode being about 3 ship-lengths from the ship and the second being a fixed distance (say 100m) from the first (Fig. 12b). The potential difference between the two electrodes is recorded continuously on a stripchart. At regular intervals of say 6 hours, the ship should steam on the reciprocal course for a few minutes, and the average of this potential and the value just before the turn gives the "zero" value. Then the difference between any individual potential and the zero is proportional to the current component perpendicular to the ship's direction. To obtain the total current vector at any time, the ship must turn by 90° for a few minutes, so that the two perpendicular components of the vector can be measured.

The GEK method has been used quite widely for particular studies, and it has been found to give good results when the calibration factor is known accurately.

Advantages of the GEK system are: (i) Relatively cheap. (ii) Can be towed behind the ship at say 10 knots with relatively little effect on the ship's schedule, apart from periodic 90° and 180° turns. (iii) Simple to operate.

Disadvantages may be: (i) It is difficult to get reliable cable and electrodes, and any small defects or leaks result in hopelessly erratic readings. (ii) It gives too low current speeds in shallow water (e.g. on the continental shelf) although the current direction is true. (iii) It cannot be used near the earth's magnetic equator.

3. *Suspended Current Drogues*

The simplest form of direct current measurement from a drifting or anchored ship involves a current drogue put over the side of the ship. As the currents immediately around the vessel are obviously affected by the hull, this method works best from fairly small boats (Fig. 12c).

As long as there is a current flowing past the boat, any drogue suspended from the vessel will be deflected by the flow, and the angle by which the cable is deflected is a rough measure of the current. The drogue cannot be lowered too deep into the water as the drag on the cable will start to affect the deflection and is difficult to correct for.

If the ship is drifting (see next section), the ship's drift vector must be added to the current vector estimated from the drogue to give the true current velocity.

Advantages are: (i) Very cheap. (ii) Easy to operate.

Disadvantages are: (i) Not very accurate, may be difficult to read the cable angle. (ii) Unsuitable for deeper measurements. (iii) May be affected by the boat's hull for near-surface measurements. (iv) Cannot be used if waves are too big.

4. *Current Meter Suspended from a Ship*

A more advanced method than that above is to use a current meter suspended on a cable from the ship (Fig. 12). Before discussing the various possibilities, the problem of ship's motion should be addressed, i.e. whether it is at anchor or not.

If a vessel is anchored, it remains nominally in one position (which is useful for time-series work, for example measuring tidal currents at a point), but in fact the boat will swing on the anchor cable to some extent, and also yaw (or change direction slowly). As a result, the motion of the vessel is very irregular and will add an unpredictable component to any currents measured by a current meter. If a rough estimate of the current is acceptable, then taking readings from the current meter at say 1 minute intervals for 15 minutes (or, better, one swing-yaw cycle of the boat) will give an average current — note however that a Savonius rotor type meter will be affected to some extent by the motion of the boat and will probably read too high. Further, if the current is strong, the current meter may be tilted by the drag of the water, and many instruments record falsely above a certain tilt angle.

It may therefore be better not to anchor the vessel but allow it to drift freely with the current and the wind. Many vessels will settle down to drift in a stable position relative to the current and the wind, and if neither of these are changing greatly over the period of measurement, then the ship's drift vector can be determined and taken to be constant. This overcomes the swing-yaw problem mentioned above, and also reduces the instrument tilting because the vessel is moving largely with the current. (This may not be true if there is a very strong wind or a large change between the surface current and that at the depth of measurement). It is important that the ship's drift be measured accurately, which involves regular fixing of the position during the drift — this is discussed in a later section. Having measured the ship's drift, this must be added vectorially to the current meter readings to give the true current velocity.

The choice of current meter is important. It must be robust enough to be handled at sea, the greatest danger being when putting it into or taking it out of the water.

Some current meters have direct read-out on a deck unit, i.e. the data are sent up a cable to the ship — this is a great advantage in that the current velocity can be seen immediately. Apart from having the real-time current available for scientific purposes, it can be checked as being reasonable, or successive readings can be compared and an average taken, etc. However, the conducting cable can be a problem and this also involves a slip-ring winch, power supply to the instrument, watertight connection to the instrument etc. It is possible to use a direct readout current meter in shallow water where the cable can be connected properly to the read-out unit and paid out by hand, but for deeper work this is impracticable.

On the other hand, if a self-recording current meter is used, it has to be retrieved before any idea of the current can be obtained. There is now no problem with a conducting cable and the instrument can be simply fastened to any suitable wire. Certain mechanical types of current meter exist which read the current speed and direction directly by gear-driven dials, balls in slots, etc, but they are inconvenient to use, and it is usually not possible to get a series of readings without retrieving the instrument. Electronically-recording current meters can record at regular intervals for long periods of time, but the data are then logged onto magnetic tape (typically), and therefore cannot be read without opening the instrument, removing the tape, and running it through a tape-reader as well as perhaps a decoder of some type. A self-recording instrument which records onto strip-chart is more suitable, as although the chart roll must be removed to read the data, the measured currents can be obtained directly without requiring machine translation into usable form.

A recent development is an instrument by Sensordata costing about $A1400, which records 16 current speeds and directions at preselected intervals, then these can later be read directly in digital form through the transparent case of the meter (Fig. 13). The memory can be reset using a magnet, and the instrument is then ready for 16 more cycles. Apart from the disadvantage of the Savonius rotor (see below), this looks a promising and cheap instrument which gives direct read-out of the data at the end of the cast and yet does not require a conducting cable to a surface deck unit.

Various types of current speed sensor have been developed. The most widely used in the past have been Savonius-type rotors or propellers. The Savonius rotor suffers from the fact that it turns in only one direction and therefore an oscillating current is rectified, so that in the wave zone a false high current reading may result. The problem is complicated by the fact that vertical motions such as the roll of the ship also accelerate the rotor, and again higher apparent speeds will be recorded. (This particular difficulty can be overcome by mounting the current meter in a hull which slides freely down the cable and is thus effectively decoupled from vertical ship motion — the University of Miami Profiling Current Meter is the prototype). Propeller meters will reproduce an oscillating current to some extent but are sometimes more fragile than rotor meters and are possibly more susceptible to fouling by marine organisms.

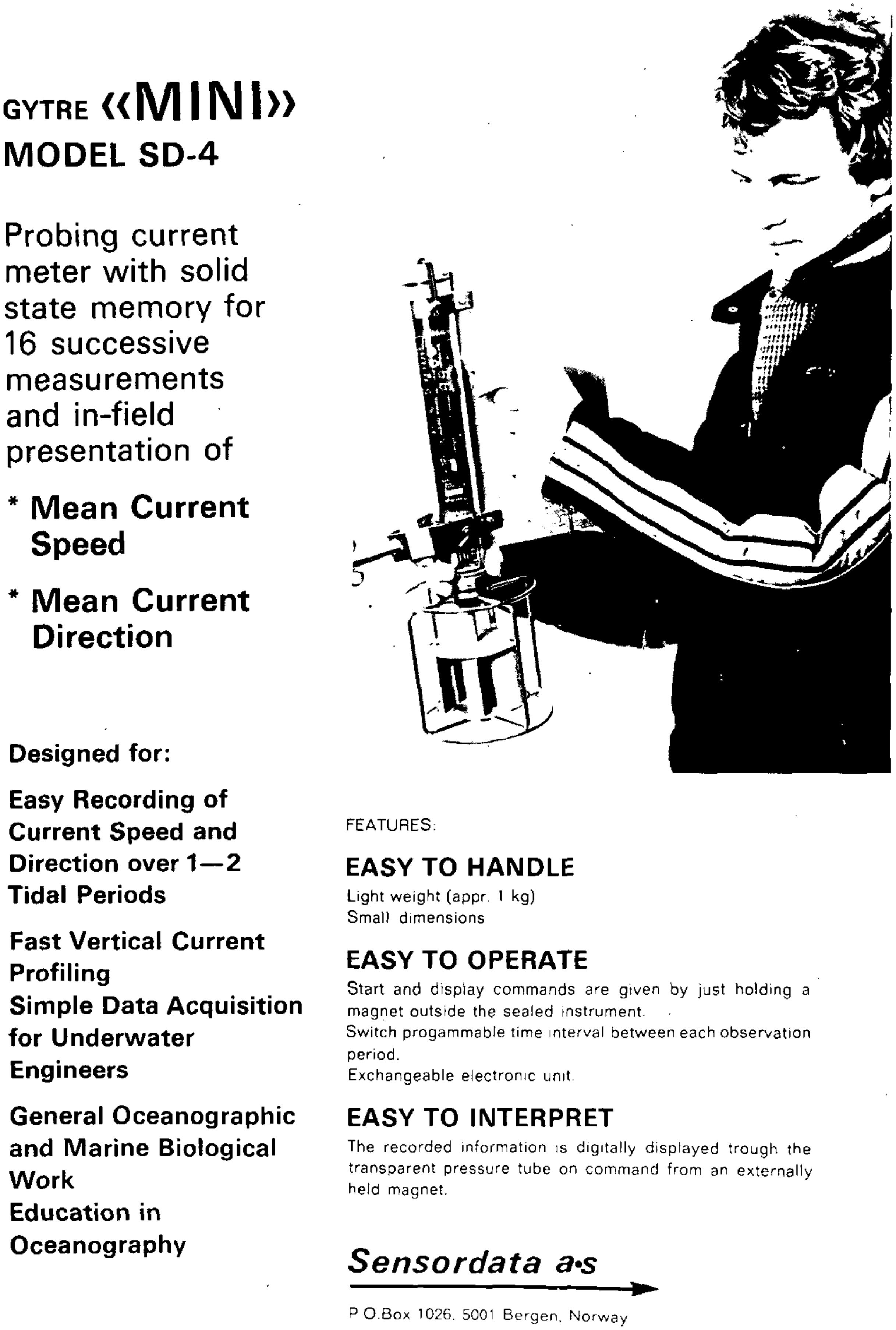
In summary, use of current meters suspended from a boat is subject to various difficulties which can result in erroneous readings. However, the method has been used by a few institutions to give a geographical coverage of velocity vertical profiles where no other method was available, and the resulting current patterns certainly appear reasonable and moderately consistent when spot checks against other methods have been made.

