Chapter 3

Lagrangian-Style Surface Current Measurements Through Tracking of Surface Drifters

Chapter Outline

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The small-scale water current structures found near fluid boundaries, such as the coast and strong hydrographic fronts, are poorly described owing to a lack of adequate measurements. Likewise, away from such boundaries, the fine-scale structure of horizontal dispersion is poorly described. In response to this void, several researchers have attempted and succeeded in developing drifter systems that would resolve small-scale, high-frequency coastal and estuarine flows. Trajectories of freely drifting bodies in coastal regions have been utilized for several other applications as well, such as understanding the pattern of coastal circulation and its role on the dispersion or retention of larvae (Edwards et al., 2006), determining the advection of discharged ballast ship water (Larson et al., 2003), and forecasting and containment of oil spills and other pollutants (Abascal et al., 2009). Furthermore, search-and-rescue operations require prediction of the path of drifting targets and of an optimal search region based on the initial location and on the coastal current field (Ullman et al., 2006).

In oceanography, the so-called *Lagrangian method*, a method that provides a quantitative description of both track and speed of flow, is often employed to obtain an overall picture of oceanic water currents over large areas. The Lagrangian method originally involved measurement of water movements by tracing the path of water parcels over sufficiently long time intervals. The combination of many such paths, termed *trajectories*, mapped on a chart (called a *current chart*), was then used to describe the overall pattern and speed of horizontal currents in a given region. Thus, the Lagrangian method is useful in establishing large as well as small water circulation routes and in detecting and identifying major ocean gyres, which contain almost 99% of the kinetic energy of the ocean circulation (Monk and Wunsch, 1979). In fact, much of the general knowledge gained on large-scale oceanic circulation has come from Lagrangian methods of measurement. Unfortunately, Lagrangian data of surf zone flows are relatively scarce, but they are important for understanding the spatial and temporal variability of water currents in the surf zone domain.

Lagrangian techniques have been used widely in the study of water currents in oceans and large lakes, both for fundamental understanding of the associated fluid dynamics as well as for solving environmental problems. The data provided by water current-following *drifters* are particularly valuable in observing the spatial and temporal structure of the flow field and providing a different insight into the flow dynamics than that which is obtainable from Eulerian data. Lagrangian data also allow diffusion coefficients to be estimated more realistically than with fixed current meters (Pal et al., 1998). This is important for ecological investigations of, for example, the fate of pollutants, algal blooms, and artificial fertilization.

Drifters have often been used to complement fixed current meters in the deep ocean (e.g., McPhaden et al., 1991) and on the continental shelf (e.g., Davis, 1985). A comprehensive overview of the development of oceangoing Lagrangian

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drifters is given by Davis (1991). Early examples include the experiments of Stommel (1949) and Swallow (1955). Recent drifters make use of SOFAR channels for subsurface applications (Rossby and Webb, 1970) and satellite systems such as Advanced Research and Global Observation Satellite (ARGOS) for near-surface applications. In the past, the use of Lagrangian drifters had been largely limited to the deep ocean and large lakes. Some work has been done over smaller scales, such as, for instance, in coastal regions (Davis, 1983; List et al., 1990; George and Largier, 1996).

Lagrangian field data of water current systems in the surf zone are extremely rare but are valuable for understanding their detailed structure, confirming model predictions of transient features, and making estimates of dispersion. The few existing Lagrangian measurements in the surf and near-shore zone were obtained with the application of a variety of techniques. Surface floats and drogued drifters were used by Shepard et al. (1941), Shepard and Inman (1950), and Sonu (1972) to investigate rip currents. Positions were obtained by compass fixes from boats and the shore. Floats were tracked using sequential aerial photographs taken from a balloon in the experiments of Sasaki and Horikawa (1975, 1978). The method of Short and Hogan (1994) used "live" floats, whereby swimmers floating in rip currents were tracked by theodolite fixes. This technique was used by Brander and Short (2000) to investigate the dynamics of a large rip system. Dye has also been used for flow visualization and measurement of current speeds (e.g., Sonu, 1972; Brander, 1999).

With rapid advancements in technology, the concept of Lagrangian measurements underwent significant leaps, particularly in the realm of surface circulation. Lagrangian paths can now be directly measured *in situ* by tracking neutrally buoyant phosphorescent tracers, although this technique is limited in scope through restricted spatial and time scales (Gaskin et al., 2002) and by satellite-tracked drifters (Gawarkiewicz et al., 2007). Today remote sensing using satellite-borne sensors as well as fixed platform-based HF/VHF Doppler radar systems permits collection of near-real-time "snapshot pictures" of oceanic surface circulation over large areas. In terms of monitoring the ever-increasing menace of oil spills from tankers and oil-drilling platforms, as well as conducting successful rescue operations, the capability of modern Lagrangian techniques for all-weather, near-real-time mapping of oceanic surface circulation is of immense practical utility.

Ocean surface currents being frequently decoupled from those at the depths, data from moored current meters cannot be readily extrapolated to the surface. One of the best viable methods for quantitative inference of water currents in the upper few meters of a wave-laden ocean is the Lagrangian technique. Basically, this technique has provided an enormous amount of data that have served to construct mean sea surface current charts as they are found today in most geographical atlases. A bird's-eye view of the primitive technologies of Lagrangian style surface current measurements and their timely upgradation in tune with technological leaps was provided in Chapter 2. As indicated, with the rapid advancement in technology, Lagrangian-style surface current measurements took on new dimensions. Several advanced methods are currently in use and are addressed here.

3.1. RADIO BUOYS

Advancements achieved in the technologies of sensor design, signal detection, data logging and communication electronics, and satellite technologies in the last few decades had a significant positive impact on detection, monitoring, and telemetric reporting of oceanic surface current measurements. Application of radio buoys is just one example. In this method, a buoy freely drifting on the sea surface is tracked by radio signals. Its position is periodically determined as it drifts along under the influence of the drag force exerted on it by the sea surface currents and winds. Radio buoys are usually released from ships. Speed and direction of the surface currents are determined by observing the distance and direction the buoy drifts in a given time interval. These buoys, meant to drift freely with the water mass, are equipped with colored flags, flashing lights, radio location beacons, or satellite transmitters.

Flow speed errors in the drifter measurements greatly depend on the design of the drogue system; the drogue is to be designed to minimize the effects of wind drag on the surface buoy. A crossed vane rigidly mounted to the bottom end of the buoy or canvas "window-blind" drogue located below the air-water interface ensures that the buoy is less influenced by wind. In bygone days of surface current mapping, the buoys were usually tracked using boats or aircrafts with the aid of HF direction-finding systems (Whelan et al., 1975). In the 1940s, measurements of tidal current structures generated at the Hayatomono-Seto of the Kanmon Strait (a strait famous not only as an important shipping traffic route to China and Korea but also as a dangerous passage with quite strong tidal currents exceeding 5 m/s at the narrowest point), located in the Sea of Japan, were traditionally made with the use of drifting floats tracked by many small boats (Fukunishi, 1948a, b). An overall feature of current structures is understood by this kind of measurement.

Many buoys can be tracked at the same time if means are provided to distinguish them individually. One method of accomplishing this is to provide individual buoys with some sort of identification number and to transmit these numbers either periodically or when interrogated from shore-based transponders or from a satellite. These buoys provide both track and speed of flow, i.e., a Lagrangian description, and have revealed many new details of eddies associated with ocean currents (note that the term *eddy* refers to rotation of water mass).

