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Low-Cost Handheld Global Positioning System for Measuring Surf-Zone Currents

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ABSTRACT

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Low-cost, handheld, L1 (1575.42 MHz) global positioning systems (GPSs) provide scientists with the opportunity to acquire position and velocity estimates at reduced expense (order of [O]$100), size (~cell phone), weight (O[70 g]), and engineering time. Two different low-cost, handheld GPS units and four different position-correcting configurations are evaluated here to determine their practicality in measuring surf-zone currents. Three of the simpler configurations result in relative position and velocity errors of O(2 m) and O(0.5 m s^{-1}) for stationary tests. Surf-zone position and velocity signal-to-noise spectral ratios for the three configurations suggest that only motions <0.01 Hz can be confidently estimated for these surf-zone systems. For the fourth configuration, a GPS handheld unit that internally records GPS carrier phase is postprocessed using more sophisticated software for position corrections to obtain absolute position and velocity estimates. Simple modifications are required to improve the position accuracy by reducing patch antenna signal multipathing. For this configuration, the absolute position error for dynamic surveys was ~0.40 m, and the velocity error on land relative to a survey-grade GPS system was 0.01 m s^{-1}. The handheld GPS was attached to a surf-zone drifter and evaluated in the field. The flow field of a rip-current system was obtained with 24 surf-zone drifters. The drifters tracked simultaneous dye releases well, verifying that the observations are valid Lagrangian estimates. Owing to the low cost and small size of the handheld GPS, a large number of drifter systems can be deployed for absolute position tracking and velocity estimates of surf-zone currents.

ADDITONAL INDEX WORDS: *Drifter, GPS, surf zone, currents, Lagrangian currents, rip currents.*

INTRODUCTION

Johnson *et al.* (2003) and Johnson and Pattiaratchi (2004a) determined that nondifferential global positioning systems (GPSs) with off-the-shelf components mounted in the interior of a drifter could provide an inexpensive method ($750/GPS drifter) of estimating *relative* position and velocity estimates inside and outside of the surf zone, which were later used to describe the surf-zone Lagrangian flow field, eddy diffusivity, and dispersion (Johnson and Pattiaratchi, 2004b). The errors associated with nondifferential GPS are typically on the order of 10 m with the removal of selective availability, the government's intentional GPS signal degradation (Johnson *et al.*, 2003). The nondifferential low-level L1 (1575.42 MHz) GPS used by Johnson *et al.* (2003) required an external logger and battery pack, therefore increasing the dimensions of the drifter for housing the components. They determined that their system could accurately resolve surf-zone motions less than 0.05 Hz (Johnson and Pattiaratchi, 2004a). During the same period, Schmidt *et al.* (2003) developed a surf-zone drifter that utilized a more position-accurate GPS for measuring *absolute* position and velocity using a L1 GPS receiver that provides the carrier phase information, allowing for submeter accurate positions to be obtained through postprocessing (Doutt, Frisk, and Martell, 1998). Their system included a radio for telemetry data backup, an external logger, a battery pack, and a GPS base station; this setup is estimated to cost approximately $3000 per drifter (without the GPS base station and shore-base telemetry receiver). Both drifters required waterproofing, owing to the electronics mounted in the interior of the drifter, thereby increasing manufacturing time (see Johnson *et al.* [2003] and Schmidt *et al.* [2003] for drifter design details). Both GPS-based drifters obtained similar surf-zone velocity estimates when compared with stationary *in situ* current meter velocity estimates. The subtle differences in performance may be related to drifter design, the particular GPS, and subsequent analysis, Eulerian verses Lagrangian estimates (Johnson and Pattiaratchi, 2004a), or the dominant surf motions during their drifter deployment.

Since the work of Johnson *et al.* (2003) and Schmidt *et al.* (2003), low-cost handheld L1 GPS units, which are the size and weight of a cell phone and have internal logging capabilities and power, have improved in horizontal position errors from 10 m to less than 3 m by incorporating corrections from Wide-Angle Augmentation System (WAAS) (remote base stations; Witte and Wilson, 2005). With WAAS-corrected positions and the reduction in size, weight, and cost (O[$100]), a number of surf-zone drifters could be developed at reduced expense and therefore increase the number of drifters that can be simultaneously deployed, further increas-

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Table 1. *Drifter component list and material cost.*

Component	Cost ($)
Waterproof case	20
Inexpensive patch antennas	25
Expensive external antennas	1000
Delorme Earthmate Blue Logger	150
Magellan MobileMapper	1800
Novatel GPS board	130
Garmin Geko 201	100
Garmin-specific serial cable	30
Delorme Earthmate Blue Logger postprocessing software	150
Bluetooth USB device	20
Survey-grade postprocessing software	2000
Ashtech survey-grade GPS (base receiver and antenna)	~12,000

ing the statistical confidence of velocity estimates. In addition, small, inexpensive (Table 1) off-the-shelf waterproof cases rated to a submersible depth of 30 m are available for most handheld GPS units, reducing engineering and production time. Owing to their small size, handheld GPS units can be mounted to the exterior of a surf-zone drifter, rather than in the interior, allowing variation in drifter design, while reducing costs and production time. Owing to the hazardous nature of the surf zone, inexpensive surf-zone drifters relax the logistical costs and pressures of drifter recovery.

Handheld GPS units use low-cost patch antennas because they are small and inexpensive (Table 1). However, patch antennas result in decreased position reliability and accuracy because signals are weak with respect to multipathing noise, and they can cause cycle slips (Saeki and Hori, 2006). Patch antennas are not commonly used to observe L1 carrier phases. For survey-grade ($<$0.01 m) applications, L1 GPS receivers typically are connected to more expensive (Table 1), sophisticated, external antennas to increase signal strength and reduce multipathing (Rama Krishna Roa, Sarma, and Ravi Kumar, 2006; Saeki and Hori, 2006). These antennas are generally too heavy and bulky for the proposed surf-zone drifter, requiring the use of smaller, lighter, external patch antennas.

Recently, one handheld GPS company began providing the option for internal recording of the carrier phase information in a small (cell-phone size), self-contained, inexpensive (Table 1) package, the Delorme Earthmate Blue Logger with a Sirf Star IIe GPS chip. To date, the Delorme Earthmate Blue Logger is the only inexpensive low-cost handheld GPS that records the carrier phase information and outputs in a RINEX (Receiver Independent Exchange) format. RINEX is the standard format for postprocessing GPS data. There are a number of commercially available systems for resolving submeter positions, but the price and/or complexity increase. For example, Magellan produces a larger handheld GPS (MobileMapper; Table 1) that internally records the carrier phase information (www.pro.magellangps.com). Novatel provides an inexpensive (Table 1) GPS board (Novatel SuperStar II), but it requires an external logging device (www.novatel.com). Sirf also provides inexpensive GPS chips (Sirf Star III GPS chip), but they also require external logging devices (www.sirf.com). Regardless of the carrier phase observing GPS system, the use of a smaller external patch antenna will degrade the position accuracy.

