⁶Performance Characteristics of "Spotter," a Newly Developed Real-Time Wave Measurement Buoy

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ABSTRACT

The Spotter is a low-cost, real-time, solar-powered wave measurement buoy that was recently developed by Spoondrift Technologies, Inc. (Spoondrift). To evaluate the data quality of the Spotter device, we performed a series of validation experiments that included comparisons between Spotter-derived motions and prescribed wave motions (monochromatic and random waves) on a custom-built, motion-controlled validation stand and simultaneous in-water measurements using a conventional wave measurement buoy, the Datawell DWR-G4 (Datawell). Spotter evaluations included time-domain validation (i.e., wave by wave) and comparisons of wave spectra, directional moments, and bulk statistical parameters such as significant wave height, peak period, mean wave direction, and directional spread. Spotter wave measurements show excellent fidelity and lend a high degree of confidence in data quality. Overall, Spotter-derived bulk statistical parameters were within 10% of respective Datawell-derived quantities. The Spotter's low cost and compact form factor enabled unique field deployments of multiple wave measurement buoys for direct measurements of wave characteristics such as ocean wave decorrelation length scales, wave speed, and directional spread. Wave decorrelation lengths were found to be inversely proportional to the width of the spectrum, and wave speeds compared well against linear wave theory.

1. Introduction

There is considerable demand for high-fidelity, lowcost wave measurements in coastal and oceanic environments for academic, government, commercial, and recreational purposes. Real-time measurements of wave parameters and wave characteristics are of interest to a multitude of sectors such as academic research groups, the military, coastal engineers, ports and harbors, the marine transportation industry, the oil and gas industry, low-lying island nations, the nascent marine renewable energy industry, and more. Present-day commercial offthe-shelf (COTS) wave measurement devices are typically cost prohibitive (order of tens of thousands of dollars), and their operations can be considered labor intensive and/or require scientific or engineering expertise, limiting its wide adoption by many public and private entities, including economically disadvantaged nations.

From a scientific and engineering perspective, the high cost and oftentimes large size and weight associated with COTS wave measurement platforms places economic and logistical restrictions that limit the number of wave buoys that can be deployed simultaneously. Thus, there is a lack of spatially diverse wave measurementsmeasurements that can yield tremendous insight into aspects of wave propagation physics that are often overlooked or restricted to the purview of ocean wave models or small-scale, laboratory-based wave tank experiments. Aspects of wave propagation such as the directional variation among various wave components have direct implications on real-world applications such as the design of offshore structures, dispersion of floating objects, and the optimization of wave energy device controls. A review of various directional estimation techniques by Benoit et al. (1997), Forristall and Ewans (1998),

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and Donelan et al. (2015) discussed the limitation of singlepoint measurements in accurate directional wave estimation, together with the improvements afforded by arrays of three or more instruments (Young 1994) or instruments with multiple degrees of freedom (Mitsuyasu et al. 1975). Young (1994) further concluded that while a single triaxial pitch/roll/heave buoy can accurately measure mean wave direction, estimates of directional spreading are typically larger than when compared to measurements obtained by a spatial array of wave gauges.

Further, wave measurements provided by most COTS wave measurement devices are restricted to statistical quantities such as significant wave height, mean and peak periods, and directional moments. While these stochastic quantities are often sufficient for a characterization of linear wave phenomena, the rich time-dependent and deterministic aspects of wave propagation are often lost because of averaging that is inherent to spectral calculation (Gerling 1992). An understanding of phenomena such as wave interference, diffraction, and extreme waves require deterministic wave measurements (Naaijen and Huijsmans 2008).

To help address the above limitations, Spoondrift Technologies, Inc. (Spoondrift), in partnership with Integral Consulting, Inc. (Integral), and Sandia National Laboratories, have developed the Spotter, a low-cost, easy-to-use, solar-powered global positioning system (GPS)-based wave measurement platform. The Spotter is capable of real-time transmission of standard sets of bulk parameters that describe wave statistics, in addition to deterministic wave motions. While GPS technology to measure waves and currents has been demonstrated for over a decade, the Spotter is distinguished as the first commercial product that leverages recent advances in low-cost microcontrollers, data acquisition and storage systems, satellite communications, solar technology, and motion sensors into a product whose ease of deployment, usability, low cost, and data quality combine to make it a powerful wave measurement platform.

GPS-based wave measurements have primarily revolved around two approaches: direct positional measurements to yield wave orbital motions or measurements of velocity whose integration yields position. Positional measurements are accomplished using either kinematic positioning, which requires the use of a reference base station and thus limits the buoy's ability to make open ocean measurements, or via precise commercialgrade point positioning using a single GPS sensor. A comparison of various positioning methods as applied to wave measurements is seen in Bender et al. (2010), who demonstrated the reliability and accuracy of postprocessed kinematic and precise point positioning methods in deriving wave heights and periods from GPS measurements, with GPS-derived wave heights showing fidelity with those estimated using a 6-degrees-of-motion inertial measurement unit strapped onto a surface buoy.