The advantages are: (i) Allow a coverage of an area. (ii) Vertical profiles down to tens or hundreds of metres can be made. (iii) The data are immediately available (with an appropriate type of current meter).

Disadvantages are: (i) Necessity for accurate ship's drift measurements. (ii) Effects of the rolling ship, especially with a Savonius rotor instrument.

INDIRECT CURRENT OBSERVATIONS

Apart from the direct current measurements described above, estimates of currents can be made by such methods as the classical "dynamic" technique and satellite observations.



GYTRE «MINI»
MODEL SD-4

Probing current meter with solid state memory for 16 successive measurements and in-field presentation of

- **Mean Current Speed**
- **Mean Current Direction**

Designed for:

Easy Recording of Current Speed and Direction over 1—2 Tidal Periods

Fast Vertical Current Profiling
Simple Data Acquisition for Underwater Engineers

General Oceanographic and Marine Biological Work
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FEATURES:

EASY TO HANDLE
Light weight (appr. 1 kg)
Small dimensions

EASY TO OPERATE
Start and display commands are given by just holding a magnet outside the sealed instrument.
Switch progammable time interval between each observation period.
Exchangeable electronic unit.

EASY TO INTERPRET
The recorded information is digitally displayed trough the transparent pressure tube on command from an externally held magnet.

Sensordata a•s

P.O.Box 1026, 5001 Bergen, Norway

Fig. 13. Sensordata self-recording current meter.

1. *"Dynamic" Method*

The dynamic or geostrophic method involves measuring the temperature and salinity profiles at two stations, calculating the dynamic heights (relative to some reference level, say 1000m), and then estimating the current speed relative to that level. The temperature and salinity measurements are described later and only the method of calculating the current is given here.

For this method, temperature and salinity measurements are made at a pair of stations, and interpolated to standard depths of 0, 10, 20, 30, 50, 75,..... metres down to the reference level of 1000m. The dynamic height is then calculated for each station (details are not given here as the calculation is laborious, and most easily done by computer — La Fond's book, in the reading list, clearly explains the procedure).

Having obtained the dynamic heights for the two stations, the average surface current (V) perpendicular to the line between the stations is given by:

$$V = 10(S_1 - S_2)/(L2\omega \sin \phi) \text{ (m/s)}$$

where S_1 and S_2 are the two dynamic heights (dyn. m).

L = distance between the stations (metres)

ω = earth's rotation (7.29×10^{-5} rad/s)

ϕ = latitude.

Thus for 2 stations 30 km apart at latitude 30°, whose dynamic heights are 1.501 and 1.525,

$$V = 10\ (0.024)/30000 \times 2 \times 7.29 \times 10^{-5} \times \sin 30^{\circ}$$

$$= 0.11 \text{ m/s.}$$

The current direction is such that the higher dynamic height is on the left-hand side of the direction flow in the southern hemisphere, or on the right in the northern hemisphere. To calculate the water transport between the two stations, the depth-averaged velocity is multiplied by the cross-sectional area between the stations and down to the reference level.

Because of the relative ease of measuring temperature and salinity compared with direct current measurements, the dynamic method has been used to study all the major currents of the world. It assumes that the currents are steady and flow in reasonably straight paths, and frictional processes are ignored. The method is applicable mainly to deep water because of the difficulty of estimating the reference level (where it is assumed the water is stationary) in shallower water. For practical purposes, therefore, its relevance for coastal studies is small, although it can be used in conjunction with direct current measurements at a single depth to give a vertical profile of velocity.

2. *Satellite Observations*

Apart from the direct observation of ocean currents by tracking drifting buoys from satellites (as described earlier), infrared or normal photographs taken by satellite can show up current patterns.

Surface temperature contrasts in the water, such as those in western boundary currents or eddy systems, can be seen clearly in infrared pictures, but the resolution is such that only fairly major features can be distinguished. Nevertheless, strong currents flowing along the continental shelf break can meander onto the shelf or shed eddies into the coastal zone, and these processes can be studied from satellite pictures.

Coastal current movements can also be traced by colour changes in the water due to suspended sediment or concentrations of plankton. Because of the short time-scale of the current variability on the shelf, and bearing in mind that cloud frequently obscures the sea, good satellite pictures are not always sufficiently frequent to show successions of events. Nevertheless, many interesting features of the shelf circulation have been revealed by satellites and then been confirmed by surface measurements, so even a few good pictures can be a useful complement to more conventional surface studies.

POSITION-FIXING AT SEA

In any oceanographic work at sea, it is important to know the position of the ship. In coastal waters this is especially true both because of the great variability of the processes being studied and because of the need to avoid navigational hazards.

The required accuracy of the position depends on its purpose and two levels may be distinguished; general positioning for occupying stations, and measuring the ship's drift during current measurements.

It is normally sufficient to know the position of a station on the continental shelf to within a few hundred metres. Because cross-shelf gradients are normally much higher than alongshore gradients, it is less critical to know the position parallel to the coast accurately than the distance offshore. Normal navigational techniques are sufficient to specify the position of a station on the inner shelf, but beyond the sight of land some form of navigational aid is desirable (e.g. radar). For measuring ship's drift during a current measuring station, on the other hand, a much higher accuracy is required. For example, if the vessel is drifting at 10 cm/s, then in ½ hour it will move only 180 m, so that the position should be fixed to an accuracy of about 10 m a few times during the drift. It is unlikely that this accuracy can be obtained without special equipment, except possibly close inshore under favourable weather conditions. It is of course possible to lay a marker buoy and estimate the ship's drift relative to it (since for current measurement purposes the absolute ship's position is not important), and retrieve the buoy at the end of the station.

1. *Normal Navigation Methods (Solely on Ship)*

Under this heading may be grouped visual observations (bearings to landmarks on the coast) and radar, which are independent of shorebased aids. Both compass and radar bearings, however, require suitable landmarks which can be clearly identified on a chart.

If the vessel has a good compass system, bearings to two or more distinctive landmarks allow the ship's position to be plotted on a chart. With a trained operator and suitable landmarks, sufficiently good drifts can be obtained provided visibility is good and the drift not too small. A sextant can be used for measuring relative angles if no suitable compass is installed on the boat.

Radar, on the other hand, requires only a single landmark from which both the range and bearing can be found, but it is better to have two or more points for a check — it is not always certain exactly from where on the target (such as a cliff) the echo is returning, and this will vary as the ship moves.

It is probably best to use both the compass and radar, if available, as the agreement (or disagreement) between the two methods will give an indication of the accuracy of each.

2. *Special Electronic Navigational Aids*

Various position-fixing systems have been (and are being) developed, some of which are global in application (such as Satellite-Navigators or Omega) while others are local and can be set up at short notice for particular studies. Some of these systems are briefly outlined here, but a complete review is beyond the scope of this report.

Satellite Navigators

These are simple to operate but can be expensive. They are independent of shore stations and global in operation, can be used in all weather situations, and any number of ships can share the system. Modern versions are reasonably accurate, say to 100 - 200m. The chief disadvantage is the irregular timing of satellite passes, which can vary from a few minutes to many hours. Because of this, as well as its lack of fine accuracy, satellite position-fixing is not generally suitable for calculating ship's drifts for current measurement purposes, or for manoeuvring in a detailed station grid. (For open ocean sailing, of course, the system is ideal).

Medium-range systems

For ranges of, say, 100 - 1000 km (i.e. over-the-horizon), many systems are available ranging in price from a few tens of thousands of dollars to well over $A100,000. Some of these are Decca, Raydist, Loran-C, Hifix, Toran and Lorac. Accuracies of a few metres can be obtained from some systems, i.e. adequate for current measuring drifts. Most of them are easy to use, but some are more "national" in character due to their expense, being more suited to installation on a permanent basis by governments, than for an individual research group to set up for local purposes. It has been found that some systems suffer from an instability problem at certain times of day, such as dawn and dusk, and they can give erratic readings at such times.