Two different handheld GPS units (Garmin Geko and Delorme Earthmate Blue Logger) and three different position-correcting techniques resulting in a total of four different configurations were evaluated to determine their field practicality, with a particular application to the surf zone. The accuracy and expense of each setup are discussed here, and techniques are described to obtain *absolute* position and velocity errors of $<$0.4 m and $<$0.01 m s^{-1} using a handheld GPS with an external patch antenna. In addition, Lagrangian GPS-derived velocity estimates are obtained for a rip-current system.

HANDHELD GPS CHARACTERISTICS

The two handheld systems evaluated are the Garmin Geko 201 and the Delorme Earthmate Blue Logger (Table 1). Both units are roughly the size and weight of a cell phone and have internal logging and power supply. The Geko was intended for hiking and has a screen for viewing position, speed, tracking, and logging amongst other navigational displays. The Delorme Earthmate Blue Logger was intended for wireless (Bluetooth) connection with a handheld personnel computer for vehicle navigation.

The Geko can record 10,000 WAAS-corrected positions with a maximum sampling rate of 1 Hz. Similar to most handheld GPS units, the Geko has a resolution of 2 m, so it will only register a new position after the unit has moved 2 m from the previous point. The Geko is powered by two disposable AAA batteries and has a run time of approximately 12 h. Tab-delimited time, date, and position data are downloaded to a personal computer using a Garmin specific serial cable (Table 1) and freeware software (FlexGPS).

The Blue Logger is configured to record WAAS-corrected positions or carrier phase information, which requires postprocessing. Delorme Earthmate provides Blue Logger postprocessing GPS software for an additional $150. The number of recordable positions is dependent upon setup. The Blue Logger can store up to 50,000 positions (~27 h) in WAAS setup and 5400 positions (~3 h) in carrier phase setup, each with a maximum sampling rate of 0.5 Hz. The Blue Logger is unique since it has 1 cm position resolution rather than the 2 m resolution provided by the Geko. It is powered by a rechargeable battery and has a run time of approximately 24 h at 0.5 Hz sampling. A Bluetooth wireless connection is required for setting up and downloading the Blue Logger position data to a personal computer. A Bluetooth USB device costs $20. Note the Bluetooth communication allows for multiple Blue Loggers to be connected to the same personal computer, providing simultaneous downloads and setups, increasing efficiency, and decreasing cable bulk.

For the evaluation, the two handheld GPS units were set up in four different configurations: (1) Geko recording WAAS-corrected positions (GW), (2) Blue Logger recording WAAS-corrected positions (BLW), (3) Blue Logger recording carrier phase information and postprocessed with Earthmate's software using CORS base-station corrections (BLCORS), and (4)

Blue Logger recording carrier phase information and postprocessed with more sophisticated GPS software using a survey-grade (BLASH; <1 cm horizontal accuracy; http://pro.magellangps.com/en/) Ashtech GPS (Table 1).

WAAS-corrected data (configurations 1 and 2) require no additional processing for obtaining positions, whereas GPS carrier phase data (configurations 3 and 4) require additional postprocessing and carrier phase information corrections from a stationary GPS base station. The GPS configuration in 3 and 4 is the same, but the configurations use different postprocessing software and GPS base-station location.

In configuration 3, GPS data were postprocessed with Earthmate's software using independent base-station data corrections from the National Geodetic Surveys Continuously Operating Reference Stations (CORS) (www.ngs.noaa.gov/). CORS is a nationwide network in the continental United States that provides free base-station corrections for postprocessing GPS data without purchasing a survey-grade GPS base station, but *absolute* position error increases with decreasing proximity, ~0.22 m/100 km (Montiero, Moore, and Hill, 2005). Note Earthmate's software will automatically download the nearest CORS data for the appropriate roving acquisition times via the internet. The nearest CORS station to our test site was approximately 16 km away (4 cm absolute position error).

In configuration 4, GPS data are postprocessed with more expensive survey-grade software using an Ashtech GPS as the base station. This configuration results in the maximum accuracy, but it is more costly and labor intensive.

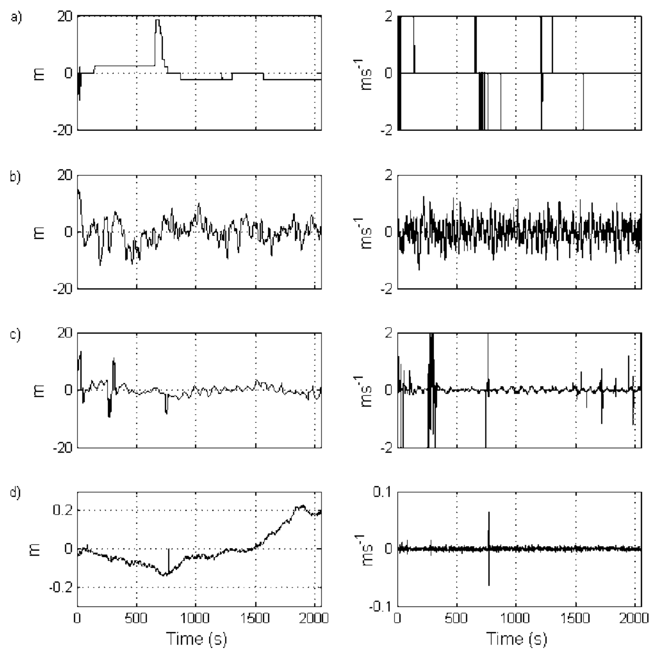

Figure 1. Stationary northing position time series (left column) and corresponding velocities (right column) calculated for the four configurations: GW (a), BLW (b), BLCORS (c), and BLASH (d). Velocities for GW and BLCORS exceed y-axis limits. Note the change in y-axis for the BLASH configuration.

RELATIVE HANDHELD GPS POSITION AND VELOCITY ERRORS

A 40 min test was performed in an open field to evaluate position and velocity errors for the four configurations. The Geko GPS and two Blue Logger GPS units were placed on metal (0.5 m × 0.5 m) plates to reduce satellite signal multipathing (Rama Krishna Roa, Sarma, and Ravi Kumar, 2006) related to their internal patch antennas (Saeki and Hori, 2006; discussed later). The plates were mounted on tripods 1.5 m off the ground in the open field, and the Ashtech GPS was placed on another 1.5 m tripod 2 m away.