An early commercial GPS-based wave measurement system, the Seatex Smart-800 buoy, relied on Doppler velocity measurements made using a differential GPS system to resolve wave parameters (Krogstad et al. 1999). This system, while capable of providing high-fidelity wave measurements, required the presence of a shore- or boatbased GPS reference station in order to constrain measurement errors. Another popular commercial system, the Datawell DWR-G family of wave buoys, is a widely sold GPS wave buoy that uses a single GPS unit to measure orbital velocities that are then integrated and high-pass filtered to yield orbital displacements. The DWR-G has been demonstrated to compare favorably with the more traditional accelerometer-based wave buoys (deVries et al. 2003). More recently, Herbers et al. (2012) and McIntyre (2013) found that wave measurements that incorporate relative horizontal positional measurements using COTS GPS devices allowed for good coastal wave measurements of wave bulk parameters such as significant wave heights, peak periods, and mean direction, albeit with higher energy levels and directional spreading observed at higher frequencies relative to the Datawell DWR-G. Iwanaka et al. (2005) described the use of a single GPS system along with a high-pass filter in making three-dimensional wave measurements with centimeter-scale accuracy, a system that now forms the basis of a wave observing network of buoys in Japan. Joodaki et al. (2013) further validated the approach of Iwanaka et al. (2005), while providing criteria for the selection of the high-pass filter cutoff frequency. Thomson et al. (2018) demonstrated methods for measuring waves using a combination of a GPS and inertial motion unit aboard an autonomous surface vehicle and showed that while comparisons of wave spectral energies to those measured by an onboard Datawell Waverider buoy were within 5%, there was a systematic overestimation of wave energy, likely because of contamination of wave measurements by device propulsion. Scripps Institution of Oceanography's miniature wave buoy (Terrill and de Paolo 2016) utilizes a GPS unit to make Doppler velocity measurements, with over 500 units field tested over seven years of deployments.

This contribution describes the Spotter wave buoy, developed in support of adaptive tuning of control systems for wave-powered renewable energy installations (Babarit et al. 2004; Hals et al. 2011; Li et al. 2012; Ringwood 2016; Wilson et al. 2016), but with broad



FIG. 1. (a) The Spoondrift Spotter wave measuring device, and (b) the Spotter web-based data dashboard.

applicability to a wide variety of wave measurement markets. The paper is organized as follows: section 2 describes the Spotter technology (patent pending). Section 3 demonstrates the validity of Spotter measurements using a custom-built motion-controlled validation stand and comparison of Spotter measurements with the Datawell DWR-G4 (referred to as Datawell). Wave characterization results from a series of field tests are described in section 4. Finally, section 5 concludes the paper and describes future improvements and ongoing efforts.

2. Technology description

The Spotter device is a globally connected surfacefollowing buoy that measures 3D surface displacements at 2.5 Hz (see www.spoondrift.co). The device computes the complete 3D cross-correlation matrix onboard and transmits spectra and directional moments to a user dashboard through the Iridium satellite communication network. Deterministic wave information is stored onboard a swappable SD card. The Spotter device is a compact (38-cm diameter) and lightweight (<5.5 kg) surface buoy, constructed from marine-grade plastics (see Fig. 1a). During the field tests described in this paper, the Spotter was deployed from a 4-m inflatable boat (Zodiac) and used in a free-drifting and moored configuration. The Spotter is solar powered and has been demonstrated to operate continuously for six months. By combining GPS, satellite communication, and solar technologies, Spotter overcomes battery storage limitations and can operate anywhere in the world. The buoy response for a spherical buoy with the same dimensions of the Spotter is computed to be 1.2 Hz, indicating that resonance effects are unlikely to be present when measuring motions below this natural frequency.

To enable easy, real-time data access and two-way communication, the Spotter device is integrated into an online dashboard (Fig. 1b). The dashboard is accessible through any mobile device (e.g., laptops, tablets, and smartphones) and provides real-time access to data 1130

from the Spotter device, system updates, and visualization tools to look at historical data. Through the dashboard, the user can change settings on the device remotely, activate live tracking, and set a geofence. These features enable real-time tracking of Spotters to alert users to unexpected buoy movement if moored or to estimate surface currents if operated in drifting mode. The dashboard also exposes an application programming interface (API) to integrate real-time data into models or other websites.

3. Data quality evaluation

The validity of Spotter measurements was demonstrated using a custom-built motion-controlled validation stand as well as through simultaneous deployments of the Spotter and a Datawell DWR-G4, with a horizontal separation ranging from roughly 30 to 100 m. For both the motion-controlled validation stand tests and the at-sea wave buoy comparisons, horizontal and vertical displacements were compared, along with bulk parameters such as significant wave height, peak period, wave direction, and directional spread.

a. Motion-controlled validation stand tests

Traditional laboratory-based wave measurement buoy validation methods have employed a Ferris wheellike apparatus, which reproduces only periodic (monochromatic) wave orbital motions (e.g., Joodaki et al. 2013). Ocean waves, however, never exhibit perfectly monochromatic orbital motions but are best represented by random wave motions of varying bandwidth. Therefore, a motion-controlled validation stand was developed and constructed that can perform user-programmable random wave motions, such as realizations of a JONSWAP spectrum for fully developed seas (Hasselmann et al. 1973) and any other parameterized or observed spectral shape (e.g., Pierson and Moskowitz 1964). The validation stand was fabricated using off-the-shelf computer numerical control (CNC) components to produce and record precise and continuous movements. The stand consists of a motion controller board, servomotors, and $2m \times 2m$ rail guides with gantry, which are mounted vertically (Fig. 2), and a custom mount to accommodate the Spotter motion sensor and electronics. The two perpendicular arms of the stand are independently controlled using two programmable stepper motors, which allow for a wide range of motions in a two-dimensional plane.