A more sophisticated drifting buoy technique is to provide the buoy with a radio transponder, which replies when interrogated from a satellite in orbit (Pickard et al., 1982). By this method the buoy's position can be determined more accurately than with the lower-frequency radio direction-finding techniques. The position of such a satellite-tracked radio buoy is calculated on board the satellite using the Doppler shift of the buoy's VHF signal, then transmitted to a ground station for recording (Royer et al., 1979; Briscoe et al., 1987).

3.1.1. Drifter-Following Radar Transponder

In situations in which surface current monitoring was desired only for short periods, the buoys were accompanied by a boat. The locations of the buoys were periodically determined by a microwave tracking system. The boat, which was used to deploy the buoy, carried the master station, which continuously interrogated two pulse-radar transponders located at fixed reference points, a few km apart on the coast or on fixed platforms in the sea. The elapsed time between the interrogation pulse (transmitted from the master station on the boat) and each of the two reply pulses (from the reference stations) was used to determine the distance (from the boat) to each fixed reference station. This information, together with the known locations of the reference station, was trilaterated to obtain a position fix on the boat. This process is shown schematically in Figure 3.1.

The tracking system accurately located the position of the boat relative to two known geographical locations (reference points). The position of the buoy at a given instant in time was measured by periodically approaching the buoy and carefully maneuvering the boat to within a few meters of the buoy, then noting the distance (i.e., range) of

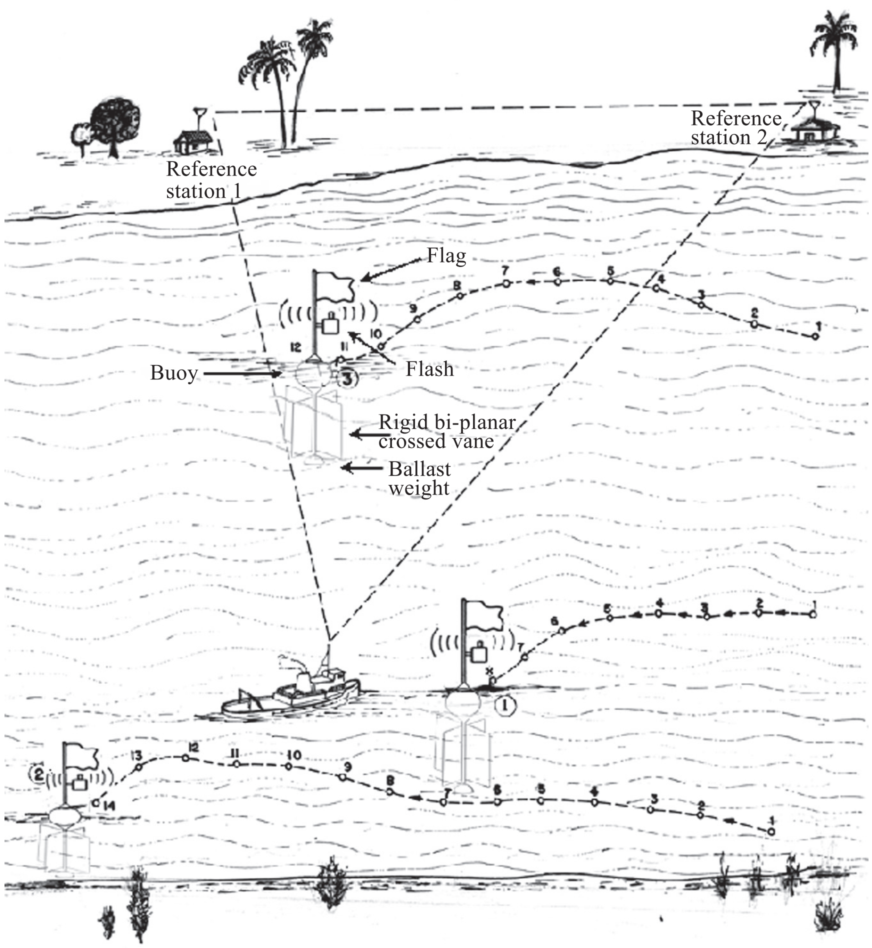


FIGURE 3.1 Illustration of radio buoys being tracked using a boat with the aid of direction-finding systems.

the boat to each of the two geographically fixed transponders. Because the boat approached a buoy only when measurements were desired, the surface current-driven free motion of the buoy remained largely unaffected by the movements of the boat. In this case, the buoy was not strictly a "radio" buoy, but the master station on the accompanying boat effectively made it a radio buoy when measurements were taken.

The buoy-position measurements were repeated at time intervals of 1 hour or longer, and sea surface current velocities were calculated from the differences in position at successive time intervals. This methodology had been employed for surface current measurements in the year 1978 during the Joint Air-Sea Interaction (JASIN) international experiment conducted in the North Atlantic off the coast of Scotland. During the development stages of the HF Doppler radar system, drifting buoys provided data for comparison of surface currents derived from the HF Doppler radar system (Teague, 1986).

3.1.2. Drifter-Borne Doppler Transponder

As noted earlier, floating objects that drift freely with the moving sea surface water parcels are considered to be Lagrangian tracers of sea surface currents. An improved radio-buoy system, for ranges less than 100 km, is a drifter-borne Doppler transponder that is tracked by a pair of HF Doppler radar systems located on shore or on offshore platforms. Utilization of the radio buoy technique for sea surface current measurements could be enhanced by the use of radar tracking, because such tracking operations can be performed regardless of weather conditions, i.e., in fog, high winds, rough seas, and at night.

Although several methods exist for measurement of sea surface current trajectories, the Doppler effect plays a key role in the technology addressed in this section. As the name suggests, the Doppler transponder system works on the Doppler effect principle, according to which the frequency of any harmonic wave motion at a receiver differs from the frequency at its source whenever the receiver or the source are in motion relative to one another. Thus, in the present case, the relative motion between a stationary radar and a radio buoy (transponder) that is freely drifting under the influence of sea surface current causes a variation in the received radio frequency. With the introduction of microcomputer-based technology, HF Doppler transponder systems have been operationally introduced to obtain a Lagrangian description of surface currents in coastal water bodies.

CODAR Ocean Sensors Ltd. (Los Altos, California) developed a system which makes radial velocity measurement of a drifting Doppler transponder. In operation, HF Doppler radar transmits a high-frequency pulsed signal from a stationary interrogating site, which is located on the coast (see Figure 3.2) or an offshore platform. As a consequence of the relative motion between the drifting radio buoy (transponder) and the stationary radar, the constant-frequency radio transmission from the radar system is received by the transponder with an apparent variation in frequency (Doppler effect). The Doppler-shifted frequency received by the transponder is immediately retransmitted to the stationary radar. The frequency received by the stationary radar suffers an additional Doppler shift in the return travel. Measurement of this Doppler shift yields an accurate estimate of the radial velocity of the transponder relative to the radar.

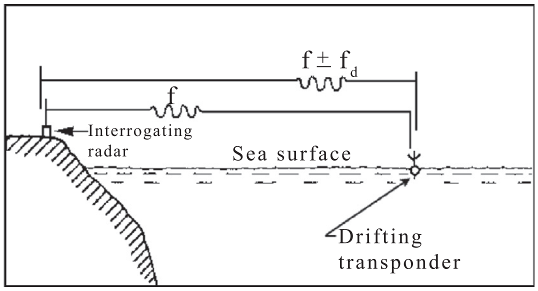


FIGURE 3.2 Diagram illustrating the principle of radial velocity measurement of a drifting Doppler transponder. *(Source: CODAR brochure, CODAR Ocean Sensors Ltd., Los Altos, CA, reproduced with kind permission of CODAR Ocean Sensors Ltd.)*

The Doppler shift, Δf, in the frequency received by the stationary radar is given by:

$$\Delta f = \frac{2fV_R}{c} \tag{3.1}$$

In this expression, f is the transmission frequency of the stationary radar, V_R is the radial velocity of the drifting transponder relative to the radar, and c is the velocity of propagation of the electromagnetic wave in air. Following conventional practice, some forms of statistical methods are applied online to extract the Doppler shift from the returned signal. This is usually achieved using a microcomputer-controlled digital signal processor (DSP) in the receiver section. The range R of the transponder from the stationary radar is computed from the round-trip travel time *(t)* using the relation:

$$c = \frac{2R}{t} \tag{3.2}$$

Measurement of velocity and position of the transponder in the Earth coordinate system requires two stationary interrogating sites separated by a known straight-line distance, usually a few tens of kilometers (see Figure 3.3). Under normal operating conditions, the radial velocity is claimed to be accurate to within ±0.1 cm/s. Position accuracy is estimated to be between ±50 and ±500 m.