All positions were converted to Universal Transverse Mercator (UTM) and de-meaned to determine *relative* errors (Figure 1, left column). Velocity estimates were determined using a forward-differencing scheme on the de-meaned position data (Figure 1, right column). The position time signals varied between system and correction technique. The GW (Geko WAAS-corrected GPS) Northing (y) positions remained constant for long periods of time and were punctuated with sudden jumps, defined as greater than three standard deviations (σ) change in position. The maximum position deviations were 31.7 m in x and 16.9 m in y (Figure 1, outside axis range). Despite relatively long periods (~500 s) of uniformity, the signal variability (σ_h) is 8.8 m. These position errors translate into jumps in the speed, resulting in a mean velocity ($U = \sqrt{u^2 + v^2}$) of 0.004 m s^{-1} with σ_U = 1.9 m s^{-1}, while the handheld remained stationary. It is possible to remove the jumps and generate a much cleaner signal (not shown). The lack of resolution should not impact the ability of the system to resolve relative surf-zone flows according to Johnson and Pattiaratchi (2004a).

The maximum deviations of the BLW (Blue Logger WAAS-corrected GPS) position were smaller than those present in the GW time series, but remained large (9.77 m in x and 14.55 m in y), resulting in a σ_h of 5.1 m, which is larger than proposed estimates of WAAS-corrected positions (Witte and Wilson, 2005). The symmetrical nature of the position deviations about the mean and a lack of significant position jumps resulted in U = 0.006 m s^{-1} and σ_U = 0.53 m s^{-1}.

The BLCORS (Blue Logger carrier phase corrected using CORS base station and Delorme less sophisticated postprocessing software) position measurements had smaller variations from the mean but included position jumps, increasing the signal variability, σ_h = 2.37 m. Two anomalous jumps in the position data gave the unit a maximum deviation in x of 20.01 m and 13.43 m in y. Despite the lower σ_h, U = 0.01 m s^{-1} and σ_U = 0.66 m s^{-1}, which are slightly larger speed errors than for the BLW system. Note that the BLW configuration is easier to obtain position estimates and allows for more positions to be recorded than BLCORS.

The BLASH (Blue Logger carrier phase corrected using ASHtech base station and more sophisticated postprocessing software) position and velocity signals had the fewest erroneous positions. The standard deviations in position were an order of magnitude lower, with σ_h = 0.15 m. The maximum position deviations in both directions were 0.23 m in x and 0.18 m in y, a vast improvement to the other systems. The

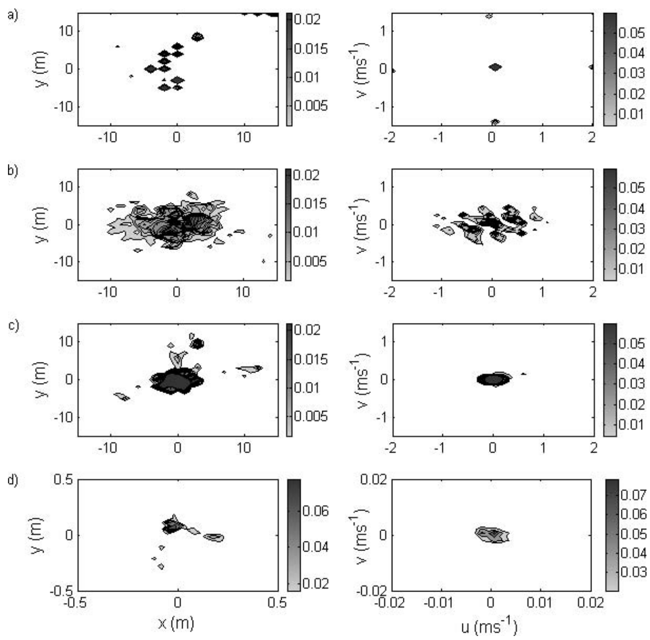

Figure 2. Histogram of position (left column) and velocity (right column) error plotted as a contour for the four configurations: GW (a), BLW (b), BLCORS (c), and BLASH (d). The color bar represents the frequency of error occurrence. Error frequencies greater than the range of color bar are mapped to the upper bound. Note the change in axis for the BLASH method.

position time series contained less noise and fewer significant jumps, resulting in $U = 0.006$ m s^{-1} and $\sigma_U = 0.005$ m s^{-1}. The magnitude of the position and velocity errors demonstrate the ability of this technique to obtain accurate position and velocity measurements for surf-zone observations. Rather than requiring a large number of more expensive systems, these handheld systems are capable of performing at a level sufficient for most scientific applications. The drawback with the BLASH configuration is that it requires additional post-processing software and may require a survey-grade base station, depending on the deployment location. Independent tests using the CORS station, as opposed to using the Ashtech station, resulted in similar results for this application (not shown).

The histograms of position and velocity errors (Figure 2) show that the errors of the GW system are infrequent but large in magnitude and random in direction. The position and velocity errors in the BLW and BLCORS data have a more orderly, almost Gaussian, distribution, although the effects of the position jumps can be seen in the outlying points of the BLCORS data. By their nature, Gaussian errors statistically average to zero, making it feasible to obtain more accurate position estimates for long averaging times. The lack of large errors in the BLASH system is evident from the lack of variability in the position and error histograms. All configurations have asymmetry in position and velocity occurrences, which can bias results in a particular orientation.

GPS SIGNAL ERROR REMOVAL

The stationary evaluation suggests that the first three configurations may not be suitable for surf-zone applications where velocities are frequently <1 m s^{-1}, whereas the last configuration is suitable. However, Johnson *et al.* (2003), using a nondifferential GPS system, determined that less accurate position time series, similar to configurations 1–3, could be used to accurately describe *relative* position and velocity estimates for low-frequency motions.

Johnson *et al.* (2003) and Johnson and Pattiaratchi (2004a) assumed that the actual position, x, is defined as $x = X - r$, where X is the recorded position, and r is the position error; x and r are assumed to be stationary and continuous random estimates. The error spectrum in position [velocity], $S_{rr}(f)$ [$V_{rr}(f)$], is produced from the position [velocity] time series generated by a stationary GPS unit, $r(t)$ (Figure 1), and it is assumed to be constant for all measurements recorded by that GPS. This stationary spectrum is compared to the $S_{xx}(f)$ [$V_{xx}(f)$] spectrum created from a position (velocity) time series acquired by a field-deployed GPS. The ratio of these spectra is defined as the signal-to-noise ratio (SNR), which is defined as

$$\mathrm{SNR}(f) = \frac{S_{xx}(f) - S_{rr}(f)}{S_{rr}(f)}. \tag{1}$$

For estimates to be considered acceptable in a certain frequency range, the SNR must be greater than 10, which means $S_{xx}(f)$ [$V_{xx}(f)$] must be an order of magnitude larger than $S_{rr}(f)$ [$V_{rr}(f)$]. This ensures that the contribution of the noise to the recorded signal is small enough to be statistically irrelevant. Johnson and Pattiaratchi (2004a) found for their GPS system and particular surf-zone motions that frequencies less than 0.05 Hz could accurately resolve the *relative* position and velocity field. A low-pass filter of the time series removes the higher frequencies, where the error is large relative to the signal.