The test stand geometry allows for a maximum wave height of 1.8 m, with wave periods that can range from 3 to 30 s. Both monochromatic and random waves were emulated in validation tests, where the stand's absolute positions and speed were prescribed relative to a



FIG. 2. Fit-for-purpose wave measurement validation stand.

reference point on the stand using a G-code software interface (Electronic Industries Association 1979). Test stand displacement measurements are sampled at 9.1 Hz while the Spotter data are sampled at 5 Hz for testing purposes. Spectral wave parameters and deterministic positioning determined by the Spotter were compared to the absolute position information provided by the test stand. This capability contributed to the development and validation of the Spotter device and demonstrated the wave data quality achievable by the Spotter.

Spotter data quality was evaluated using two sets of prescribed motions that represent 1) a monochromatic wave and 2) a random wave that represents one realization of a JONSWAP spectrum for fully developed seas. The prescribed monochromatic waves have a peakto-peak amplitude of 1.3 m, with a wave period of 12.5 s.



FIG. 3. Comparison of (a) horizontal and vertical displacements and (b) vertical spectra, for a prescribed monochromatic wave, measured on the Spotter and motion-controlled validation stand. Shaded regions represent 95% confidence intervals.

1) MONOCHROMATIC WAVES

A 6-min-long segment of data is considered over which horizontal and vertical displacement time series are compared along with the power spectral density of vertical displacements. Figure 3 shows a deterministic comparison of two-dimensional monochromatic orbital motion exhibited by the validation stand compared to motions measured by the Spotter, which were bandpass filtered between 0.05 and 0.3 Hz using a second-order Butterworth filter. The filter has the effect of damping spurious motions that might be imparted by vibration of the test stand and removing any low-frequency drift in the GPS absolute positional measurements. This frequency band is chosen since it represents peak periods of 3-20s, the primary frequency band of ocean surface gravity waves that the Spotter is designed to measure. Spotter estimates of horizontal displacements are in the true east-west/ north-south plane. Comparison of horizontal motions requires that these measurements are first translated to the plane of the validation stand using the measured angle between the plane of the validation stand relative to geographic north. Root-mean-square (RMS) difference in horizontal displacement was found to be 7.7 cm (within 6% actual) and the RMS difference in vertical displacement was found to be 5.8 cm (within 5% of actual) (Fig. 3a).

Next, the power spectral density of vertical displacements is computed for the test stand motion and the Spotter. Power spectral densities for the Spotter are computed using a 512-point fast Fourier transform (FFT), windowed using a 512-point Hanning window with 50% overlap between windows. To account for the differing sampling rates, and maintain the same frequency resolution, power spectral densities for the test stand are computed using a 1024-point FFT, windowed using a 1024-point Hanning window with 50% overlap between windows. This results in eight spectral samples for the Spotter and the test stand. Figure 3b shows the



FIG. 4. Comparison of (a) horizontal and vertical displacements and (b) vertical spectra, for a prescribed random wave, measured on the Spotter and motion-controlled validation stand. Shaded regions represent 95% confidence intervals.

vertical frequency power spectra for the motioncontrolled stand and Spotter with the shaded area representing the 95% confidence interval. Because of the highly narrowband nature of the signal, power spectra are plotted on a logarithmic scale to better highlight differences in the noise floor of the Spotter and test stand. The Spotter is seen to correctly reproduce the monochromatic frequency peak with the correct energy content. Differences in the high-frequency noise floor are observed, particularly above 0.15 Hz. With a monochromatic spectrum, energy levels in this high-frequency band are several orders of magnitude lower than that of the peak period of 12.5 s. Nondirectional parameters such as wave height and period were measured within 4.8% and 2.1% of that prescribed, respectively.

2) RANDOM WAVES

Recognizing that real ocean waves are never perfectly monochromatic, a comparison was made using random wave motions that represent a realization of a two-dimensional JONSWAP spectrum. A 15-min-long time series of a random wave realization was prescribed to the test stand motion controller with a significant wave height of 0.58 m and peak wave period of 12.2 s (Fig. 4a). Comparisons between actual motioncontrolled validation stand horizontal and vertical displacements and displacements measured by the Spotter indicate agreement (Fig. 4). Horizontal displacement RMS differences (calculated in the time domain using the raw displacement time series) between the two methods were found to be 5.7 cm (5.3%of actual) and the RMS difference between the prescribed validation stand motion and Spotter vertical displacements was found to be 9.3 cm (7.7% of actual). Correlation coefficients at zero lag for horizontal and vertical random wave displacements were 0.92 and 0.83, respectively.