Short-range systems

These are taken here to comprise the "line-of-sight" methods, i.e. ranges of a few tens of kilometres depending largely on the height of the shore stations. Prices are from $A30,000 upwards, and the shore equipment is generally simple to set up and automatic in operation, so these systems are quite suitable for coastal studies by research organisations. For this reason, they are discussed in a little more detail than the medium-range outfits.

Two basic principles of operation (which, in fact, also apply to the medium-range systems) are used: range-range, or hyperbolic. Range-range systems (Fig. 14a) give the ranges from two shore stations, so the position of the ship can be plotted on any standard chart, or calculated using trigonometry. The hyperbolic systems work on a series of hyperbolic curves (Fig. 14b) and the position has to be worked out from the lane numbers — special charts with the hyperbolic lanes printed on them must be used for plotting the fixes. (In either method, the position information can be recorded on an electronic data-logger if required).

Typical systems are the Motorola Miniranger, Tellurometer, Trident and Decca Trisponder. One of the most widely-used is the Miniranger, which consists of a deck console (containing the two-range read-out), the antenna, and two shore-based transponders. A pair of ranges is obtained every few seconds, and these are accurate to about 3m. The shore transponders are small and light,

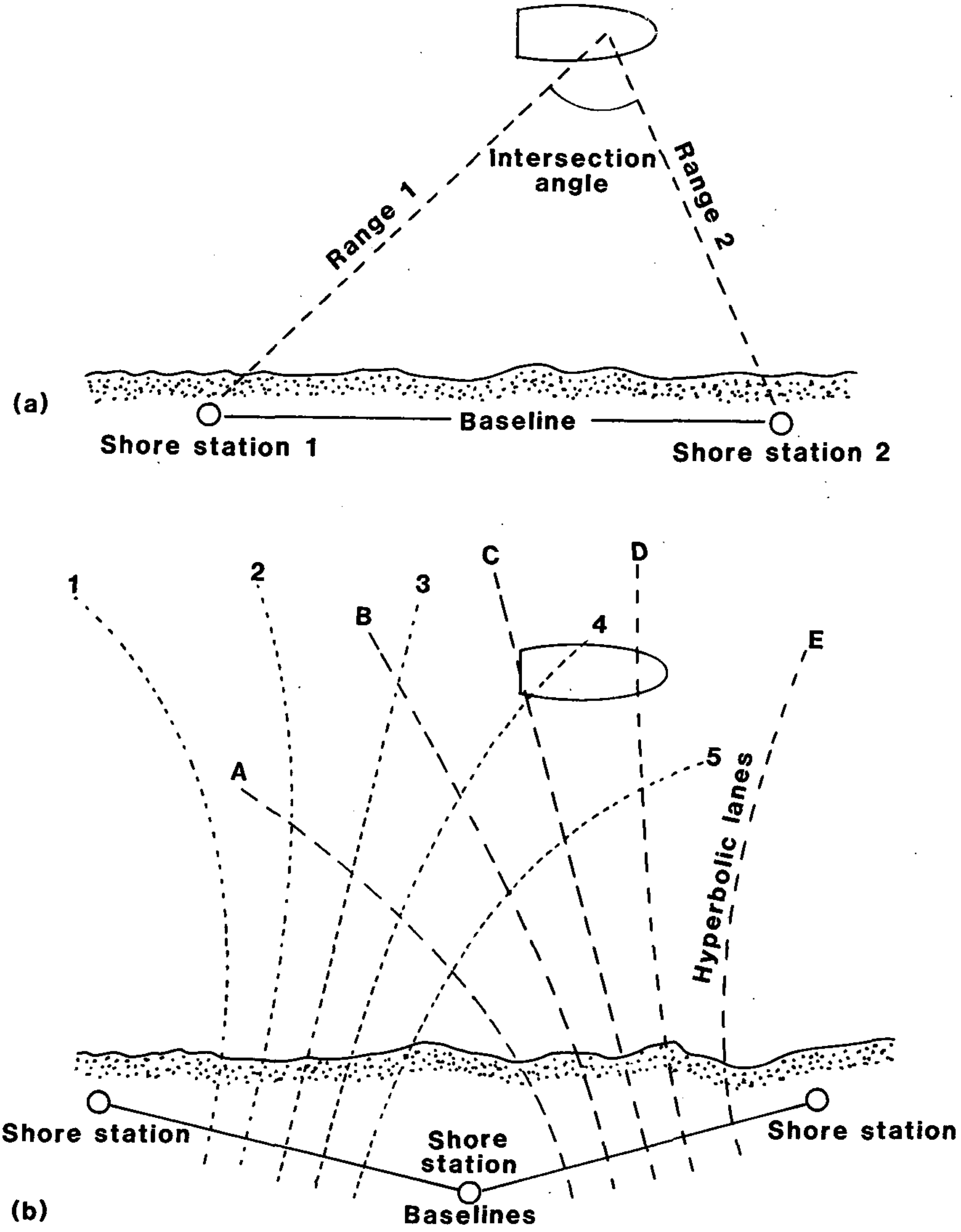


Fig. 14. (a) Range-range system.
(b) Hyperbolic system.

require 24 to 30V DC (e.g. from two car batteries) and can be set up in minutes. The requirements for the ideal shore site are: (i) Security (from tampering by vandals). (ii) Accessibility. (iii) As high as possible. (iv) Clear line of sight to the sea. (v) Known position.

The two sites should be 10 to 20 km apart so that the "intersection angle" of the two ranges at sea is good in the survey area. Of course, further transponders can be set up if work is to be done along a large length of coastline. Good radio communication between the shore party setting up the stations and the ship is generally important to this kind of work. The maximum range from a transponder is nominally line-of-sight; if the antenna on the ship is 10m above the waterline, the maximum ranges from various transponder heights above sealevel will be approximately:

Height (m)	20	50	100	200	300
Range (km)	30	43	55	70	82

PART 2: OTHER OCEANOGRAPHIC MEASUREMENTS

DEPTH

The depth of water between the sea surface and the seabed is of interest to oceanographers for two main reasons. Firstly, the seabed must be sufficiently well mapped for the major features to be known before any kind of oceanographic investigation can be carried out. This general survey is needed so that other investigations such as current studies can be properly planned, and also so that the vessels used will not be endangered by reefs or shoals. At this level, the conventional hydrographic charts (available for most coastal areas of the world) are adequate. Secondly, however, it is important to know the water depth quite accurately at an oceanographic station, so that the instruments suspended from the boat do not foul the seabed. The closer to the seabed that the measurement is needed, the more accurately must the depth be known, and it is therefore convenient if the depth can be measured at the time of the station.

Before instruments were available, water depth was measured using a lead-line, i.e. a line which was marked off in depth intervals and had a weight on the end (Fig. 15a). This was lowered into the water until it reached the seabed, and the depth was determined from the marks on the line. This method is still adequate for shallow work, the only difficulties being handling the line, and possibly deflection of the line by strong currents. For deeper water, wire was used, with some kind of winch, and the weight could be dropped off the end after reaching the seabed to facilitate rapid recovery of the line.

Nowadays ships use echosounders, which are acoustic devices installed in the ship's hull and transmit regular pulses of sound vertically downwards (Fig. 15b)). The time interval between the sound pulse leaving the hull and the echo returning from the seabed is a measure of the water depth. The speed of sound in seawater is about 1500 m/s. This method is vastly superior to the lead-line technique, as it enables the shape of the seabed to be recorded continuously on a chart while the ship is steaming at full speed.

As in any oceanographic work, it is important to fix the ship's position very accurately when carrying out a detailed survey of the seabed. For normal station work, on the other hand, if the depth is being measured only as a check before lowering instruments, such positional accuracy is not required.