Position and velocity spectra (Figure 3) for the Blue Loggers were computed using seven 256 point, linear-detrended, Hanning windowed records with 50% overlap resulting in eight degrees of freedom (DOF). To maintain the same frequency resolution owing to differences in maximum sampling rate, the Geko position and velocity spectra (Figure 3) were computed using seven 512 points, linear-detrended, Hanning windowed records with 50% overlap resulting in eight DOF. Note GW time series are non-Gaussian, but spectral estimates are still computed. All spectral estimates have a frequency resolution of 0.0019 Hz and 8 DOF, similar to Johnson and Pattiaratchi (2004a), allowing direct comparisons to their results.

Two spectral observations are provided: (1) surf-zone observations for three different drifters deployed in Monterey, California (described later), and (2) stationary field observations described already (Figure 3). Absolute position and speed spectra are computed for the surf-zone and stationary observations, owing to the asymmetry in the variability (Figure 3), using the BLASH configuration. The position and velocity spectra have energetic peaks for frequencies less than 0.01 Hz for all three drifters.

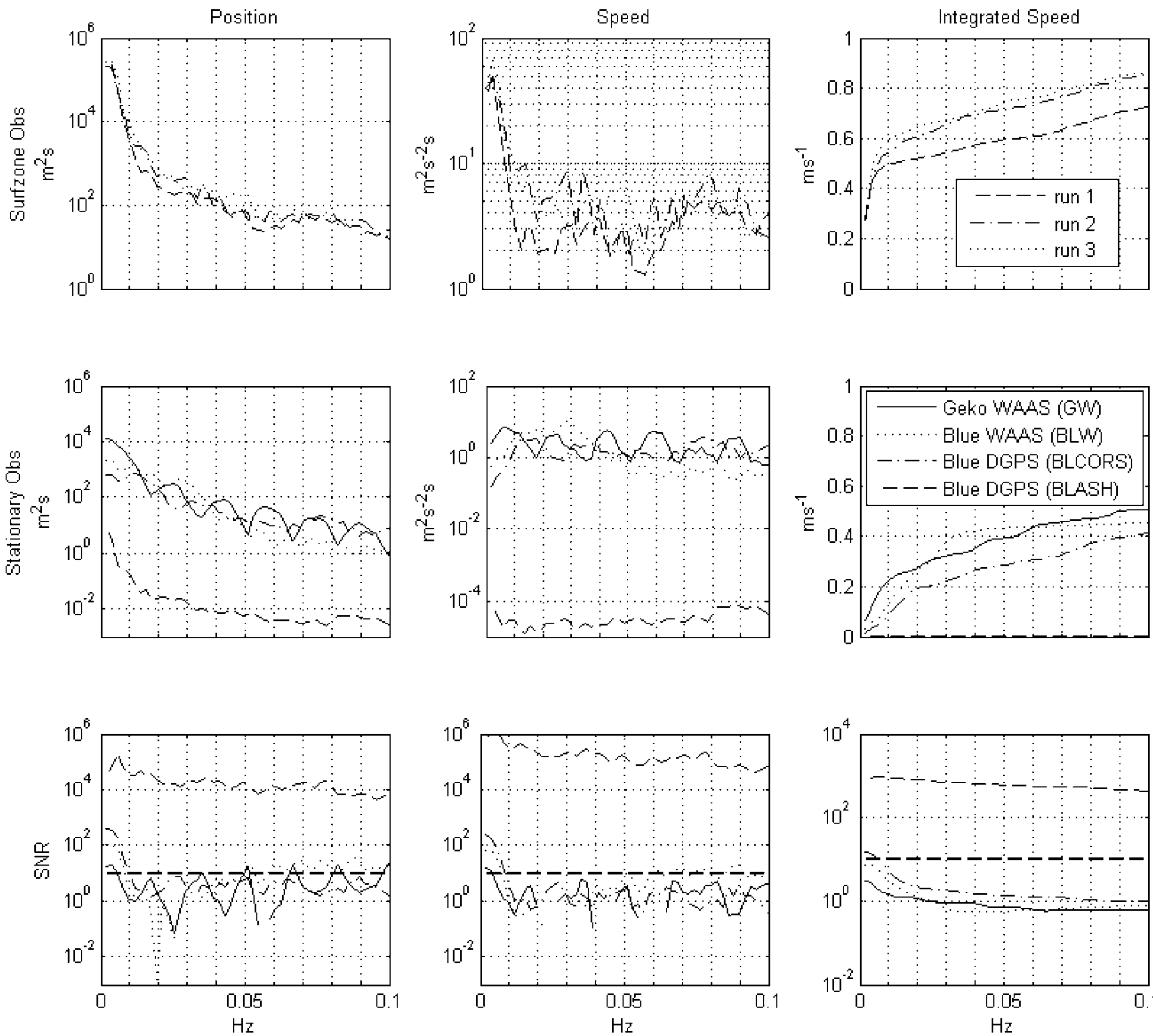

Figure 3. The stationary position error spectrum, $S_{rr}(f)$, generated from the time series of the four configurations (Figure 1). Spectrum of stationary velocity errors, $V_{rr}(f)$, is plotted relative to frequency for the four velocity series (Figure 1). Velocity errors are plotted as a function of cutoff frequency for the four configurations.

The GW, BLW, and BLCORS stationary position errors have similar low-frequency plateaus, representing Gaussian white noise, but the magnitudes of these plateaus vary in amplitude and cutoff frequency. The low-frequency plateau of the GW has the sharpest roll off, peaking at ~12,000 m^2 s and decreasing in amplitude at 0.011 Hz. The amplitude of the BLW low-frequency plateau (~2200 m^2 s) is an order of magnitude smaller than GW and decreases in amplitude at 0.027 Hz. The amplitude of the BLCORS low-frequency plateau (~700 m^2 s) is smaller than GW and BLW and decreases in amplitude at 0.018 Hz. BLASH amplitude does not have a low-frequency plateau, but it has a red spectrum at two to three orders of magnitude (~8.48 m^2 s) smaller than the other configurations.

