DRIFTERS AND FLOATS

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Introduction

Starting in the 1970s, surface drifters and subsurface neutrally buoyant floats have been developed, improved, and tracked in large numbers in the ocean. For the first time we have now obtained worldwide maps of the surface and subsurface velocity at a few depths. New profiling floats are measuring and reporting in real time the evolving temperature and salinity structure of the upper 2 km of the ocean in ways that were impossible a decade ago. These measurements are documenting variations of the world ocean's temperature and salinity structure. The new data are revealing insights about ocean circulation and its time variability that were not available without drifters and floats.

Surface drifters and subsurface floats measure ocean trajectories that show where water parcels go, how fast they go there, and how vigorously they are mixed by eddies. Ocean trajectories, which are called a Lagrangian description of the flow, are useful both for visualizing ocean motion and for determining its velocity characteristics. The superposition of numerous trajectories reveals that very different kinds of circulation patterns occur in different regions. Time variability is illustrated by the tangle of crossing trajectories. Trajectories often show the complicated relationship between currents and nearby seafloor topography and coastlines. Drifters and floats have been used to follow discrete eddies like Gulf Stream rings and 'meddies' (Mediterranean water eddies) continuously for years. When a drifter becomes trapped in the rotating swirl flow around an eddy's center, the path of the eddy and its swirl velocity can be inferred from the drifter trajectory. Thus the movement of a single drifter represents the huge mass of water being advected by the eddy. Trajectories of drifters launched in clusters have provided important information about dispersion, eddy diffusivity, and stirring in the ocean.

When a sufficient number of drifters are in a region, velocity measurements along trajectories can be grouped into variously sized geographical bins and calculations made of velocity statistics such as mean velocity, seasonal variations, and eddy energy. Gridded values of these statistics can be plotted and contoured to reveal, for example, patterns of ocean circulation and the sources and sinks of eddy energy. Maps of velocity fields can be combined with measurements of hydrography to give the three-dimensional velocity field of the ocean. Oceanographers are using the newly acquired drifter data in these ways and also incorporating them into models of ocean circulation.

Care must be used in interpreting drifter measurements because they are often imperfect current followers. For example, surface drifters have a small downwind slip relative to the surrounding water. They also tend to be concentrated by currents into near-surface converge regions. The surface water that converges can descend below the surface, but drifters are constrained to remain at the sea surface in the convergence region. Surface currents sometimes converge drifters into swift ocean jets like the Gulf Stream. This can result in oversampling these features and in gridded mean velocities that are different from averages of moored current meter measurements, which are called Eulerian measurements of the flow. Bin averages of drifter velocities can give misleading results if the drifters are very unevenly distributed in space. For example, drifters launched in a cluster in a region of zero mean velocity tend to diffuse away from the cluster center by eddy motions, implying a divergent flow regime. The dispersal of such a cluster gives important information about how tracers or pollutants might also disperse in the ocean. Drifters tend to diffuse faster toward regions of higher eddy energy, resulting in a mean velocity toward the direction of higher energy. This is because drifters located in a region of high eddy kinetic energy drift faster than those in a region of low kinetic energy. Errors concerning array biases need to be estimated and considered along with gridded maps of velocity.

Surface Drifters

Surface drifter measurements of currents have been made for as long as people have been going to sea. The earliest measurements were visual sightings of natural and man-made floating objects within sight of land or from an anchored ship that served as a reference. Starting at least 400 years ago, mariners reported using subsurface drogues of different shapes and sizes tethered to surface floats to measure currents (Figure 1). The drogues were designed to have a large area of drag relative to the surface float so that