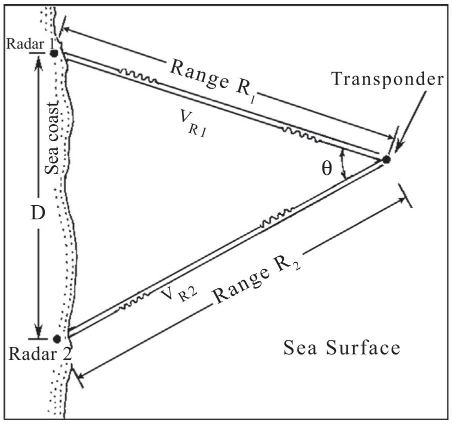


FIGURE 3.3 Diagram illustrating the scheme used for velocity and position determination of a drifting transponder with the aid of two known spatially separated stationary interrogating-sites. *(Source: CODAR brochure, CODAR Ocean Sensors Ltd., Los Altos, CA, reproduced with kind permission of CODAR Ocean Sensors Ltd.)*

In the case of CODAR transponder, the two interrogating sites need to be separated by approximately 30 km to obtain the best accuracy and resolution. With a dual-site system, the absolute velocity and position of the transponder are determined by the usual triangulation methods commonly employed by marine surveyors. The transponder established on each freely drifting radio buoy is activated by a unique address code, which allows sequential interrogation of several transponders. The CODAR systems are capable of simultaneously measuring the positions and instantaneous velocities of as many as 126 different transponders drifting at range up to 100 km with velocity accuracies typically 0.2 cm/s and position accuracies between ± 50 and ± 500 meters. The maximum range at which a transponder can be interrogated and the accuracy of the surface current velocity measurements are both governed by the strength of the transponder signal relative to the atmospheric and manmade noises at the operating frequency as well as the dielectric properties of the medium over which the signals travel.

3.1.3. Radio Buoys Tracked by Polar-Orbiting Satellites

In situations in which trajectories of surface currents are to be tracked over long distances in the open ocean regions for long periods of time, the radio buoys are tracked by polar orbiting satellites. Satellite-tracked drifting radio buoys, with operating lifetimes of a year or more, are attractive tools for measuring the spatial structure of sea surface currents. Deployed in large arrays, they offer an unmatched capability of mapping the two-dimensional field of surface/near-surface currents in the open oceans over long periods of time (D'Asaro, 1992). Freely drifting radio buoys deployed in the open ocean are tracked by polar orbiting satellites. The satellite technology meets the majority of drifting buoy-tracking needs and has the virtues of continuity over time, remote monitoring, true global coverage, all-weather operation, relatively good immunity to natural and manmade interferences, frequent availability of buoy position fixes, and good location accuracy. Such features also make satellite tracking far more affordable than more conventional techniques. In fact, satellite-tracked radio buoy experiments have helped in locating several large-scale eddies. When the existence of large current paths or current loops with large radii are to be studied, comprehensive ship surveys prove very costly and often ineffective. Alternatively, satellite-tracked buoys, with an estimated life of about 300 days, provide an ideal tool to study the movement of water bodies. Such studies, initially supported by NASA satellite NIMBUS and later by NOAA satellites, have produced direct Lagrangian current measurements on large time and spatial scales in many regions. The presence of cyclonic and anticyclonic drifting eddies could be readily identified from the spiraling motion of the buoy track. Today NOAA is a leading organization that provides such satellite facilities.

The radio buoys are equipped with transmitters (platform transmit terminals) to facilitate their tracking by polar orbiting satellites. Since 1978, the Service Argos, France, offers capabilities for satellite-based position fixing of radio buoys. The footprint of the polar orbiting satellites on the surface of the Earth is ~5,000 km in diameter (see Figure 3.4). A satellite can receive signals from any radio buoy located at any point within its footprint. Further, the visibility time of a satellite is only 10–13 min. Special

FIGURE 3.4 Footprint of a polar orbiting satellite centered on its ground track on the Earth's surface. *(Source: ©CLS 2012, reproduced with kind permission of CLS Service Argos, Toulouse Cedex, France.)*

precautions are therefore needed to identify each drifting buoy and to determine its location. The buoy identification is achieved from its assigned unique *identification number,* which is transmitted by the radio buoy. Determination of the position of a radio buoy within the 5,000-km-diameter footprint of the satellite, without ambiguity, requires the measurement of the Doppler shift in the frequency received by the satellite.

The platform transmit terminal (PTT) onboard the radio buoy, featuring microcircuitry, transmits at a nominal frequency of ~400 MHz. The whole PTT message is transmitted in less than 1 second and includes 160 ms of unmodulated carrier to allow the satellite's receiver to lock onto the carrier. To maximize the probability of accurate message reception by the satellite, the PTT message is transmitted several times. The probability of message reception is claimed to be 0.9920 for PTT messages repeated three times and 0.9999 for messages repeated six times.

The satellite-borne data collection and location system (DCLS) receives and records all transmissions from the radio buoys, which are located in the visibility zone of the orbiting satellite. The relative motion between the polar orbiting satellite and the radio buoy causes a Doppler shift in the PTT signal received by the satellite. As the satellite passes through its point of closest approach to the PTT, there is a Doppler shift in the carrier frequency received by the satellite. As the satellite approaches the PTT, the received frequency f_r is higher than the transmitted frequency f_t (i.e., the Doppler shift is positive); at the point of closest approach, f_r is equal to f_t (i.e., the Doppler shift is zero); and as the satellite goes away, f_r is less than f_t (i.e., the Doppler shift is negative). The Doppler shift is a function of the relative velocity between the satellite and the PTT. If the PTT is stationed below the orbital path of the polar orbiting satellite (which is along a longitude over the Earth), the Doppler shift would remain constant at all times, the only change being a sudden jump from positive to negative as the satellite passed over the PTT. However, if the PTT is a little farther away from the orbital path of the satellite, the closest approach range is larger, and therefore the slope of the Doppler curve will be less steep (Figure 3.5). There is thus a direct correlation between the change of slant range and the shape of the Doppler curve.