The position stationary (error) spectra generated by Johnson *et al.* (their Figure 2, 2003) and Johnson and Pattiaratchi (their Figure 9, 2004a) have a similar shape to those shown here, but the magnitude of the spectral plateau O(100 m^2 s) and O(10 m^2 s) for their GPS is one to two orders of magnitude smaller than the plateaus obtained in either the Northing or Easting for BW, BLW, and BLCORS spectra (not shown). Johnson and Pattiaratchi (2004a) suggested that the position spectrum should exceed the error spectrum by an order of magnitude for the frequencies of interest. Johnson and Pattiaratchi (2004a) found for their GPS that the magnitude of the spectral plateau for surf-zone position spectra met the order of magnitude criteria for motions occurring at $f < 0.05$ Hz. For our tested GPS and surf-zone motions, we found that the signal-to-noise ratio is larger than 10^1 for motions occurring at $f < 0.01$ Hz. The differences between the frequency cutoff limit here (0.01 Hz) and for Johnson and Pattiaratchi (2004a) (0.05 Hz) are related to the particular motions of interest and differences in stationary results. On a different drifter deployment day, which measured alongshore currents, the position and velocity SNR were below 10^1 for all frequencies. In addition, some deployments resulted in short records, which pose problems for filtering.

The stationary velocity error spectra [$V_{rr}(f)$] (Figure 3) vary with frequency, reaching maxima greater than 1.0 m^2 s^{-1} in the frequency band of interest (<0.01 Hz). As discussed already, application of a Fourier low-pass filter will reduce the velocity errors. Velocity errors as a function of low-pass filter frequency cutoff (Figure 3) are determined by

$$V(f_c) = \int_0^{f_c} V_{rr}(f)\, df. \tag{2}$$

Velocity errors of 0.22, 0.13, and 0.08 m s^{-1} are expected for the GW, BLW, and BLCORS configurations, respectively, for $f_c = 0.01$ Hz, restricting velocities that can be evaluated to greater than 2.2, 1.3, and 0.8 m s^{-1}. In the surf zone, alongshore velocities can range from 0.1 m s^{-1} to 1.4 m s^{-1} (Feddersen *et al.,* 1998), and rip-current velocities can range from 0 to 1 m s^{-1}, with a mean velocity of ~0.35 m s^{-1} (MacMahan, Thornton, and Reniers, 2006). Only the BLASH configuration (errors ≈ 0.01 m s^{-1} for <0.1 Hz) can be guaranteed to resolve the flows of interest in this region.

EXTERNAL PATCH ANTENNA MULTIPATHING EVALUATION

For handheld systems, the largest source of positioning error is related to signal multipathing associated with the low-cost internal or optional external patch antennas (Saeki and Hori, 2006). A handheld GPS system utilizes all of the received satellite signals because these systems are intended to be used in cars or boats, near buildings, and in the woods (*i.e.,* general conditions that are not ideal for subcentimeter surveying). The exact GPS antenna signal filtering algorithm for a handheld system is unknown because it is proprietary.

Since the BLASH is the most accurate setup and the least restricted, additional tests were performed to evaluate external antenna multipathing. Two 1 h tests were performed for the handheld GPS for kinematic (described later) GPS estimates using postprocessing software: (1) a stationary test to evaluate multipathing, and (2) a roving test to estimate absolute position and speed errors. An Ashtech survey-grade GPS was used as the reference base for these tests.

The first test evaluated the performance improvement by placing the external antenna on a horizontally oriented plate to avoid multipathing, and it was compared with an external antenna not placed on a circular plate. The external antenna was 0.038 × 0.043 m, and the flat plate was 0.07 m in diameter. The finalized flat plate dimension was determined

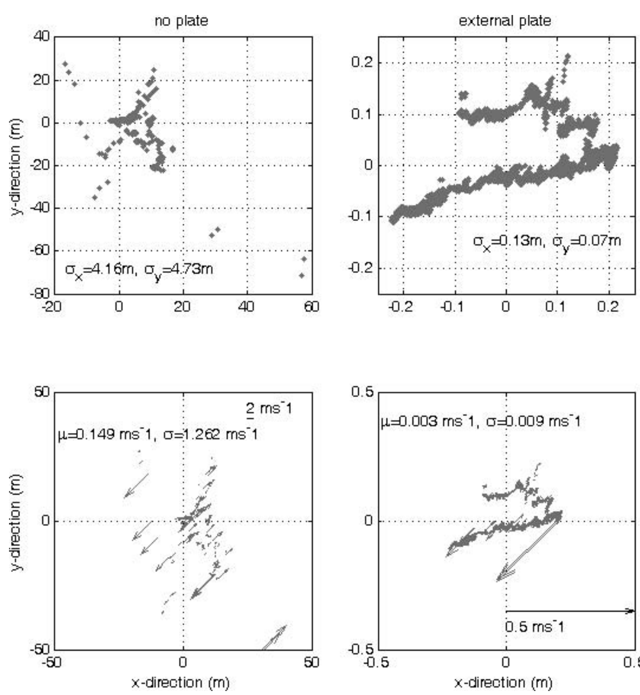

Figure 4. De-meaned position estimates for the handheld GPS (BLASH) system with an external antenna (upper left) and with external antenna mounted on a 0.07-m-diameter plate (upper right). Velocity vectors are for a stationary test for handheld GPS system with an external antenna (lower left) and with external antenna mounted on a 0.07-m-diameter plate (lower right). Note the order of two magnitude difference of scale between left and right panels.

through trial and error tests by reducing the plate size until the measured position locations started to degrade. The smallest plate dimension is required for the proposed surf-zone drifter application to reduce windage effects and maintain drifter stability. The two handheld systems (BLASH configurations) were simultaneously set up within a 4 m radius, ~2 m from the common base-station receiver. The handheld GPS system with the external antenna referenced to mean position (0,0) had a horizontal standard deviation of $\sigma_h = 4$ m (Figure 4), while the handheld GPS system that had the external antenna mounted on the plate had $\sigma_h = 0.1$ m. The stationary Ashtech survey-grade rover unit was also evaluated for comparison and had $\sigma_h < 0.03$ m for this experiment (not shown).

Velocity estimates were computed (forward-difference scheme) next for this same test. Again both handheld GPS systems were stationary, yet the handheld system with the external antenna but no plate had a $U = 0.15$ m s^{-1} and a $\sigma_U = 1.2$ m s^{-1} (Figure 4), which are unacceptable for most scientific applications involving velocities less than 3 m s^{-1}. The handheld with the external antenna mounted on a plate had an error of 0.003 m s^{-1} at zero velocity with $\sigma_U = 0.01$ m s^{-1}, suggesting that this system can be used for most scientific applications.