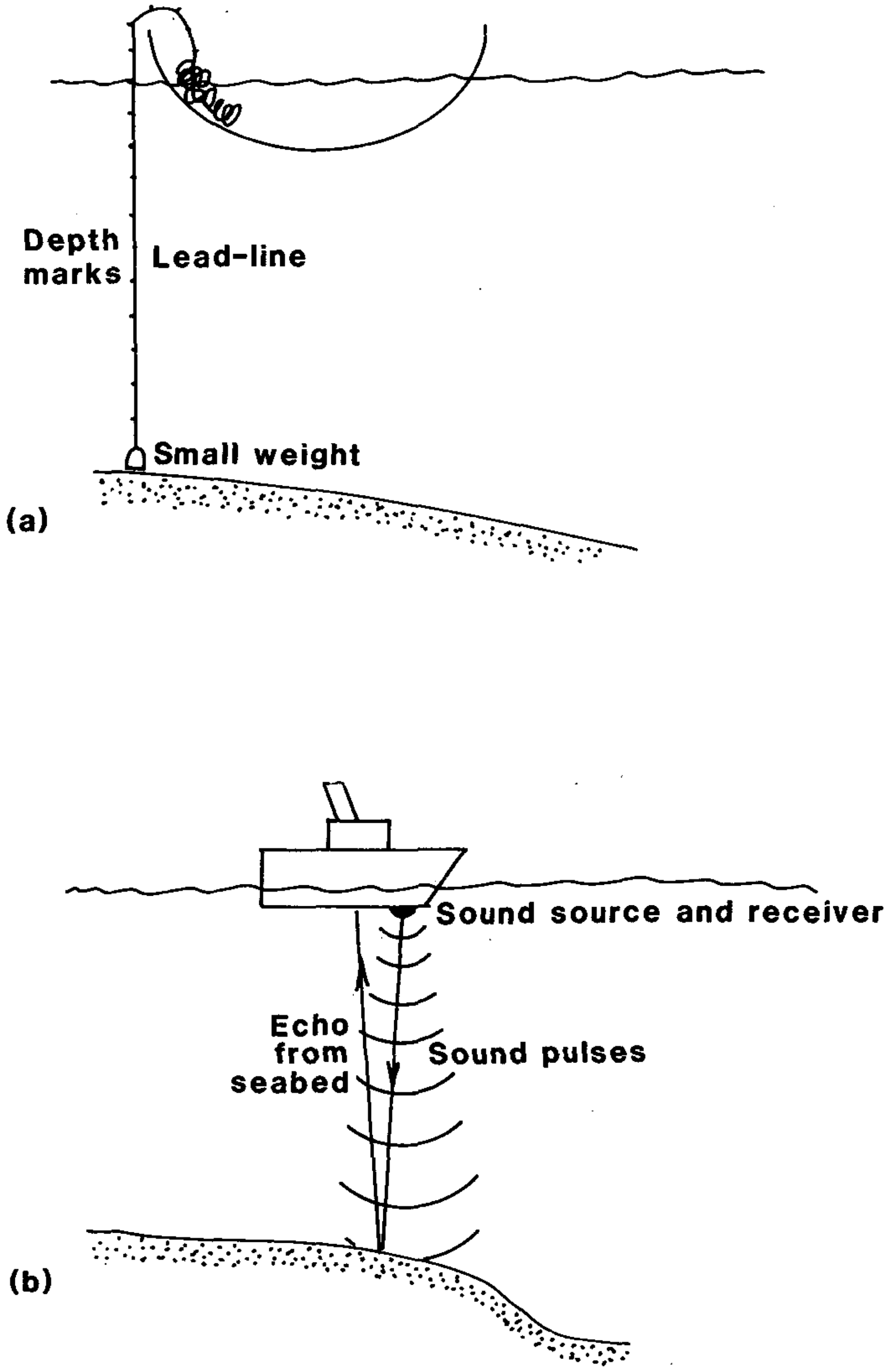


Fig. 15. (a) Bottom sounding using hand-held lead-line.
(b) Underway echo-sounding, using sound signals transmitted continuously from the ship.

A separate consideration is the measurement of the depth of an instrument below the surface, for example during a vertical profile measurement. The simplest method is merely to note the length of cable out, and this can be conveniently measured using a meterwheel, which has indicators showing how much cable has passed over the pulley. It is quite accurate if the meterwheel is carefully made and the wire is hanging vertically, but if a current (or the ship's drift) is causing the wire to deflect then the true instrument depth can be much less than the meterwheel reading, particularly in deep water. It is better, therefore, if the instrument itself has a pressure device such as a conventional pressure-tube, which measures the depth in the same way as the temperature or current is being logged. Some instruments have an acoustic pinger which can be recorded on the ship's sonar, or the instrument trace may be visible on the echo-sounding chart. In shallow water of say up to 200 m depth, where vertical gradients can be large, it is desirable that the instrument depth be recorded to an accuracy of about a metre. For deep measurements, the comparison of temperatures measured on a "protected" and on an "unprotected" reversing thermometer (discussed later) enables the depth of the measurement to be found surprisingly accurately. The pressure of the water on the bulb of the unprotected thermometer forces the mercury up the tube to register an artifically high temperature by roughly 1°C per 100 m depth change, while the true temperature is recorded by the protected thermometer whose bulb is not exposed to the water pressure.

TEMPERATURE

Measurement of the water temperature is one of the simplest and yet most important measurements in oceanography. Physical processes on the continental shelf are often shown by the temperature patterns associated with them, and the influence of temperature on marine life is obvious.

Many techniques have been developed for measuring temperature and only a few can be dealt with here. For convenience, the methods will be divided into surface, subsurface, and moored instruments or techniques.

1. *Surface Temperature*

It is not easy to define unambiguously the "surface" temperature of the sea, as there can be quite large changes of temperature in the top few metres (or even centimetres) of the water, and the depth of measurement is therefore important. For this reason, the different methods of measuring so-called surface temperature usually give slightly different (and occasionally very different) results.

The simplest method of finding the temperature of the surface of the sea (perhaps the top 30 cm) is to take a bucket sample of seawater and measure its temperature using an ordinary mercury thermometer (Fig. 16a). The thermometer should be immersed in the water and the reading should be noted with the thermometer shaded; this should be done as soon as the sample has been taken before heating or cooling of the water occurs.

Many ships have a built-in thermometer in the engine cooling-water intake, recording either on a chart or on an indicator of some sort (Fig. 16b). This is a convenient way of measuring the temperature, but the depth of the water intake varies on different ships and this can lead to different values being recorded from ships of various sizes. On research vessels, there is usually an accurate temperature sensing element installed

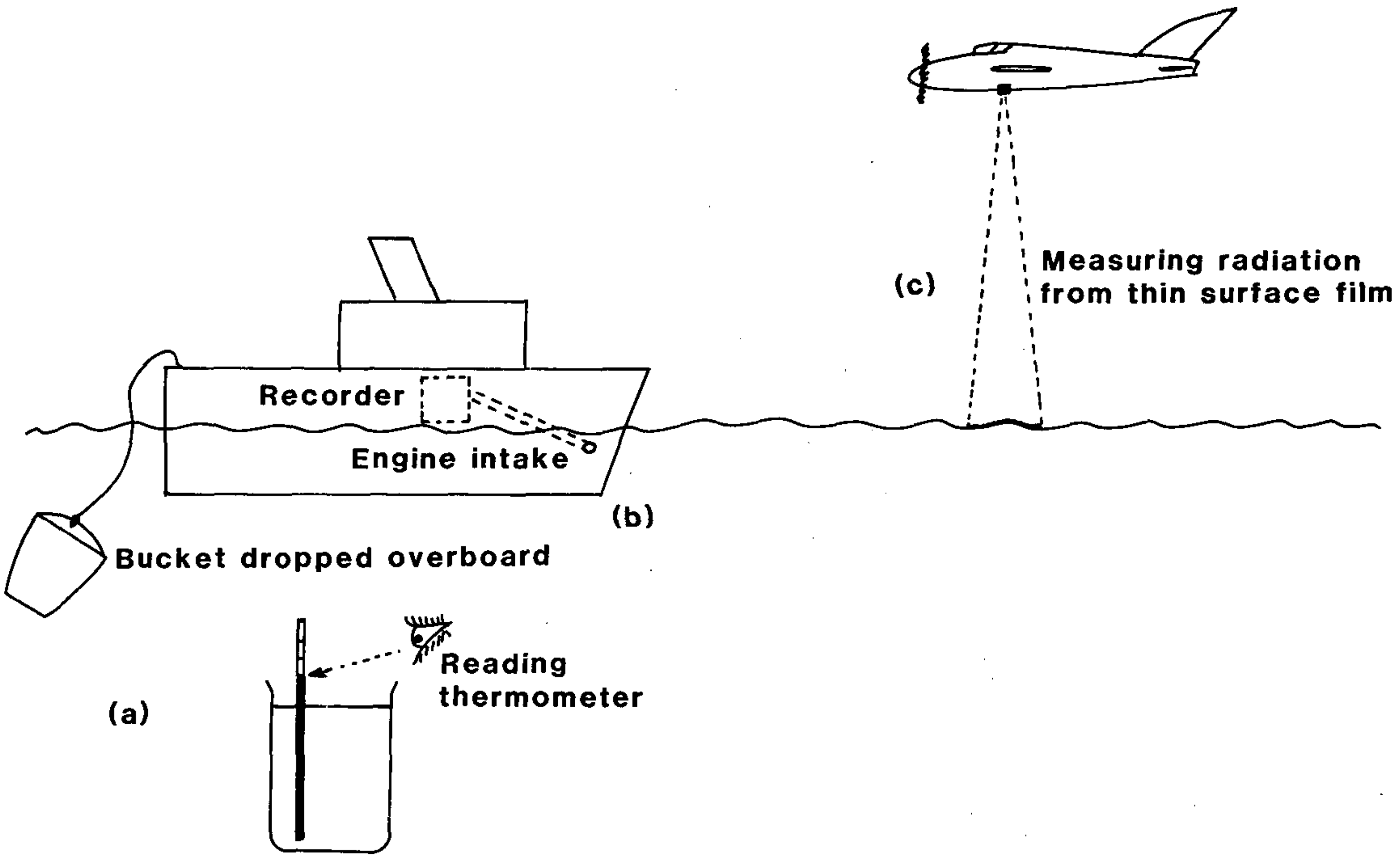


Fig. 16. Measuring surface temperature. (a) By bucket sample and thermometer.
(b) Intake water temperature.
(c) Airborne radiation thermometer (ART).

either in the engine cooling system or in a special pipe circuit, and this records on a chart recorder or on magnetic tape in the laboratory. This thermograph (as the system is called) is one of the most useful items of equipment on a research vessel, especially in coastal water where changes in surface temperature often reflect current processes. As in all oceanographic measurements, it is very important to mark the chart clearly at regular intervals (e.g. hourly) with time, date, temperature scale used, and perhaps ship's position, station number, etc.