Because the frequency transmitted by the PTT and the latitude and longitude of the satellite at every instant are known, measurement of the Doppler shift defines the field of possible positions for a given PTT (a radio buoy in the present case). The field is in the form of a half-cone, with the satellite at its apex, and the satellite velocity vector (**V**) as the axis of symmetry (Figure 3.6). The Doppler shift is related to the apex half-angle *(A)* of the cone, the satellite velocity *(v)* relative to the PTT, and the velocity *(c)* of the electromagnetic wave by the expression (Carpiniello and Buell, 1972):

$$\cos A = \frac{(f_r - f_t)c}{v f_t} \tag{3.3}$$

In this expression, f_t and f_r are the transmitted and the received frequencies, respectively. Different location cones, obtained from successive Doppler measurements in a given satellite pass, intersect the sea surface to yield the two possible positions of the radio buoy. Such positions are symmetrical with respect to the trajectory (longitude) of the satellite ground track. Additional information such as previous position of the buoy, range of possible speeds, and so forth are used to determine which of the two possible positions are realistic. The processor in the satellite calculates the location of that radio buoy, from which at

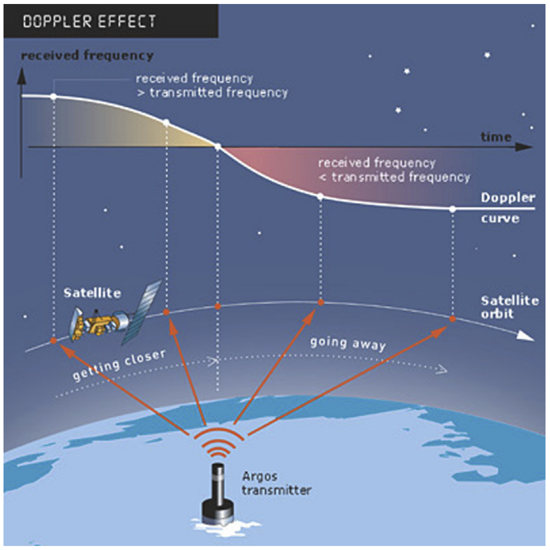


FIGURE 3.5 Doppler curve corresponding to differing distances of the buoy-borne platform transmit terminal (PTT) from the satellite's orbital path. *(Source: ©CLS 2012, reproduced with kind permission of CLS Service Argos, Toulouse Cedex, France.)*

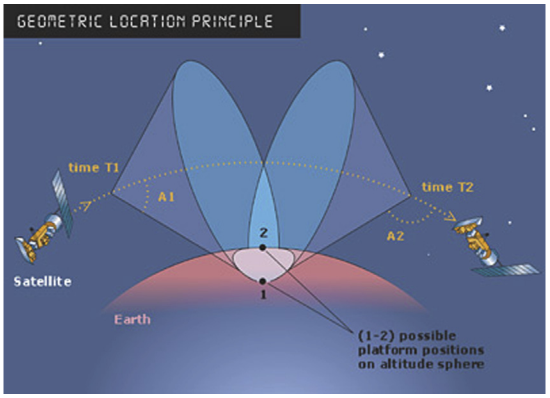


FIGURE 3.6 Half-cone that defines the field of many possible positions for a PTT. *(Source: ©CLS 2012, reproduced with kind permission of CLS Service Argos, Toulouse Cedex, France.)*

least four messages were collected, and of which the first and the last messages were separated by at least 4 min. To minimize the ambiguity in the estimation of the buoy location, we use certain criteria, such as lowest least-squares value, absurdity test on distance covered by the PTT since last estimated location, and so forth. The estimated buoy location is rejected by the location estimation algorithm if the number of PTT messages were lower than a preset value or if the PTT was not within the required range of the satellite. The location estimation algorithm assumes the PTT to be stationary. Any movement of the PTT, which occurs in the case of a drifting radio buoy, therefore causes an error in the location estimation unless it is factored into the location estimation as uniform motion from one satellite pass to the next.

The real-time or recorded location information for each radio buoy is accessible to the user from the processing centers via international telex network, switched telephone network, data transmission network, or the Global Telecommunication System (GTS), which is reserved for meteorological and oceanographic data.

Two NOAA satellites are simultaneously in circular mutually orthogonal polar orbits. The orbit altitudes are different (~830 km and ~870 km), producing a ~1-min difference in the orbital period. Each satellite makes ~14 revolutions in a day. As the satellite orbits the Earth, the visibility zone sweeps a swath of ~5,000 km in width. As a result of the Earth's rotation to the east, this swath shifts 25° west about the polar axis on each revolution (Figure 3.7), corresponding to a distance of ~2,800 km at

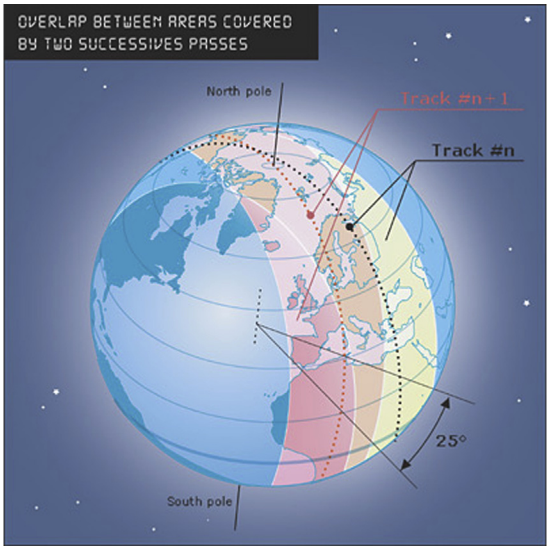


FIGURE 3.7 Schematic picture illustrating the mechanism of satellite orbit providing complete coverage of the Earth's surface as a result of the satellite's visibility zone (comprising a swath of ~5,000 km in width) shifting 25° west about the polar axis of the Earth on each of its revolution to the east. *(Source: ©CLS 2012, reproduced with kind permission of CLS Service Argos, Toulouse Cedex, France.)*

the equator. As a result, the satellite orbits provide complete coverage of the Earth's surface. In polar regions, the PTTs can be deployed on icebergs, the drift of which provides a description of the surface circulation in the region.

Different PTTs (distinguished by their unique identification numbers) have different repetition periods and transmission frequencies. Furthermore, transmissions by different PTTs are asynchronous. Theoretically, these schemes would enable the onboard DCLS to pick up and sort messages from all the PTTs in the visibility zone. However, the PTT is ignorant of the three possible states of its message (Sherman, 1992): (1) there is no satellite in reception range, (2) due to bad signal quality, the satellite has rejected the message completely, and (3) the message has been received, but with some undetermined number of bit errors. Further, the PTT receives no acknowledgment from the satellite and does not know whether the message has been successfully received. An analysis by Sherman (1992) revealed that only 6% of the transmitted messages are received by the *Argos* satellite, with 17% rejected while a satellite was in view and 9% of received messages containing at least one error. Inclusion of the satellite's orbital information in the PTT's memory and transmission only when the satellite is in its visibility zone are expected to improve the overall efficiency.

A source of error in the sea surface currents, estimated from radio buoys, is the random error in the position fixes. The root-mean-squared error in position fixes is quoted to be less than 350 m. For moving drifters, additional nearly random errors will be contributed by unresolved high-frequency motions induced by surface and internal gravity waves. Messages received at the ARGOS center in Toulouse, France, are sorted according to the user identification number and coded with the time of reception at the satellite-borne ARGOS DCLS (Bellamy and Rigler, 1986).

Despite many limitations, satellite tracking of radio buoys has revealed many new details of eddies associated with ocean currents. In fact, the existence of gigantic gyres of more than 100 km in diameter, described in the literature as *mesoscale eddies* (and sometimes as *ocean storms*), has been confirmed after an accidental discovery during remote monitoring of some radio buoys that were trapped for several weeks within the periphery of a drifting gyre. Further observations have indicated that such gyres are occasionally present in many regions of the oceans. A conceptual impression of the satellite tracking of a gyre based on messages received from a conglomeration of drifting buoys is given in Figure 3.8. Synoptic surface current measurements by satellite tracking of freely drifting buoys in offshore areas have helped in the past in identifying ocean eddies (gyres) as large as 200 km in diameters and in monitoring their movement (Cresswell, 1977; Grundlingh, 1977).