An additional dynamic evaluation was performed by mounting the Ashtech GPS and handheld GPS with an ex-

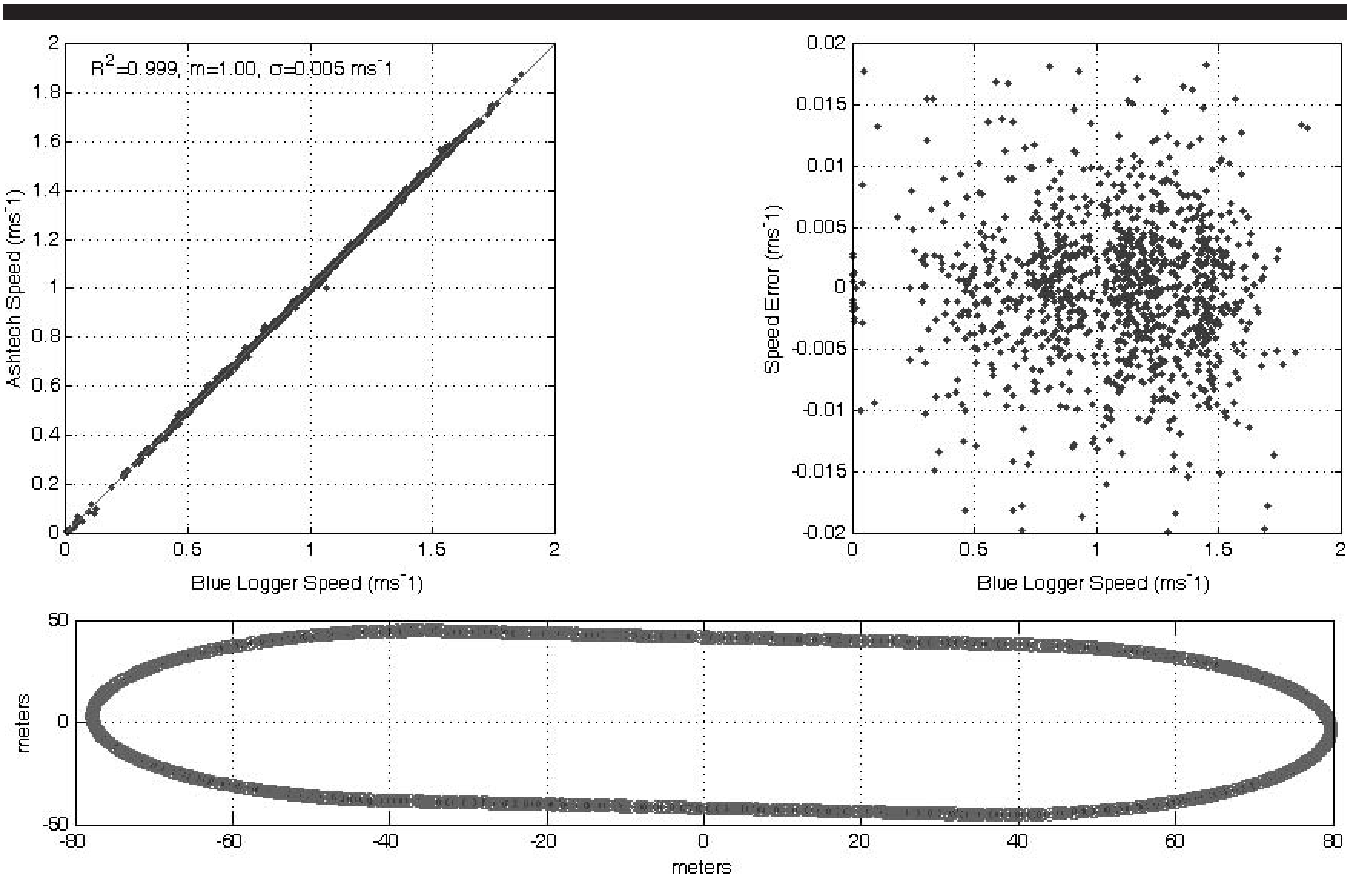

Figure 5. (top left) Comparison of Ashtech and handheld (BLASH) GPS estimated speeds. (top right) Speed error as function of speed. (bottom) Demeaned position estimates are given for both systems, illustrating the ellipse of the local track that the golf cart was pushed.

ternal patch antenna mounted on a flat plate at the same elevation with a small horizontal separation on a golf cart. The golf cart was pushed around a track at varying speeds. The Ashtech speed was used to evaluate the handheld GPS speed. Low speeds (<3 m s^{-1}) representative of surf-zone currents were evaluated in this test. Average absolute handheld position error (ε_h) around the track compared to the Ashtech GPS position (Figure 5) was estimated using

$$\varepsilon_h = \left[\frac{1}{N}\sum_1^N (X_{\text{Handheld}} - X_{\text{Ashtech}})^2 + \frac{1}{N}\sum_1^N (Y_{\text{Handheld}} - Y_{\text{Ashtech}})^2\right]^{1/2} \quad (3)$$

as 0.43 m with a maximum error of 0.95 m. The speeds of the Ashtech GPS and the handheld GPS are significantly correlated ($r^2 = 0.99$). The handheld GPS speed error (ε_U), computed as the average absolute difference between the handheld and Ashetch GPS,

$$\varepsilon_U = \sqrt{\frac{1}{N}\sum_1^N (U_{\text{Handheld}} - U_{\text{Ashtech}})^2} \quad (4)$$

is 0.01 m s^{-1} (Figure 5). The maximum speed error was 0.06 m s^{-1}. Speed errors were found to be independent of speed (Figure 5).

RIP-CURRENT FIELD DEMONSTRATION

The drifters are based on the design of Schmidt *et al.* (2003) and consist of a subaqueous 10-cm-diameter polyvinyl chloride (PVC) cylinder with a flat circular piece of PVC affixed to the bottom and a subaerial, 2.5-cm-diameter mast rising from the top (Figure 6). The dampener (circular bottom plate) reduces vertical motions and reduces surfing effects (Schmidt *et al.,* 2003). A steel plate of a predetermined weight was affixed below the flat PVC to provide a low center of gravity for drifter stability and the appropriate buoyancy. The drifter locations were tracked by a Delorme Earthmate Blue Logger GPS placed in a waterproof OtterBox attached to the drifter near the water line. The external patch antenna was affixed to a 0.07-m-diameter circle of aluminum sheeting on the top of the mast to reduce multipathing. Tests involving dye and different drifter designs showed drifters with vertical fins mounted off the subaqueous cylinder tracked the leading edge of the dye cloud better than those without, so three fins (0.33 m × 0.075 m) were attached to the main body of the drifter.