A very rapid method of measuring surface temperature (in this case the thin surface film) is by using an airborne radiation thermometer (ART) installed in a low-flying aircraft — Fig. 16c. This instrument can measure the radiation from the sea-surface and interpret it as a surface temperature. By flying the aircraft in a specified pattern over the sea, the surface temperature of a large area can be mapped very quickly, and in some areas (such as western boundary currents) the current patterns usually show up very clearly on ART pictures. The concept of "remote sensing", of which ART is but one aspect, can be carried even further to satellite observations where major surface temperature structures in the ocean can be mapped regularly, cloud permitting.

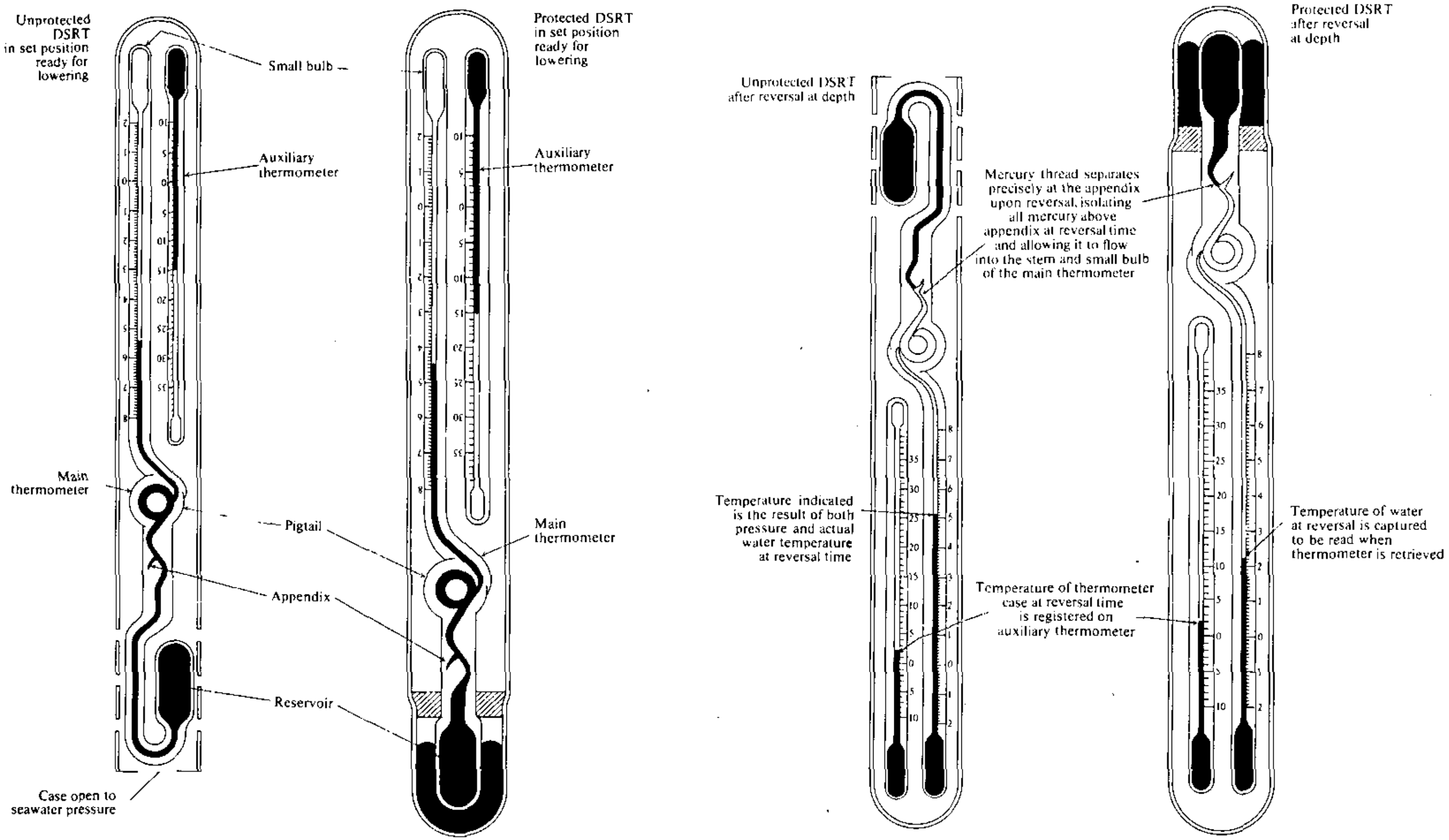
2. *Subsurface Temperature*

For temperature measurements below the sea surface, the well-known "reversing thermometer" technique (usually in association with Nansen bottles for obtaining water samples) is widely used. These thermometers are constructed in such a manner that when they are turned over (reversed), the mercury column separates at a constriction (Fig. 17a, b,) and the temperature at the time and depth that the bottle reversed can subsequently be read on the ship. Reversing thermometers are carefully calibrated, and are accurate to ± 0.01°C if certain corrections are made.

A more convenient method of measuring a vertical temperature profile is by means of an STD (or salinity-temperature-depth) instrument (Fig. 18a). These are of two types: some transmit the data up a conducting cable to the ship where the temperature and salinity are plotted on a chart to show the actual profiles immediately, while in others the data are recorded internally on magnetic tape or on stripchart and can be accessed only when the instrument has been brought on board again. Some modern profilers are as accurate as the reversing thermometers (at least in temperature measurements) and have the great advantage of showing the whole profile, whereas reversing thermometers of course give the temperatures only at preselected depths.

A CSIRO-designed profiler, known as the Bathysonde, does not require a conducting cable as the signals are relayed acoustically through the water. A hydrophone on the ship receives the data, and the temperature and salinity profiles are plotted onto a chart as the Bathysonde is being raised or lowered. It is an instrument of great potential, but has a few technical problems and is not commercially available.

STD profilers, complete with cables and deck units (or with selfcontained recorders) are very expensive, and for shallow water work much cheaper alternatives are available. In the simplest case, an ST (salinity-temperature) meter will fulfil the same purpose but less accurately — depth is not given, so the cable length out must be used as an indication of instrument depth; the temperature and salinity can be read directly from meters on the deck unit and recorded by hand. In an area of



(a) A deep-sea reversing thermometer (DSRT) in set position

(b) A deep-sea reversing thermometer in reversed position

Fig. 17. Reversing thermometers (DSRT). (a) Before. (b) After reversing. (From Duxbury, THE EARTH AND ITS OCEANS, 1971, Addison-Wesley Publishing Company Inc., Chapter 18, Figs 18.4a, 18.4b, pp. 343 and 345 respectively. Reprinted with permission).

weak currents and low ship drift; where the cable hangs almost vertically, such an instrument can be used for profiling down to a few tens of metres as long as the cable can be handled on deck without tangling or kinking.

Temperature profiles in the upper region of the sea can be obtained while the ship is steaming at up to 10 knots by using a bathythermograph (BT) (Fig. 18b). This instrument has a pressure sensitive bellows which moves a gold-plated or smoked glass slide as the BT is lowered, and a temperature sensor then draws the temperature profile on the slide. When the BT is brought on board again, the glass slide is retrieved and stored, to be later digitized using a special calibration grid from which the temperatures and depths can be noted. It is a fairly robust instrument, reasonably easy to operate and read, but can be used only in depths down to 300m and is not very accurate (roughly ± 0.2°C and 2m if well calibrated and carefully read).

A more convenient method is the expendable bathythermograph (XBT), shown in Fig. 18c. This consists of a chart recorder linked to an XBT launcher; an XBT probe is dropped into the water from the launcher, and as it falls, wire is unspooled from the probe as well as from the moving ship. The probe therefore falls vertically as the ship moves away at normal speed and a temperature profile is drawn on the recorder chart until the wire reaches the end and breaks. Various probes are available, the T4 being the most popular: it records the temperature profile down to about 480m, but deeper probes are also available. XBT temperatures are accurate to about ± 0.1°C, which is adequate for most studies in the upper few hundred metres of the sea, and an advantage of the electrical recording system is that the profiles can be logged onto magnetic tape on a datalogger if required — this can greatly facilitate subsequent computer checking and processing of the data. XBT's can be used for temperature measurements in very rough weather when other methods are no longer possible.

Disadvantages of the XBT system are the cost of the expendable probes (now about $A50 in Australia, — however this is not expensive if compared with the time-cost of stopping the ship for say 20 minutes to get a profile by STD or Nansen cast), the fact that some 5% of profiles fail for various reasons, and the reluctance to deliberately litter the seabed with the expended probes. In shallow water, of course, the 450m capability is wasted. Nevertheless, the method is popular because of the convenience and all-weather usage.

A further development, which is more expensive again, is the airborne XBT (AXBT), which enables temperature profiles to be obtained from a low-flying aircraft, thus covering a large area of sea very quickly.