Power spectral densities for the Spotter and test stand vertical displacements are computed using the parameters outlined in the section above. A total of 18 spectral samples are utilized to compute the power spectral density for the Spotter and test stand. Figure 4b shows the vertical frequency power spectra for the motioncontrolled stand and Spotter with the shaded area representing the 95% confidence interval. The Spotter is seen to correctly represent the shape and energy levels of the test stand power spectrum, within the 95% confidence interval, with the exception of the estimate near 0.06 Hz. Nondirectional bulk parameters such as significant wave height and peak period were measured within 10% and 3% of that prescribed, respectively. Intersensor comparisons of wave displacement time series have been previously undertaken by multiple researchers under the Office of Naval Research Environmental Ship and Motion Forecasting program. For example, Drazen et al. (2016) compared a Datawell DWR MKIII to multiple miniature wave buoys. Terrill (2012) compared wave measurements at a single pixel of an X-band radar with those made by a Datawell wave measurement buoy. The validation of wave buoy displacement time series with random motions generated on a test stand represents an additional, controlled environment under which the performance of wave measurement buoys can be evaluated.

b. At-sea statistical validation

Following the verification of Spotter data quality in a controlled environment, at-sea testing was conducted in Waimanalo, Hawaii; Santa Cruz, California; and Half Moon Bay, California. During each of these tests (Fig. 5), multiple Spotters were deployed alongside a Datawell or an acoustic Doppler current profiler (ADCP) capable of measuring surface gravity waves. Given that the Datawell and ADCP are established technologies, they are treated as the "control" measurements against which Spotter data quality is evaluated. Described in this section are the experimental configurations for each of the three field validation tests followed by results from each field test. Table 1 summarizes the locations and dates during which all the motion-controlled stand and field tests were conducted. This section presents quantitative data quality metrics obtained during the three field tests between 2016 and 2018. Table 2 displays the statistical data comparisons for all three tests that shows Spotter estimates of significant wave heights, peak periods, mean wave direction, and directional spread (where applicable) compared against the Datawell or ADCP during the validation tests. Prototype buoys (Spotter predecessors) were deployed during the Waimanalo Bay and Santa Cruz tests and sampled at 5 Hz. The commercialized version of the Spotter device, deployed during the Half



FIG. 5. (a) Map of 21 March 2016 testing and mooring locations (Waimanalo, HI). Inset shows mooring locations for the Spotter03 (03), Spotter04 (04), Spotter05 (05), and the Datawell (DW). (b) Map of 14 June 2016 testing and mooring locations (Santa Cruz, CA). Inset shows mooring locations for Spotter02, Spotter05, and the Datawell. (c) Map of March 2018 testing and mooring locations (Half Moon Bay, CA). Inset shows mooring locations for Spotter098, Spotter101, and the Datawell.

Moon Bay tests, sampled at 2.5 Hz. Averaged error metrics for all field trials are reported in Table 2. Consistency between various buoy measurements is seen, lending confidence to computations of bulk statistics by the numerous buoys.

1) VALIDATION EXPERIMENT—WAIMANALO BAY

The first set of field tests described were conducted between 21 and 26 March 2016 in Waimanalo Bay, Oahu, Hawaii (Fig. 5a). The Waimanalo Bay field tests

Location	Date	Duration	Notes
Validation stand	28 Nov 2016	6–15 min	Spotter and Datawell compared to prescribed motion
Waimanalo, HI	21-26 Mar 2016	$4-8 h day^{-1}$	Three Spotters and Datawell moored in 10-m water depth
Santa Cruz, CA	14 Jun 2016	2 h	Spotter deployed alongside Datawell and ADCP in 10-m water depth
Half Moon Bay, CA	16 Mar 2017	4 h	Two Spotters moored and allowed to free drift in 40-m water depth
Half Moon Bay, CA	13 Mar 2018	10 days	Two Spotters and Datawell moored 100 m apart in 40-m water depth

TABLE 1. List of field deployments.

consisted of the deployment of three prototype Spotters (identification numbers 7001, 7002, and 7003) moored in approximately 10-m-deep water, adjacent to a Datawell (Fig. 5a). Buoys were spaced approximately 30 m apart. Vertical and horizontal displacement spectra, derived from displacement time-series data, were used to calculate various bulk statistics, such as significant wave height, peak period, mean direction, and directional spread (calculations described in the appendix). The frequency band of interest lies between 0.05 and 0.3 Hz, corresponding to wave periods of 3-20 s, adequately representing most wind-sea and swell waves. Waimanalo Bay, located on the windward side of Oahu (Fig. 5a), is subject to a wide variety of swell conditions. The climatological average significant wave height from the nearest wave monitoring location, Mokapu Point [Coastal Data Information Program (CDIP) Station 098 in 88-m water depth], for the month of March is 1.97 m, with a climatological mean wave period of 9.9 s. Typical wave directions at the site range from westerly to northwesterly. Spotter measurements during this test are compared against the Datawell as a control measurement. The prototype Spotters used in this test had limited fidelity of vertical measurements, and vertical displacement power spectra were computed from horizontal displacement power spectra using linear wave theory (Herbers et al. 2012).