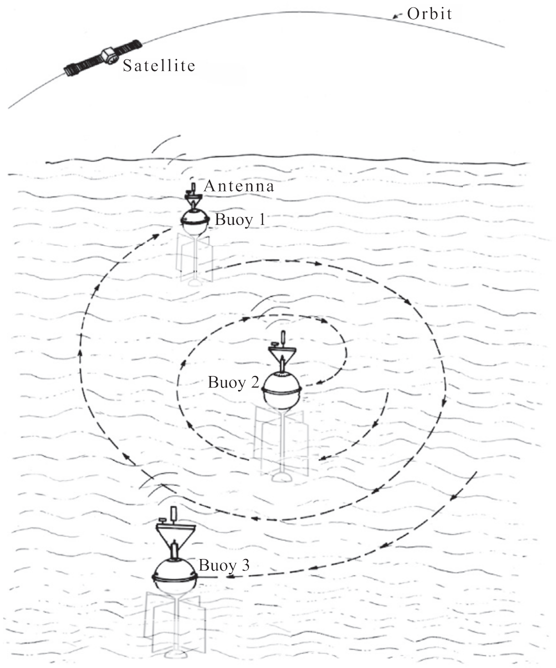


FIGURE 3.8 A conceptual impression of the satellite tracking of a gyre based on messages from a conglomeration of drifting buoys.

Figure 3.9 shows a plot of the trajectory of a satellite-tracked drifting buoy deployed off Goa, India.

Starting on 15 March 2011, the Argos user communities were provided the option to choose between two location processing algorithms:

- The algorithm based on the classical least-squares method that has been employed since Argos processing began in 1986
- The algorithm based on Kalman filtering

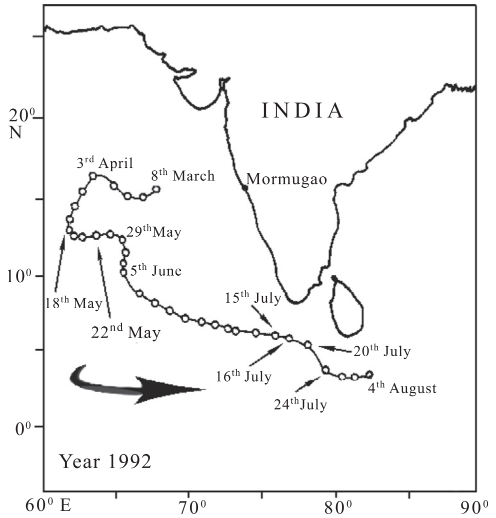


FIGURE 3.9 Plot of the trajectory of a satellite-tracked drifting buoy deployed off Goa, India. *(Source: Nayak et al., 1993, Reproduced with kind permission of Osservatorio geofisico sperimentale [OGS].)*

The trajectory of an Argo float in the Pacific calculated with the algorithm based on Kalman filtering and least-squares analysis is given in Figure 3.10.

3.1.4. GPS-Tracked Drifters

Resolving spatially complex water current circulations, such as the surf zone circulation, would require deployment of a large number of current meters. The surf zone is a challenging environment in which to make hydrodynamic measurements through deployment of drifters as well. Instruments must be very robust to withstand wave breaking, and there are significant difficulties in deployment and retrieval. Although Lagrangian measurements are valuable in revealing the horizontal current structure in the surf zone, few such measurements have been made in the past because of the practical difficulties involved. The main problem to overcome in the deployment of drifters is the tendency of any floating object to surf shoreward when caught in a breaking wave; its velocity is then the phase speed rather than water particle motion. The less an instrument penetrates into the water below the breaking region of the wave, the worse the surfing effect. A second problem is that the depth varies greatly from deep water offshore to the swash zone, where there is water only part of the time. Any floating instrument, therefore, has to have the apparently incompatible requirements of significant drag in the deeper section of a wave and the ability to move into shallow water. Finally, the only way to deploy and recover drifters within the surf zone is to physically carry them; they need to be small and light enough to accomplish this easily and safely.

Lagrangian drifters equipped with GPS came as a great relief to the hitherto difficult situation faced by oceanographers, ocean engineers, and environmentalists in the tracking of surf zone currents (Muzzi and McCormick, 1994; George and Largier, 1996). GPS is a worldwide radio-navigation system that employs a constellation of 24 satellites; up to eight are used at any time to determine the position of a receiver. Until May 2000, Selective Availability (SA) deliberately degraded the publicly available signal for military purposes and limited the accuracy to approximately 100 m. This practice effectively restricted the scales of motions that could be resolved. Improved position fixing was possible with differential correction, but this required a fixed base station and additional signal processing. Since the removal of SA, the nondifferential GPS proved to be a valuable device for position-fixing applications. Standard GPS receivers are small and low-cost and can fix their position within a few meters anywhere in the world.

With the availability of GPS coverage, surface drifters began to be tracked using GPS techniques. The small spatial (of the order of 5 m) and short temporal (of the order

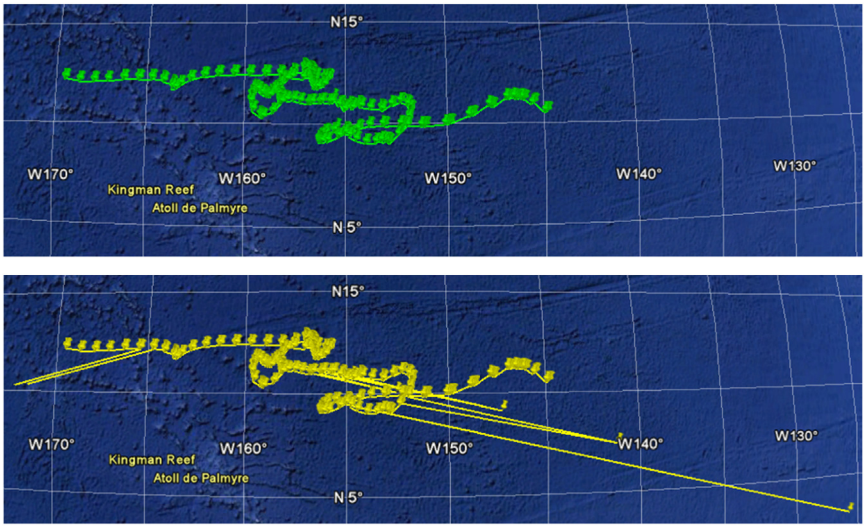


FIGURE 3.10 Trajectory of an Argo float in the Pacific Ocean calculated with the algorithm based on Kalman filtering (top image) and least-squares analysis (bottom image). *(Source:* ARGOS SYSTEM *newsletter, FLASH #20, February 2011, ©CLS 2012, reproduced with kind permission of CLS Service Argos, Toulouse Cedex, France.)*

of 1 min) scales of interest in surf zone circulation are resolved with GPS techniques used in coastal and near-ship drifters (e.g., real-time DGPS, 3–5-m accuracy [George and Largier, 1996] and carrier phase post-processing, 1-m accuracy [Doutt et al., 1998]). Drifters that autonomously record their position enable high-frequency Lagrangian data to be collected.