3. *Moored Instruments*

The above methods all require the presence of a boat or aircraft of some kind. Most self-recording current meters, such as the Aanderaa, measure temperature as well as currents, thus enabling a time-series of temperatures at a point to be obtained. There are also much cheaper instruments which record only temperature. For details on moorings, refer to the earlier discussion on current meter moorings.

SALINITY

Dynamic processes which depend on the density of the water require measurements of both temperature and salinity. While in many areas

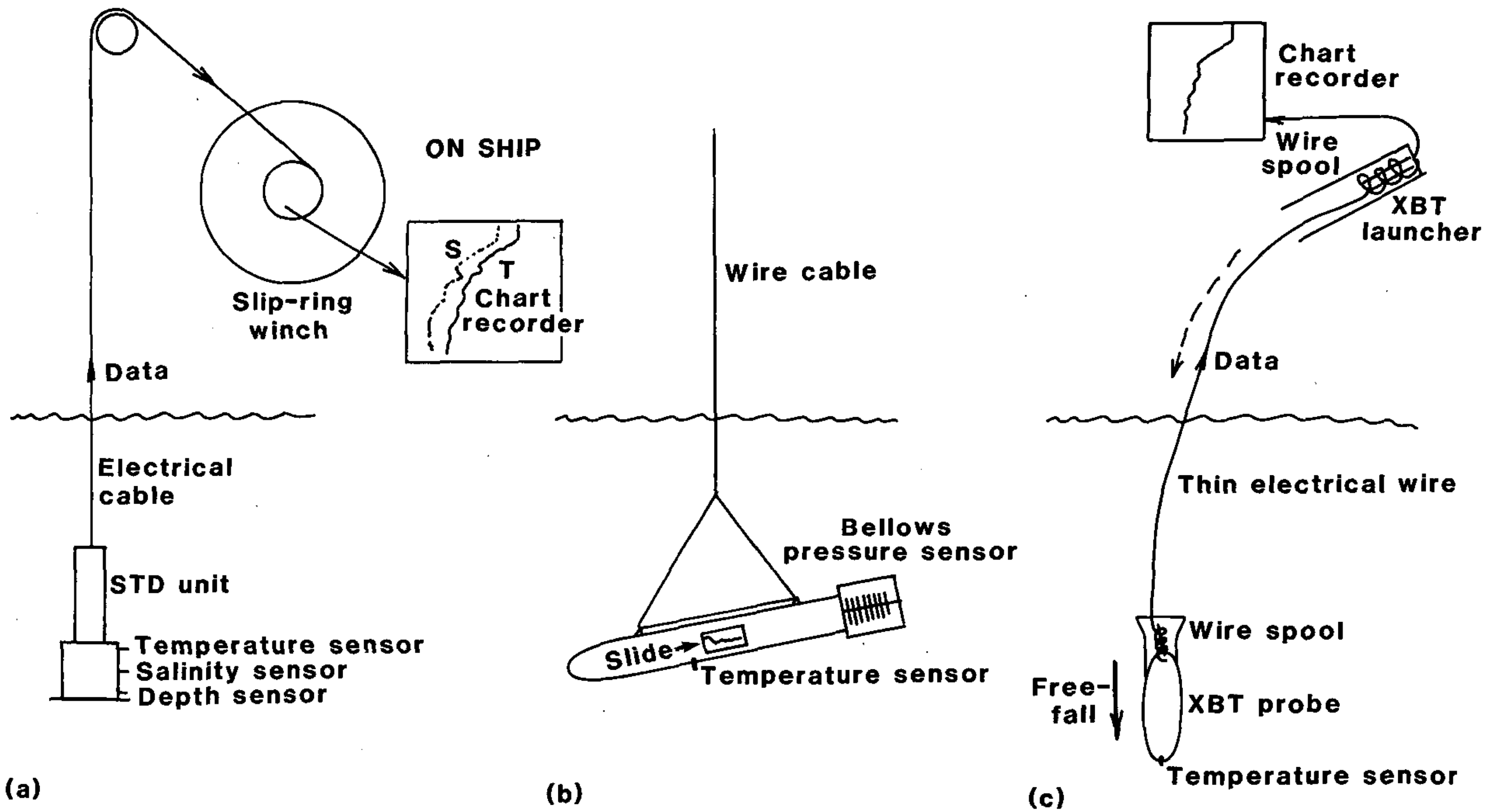


Fig. 18. Temperature profiling. (a) Salinity-temperature-depth (STD) profiler.
(b) Bathythermograph.
(c) Expendable bathythermograph (XBT).

salinity changes are small enough for the density to be almost a function of temperature alone, in other cases the salinity can be of prime importance.

Salinity may be determined by two methods: by taking a water sample and finding the salinity by the old-established titration method or by an inductive salinometer; or by directly measuring the conductivity *in situ* using a conductivity cell.

1. *Surface Salinity*

The salinity of the top 30 cm or so of the sea is most easily found by taking a bucket sample, tapping off the required amount into a glass sample bottle, and then measuring the salinity (or in fact the conductivity – see below) on a salinometer. Certain precautions such as rinsing the sample bottle thoroughly with the bucket water before drawing the sample itself, and capping the bottle with a polythene cap insert, must be followed.

Some ships are fitted with a salinograph (often combined with a temperature sensor, as a thermosalinograph) which records the surface salinity continuously on a stripchart, by measuring the conductivity of surface water pumped through a conductivity cell. Such instruments are very convenient as they show the surface salinity continuously and immediately, but they are not as accurate as the sample plus salinometer method, and should be regularly checked and calibrated.

2. *Nansen Bottles*

As mentioned earlier in the section on temperature, the classical hydrological station consists of a series of Nansen bottles with reversing thermometers clamped to the hydro wire. The Nansen bottle (Fig.19) is a metal tube fitted with valves which remain open while the hydro cast is being lowered; when a messenger, which is a small weight free to slide down the wire, is released from the surface, it strikes a trigger on the Nansen bottle which causes the tube to flip over. This process closes both valves, thus trapping the water sample, and also operates the reversing thermometers which record the temperature at that time. In addition, another messenger is released from this bottle, and it slides down the wire to operate the next Nansen bottle, and so on to the deepest bottle on the cast. The entire series of bottles is then retrieved, the water samples tapped off into suitable bottles and sample tubes for salinity and chemical analyses, and the thermometers read.

Other simpler types of bottles have been designed, using a variety of balls and caps for sealing the water sample, but they all achieve the same objective.

The salinity samples are later analysed on a salinometer which measures the conductivity of each sample, and after correcting for temperature, the salinity can be found either by reference to a set of tables or calculated from formulae. The resulting salinity is accurate to within ± 0.003‰ which is better than STD units, and also better and more convenient than the early titration method which gave a routine accuracy of ± 0.02‰.

3. *CTD and STD Equipment*

Instead of a Nansen cast, the salinity or conductivity of the water column can be measured using an STD (salinity-temperature-depth) or CTD (conductivity-temperature-depth) profiler. These give continuous profiles with depth, thus showing up small-scale salinity features which are usually missed by the Nansen bottles, but they may not be as