Vertical power spectra and bulk statistics are computed for a 4-h deployment on 21 March 2016. Power spectral estimates for the Spotter were computed using 1024-point fast Fourier transforms, with a 50% overlap between Hanning-windowed segments, yielding a total of approximately 156 spectral samples. The number of FFT points was reduced to 256 points for the Datawell measurements in order to preserve the same frequency resolution between measurement buoys (recall the Datawell samples at 1.28 Hz). Bulk statistics (significant wave height, peak period, mean direction, and directional spread) were computed over 30-min intervals, which results in a total of 11 spectral samples used in the spectral computations.

Figure 6 compares vertical displacement spectra along with 95% confidence intervals and bulk wave statistics for the Spotter wave buoys compared to that computed from the Datawell displacement measurements. Power spectra for all three Spotters and the Datawell are consistent up to 0.17 Hz, with spectra overlapping within the confidence bands. Above 0.17 Hz, the prototype Spotters show a dampened higher-frequency response relative to the Datawell. The cause of this dampening was found to be related to Spotter firmware configuration during this developmental phase of the device.

Bulk statistics (significant wave height, peak period, mean direction, and directional spread) were computed over 30-min intervals, and shown in Fig. 6b. The significant wave height, peak period, mean direction, and directional spread for the entire 4-h wave record were computed and are listed in Table 2. The Spotter-derived significant wave height was 0.09% higher, while the peak period was 0.16% higher than the Datawell measurement. The mean direction and directional spread were

TABLE 2. Comparison of bulk wave parameters. Tests were conducted on the motion-controlled stand (test stand) and in a series of field tests. Where multiple Spotters were deployed (three in Waimanalo and two in Half Moon Bay), results from the Spotter closest to the Datawell are reported. "Control" during the Waimanalo and Half Moon Bay tests represents the Datawell, while "control" during the Santa Cruz tests represents the ADCP.

	$H_{s}\left(\mathbf{m} ight)$		T_p (s)		θ		$\sigma_{ heta}$	
Bulk parameter	Control	Spotter	Control	Spotter	Control	Spotter	Control	Spotter
Test stand (monochromatic)	0.46	0.44	12.5	12.8	_	_	_	_
Test stand (random)	0.60	0.65	12.8	12.5		_	_	_
Waimanalo, March 2016	1.04	1.05	12.5	12.8	71.0°	66.7°	13.3°	13.2°
Santa Cruz, June 2016 Half Moon Bay, March 2018	0.83 1.84	0.75 1.75	18.1 10.0	17.1 10.2	203.0° 266.5°	209.0° 271.6°	 36.9°	34.0° 36.2°



FIG. 6. Comparison of Spotter data quality to that measured by a Datawell DWR-G4 in Waimanalo, HI, in March 2016. (a) Vertical displacement power spectra, where shaded regions represent 95% confidence intervals, and (b) bulk wave statistics computed every 30 min.

6% lower and 0.75% lower than the Datawell measurement, respectively.

2) VALIDATION EXPERIMENT—SANTA CRUZ

Testing in Santa Cruz took place on 14 June 2016. Two prototype Spotters were deployed alongside a Datawell and a bottom-mounted ADCP capable of measuring waves, in approximately 10-m-deep water (Fig. 5b). Wave heights during this test were primarily characterized by a long period southerly swell, with significant wave heights ranging from 0.75 to 0.83 m over the course of the day. Datawell displacement measurements in the y direction were found to be in anomalously high, likely because of an incorrect user setting prior to deployment. Consequently, Spotter data from this deployment are compared with the ADCP data as the control measurement.

Vertical power spectra and bulk statistics are computed over a 2-h period on 14 June 2016. Power spectral estimates for the Spotter were computed using 1024-point fast Fourier transforms, with a 50% overlap between Hanning-windowed segments, yielding a total of 55 spectral samples. The number of FFT points was reduced to 256 points for the Datawell measurements in order to preserve the same frequency resolution between measurement buoys (recall the Datawell samples at 1.28 Hz).

Bulk parameters as measured by Spotter05 (located east of the ADCP; Fig. 5) were computed over the 2-h wave record and compared to those measured by the ADCP in Table 2. This buoy was chosen over Spotter02 because dampening of wave spectra was observed for Spotter02 that was deployed in the middle of a thick kelp patch. The Spotter-derived significant wave height was 9% higher, while the peak period was 5.5% lower than the ADCP measurement. The mean direction was 2.9% higher than the ADCP measurement, respectively.