Near-shore drifters are intended for use in confined or near-shore environments over timescales of up to several days and are a low-cost alternative for applications that do not require drifters with full ocean-going capabilities. According to George and Largier (1996), near-shore drifters must be inexpensive so that large numbers can be deployed simultaneously to provide both statistical reliability and spatial resolution over the domain of interest. The system must be self-contained, reliable, rugged, and easily transportable. The drifters are to be retrievable. The drifter package should be modular, allowing for the possibility of using different drogue, float, and visibility device designs. The drifter should be easily adjusted for drogue at depths from 1 to 15 m for use in vertically sheared flow in a wide variety of applications. Positioning error must be small (less than 5 m) in order to resolve the small-scale structure of the flows of interest. Sample interval must be short (less than 10 m) and not dependent on the number of drifters deployed at one time. Position accuracy and sample rate must be maintained at distances of up to 20 km from the base of operations. In the presence of moderate wind and wave conditions, the errors in the water-following performance of the drifter must be known and the wind-induced drift-to-wind-speed ratio must not exceed 0.005.

A near-shore GPS drifter constructed of canvas mounted on a fiberglass frame has been described by George and Largier (1996). The projected area of this drogue is approximately 1 m^2, and the electronics package is carried in a central PVC pressure case. This drifter has known surface-following characteristics in a wave field, has low mass, and can be inexpensively constructed. However, high impacts from breaking waves and the tendency to "surf" shoreward often precluded the use of this device.

Schmidt et al. (2003) described a surf zone drifter and results from a deployment near a rip current. In this system, an impact-resistant body of tubular PVC is ballasted for nearly complete submergence (Figure 3.11). They circumvented the problem of surfing by attaching a PVC disk to the base of their 50-cm-long main casing. This disc strongly dampens the vertical response of the drifter, allowing broken and near-breaking waves to pass over without rapidly pushing the drifter ashore. This mechanism was found to be effective in resisting surfing. Their longer receiver casing also penetrates deeper into the water below, breaking wave rollers, and thereby precludes some of the need for an additional drogue. The heave and roll of the drifter, which can degrade GPS position estimates by causing large, rapid deviations of the antenna orientation from vertical, are reduced by the damping plate and by the vertical separation of the centers of buoyancy and mass. A shoreward mass flux is associated with breaking waves and bores, but by design, bores and breaking waves pass over the drifters.

In the design of Schmidt et al. (2003), each drifter records GPS pseudo-range and carrier phase data at 1-Hz for post-processing and transmits this information to shore at 10-s intervals for real-time differential GPS (DGPS) tracking and partial data backup (Figure 3.12). The telemetry range is about 5 km for a shore antenna elevation of 10 m. Battery storage limits the deployment duration to 24 h. Figure 3.13 shows a conglomeration of drifter trajectories observed in a surf zone. Field intercomparison measurements have indicated that the mean alongshore

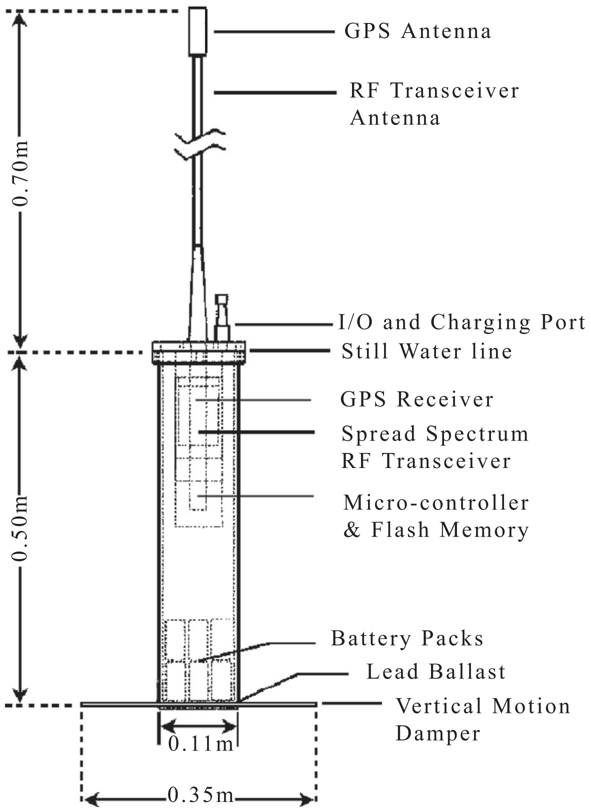


FIGURE 3.11 Schematic of a surf zone drifter. Surface-piercing antennae for receiving GPS signals and for radio-frequency (RF) communication with shore are molded permanently to the drifter top cap. *(Source: Schmidt, W. E., B. T. Woodward, K. S. Millikan, R. T. Guza, B. Raubenheimer, and S. Elgar: A GPS- tracked surf zone drifter, J. Atmos. Ocean. Technol., 2003 (20) 1069−1075. ©American Meteorological Society. Reprinted with permission.)*

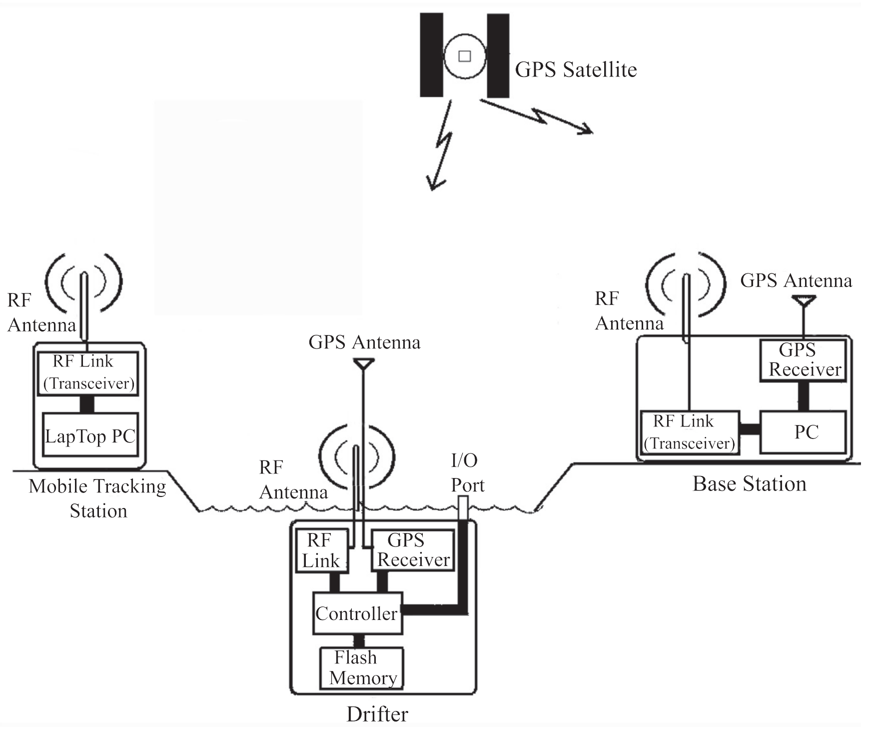
currents estimated from trajectories of the 0.5-m-draft drifters in 1−2-m water depth and nearby fixed current meters within the surf zone agreed well with measurements obtained from nearby bottom-mounted acoustic current meters (correlation 0.95 and rms differences of 10 cm/s). Drifters deployed near a rip current often followed eddy-like trajectories before being advected seaward of the surf zone (Figure 3.14).

In Johnson et al. (2003), a simple, robust receiver unit suitable for use in environments such as the near-shore zone, lakes, and estuaries was described, and specialized drogue arrangement for use in the surf zone was briefly discussed.

Johnson and Pattiaratchi (2004a) reported a simple, low-cost drifter design for surf zone applications based on nondifferential GPS position fixing and having the capability to collect high-frequency, accurate, Lagrangian data. They also addressed the main issues of the dynamic response of the drifters, a robust design capable of autonomous position fixing, position-fixing accuracy, and field validation.