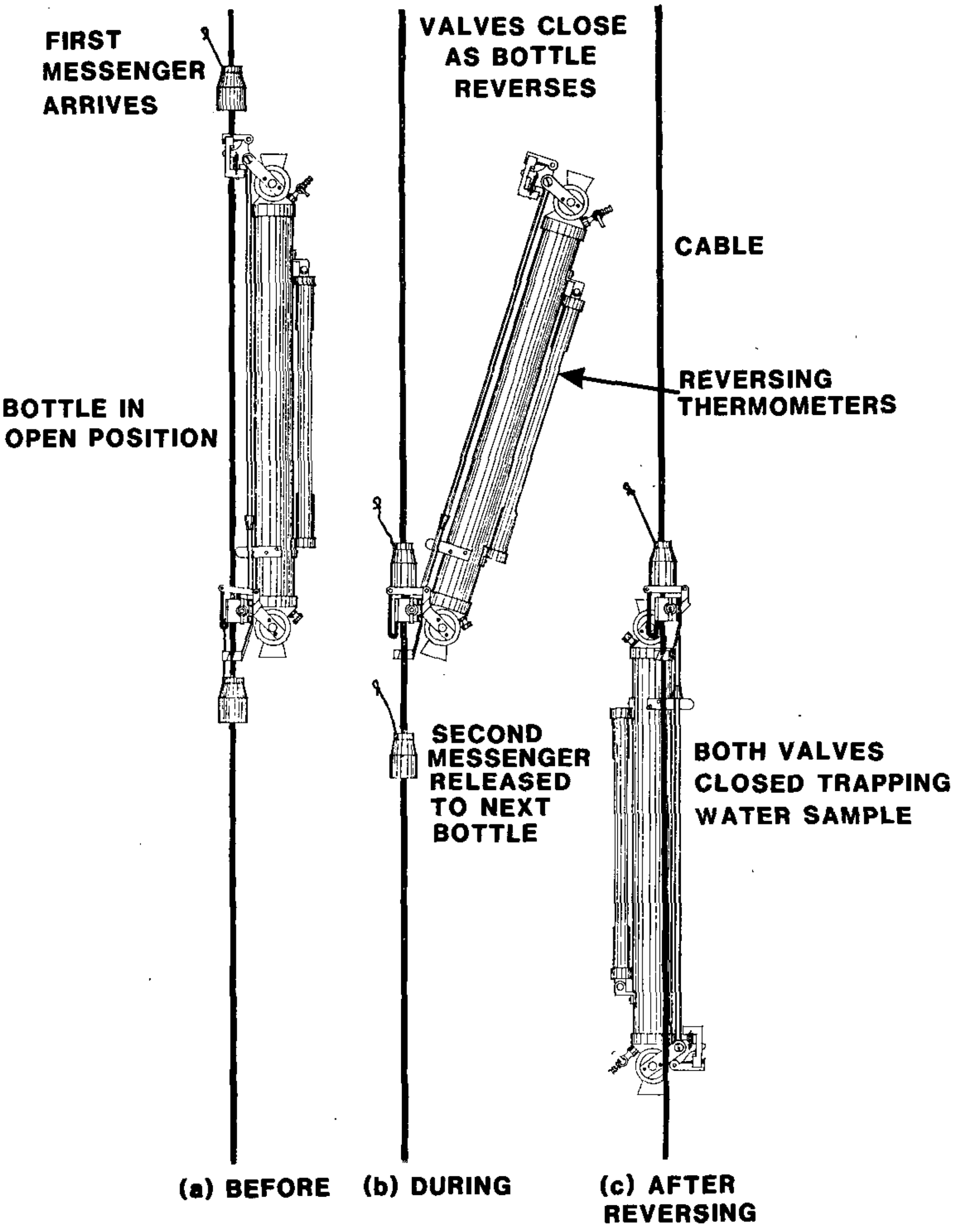


Fig. 19. Nansen sample bottles.
(From Defant, A. PHYSICAL OCEANOGRAPHY, Vol. I (1961).
Pergamon Press Ltd. Fig. 19. Reprinted with permission).

accurate in absolute terms. This can be improved by putting a conventional Nansen bottle at the bottom of the cast, i.e. just above the STD, as well as at the surface, and then adjusting the whole STD-measured salinity profile using the two Nansen salinity samples as absolute reference points.

The STD or CTD profiler is much more convenient to use than Nansen bottles, but of course water samples for chemical nutrient analysis are not obtained. This problem can be overcome by attaching a rosette sampler to the STD (the rosette sampler is a ring of Nansen-like bottles which can be closed on command from the surface) and then triggering the rosette sample bottles at important depths as determined from the STD salinity trace.

As mentioned above, simpler ST equipment is available which will give an approximate value of the salinity at various depths, usually to a lower accuracy than an expensive STD. In coastal waters where salinity changes may be fairly large, such lower accuracies may be quite acceptable for the advantage of the simpler operation of the cheaper system.

SEA-LEVEL

Sea-level gauges for measuring tides are often operated by hydrographic departments, maritime services, or port authorities, but instruments may also be laid by research institutions for scientific purposes. The main difficulty with tidal measurements is the presence of surface waves which make direct observation of the longer period tidal oscillations impossible. Two methods of measuring tides are briefly outlined here.

The conventional tidewell (Fig. 20a) works on the principle that high frequency waves are not transmitted through the small hole in the tidewell, and are thus effectively filtered out. The water level in the well therefore reflects only the sea-level averaged over many surface wave periods; it is recorded by a float-recorder system, either on a stripchart or electronically.

Sensitive pressure gauges (Fig. 20b) can be installed on the seabed, and record the pressure (and therefore the height of the water surface above the gauge) at regular intervals for a period of weeks to months. The resulting data can then be analysed by normal tidal analysis techniques.

WAVES

The simplest method of measuring ordinary surface waves near the coast is by visual (or instrument-aided visual) observation, and for many purposes these methods are adequate. The very roughest estimates of waveheight and wave period, which are two of the most important wave parameters, can be obtained by using a fixed wave staff (Fig. 21a). This is a pole graduated in feet or metres, and by watching the waves pass the pole some idea of the crest-to-trough waveheight can be obtained, and the number of wave crests passing the pole in a fixed time interval will give the wave period. Such observations must obviously be made offshore of the breaker zone so that the smooth swell crests can be clearly seen. It is much more difficult to estimate the wave direction, partly because the direction of the swell crests is not easy to observe, and also because of the refraction of the swell as it moves into shallowing water on approaching the beach.

A wave clinometer has been developed which is basically a modified telescope. This is used from an elevated shore site to estimate wave height, period and direction by observing a buoy anchored outside the breaker zone. All such visual methods rely on good visibility and may be

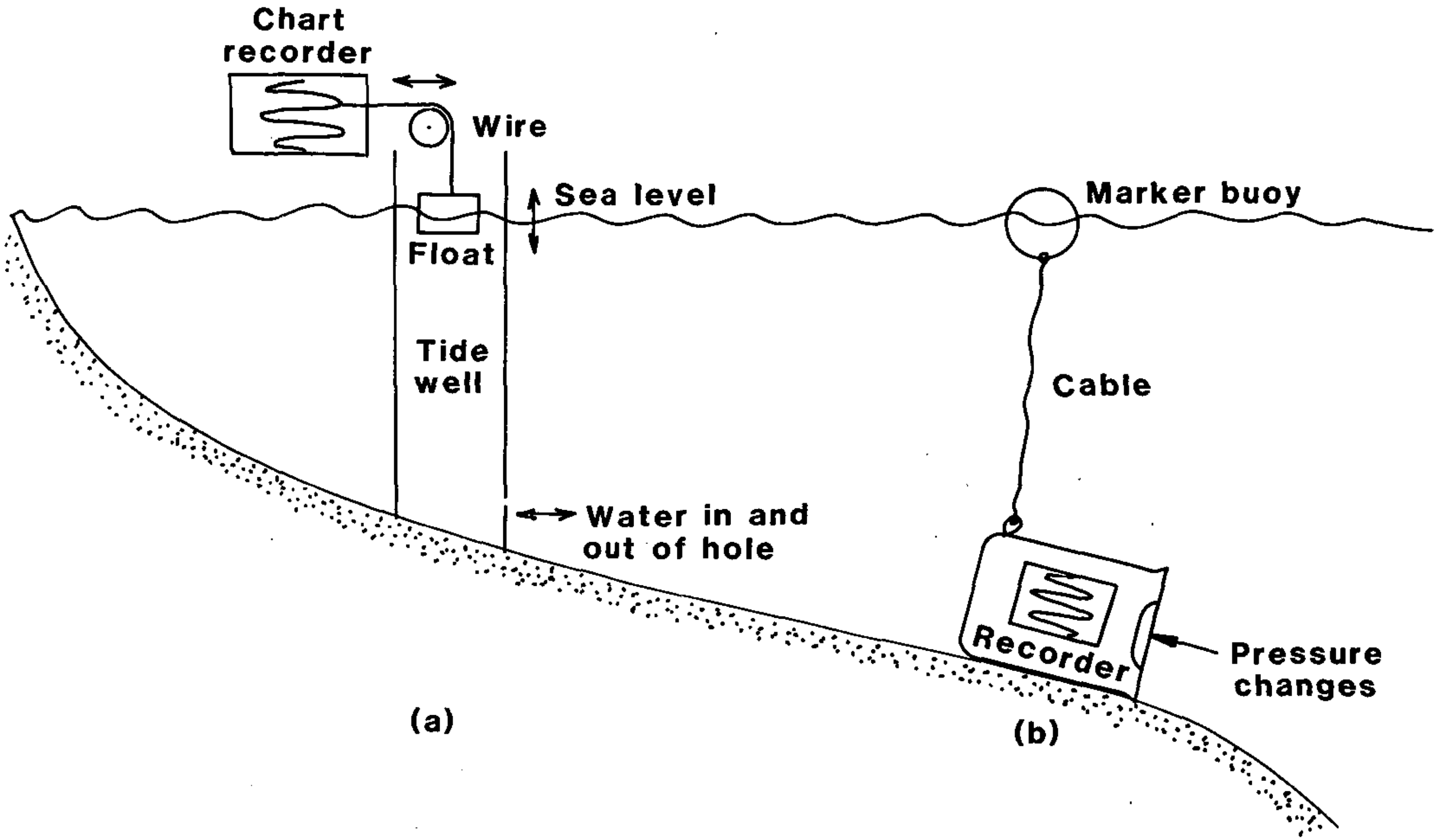


Fig. 20. Measuring sea level (tides). (a) Tidewell and chart recorder.
(b) Pressure recorder.

difficult to apply in rough sea conditions, but much valuable wave data have been obtained.

Wave-recording instruments operate on a wide variety of principles but may be considered in three classes: "remote" sensing, surface instruments, and subsurface equipment.

1. *Remote-sensing Methods*

These include such techniques as radar or stereophotography from coastal towers or aircraft, and even satellites can give reasonable estimates of some wave parameters. Photographic methods are easy to carry out, but are limited to conditions of good visibility and the photographs may be difficult to interpret. Shore-based radar methods have a range to a few kilometres offshore, and in fact are most useful under rough conditions where the large turbulent waves give good radar echoes.