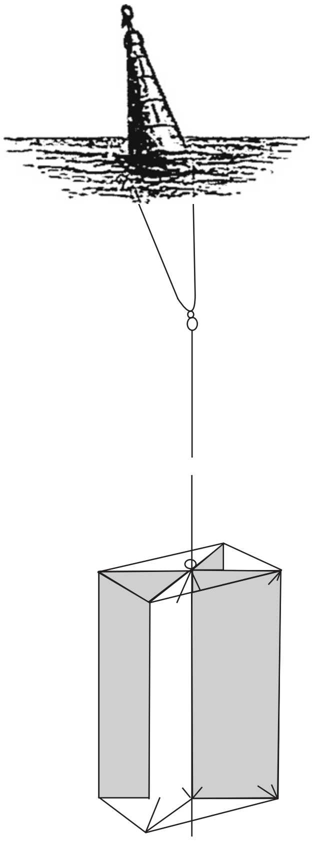

Figure 1 Schematic of an early drifter and drogue from the *Challenger* expedition (1872–76). Adapted from Niiler PP, Davis RE, and White HJ (1987) Water following characteristics of a mixed layer drifter. *Deep-Sea Research* 24: 1867–1881.

the drifter would be advected primarily with the water at the drogue depth and not be strongly biased by wind, waves, and the vertical shear of near-surface currents. Over the years many kinds of drogues, tethers, and surface floats have been tried, including drogues in the form of crossed vanes, fishing nets, parachutes, window shades, and cylinders.

Ship Drifts

Probably the most successful historical drifter is a ship; the drift of ships underway as they crossed oceans provided millions of ocean current measurements. A ship drift measurement is obtained by subtracting the velocity between two measured position fixes from the estimated dead reckoning velocity of the ship through the water over the same time interval. The difference in velocity is considered to be a measure of the surface current. This technique depends on good navigation, which became common by the end of the nineteenth century. Most of what we have learned about the large-scale patterns of ocean currents until very recently came from compilations of historical ship drift measurements. Pilot charts used by most mariners today are still based on historical ship drifts. Problems with the ship drift technique are the fairly large random errors of each velocity measurement ($\sim 20\,\mathrm{cm\,s^{-1}}$) and the suspected systematic downwind leeway or slip of a ship through the water due to wind and wave forces. New velocity maps based on satellite-tracked drifters are providing a much more accurate and higher-resolution replacement of ship drift maps.

Drifting derelict ships gave an early measurement of ocean trajectories during the nineteenth century. Wooden vessels that had been damaged in storms were often abandoned at sea and left to drift for months to years. Repeated sightings of individual vessels reported in the US pilot charts provided trajectories.

Other Drifters

Bottles with notes and other floating objects have been a popular form of surface drifter over the years. The vectors between launch and recovery on some distant shore provided some interesting maps but ones that were difficult to interpret. The technique was improved and exploited in the North Atlantic by Prince Albert I of Monaco during the late 1800s. More recently, 61 000 Nike shoes and 29 000 plastic toy animals were accidentally released from damaged containers lost overboard from ships in storms in the North Pacific. The recovery of thousands of these drifters along the west coast of North America has given some interesting results about mean currents and dispersion.

Bottom drifters are very slightly negatively buoyant and drift along the seafloor until they come ashore and are recovered. The vectors between launch and recovery show long-term mean currents near the seafloor.

Tracking

Early measurements of drifters were visual sightings using telescopes, compasses, and sextants to measure bearings and locations. Later during the 1950s, radio direction finding and radar were used to track drifters over longer ranges and times from shore, ship, and airplane. Some drifter trajectories in the 1960s were obtained by Fritz Fuglister and Charlie Parker in the Gulf Stream and its rings using radar. These early experiments did not obtain very many detailed and long trajectories but did reveal interesting features of the circulation. It was clearly apparent that a remote, accurate, relatively inexpensive, long-term tracking system was needed. This was soon provided in the 1970s by satellite tracking, which revolutionized the tracking of drifters in the ocean.