The solution found by Johnson and Pattiaratchi (2004a) to overcome the challenging environment of the surf zone was to use a series of "soft" drogues attached to a small, compact receiver unit. The drifter arrangement, shown in Figure 3.15, is a cylindrical receiver unit connected to a series of soft parachute drogue elements. This type of drogue opens and dramatically increases its drag when there is a differential velocity between the upper and lower part of the water column, as is the case in wave breaking. The parachute drogue also stabilizes the drifter and

FIGURE 3.12 Drifter system schematic. The base station performs DGPS and data-logging functions and can serve a fleet of 10 drifters. A mobile tracking station monitors drifter DGPS positions in real time. *(Source: Schmidt, W. E., B. T. Woodward, K. S. Millikan, R. T. Guza, B. Raubenheimer, and S. Elgar: A GPS- tracked surf zone drifter, J. Atmos. Ocean. Technol., 2003 (20) 1069−1075. ©American Meteorological Society. Reprinted with permission.)*



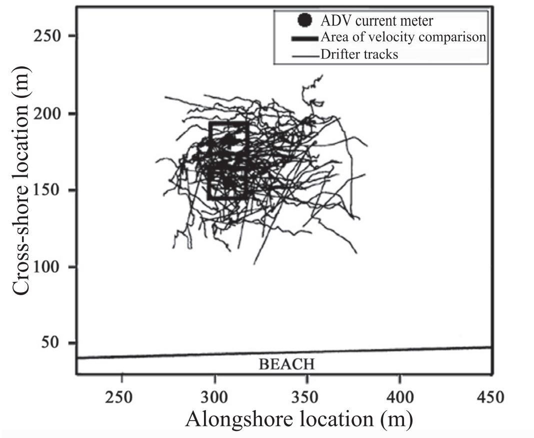


FIGURE 3.13 A conglomeration of drifter trajectories observed in a surf zone. Thin curves and filled circles represent drifter trajectories and ADV current meter locations, respectively. *(Source: Schmidt, W. E., B. T. Woodward, K. S. Millikan, R. T. Guza, B. Raubenheimer, and S. Elgar: A GPS- tracked surf zone drifter, J. Atmos. Ocean. Technol., 2003 (20) 1069–1075. ©American Meteorological Society. Reprinted with permission.)*

prevents it from rolling excessively. The drifter floats with only 2 cm of the receiver casing above the water, so the effect of windage (i.e., stress exerted by the wind directly on the float) is expected to be very small.

The receiver units are 32 cm long and 10 cm in diameter and obtain and record a GPS position fix at 1-second interval. These units consist of an integrated GPS antenna/receiver wired to a data logger and a power source in a highly robust waterproof housing. Details of their construction and the internal components can be found in Johnson and Pattiaratchi (2004b). They are deployed and recovered manually and can easily be used for repeated

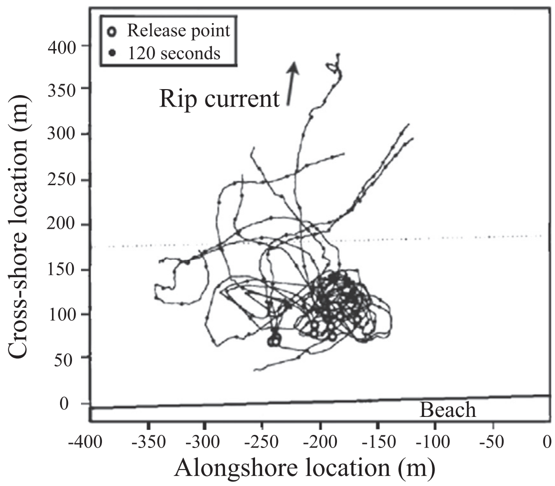


FIGURE 3.14 Trajectories of drifters released (locations shown with large circles) near the base of a rip current. The small filled circles on each trajectory indicate 120-s intervals. *(Source: Schmidt, W. E., B. T. Woodward, K. S. Millikan, R. T. Guza, B. Raubenheimer, and S. Elgar: A GPS-tracked surf zone drifter, J. Atmos. Ocean. Technol., 2003 (20) 1069–1075. ©American Meteorological Society. Reprinted with permission.)*

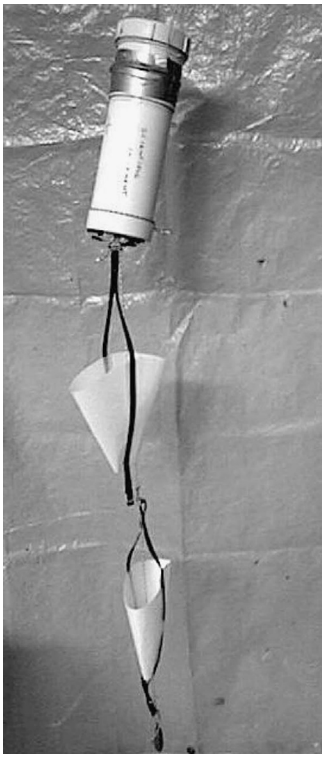


FIGURE 3.15 Drifter specifically designed for the surf zone, with drogue attached. *(Source: Johnson and Pattiaratchi, 2004a.)*

runs over a short period of time; their ease of deployment makes them effective for measuring rapidly developing transient features. To minimize windage and inertial effects, the drifter units are designed for nearly neutral buoyancy so that only the upper surface covering the internal GPS antenna projects above the water. In calm water, only 2 cm of the instrument projects above the surface; therefore, it is reasonable to assume that windage is negligible. A wire with a small ribbon is extended above the main unit to serve as a visual aid to enhance visibility.

The drogue is a series of parachute-shaped elements that hang below the GPS drifter casing. The parachutes are made of a cone of Dacron sailcloth with webbing attachments and are almost neutrally buoyant. A small weight is attached at the end of the parachutes to keep them hanging below the receiver unit. When the receiver unit is pulled shoreward by the breaking section, the parachutes open and anchor the drifter to the orbital velocities below the breaking region. In nonbreaking waves, the parachutes are closed and hang almost vertical and therefore present only their cross-sectional area. The drogue has also been found to be very effective in stabilizing the receiver unit by strongly damping the oscillatory motions that an "un-drogued" receiver experiences. In water depths less than the length of the complete drifter arrangement, the drogue may touch the seabed, which inevitably causes some measurement error. This means that the minimum operating depth is the length of the receiver unit (32 cm), though the drogue still provides sufficient resistance to surfing in large waves.

Careful visual observation by Johnson and Pattiaratchi (2004a) of the drifter in breaking waves indicates that the parachutes are extremely effective in resisting surfing. When in the overturning section of a plunging breaker, the parachutes prevent the receiver from accelerating up the face and forward with the plunging lip. In spilling breakers, the receiver unit ducks underneath the foaming roller section and reappears at the surface a couple of seconds later as the wave passes over. The only situation in which the drifters do not perform well is when they're caught at the plunge point of a strongly plunging wave. However, due to the strong downward velocities, the whole assembly may be completely disrupted and rolled by the wave, the parachutes no longer correctly oriented, and the drifter then tends to surf in the developing roller section. When caught in strong breaking events, the drogue is ineffective at anchoring the drifter to the wave orbital motion and the whole unit travels at close to the wave phase speed. Surfing events are very easy to identify in the data, since the phase speed is much greater than orbital velocities of water particles and typical wave-averaged current speeds. Data contaminated by surfing can then easily be excluded from any analysis.

There are errors inherent in both the position fixing of the GPS receiver and in the calculation of velocities and accelerations from raw position data. Although the removal of SA has greatly improved the performance of non-differential GPS, there are still errors in the reported positions due to various factors (Hofmann-Wellenhof et al., 1997). The magnitude of errors can be greatly reduced and decimeter accuracy obtained in a differential mode using either code phase or carrier phase data. However, this does introduce an additional level of complexity and significant additional cost into the drifter design.