2. *Surface Methods*

Techniques using surface wave followers or staffs projecting through the water surface have been widely used. Examples include: (i) Electrical wave staffs, which use the conductivity of seawater as it rises past a series of closely-spaced electrodes to indicate the wave motion, and the electrical signal can be recorded onto a stripchart or magnetic tape. (ii) Waverider floating buoys, fitted with internal accelerometers which measure the vertical accelerations as the buoys follow the water surface (Fig. 21b). The Datawell buoy transmits this data to a radio receiver ashore at regular intervals where the waves are recorded on stripchart. These waveriders are very popular. (iii) Waverecorders fitted to ships operate on a principle similar to waveriders, except that the ship itself is the floating buoy. Both the motion of the ship and the height of the waves as they move past the ship are recorded, and from these two components the true waveheight can be found.

3. *Subsurface Methods*

Bottom-mounted waverecorders may record internally, or may relay the wave data along a seabed cable to a shore recording unit. One series of instruments measures the water pressure, which is related to the surface wave field, although not linearly. Such instruments are generally reliable and fairly inexpensive, but higher frequency waves are not recorded correctly in deeper water. Nevertheless it is a useful method.

A second class of instruments works on an inverted echosounder principle. Acoustic signals are transmitted vertically upwards from the bottom-mounted instrument, and the time interval before the echo from the surface returns to the unit is a measure of the waveheight (Fig. 21c). If there is much sediment or turbulent bubbles in the water the record may be difficult to interpret.

WIND AND ATMOSPHERIC PRESSURE

Meteorological measurements are important to the coastal oceanographer because of the energy input to the sea from atmospheric processes.

1. *Pressure*

Atmospheric pressure is simple to measure as almost any location is suitable. Standard mercury or aneroid barometers are readily available at relatively small cost. Recording barographs are more expensive but simple to operate, and the resulting stripcharts are easy to digitise for subsequent analysis. For purposes where data from a number of barometer stations are to be used together, standardization of

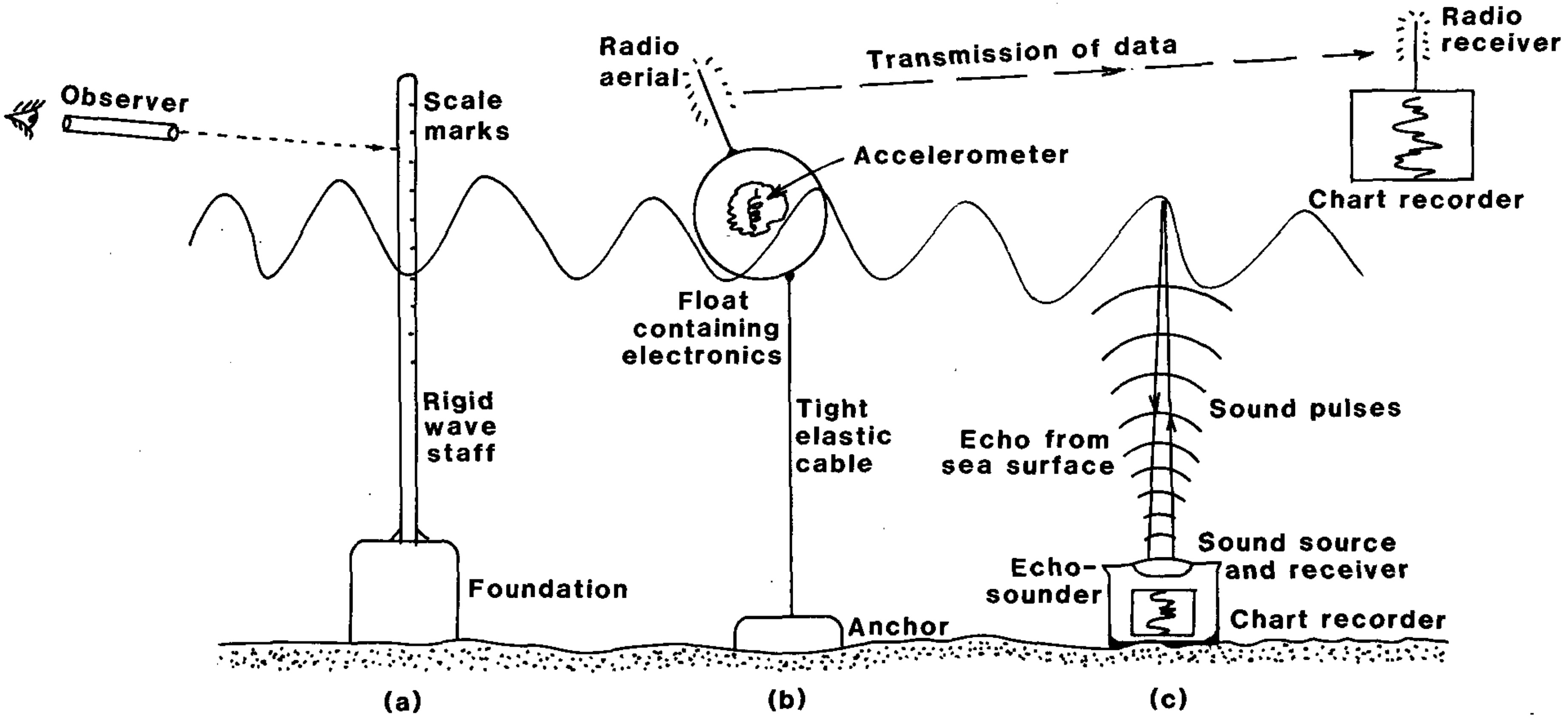


Fig. 21. Wave measurements. (a) Visual wave staff.
(b) Waverider buoy.
(c) Inverted echosounder.

the various pressures to a reference level (usually sea-level) is necessary by correcting for the different heights of the individual instruments above sealevel. More recently, dataloggers such as the Aanderaa model have become available, enabling pressure to be measured for long periods and recorded on magnetic tape, thus permitting continuous measurements to be made at unattended remote stations. Such records are of course immediately suitable for computer time-series analysis.

2. *Wind*

Wind is less easy to measure than pressure. Because of the wind velocity gradient in the boundary layer just above the surface of the land or ocean, a standard measuring height must be specified, usually 10 m. Further, the area in the vicinity of the anemometer should be clear of obstructions such as trees or buildings which may disturb the wind field. Wind measurements at sea are free from nearby obstructions, but anemometers mounted on ships or buoys suffer from an added wind component due to the motion of the ship and rolling of the vessel or buoy. (The problem is rather like wave contamination of a Savonius rotor current record in shallow water).

It is desirable to measure the winds out at sea if possible, by mounting an anemometer on a small island, reef, oil platform, etc., as it appears that the wind over the sea (even close to land) may be very different from that measured at a land-based station. Land-measured winds, therefore, may not be representative of the wind stress driving the water on the continental shelf. In recording wind directions, it should be recommended that the direction is conventionally taken as that <u>from</u> which the wind blows (e.g. a northerly wind blows <u>from</u> the north, whereas a northerly current flows <u>to</u> the north).

Simple Techniques

A rough idea of the wind speed at sea may be obtained by reference to the Beaufort wind scale (Table 1) which estimates the wind from observation of sea state (or motion of trees, etc., on land). This will give only an approximation of the wind speed which may be suitable for climatological-type work but inadequate for most other studies.

Various simple devices such as vanes and hand-held anemometers have been devised for simple measurements of the wind, but again these are unlikely to be suitable for accurate work.

Recording Equipment

Mechanical or electrical anemographs are available, which will record wind speed and direction continuously or at pre-selected intervals for long periods. Such equipment, if correctly installed, well calibrated, and carefully maintained is the only method of conveniently obtaining reliable, long-term wind data. If the recording is done on computer-compatible form such as magnetic tape, subsequent processing and analysis of the data are facilitated.

Table 1. Simplified Beaufort wind scale for use at sea

Beaufort No.	Approximate speed (knots)	Observations
0	<1 (calm)	Sea like mirror
1	1- 3 (light air)	Ripples like scales; no foam crests.
2	4- 6 (light breeze)	Small wavelets; crests of glassy appearance, not breaking.
3	7-10 (gentle breeze)	Large wavelets; crests begin to break; scattered whitecaps.
4	11-16 (moderate breeze)	Small waves, becoming longer; numerous whitecaps.
5	17-21 (fresh breeze)	Moderate waves, of longer form; many white caps; some spray.
6	22-27 (strong breeze)	Larger waves forming; whitecaps everywhere; more spray.
7	28-33 (moderate gale)	Sea heaps up; some white foam streaks from breaking waves.
8	34-40 (fresh gale)	Moderately high waves; foam blown in well-marked streaks.
9	41-47 (strong gale)	High waves; sea begins to roll; dense streaks of foam.
10	48-55 (whole gale)	Very high waves with overhanging crests; sea is white with foam; heavy rolling, reduced visibility.
11	56-63 (storm)	Exceptionally high waves; sea covered with foam.
12	>64 (hurricane)	Air filled with foam, sea completely white with driving spray.

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