The first satellite tracking of drifters occurred in 1970 using the Interrogation Recording and Location System (IRLS) system flown on *Nimbus 3* and *4* satellites. This system measured the slant range and bearing of a radio transmitter on a drifter. The IRLS drifters were very expensive, too expensive at $50 000 to be used in large numbers (but cheap compared to the cost of the satellite). During 1972–73, several drifters were tracked with the (Corporative Application Satellite) EOLE system, which incorporated Doppler measurements of the drifter radio transmissions to determine position. In the mid-1970s, NASA developed the Random Access Measurement System (RAMS), which used Doppler measurements and was flown on the *Nimbus* 6 satellite. The radio transmitters were relatively inexpensive at $1300, and tracking was provided free by NASA (as proof of concept), which enabled many oceanographers to begin satellite tracking of surface drifters. The modern Doppler-based satellite tracking used today, the French Argos system flown on polar orbiting satellites, is similar to the early RAMS but provides improved position performance. The modern drifter transmitter emits a 0.5-W signal at 402 MHz approximately every minute. Positions are obtained by Service Argos about six times per day in the equatorial region increasing to 15 times per day near 60° N. Position errors are around 300 m. The cost per day of satellite tracking is around $10, which becomes quite expensive for continuous year-long trajectories. To reduce costs, some drifters have been programmed to transmit only one day out of three or for one-third of each day. This causes gaps in the trajectories that need to be interpolated.

Recently, drifters with Global Positioning System (GPS) receivers have been deployed to obtain more accurate ($\sim$ 10 m) and virtually continuous fixes. GPS position and sensor data need to be transmitted to shore via the Argos system or another satellite that can relay data. Experiments are underway using new satellite systems to relay information both ways – to the drifters and to the shore – in order to increase bandwidth, to decrease costs, and to modify sampling.

WOCE drifter The development of satellite tracking in the 1970s quickly revealed the weakness of available drifters – most performed poorly and most did not survive long at sea. Many problems needed to be overcome: fishbite, chafe, shockloading, biofouling, corrosion, etc. Early drogues tended to fall off fairly quickly and, since drogue sensors were not used or did not work well, no one knew how long drogues remained attached. Over the years many people tried various approaches to solve these problems, but it was mainly due to the impetus of two large experiments, Tropical Ocean and Global Atmosphere (TOGA) and World Ocean Circulation Experiment (WOCE), and with the persistent efforts of Peter Niiler and colleagues that a good surface drifter was finally developed, standardized, and deployed in large numbers. The so-called WOCE drifters have good water-following characteristics and the slip of the drogue has been calibrated in different conditions. The WOCE drifter works fairly reliably and often survives longer than a year at sea. As of March 2007 there were around 1300 drifters being tracked in the oceans as part of the Global Drifter Program. Data assembly and quality control is performed by the Drifter Data Assembly Center at the National Oceanic and Atmospheric Administration (NOAA) in Miami, Florida. Recent analyses include mapping surface velocity over broad regions and the generation of maps of mean sea level pressure based on drifter measurements.

The WOCE drifter consists of a spherical surface float 35 cm in diameter, a 0.56-cm diameter plastic-impregnated wire tether, with a 20-cm diameter subsurface float located at 275 cm below the surface and a drogue in the shape of a 644-cm-long cloth cylinder 92 cm in diameter with circular holes in its sides (Figure 2). The fiberglass surface float contains a radio transmitter, batteries, antenna, and sensors including a thermometer and a submergence sensor that indicates if the drogue is attached. Additional sensors can be added to measure conductivity, atmospheric pressure, light, sound, etc. The basic WOCE drifter costs around $2500, ready for deployment.

The WOCE drifter's drogue is centered at a depth of 15 m below the sea surface. The ratio of the drag area of the drogue to the drag area of tether and float is around 41:1, which results in the drogue's slip through the water being less than 1 cm s^{-1} in winds of 10 m s^{-1}. The slip was measured to be proportional to wind speed and inversely proportional to the drag area ratio. From this information, the slip can be estimated and subtracted from the drifter velocity.