There were seven ~3 h surf-zone drifter deployments over the course of a rip-current experiment (RCEX) during the months of April and May 2007 at Sand City, Monterey Bay, California (details of the experiment can be found in Mac-

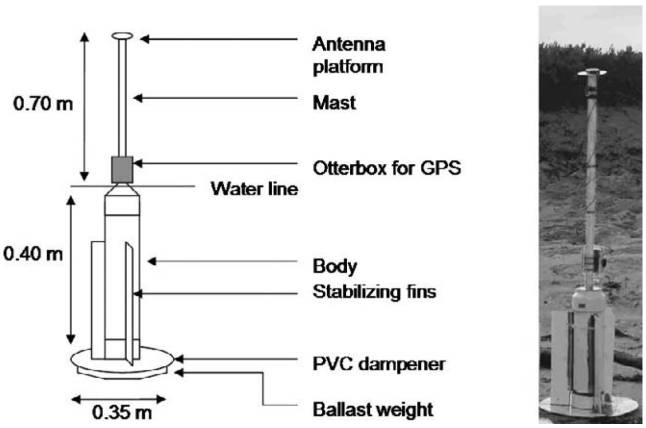

Figure 6. Picture (left; not to scale) and diagram (right) of the inexpensive (O[$213]/drifter) surf-zone drifter that the GPS unit was deployed on. The body is built entirely of PVC with a round, flat piece of PVC serving as a dampener to prevent surfing. The design is based on that of Schmidt *et al.* (2003).

Mahan *et al.,* 2008). Drifters were released in ~1 m of water in a rip channel and allowed to drift until they either exited the surf zone or grounded on the seabed. Drifters were deployed over a variety of wave and tidal conditions. All deployments took place in the morning to avoid adverse windage effects from diurnal afternoon sea breezes. Typical wind speeds were ~1 m s^{-1}, with a maximum of 6 m s^{-1}. Murray (1975) and Schmidt *et al.* (2003) outlined the importance of wind slippage and found ~0.01 m s^{-1} per 1 m s^{-1} of near-surface (0.5 m elevation) wind speed. No accessible facility or funding was available for evaluating the wind slippage of the RCEX drifters. However, the flag pole used by Murray (1975) was 0.03 m in diameter and 1.5 m in length (cross-sectional area 0.045 m^2). The antenna pole used on the drifter herein had a diameter of 0.05 m and length of 0.7 m, resulting in slightly smaller cross-sectional area (0.035 m^2). We assumed the wind slippage to be similar to that of Murray (1975), resulting in maximum biased error for the experiment of 0.06 m s^{-1}. As mentioned by Schmidt *et al.* (2003), the windage effects within an energetic surf zone are unknown.

The drifter positions were transformed to a local cross- and alongshore coordinate frame. Cross- and alongshore velocities were estimated by a forward-difference scheme on the local position time series. The experimental area was divided into 10 m × 10 m bins. Based on the position information, the velocity data were sorted into the appropriate bin and averaged over the deployment duration (Figure 7). Only bins with five or more velocity measurements were included, resulting in statistically confident results (Spydell *et al.,* 2007).

To check the validity of the velocity measurements obtained with the drifters, the drifter velocities were compared to stationary colocated pressure (P), cross-shore (U), and alongshore (V) velocity (PUV) measurements (Figure 7). Velocities for both the drifters and PUVs were time averaged over 1 min to remove the sea-swell wave action. The cross-shore and alongshore velocities are compared for all times

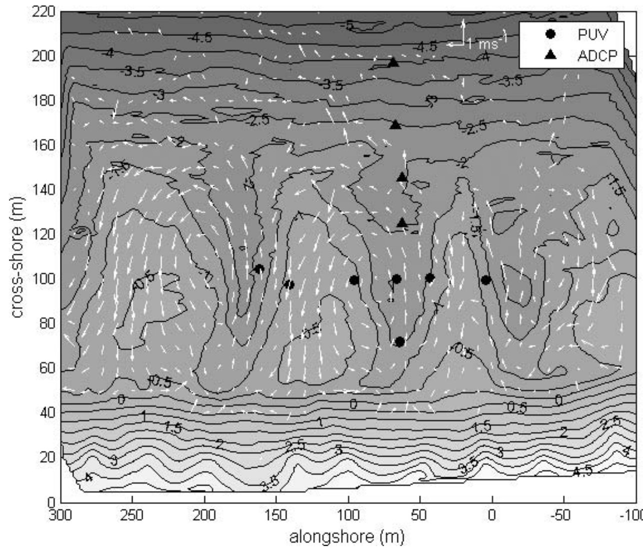

Figure 7. Three-hour and 10 m × 10 m bin-averaged velocity estimates (white arrows) computed using a forward-difference scheme of positions obtained from GPS units mounted on surf-zone drifters deployed on 4 May 2007 at Monterey Bay, California, a natural beach with persistent rip currents. Small white dots represent 10 m × 10 m spatial bins with less than five observations. The arrows and text in the upper right-hand corner provide vector scales.

when a drifter entered a 1.5 m × 1.5 m box centered on any of the instruments (Figure 7). They are correlated in the cross-shore with an r value of 0.70, a best-fit slope of 1.04, and an intercept of −0.01 (Figure 8). In the alongshore, they are also correlated (r = 0.70), but the best-fit line has a slope

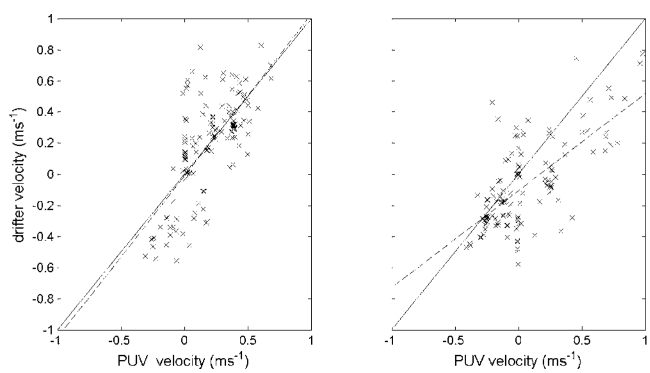

Figure 8. Comparison between drifter and *in situ* measurements of cross-shore (left) and alongshore (right) velocities; r is 0.70 for the cross-shore and 0.70 for the alongshore. The best fit (dashed red line) is better for the cross-shore, with a slope of 1.0 and an intercept of −0.01, while the alongshore best fit has a slope of 0.63 and an intercept of −0.1. Correlation is similar to other comparisons between drifters and *in situ* measurements (Johnson and Pattiaratchi, 2004a; Schmidt *et al.,* 2003). The scattered appearance is attributed to the difficulties in comparing different types of measurements and in ensuring that the drifter and Eulerian instrument are evaluating the same observation. Solid line represents perfect correlation.