?>In the surf zone, there are motions over a wide range of frequencies, and it is necessary to determine how much different frequency ranges are affected by the positioning errors. Error analysis by Johnson and Pattiaratchi (2004a) indicates that nondifferential GPS position fixing is sufficient for accurately measuring motions with frequencies below about 0.05 Hz. The relative RMS error can be greatly reduced using differential methods and effectively allows accurate positioning for motions at frequencies of 1 Hz (Schmidt et al., 2003).

Intercomparison studies (drifter versus vertical profile measurements using a bottom-mounted acoustic Doppler current profiler) have suggested that the drifters slightly underestimate the depth-averaged velocity in both directions. It must, however, be borne in mind that direct validation of the drifters in the surf zone is somewhat problematic. For example, whereas the drifter measures near-surface velocities, the profile instrument near the bed measures near-bed velocities. This highlights the difficulties of comparing different types of surf zone measurements and the care required in assessing exactly what drifters are measuring. The type of drifter design, in terms of receiver and drogue arrangement, is also clearly important in determining the response in the cross-shore direction. Unfortunately, in the absence of any "true" Lagrangian velocity information, it requires comparison of wave-averaged Lagrangian drifter velocities with fixed Eulerian depth- and wave-averaged data. Therefore, the two instruments are not actually measuring the same parameter. This is particularly the case in the surf zone, because the speed and short length scales of typical surf zone currents mean that the two instruments are quickly separated and measure different parts of the water current field.

The cost, size, and weight of the GPS-based surf-zone drifter (based on the design of Schmidt et al., 2003) reported by MacMahan et al. (2009) allow for a large number of independent observations to be obtained for various meteorological and oceanographic applications. In a field experiment they conducted in May 2007 at Monterey Bay, California (a natural beach with persistent rip currents), a cluster of 10 drifters was simultaneously released with dye. Fluorescent dye represents a "true" Lagrangian measurement of water movement. The bulk of the dye patch and the drifter cluster remained co-located for one rip-current circulation, suggesting that the drifters provide accurate Lagrangian estimates. Both the dye and the drifters were spreading slightly, but they remained together in a similar patch/cluster for the initial circulation. The dye followed the average drifter velocity estimates and completed a revolution in 5 min, similar to the drifters. The experimental results enabled them to arrive at a confident conclusion that the drifters represent Lagrangian estimates.

The ability to obtain Lagrangian velocity observations in a rip-current system is a good example of the usefulness of the inexpensive handheld GPS. The flow field of rip currents has a large spatial variability that is difficult to measure with *in situ* instruments owing to expense and deployment complexities. The inexpensive system reported by MacMahan et al. (2009) has the ability to fill in the voids between *in situ* instruments, thereby advancing our understanding of the hydrodynamics of a rip-current system.

3.1.5. Telephonically Tracked Drifters

A coastal environment is usually characterized by more stratified conditions, thinner layers of water, and higher vertical shears than the open ocean; thus the requirements are for wider and shorter drogues. Several drifter designs seek to satisfy such criteria. The one reported by Zervakis et al. (2005) is such a drifter, which addresses the need to perform coastal studies.

The great expansion of Global System for Mobile (GSM) communication technologies that took place in the late 1990s permitted the exploitation of a low-cost, readily available and widely expanded technology in the design of surface/subsurface drifters for use in coastal and land-locked seas, archipelagos, estuaries, and lakes. The idea of developing a GSM/GPS drifter suitable for coastal studies but fully satisfying the needs for small seas and archipelagos was born in the Hellenic Centre for Marine Research (HCMR). The technology was subsequently adopted by MARAC Electronics.

The novelty of the design lies in the use of a hollow PVC cylinder as a spine to which the drogue is attached. The surface module, equipped with the electronics (GSM, GPS, and ultra high-frequency, or UHF, modules; micro-processor; and batteries) has a cylindrical body of slightly smaller diameter than the drogue spine. In the configuration for measuring surface currents, the surface module is placed inside the drogue spine and the four donut-shaped floats are attached on the four top comers of the drogue.

The power source comprises four alkaline D-cell batteries. There are no cables and connectors for programming and data transfer. The drifter is provided with a GSM and a short-range UHF communication module. As soon as the drifter is turned on, it calls the base station (using both modules) and receives the program of its new mission. The GSM sampling rate as well as the frequency of data transmission to the base station are fully controlled by the user-friendly software at the base station provided with the drifters. All communication, programming and data exchange are performed through either the GSM or the UHF modules. The GSM technology offers the capability to monitor the drifter fleet anywhere, provided there is a GSM signal both at the measurement site and at the base station site. The base station can also be located on a vessel that follows the drifters. The software can foresee whether the condition of the GSM signal is too low for communication. In that case, the drifter position values are stored in the drifter's memory and are transmitted to the base station when the GSM or UHF signals allow such communication. Thus, there is no loss of data regardless of the GSM coverage.

The base station software provides the ability not only to program and monitor the drifter fleet, but also to analyze the data and facilitate the following and recovering of the drifters. A special module of the software enables the connection to a GPS onboard the vessel for the recovery of the floats. As soon as a drifter is selected for recovery, the software provides the necessary information (heading and distance) for finding and recovering the instrument. This module, along with the two-way communication, changes the nature of the drifter from an expendable instrument to a recoverable one that can be reused. This change in the use of the instrument significantly lowers the actual purchase cost due to the added value through its repeated use.

Another software module enables monitoring of the status of each drifter (power of each battery, memory capacity, and level of GSM and UHF signal) before and during the measurements. If the energy levels of certain drifters are running dangerously low, it is possible through the two-way communication capability to reprogram the sampling and reporting strategy of that particular drifter in order to continue the measurements uninterrupted.

The telephonically tracked drifters are aimed not only for oceanographic research applications but also to support scientists dealing with coastal constructions, pollution, coastal managements, and so on. The main application of the telephonically tracked drifters is real-time monitoring and analysis of coastal (as well as lake and reservoir) advection and dispersion. The spatial scale of the phenomenon is limited only by the GPS position error on one hand (a few meters) and, on the other hand, the scale of GSM coverage of the order of 30 kilometers from the coast. An example of use in a small aquatic basin is their deployment in the rowing facilities for the 2004 Olympic Games, a reservoir about 1,500 by 120 meters.

3.2. LIMITATIONS OF SURFACE DRIFTERS

We have seen that the devices used for Lagrangian-style current measurements are of several functional types. Trajectories of the surface water masses of the ocean can be determined by following the drift of floating bodies that are carried by the currents. It is necessary, however, to exercise considerable care in interpreting the data derived from such bodies, because often the wind has carried them through the water. In practice, a Lagrangian drifter of any design is only a quasi-Lagrangian device because it never "perfectly" locks to a particular water mass (Vachon, 1977, 1980). This is particularly true in the surf zone current measurements wherein the drifter performance can be degraded by both the rectification of oscillatory wave motions and by windage. To ensure that the buoys do move with the water and to minimize the effect of wind, they are frequently fitted with a subsurface drogue to provide additional water drag and more effective coupling with the water motions. This drogue may be in the form of either a parachute or a window shade. Despite these precautions, rectification can occur because the drifter behaves as a damped, nonlinear oscillator forced by buoyancy, flow drag forces, and pressure gradients (Davis, 1985). For example, if the area submerged or the tilt of the drifter from vertical (and hence drag) depends on the wave phase, the mean drifter velocity may be nonzero, even for a zero-mean orbital velocity.

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