Drogue Depth

Drogues have been placed at many different depths to suit particular experiments. The drogues of Coastal Ocean Dynamics Experiment (CODE) drifters developed by Russ Davis were located in the upper meter of the water column to measure the surface velocity. WOCE drogues are placed at 15 m

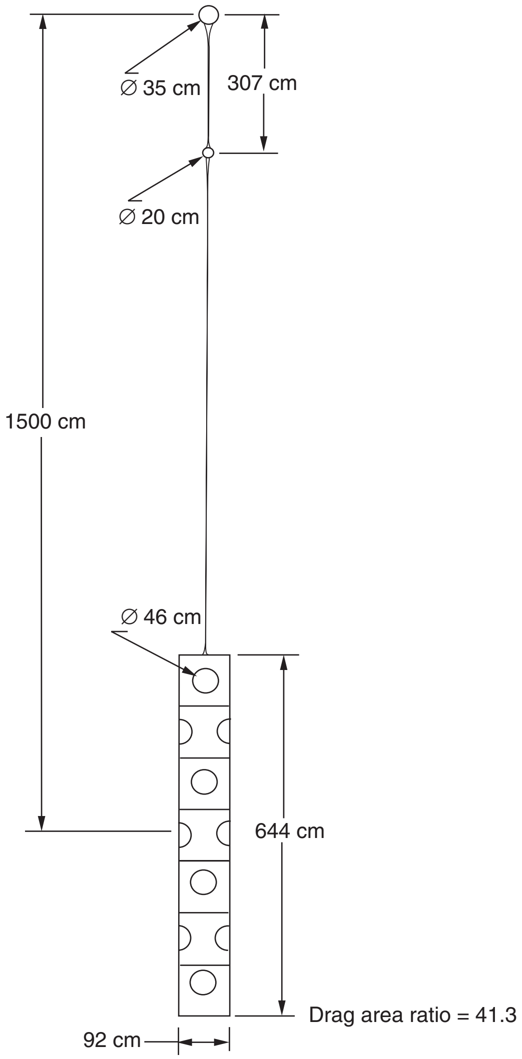

Figure 2 Schematic of WOCE surface drifter. Adapted from Sybrandy AL and Niiler PP (1991) *WOCE/TOGA Lagrangian Drifter Construction Manual*, SIO Reference 91/6, WOCE Report No. 63. La Jolla, CA: Scripps Institution of Oceanography.

to measure a representative velocity in the Ekman layer but below the fastest surface currents. Many scientists have deployed drogues at around 100 m to measure the geostrophic velocity below the Ekman layer. An argument for the 100-m depth is that it is better to place the drogue below the complicated velocity structures in the Ekman layer, Langmuir circulations, and near-surface convergence regions. An argument against the 100-m depth is that the drag of the long tether and surface float in the relatively fast Ekman layer could create excessive slip of the drogue and bias the drifter measurement of geostrophic velocity. The controversy continues. The 15-m depth is widely used today, but many earlier drifters had deeper drogues at around 100 m. Some drogues have been placed as deep as 500–1000 m often to track subsurface coherent eddies such as meddies.

Subsurface Floats

Many kinds of freely drifting subsurface floats are being used to measure ocean currents, although most floats are usually either autonomous or acoustic. An autonomous float measures a series of subsurface displacements and velocities between periodic surface satellite fixes. An acoustic float measures continuous subsurface trajectories and velocities using acoustic tracking. Acoustic floats provide high-resolution ocean trajectories but require an acoustic tracking array and the effort to calculate subsurface positions, both of which add cost. Thousands of autonomous and acoustic floats have been deployed to measure the general circulation in the world ocean at various depths but concentrated near 800 m. Historical and WOCE era float data can be seen and obtained on the WOCE float website along with references to a series of detailed scientific papers, and newer float data on the Argo website.