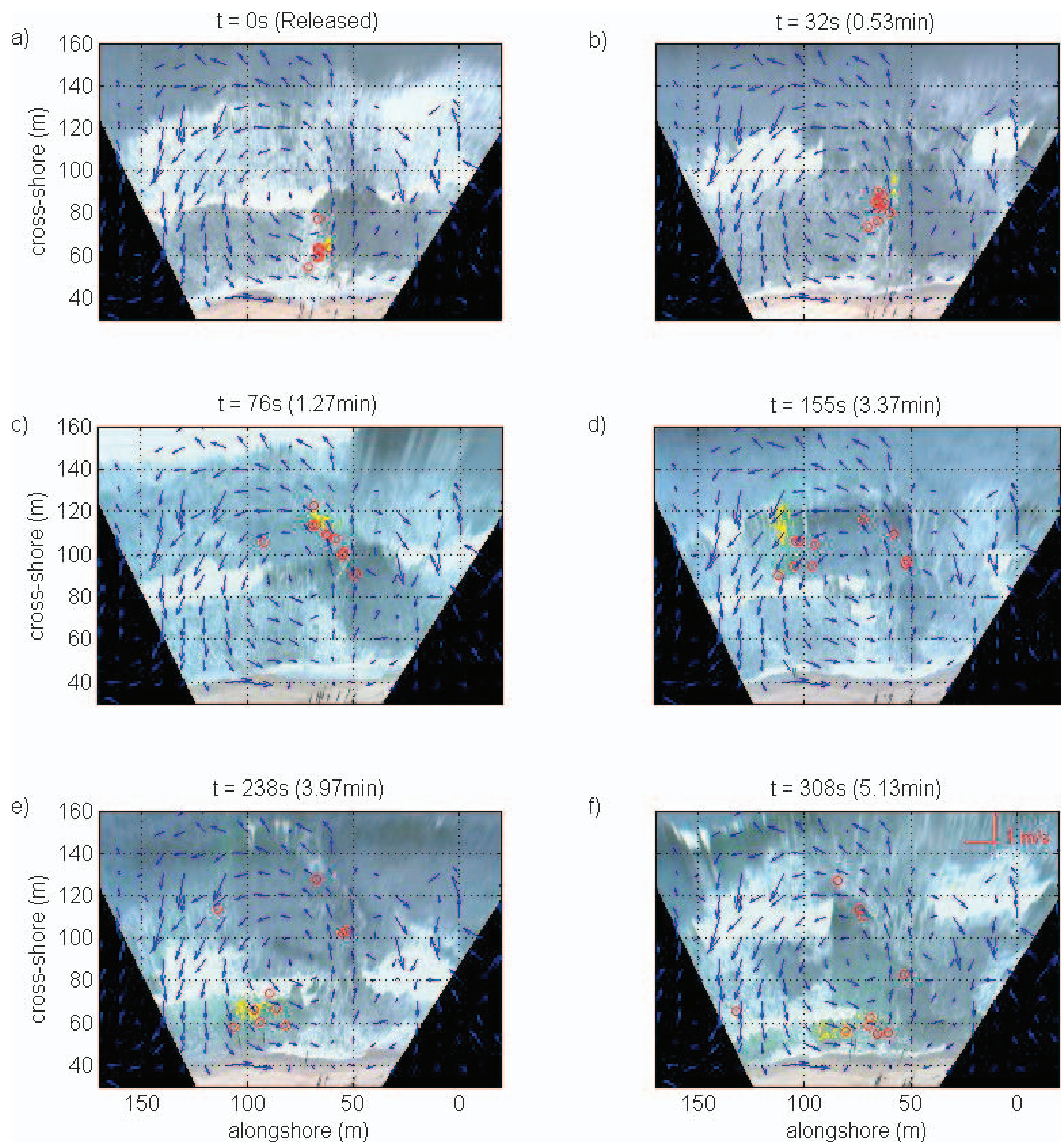

Figure 9. Six time-elapsed rectified video images with dye enhancement for simultaneous dye and drifter cluster deployment for year-day 124. Yellow represents the dye, and the red circles represent the drifters. Blue vectors are 10 m × 10 m bin-averaged velocities, and the red vectors are 1 m s^{-1} velocity legend.

of 0.63 and an intercept of −0.10. We believe that the poor correlation is a result of the spatial and temporal average of the Lagrangian observation (drifters) compared to the temporal average of an *in situ* Eulerian observation, particularly for a nonhomogeneous rip-current circulation pattern. Surprisingly, only a few of drifters throughout the experiment were within close proximity to the stationary instruments. These correlations are similar to Johnson and Pattiaratchi (2004a) (r = 0.77 in the cross-shore and r = 0.75 in the alongshore). Schmidt *et al.* (2003) found better agreement (r =

0.95) in the alongshore but similar agreement in the cross-shore, which they attributed to the drifter measuring near-surface velocities and the Eulerian instrument measuring near-bed velocities.

Johnson and Pattiaratchi (2004a, p.468) described the problematic nature of field validation of the drifters in the surf zone, because "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." This results in two different estimates that are not comparable. Thus, true field verification remains unknown. To overcome this problem, a cluster of ten drifters was simultaneously released with dye (Figure 9). Fluorescent dye represents a "true" Lagrangian measurement of water movement. The bulk of the dye patch and the drifter cluster remained colocated for one rip-current circulation, suggesting that the drifters were behaving as an accurate Lagrangian estimate. 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. In conclusion, the drifters represent Lagrangian estimates with confidence.

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 proposed inexpensive system has the ability to fill in the voids between *in situ* instruments, advancing our understanding of the hydrodynamics of a rip-current system.

CONCLUSIONS

The position and velocity errors computed from a stationary test of two inexpensive handheld GPS units indicate that neither can be used for low-velocity scientific applications without modification. The spectra of the position signals indicate that there is the possibility of using the velocity-resolution method presented in Johnson and Pattiaratchi (2004a) for a moving system with the GW, BLW, and BLCORS systems, provided the velocities involved are larger than 0.8, 0.13, or 2.2 m s^{-1}, respectively. The BLCORS provides a better error signal for velocity processing, since the expected velocity errors (0.08 m s^{-1}) are roughly two-thirds the magnitude of the BLW (0.13 m s^{-1}) and roughly one-third the GW spectra (0.22 m s^{-1}) in the region of interest. The applicability of this method depends on the position signal acquired, especially the number of points acquired and the background processes present. The BLASH configuration requires the additional cost for a base station or the use of CORS and third-party survey-grade postprocessing software, but it can result in O(0.10 m) accuracy in determining actual position coordinates and the ability to resolve flows on the order of 0.05 m s^{-1} with no restrictions on data series length or background processes. Absolute BLASH position and speed errors were ε_h = 0.4 m and ε_U = 0.01 m s^{-1}. Reducing patch antenna multipathing reduced the position errors from 4 m to 0.1 m. The feasibility of BLASH method for tracking surf-zone flows with a GPS drifter was demonstrated, showing good correlation (r = 0.7) between drifter velocity and stationary velocity. The drifters tracked simultaneous dye releases well, verifying that the observations are valid Lagrangian estimates. The cost, size, and weight of the handheld GPS allow for a large number of independent observations to be obtained for various meteorological and oceanographic applications.

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