3) VALIDATION EXPERIMENT—HALF MOON BAY

Most recently, two Spotters and a Datawell were deployed in Half Moon Bay, offshore of Pillar Point (Fig. 5c), between 12 and 30 March 2018. The Spotters deployed in this test belonged to the first commercial version of the buoys, and sampled at 2.5 Hz (recall that



FIG. 7. Comparison of Spotter data quality to that measured by a Datawell DWR-G4 in Half Moon Bay, CA, in March 2018. (a) Vertical displacement power spectra, where shaded regions represent 95% confidence intervals, and (b) bulk wave statistics computed every 30 min.

the previous prototype versions sampled at 5 Hz). The wave buoys were deployed in 40-m water depth, 100 m apart from each other. Wave statistics during this testing period were primarily characterized by northwesterly swell, accompanied by shorter-period wind waves resulting from prevailing northwesterly winds typical of springtime conditions in Northern California. During recovery operations for the Datawell, the mooring was found to have drifted approximately 1.5 km from its original deployed location. Analysis of the time series data indicated that this motion, likely because of snagging of the mooring line by a vessel, occurred on 23 March. Therefore, data from the two Spotters and Datawell are analyzed for intercomparison between 12 and 22 March 2018, with the Datawell representing the control measurement.

Vertical power spectra and bulk statistics are computed over the time period 12–22 March 2018. Power spectral estimates for the Spotter were computed using 256-point fast Fourier transforms, with a 50% overlap between Hanning-windowed segments, yielding a total of approximately 34000 spectral samples over which vertical spectra are averaged. The number of FFT points was reduced to 128 points for the Datawell measurements in order to preserve the same frequency resolution between measurement buoys (recall the Datawell samples at 1.28 Hz). Bulk statistics (significant wave height, peak period, mean direction, and directional spread) were computed over 30-min intervals, which results in a total of 72 spectral samples used in the spectral computations.

Figure 7 compares vertical displacement power spectra and bulk wave statistics for the Spotter wave buoys compared to that computed from the Datawell displacement measurements, for the Half Moon Bay tests, where two Spotters were deployed alongside a Datawell. Power spectra for the Spotters and the Datawell are seen to be nearly identical, with discrepancies confined to within the 95% confidence intervals. The wave record used to compute the spectra in the Half Moon Bay test is likely nonstationary, and wave statistics can be expected to evolve over the 10-day measurement period. Therefore, while the spectrum is not representative of realistic wave conditions, it remains a useful means of instrument intercomparison to evaluate signal quality.

Bulk statistics (significant wave height, peak period, mean direction, and directional spread) were computed over 30-min intervals, and are shown in Fig. 7b for the Spotter buoys and the Datawell. As mentioned above, the 10-day duration of the wave record reflects multiple swells arriving from different directions, with different peak periods. The bulk statistics shown in Table 2 therefore reflect nominal values intended to highlight data quality. The Spotter-derived significant wave height was 4.8% lower while the peak period was 2% higher than the Datawell measurement. The mean direction and directional spread were 1.9% higher and 1.8% lower than the Datawell measurement, respectively.

4. Wave characterization enabled by Spotter

The Spotter motion-controlled and field validation results suggest that the newly developed Spotter device can provide deterministic wave data at the quality necessary for computations of wave properties from direct measurements. As a preliminary demonstration, calculations of horizontal decorrelation length scales and propagation speed of surface waves were undertaken using two Spotters over the course of two different field tests: 1) one Spotter deployed in free-drift mode and the other in a moored configuration initially separated by no more than a few meters (referred to as the drift test or drift experiment) and 2) two Spotters moored at various separation distances between 30 and 500 m (referred to as the distance test or distance experiment). Drift and distance tests were conducted over 4-h periods in Half Moon Bay on 16 March 2017 in approximately 40-m-deep water.

a. Drift test

For the drift test, wave measurements on the drifting buoy were compared against those on a fixed mooring, allowing for insights into temporal and spatial decorrelation scales of wave measurements, as the drifting buoy is transported by the mean wind-driven surface current. A series of four drift tests were performed, each approximately 15 min in duration, after which the drifting buoy was relocated adjacent to the moored buoy (within a few meters) and allowed to drift again. Wind speeds during the drift tests were on the order of 2 m s^{-1} and predominantly from a westerly direction. The sea surface conditions during the tests were characterized by a significant wave height of 1.51 m, peak period 10 s, with a mean wave direction of 270° .

During the second of four drifts, the free-drifting buoy drifted almost uniformly over a distance of approximately 120 m over a 12-min period (mean speed $0.16 \,\mathrm{m \, s^{-1}}$). Measured time series of horizontal and vertical displacements show a gradual phase shift and horizontal decorrelation as the free-drifting Spotter was transported away from the moored Spotter (Fig. 8). Also observed in the Spotter data record are the effects of directional spreading that effectively "smears" displacement measurements such that wave heights measured by the free-drifting buoy downstream of the mean wave direction are dampened relative to the moored buoy. Correlation coefficients were computed from the vertical displacement time series using minute-long segments overlapped by 30 s. Figure 9 shows the timevarying correlation coefficient along with the buoy separation distance. Wavelengths spanning the spectral width were calculated using linear wave theory (Hunt 1979), and the decorrelation distance ($\sim 50 \,\mathrm{m}$) was found to be inversely proportional to the width of the spectrum.1

These results enabled by the Spotter's deterministic wave measurements offer insight into wave characteristics that otherwise cannot be determined and provide information necessary for a better understanding of surface wave phenomena. For example, characterization of the shape and slope of the sea surface requires deployment of an array of multiple buoys. The buoys in the array would need to be spaced at distances of less than the decorrelation scale to allow for the coherent processing of wave measurements.

b. Distance test

The goal of the distance test was to infer the wave speed as a function of time, as surface waves propagated from one Spotter to the next. The ability to measure wave speeds is particularly important in applications where the time of arrival of discrete wave packets is important, such as for safety consideration at beaches, revetments, bridges, harbors, piers, and offshore installations; routing traffic through shipping lanes; or wave energy converters that aim to employ control algorithms to increase their efficiency of energy capture.