WOCE Autonomous Float

The autonomous WOCE float was developed in the 1990s by Russ Davis and Doug Webb. The float typically drifts submerged for a few weeks at a time and periodically rises to the sea surface where it transmits data and is positioned by the Argos satellite system. After around a day drifting on the surface, the float resubmerges to its mission depth, typically somewhere in the upper kilometer of the ocean, and continues to drift for another few weeks. Around 100 round trips are possible over a lifetime up to 6 years.

The float consists of an aluminum pressure hull 1 m in length and 0.17 m in diameter (Figure 3). A hydraulic pump moves oil between internal and external bladders, forcing changes of volume and buoyancy and enabling the float to ascend and descend. An antenna transmits to Argos and a damping plate keeps the float from submerging while it is floating in waves on the sea surface. Some floats are drogued to follow a pressure surface; others can be programmed with active ballasting to follow a particular temperature or density surface; more complicated sampling schemes are possible.

Autonomous floats have been equipped with temperature and conductivity sensors to measure vertical profiles as the floats rise to the surface. Electric potential sensors have been added to some floats by Tom Sanford and Doug Webb in order to measure vertical profiles of horizontal velocity. These

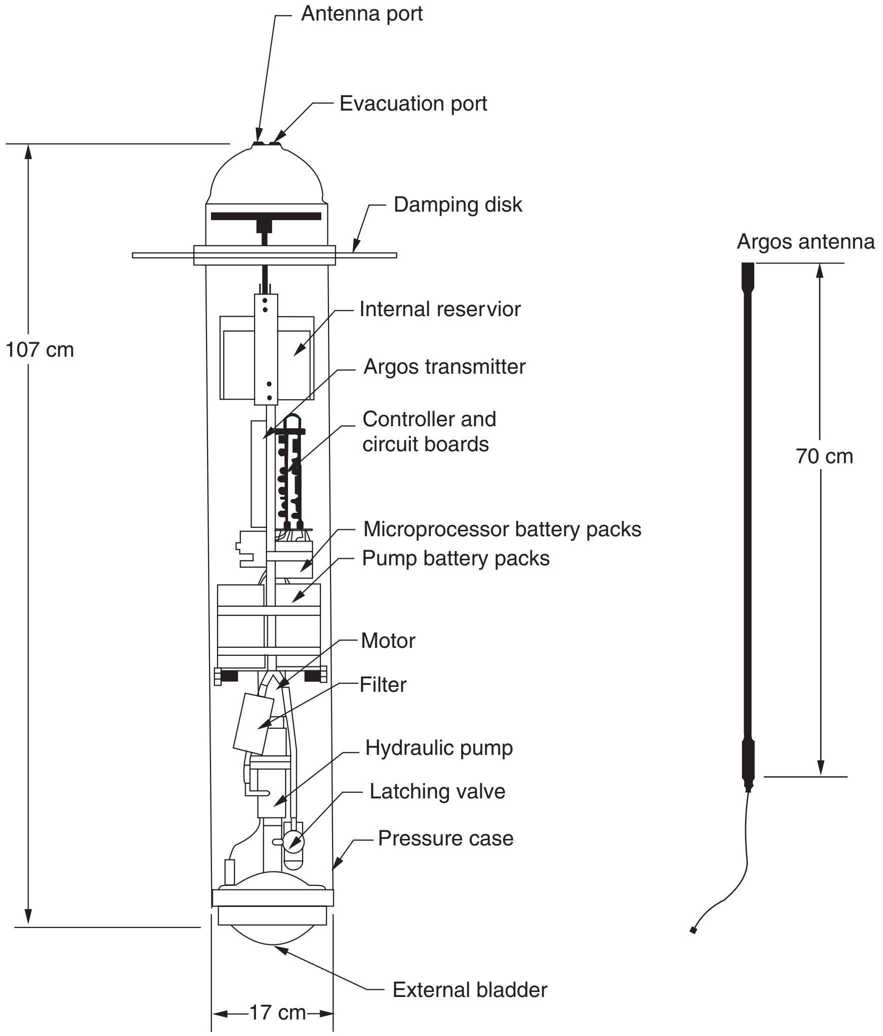

Figure 3 Schematic of Autonomous Lagrangian Circulation Explorer (ALACE) float. For ascent, the hydraulic pump moves oil down from an internal reservior to an external bladder. For descent, the latching valve is opened, allowing oil to flow back into the internal reservior. The antenna shown at the right is mounted on the top hemispherical end cap. Adapted from Davis RE, Webb DC, Regier LA, and Dufour J (1992) The Autonomous Lagrangian Circulation Explorer (ALACE). *Journal of Atmospheric and Oceanic Technology* 9: 264–285.

floats were recently used to measure the ocean response of hurricanes.

Starting in 2000, an array of profiling floats began to be launched as part of an international program called Argo. Plans are to build up the float array reaching 3000 profiling floats by 2007 and to replace them as they are lost. As of March 2007, there are around 2800 Argo floats operational. The floats profile temperature and salinity to a depth of 2000 m and measure velocity at the drift depth near 1000 m. Profiles of temperature and salinity are being used to map large areas of the ocean including velocity at the drift depth and are being incorporated into predictive numerical models. The profiles are being combined with earlier and sparser hydrographic profiles to document oceanic climate changes.

The basic drift data from an autonomous float are subsurface displacements or velocity vectors between surface satellite fixes or between extrapolated positions at the times of descent and ascent. Errors in position are estimated to be around 3 km. The surface drifts cause gaps in the series of subsurface displacements, so the displacements cannot be connected into a continuous subsurface trajectory. Subsurface displacements are typically measured over several weeks, which attenuates the higher-frequency motions of ocean eddies. The main benefit of these floats is that they can be used to map the low-frequency ocean circulation worldwide relatively inexpensively. The cost of a WOCE profiling autonomous float is around $16 000 (cheaper than a day of an ocean-going ship).

A recent development is the addition of small wings plus streamlining that transforms the float into a simple autonomous glider as it ascends and descends. These gliders are self-propelled through the ocean with typical horizontal speeds of $30\,\mathrm{cm\,s^{-1}}$ while moving vertically. Movable internal ballast is used to bank a glider, forcing it to turn. Gliders can be programmed to return to a specific location to hold position, to execute surveys, and to transit ocean basins along lines. Doug Webb at Webb Research Corporation is equipping some with thermal engines that extract energy from the ocean's thermal stratification in temperate regions in order to continuously power the glider. Phase changes of a fluid are used to force buoyancy changes. Some gliders incorporate suitable navigation and measure vertical profiles of velocity. Recently, fleets of gliders have been directed from shore to survey the evolving structure of coastal regions.

Acoustic Floats

In the mid-1950s, Henry Stommel and John Swallow pioneered the concept and development of freely drifting neutrally buoyant acoustic floats to measure subsurface currents. The method uses acoustics because the ocean is relatively transparent to sound propagation. The deep sound channel centered at a depth around 1000 m enables long-range acoustic propagation. The compressibility of hollow aluminum and glass pressure vessels is less than that of water, so that a float can be ballasted to equilibrate and remain near a particular depth or density. For example, if the float is displaced too deep, it compresses less than water and becomes relatively buoyant, rising back to its equilibrium level, which is consequently stable. Once neutrally buoyant, a float can drift with the currents at that depth for long times.