Wave properties such as wave speed are typically calculated in the spectral domain, which inhibits the calculation of the wave speed of discrete wave packets. A primary practical advantage of spectral calculations is the

¹ A purely monochromatic wave field, that is, a single frequency arriving from a single direction, has an infinite decorrelation scale. Conversely, a wideband field with a flat frequency spectrum (white noise) has a decorrelation scale of zero.

FIG. 8. Time series of displacements when one Spotter is moored (BETA07), and the other freely drifts (BETA06), Half Moon Bay, 16 Mar 2018.

gain in signal-to-noise ratio associated with averaging over longer (\sim 30 min) time segments. Time-domain wave speed computations, by their very nature, do not have the same signal-to-noise-ratio gains as spectral processing, thereby placing more stringent data quality requirements. The ability to perform wave speed calculations in the time domain can therefore be considered another demonstration that lends confidence in data quality when estimates compare favorably with linear wave theory.

The distance test involved deployment of two Spotters that were spaced 100 m apart along the 40-m depth contour over the duration of 1 h. Wave speeds from Spotter measurements were calculated by correlating minute-long segments from the Spotter elevation timeseries record. The time lag associated with the peak in the correlation time series indicates the propagation time of a wave train from one buoy to the next. The mean GPS location during the time segment of interest provided a measure of distance between buoys, allowing for a calculation of wave speed between buoys. Since the water depth (40m) is greater than one-half the wavelength at the peak period (50m), the theoretical wave speeds were computed using the deep water dispersion relation as

$$c_p = \frac{gT}{2\pi} \cos\theta, \qquad (1)$$

where θ is the angle between the mean wave direction and the buoy distance vector and *T* is peak wave period during a time segment of interest.

Figure 10 compares measured wave speeds as wave trains propagate from one buoy to the next over minutelong segments, with theoretical estimates using linear wave theory. Wave speeds computed directly from Spotter measurements are seen to be similar to those computed using linear wave theory [Eq. (1)]. The average measured error in wave speed between the measured and theoretical estimate was found to be 6.5%.

From Fig. 9, it is seen that correlations drop to a value of 0.3 at a 100-m buoy separation. One can therefore expect that at larger buoy separations, the correlation is low enough that wave speed computations using the method described above will significantly diverge from theoretical estimates. Indeed, it was found that a buoy separation of 150 and 300 m resulted in errors of 38% and 75%, respectively. Expectedly, the coherent processing of multiple buoy data to infer wave speeds requires that wave time series across buoys be somewhat correlated.

5. Summary and conclusions

Wave measurements gathered using off-the-shelf GPS and inertial motion units from a wide variety of platforms such as buoys, sailing vessels, and ships have been widely

FIG. 9. Evolution of displacement correlation with buoy separation distance, Half Moon Bay, 16 Mar 2017.

FIG. 10. Comparison of measured wave speed with theoretical predictions, Half Moon Bay, 16 Mar 2017.

documented in recent literature (Joodaki et al. 2013, and references therein). The Spotter represents a low-cost commercial realization of these efforts, with data quality sufficient for scientific needs. Additionally, widespread spatial wave measurements in coastal and open-ocean regions are hindered by the relatively complex logistics of operations, deployment, and maintenance that are associated with COTS wave measurement systems. The ability to hand deploy the Spotter using a small inflatable boat as was utilized during the field tests described can help enable more widespread coastal wave measurements.

An evaluation of the data quality and preliminary scientific results are presented for the Spotter. Results indicate deterministic data fidelity of Spotter measurements compared against controlled motions on a custom-built test stand. Deterministic tests consisted of prescribed two-dimensional orbital displacements, followed by realizations of two-dimensional JONSWAP spectra for fully developed seas. Following successful motion-controlled stand testing, a series of in-water field tests were conducted, where a number of Spotters were deployed alongside a wave measurement system such as the Datawell DWR-G4 and an ADCP.

Spotter measurements were comparable to the Datawell bulk parameters such as significant wave height, peak period, mean direction, and directional spread. In general, Spotter-derived significant wave height is within 10% of Datawell "control" values and peak wave period is derived to within 5% of Datawell's measurements. Mean wave directions and directional spread differences are within 6° and 1°, respectively. The slight differences are expected because of spacing of buoys up to 100m during the Half Moon Bay tests, which lead to statistical variability from directional spreading and small-scale random wave motions. Gemmrich et al. (2016) found that the reduction of random oceanic wave fields to single dominant parameters can yield significant uncertainties, which nevertheless exceed measurement uncertainties. Drazen et al. (2016) showed that the processing of finite-length bursts of wave data can yield significant wave height uncertainties of up to 20%. These studies therefore indicate that in the absence of any systemic biases, measurement intercomparisons within approximately 20% of each other can be reasonably expected when measuring random oceanic wave fields at different locations.