In 1955, Swallow built the first successful floats (since called Swallow floats) and tracked them for a few days by means of hydrophones lowered from a ship. A moored buoy provided a reference point for the ship positioning. The first pressure hulls were made out of surplus aluminum scaffolding tubes; Swallow thinned the walls with caustic soda to adjust compressibility and buoyancy. Although several floats failed, two worked successfully, which led to further experiments. In 1957, Swallow tracked deep floats as they drifted rapidly southward offshore of South Carolina, providing the first convincing proof of a swift, narrow southward flowing deep western boundary current previously predicted by Stommel. A second experiment in 1959 tracked deep Swallow floats in the Sargasso Sea west of Bermuda. Instead of drifting slowly in a generally northward direction as had been predicted, the floats drifted fast and erratically, providing convincing evidence of eddy motions that were much swifter than long-term mean circulation. Previously, the deep interior flow was considered too sluggish to be measured with moored current meters. The discovery of mesoscale variability or ocean eddies by Swallow and James Crease using floats radically changed the perception of deep currents and spurred the further developments of both floats and current meters.

Swallow floats had a short acoustic range and required a nearby ship to track them, which was difficult and expensive. It was quickly realized that much longer trajectories were needed in order to measure the ocean variability and the lower-frequency circulation. Accomplishing this required a neutrally buoyant float capable of transmitting significantly more acoustic energy and operating unattended for long times at great pressures. Second, access was required to military undersea listening stations, so that the acoustic signals could be routinely recorded and used to track the floats. In the late 1960s, Tom Rossby and Doug Webb successfully developed and tested the sound fixing and ranging (SOFAR) float, named after the SOFAR acoustic channel.

SOFAR floats transmit a low-frequency (250 Hz) signal that sounds in air somewhat like a faint boat whistle. The acoustic signal spreads horizontally through the SOFAR channel and can be heard at ranges of roughly 2500 km. The acoustic arrival times measured at fixed listening stations are used to calculate distances to the float and to triangulate its position. The first success with a SOFAR float drift of four months in 1969 led to further developments and the first large deployment of floats in 1973 as part of Mid-Ocean Dynamics Experiment (MODE). Very interesting scientific results using the float data led to many more experiments and wider use of floats. Later improvements included swept-frequency coherent signaling in 1974, active depth control in 1976, higher power for longer range in 1980, and microprocessors and better electronics in 1983. Moored autonomous undersea listening stations were developed in 1980, freeing experiments from military stations and enabling floats to be tracked in the Gulf Stream and other regions for the first time. SOFAR floats are large (~5-m long) and heavy (~430 kg), which makes them difficult to use in large numbers. In 1984, Rossby developed the RAFOS (SOFAR spelled backward) float, a much smaller, cheaper float that listens to moored sound sources and at the end of its mission surfaces and reports back data via satellite. This float made it much easier and cheaper to conduct larger experiments; this style of float was improved and tracked in large numbers in the North and South Atlantic as part of WOCE. Various float groups have collaborated in tracking floats at different depths and in maintaining moored tracking arrays.

WOCE RAFOS Float

The modern acoustic RAFOS float consists of a glass hull 8.5 cm in diameter and 150–200-cm long, enclosing an electronic package, Argos beacon, and temperature and pressure sensors (Figure 4). An acoustic transducer and external drop weight are attached to an aluminum end cap on the bottom. RAFOS floats are capable of operating at depths from just below the sea surface to around 4000 m. Usually several times per day they listen and record the times of arrival of 80 s 250-Hz acoustic signals transmitted from an array of moored undersea sound sources. At the end of the mission, a few months to a few years in length, the float drops an external weight, rises to the sea surface, and transmits recorded times of arrival, temperatures, and pressures to the Argos system. The float remains drifting on the surface for roughly a month before all the data are received and relayed ashore by satellite. A typical float costs $4000–5000 and is considered expendable because it is difficult and expensive to retrieve. The times of arrival are used with the known transmit times of sources and the estimated speed of sound to triangulate the float's position.

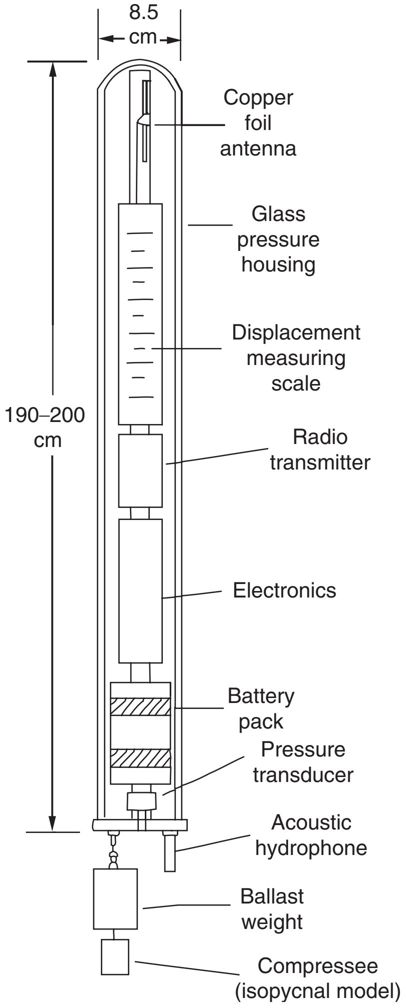

Figure 4 Schematic of RAFOS acoustic float. Adapted from Rossby HT, Dorson D, and Fontaine J (1986) The RAFOS system. *Journal of Atmospheric and Oceanic Technology* 3: 672–679.

A drifting RAFOS float closely follows a pressure surface. A compressee consisting of a spring and piston in a cylinder is sometimes suspended below a RAFOS float, so that it matches the compressibility of seawater. If the compressibilities are the same, the float will remain on or close to a constant density surface and more closely follow water parcels. Some floats have active ballasting and can track a column of water by cycling between two density surfaces.

To ballast a RAFOS float, it is weighed in air and water, which gives its volume. Its compressibility is measured by weighing the float at different pressures in a water-filled tank. The amount of weight to be added to make the float neutrally buoyant at the target depth (or density) is calculated using the compressibility and thermal expansion of the float and the temperature and density of the water in the tank and at the target depth. Floats usually equilibrate within 50 m of their target depths or density.

Some floats combine acoustic tracking with the active buoyancy of the autonomous float, so that the float can periodically surface and relay data to shore at intervals of a few months. This avoids the long wait for multiyear RAFOS floats to surface and avoids the loss of all data should a float fail during its mission. French MARVOR floats developed by Michel Ollitrault report data back every 3 months and typically survive for 5 years.

Drogues have been added to neutrally buoyant floats by Eric d'Asaro to enable them to better measure three-dimensional trajectories. Vertical velocities from these floats are especially interesting in the upper ocean and in the deep convective regions like the Labrador Sea in winter. Another technique used to measure vertical water velocity is the addition of tilted vanes attached to the outside of a float. Water moving vertically past the vanes forces the float to spin and this is measured and recorded.

At least two moored sound sources are required to position a RAFOS float. Often three or more are used to improve accuracy. The sources transmit an 80-s swept-frequency 250-Hz signal a few times per day for up to 5 years. Sources are similar to the old SOFAR floats and cost around $33 000. Mooring costs of wire rope, flotation, acoustic release, and other recovery aids can double this figure. Recently, louder, more efficient, and more expensive sound sources have increased tracking ranges up to 4000 km.

Errors of acoustic positioning are difficult to estimate and vary depending on the size and shape of the tracking array, the accuracy of float and source clocks, how well the speed of sound is known, etc. Estimates of absolute position errors range from a few kilometers up to 10 km (or more). Fix-to-fix relative errors are usually less than this because some errors cancel and others such as clock errors vary slowly in time. Corrections are made for the Doppler shift caused by a float's movement toward or away from a source. The typical correction amounts to around 1.3 km for a speed of $10\,\mathrm{cm\,s^{-1}}$. Tides and inertial oscillations add high-frequency noise to positions and velocities, but since a float integrates these motions, it provides an accurate measure of lower-frequency motions.

See also

Acoustics, Deep Ocean. Meddies and Sub-Surface Eddies. Mesoscale Eddies. Ocean Circulation.

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