Finally, insights into wave physics such as decorrelation scales and wave speed were gleaned from deployments of two Spotters in free-drifting and moored configurations. Results show a rapid decorrelation with the decorrelation distance related to the spectral width of vertical displacement measurements. Time-domain estimates of wave speeds compared favorably against those predicted by linear wave theory, with errors in wave speed estimates of 6.5% compared to theoretical values. The analyses presented a preliminary examination of the ability to make time-domain calculations of wave decorrelation and speed. More detailed studies, such the ability to track individual crests and coherent processing of array data using beamforming techniques is the subject of a subsequent contribution.

The low cost and ease of deployment of the Spotter facilitates widespread adoption of wave buoy technologies among hitherto unrealized users such as local ports and harbors, island communities, recreational wave enthusiasts, and economically disadvantaged nations. While the Spotter is not specifically designed as a replacement for any single commercial wave measurement device, the technology will enable the adoption of wave buoy arrays to help provide realtime, three-dimensional measurements of the timeevolving sea surface. Applications where measured waves across an array of wave buoys are propagated deterministically across space require accurate timedomain wave speed computations. Further, insight into decorrelation scales provides an estimate of how far in space wave buoy array measurements can be

accurately propagated before the wave field ceases to resemble that measured at the wave buoy.

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APPENDIX

Validation Metrics

Traditionally, measurements using GPS buoys have had limited vertical accuracy to allow for a calculation of wave frequency spectra directly from vertical displacement measurements. Instead, the wave frequency spectrum was calculated using the considerably more accurate measurements of horizontal displacements, by relating horizontal displacements to the vertical using linear wave theory (Herbers et al. 2012). Here, Spotter measurements of vertical displacement are shown to be sufficiently accurate to be transformed into wave frequency spectra. Significant wave heights are computed using the common definition, $H_s \equiv 4E^{1/2}$, where $E = \int_{0.05\text{Hz}}^{0.3\text{Hz}} E(f) df$, the surface elevation variance in the frequency range of wind sea and swell. The peak wave period (T_p) is defined as the period associated with the peak value of the wave frequency spectrum.

Directional moments such as mean wave direction $(\overline{\theta})$ and directional spread (σ_{θ}) are analyzed using standard methods (Longuet-Higgins et al. 1963; National Data Buoy Center 1996) to calculate wave directional moments as a function of frequency. These formulations are reproduced below for completeness. These methods estimate wave directional moments using the lowest four Fourier moments of the wave directional spectrum $S(\theta)$, expressed in terms of the normalized cross-spectra as

$$\begin{pmatrix} a_1 \\ b_1 \\ a_2 \\ b_2 \end{pmatrix} = \int_0^{2\pi} \begin{pmatrix} \cos\theta \\ \sin\theta \\ \cos2\theta \\ \sin2\theta \end{pmatrix} S(\theta) \, d\theta,$$
 (A1)

$$= \begin{vmatrix} Q_{xz}/\sqrt{(E_{xx} + E_{yy})E_{zz}} \\ Q_{yz}/\sqrt{(E_{xx} + E_{yy})E_{zz}} \\ (E_{xx} - E_{yy})/(E_{xx} + E_{yy}) \\ 2C_{xy}/(E_{x}x + E_{yy}) \end{vmatrix},$$
(A2)

where a_1, b_1, a_2 , and b_2 represent the lower four Fourier moments of the wave directional spectrum; E_{xx} , E_{yy} , and E_{zz} represent the displacement autospectra; C_{xy} represents the cospectrum of horizontal displacements; and Q_{xz} , Q_{yz} represent the quadrature spectrum of horizontal and vertical displacements. Estimates of $\overline{\theta}$ and σ_{θ} can be obtained using either firstorder [using a_1 and b_1 in Eq. (A2)] or second-order moments [using a_2 and b_2 in Eq. (A2)]. First-order moments are defined on a full circle and therefore have no directional ambiguity in their estimates. However, directional wave estimates using the first-order moments require the calculation of horizontal and vertical cross-spectra, and necessitate accurate horizontal and vertical displacement measurements. Second-order spectra utilize only horizontal spectral estimates, but are defined on a half circle, and therefore suffer a 180° ambiguity, which can be hard to reconcile in open-ocean applications. Here, first-order moments are utilized to calculate directional parameters for both the Datawell and Spotter measurements. The mean direction and directional spread, expressed using first-order moments, is given by

$$\overline{\theta} = \tan^{-1}(b_1/a_1)$$

$$\sigma_{\theta} = \sqrt{2(1 - \sqrt{a_1^2 + b_1^2})}.$$
(A3)

REFERENCES

- Babarit, A., G. Duclos, and A. Clement, 2004: Comparison of latching control strategies for a heaving wave energy device in random sea. *Appl. Ocean Res.*, 26, 227–238, https://doi.org/ 10.1016/j.apor.2005.05.003.
- Bender, L. C., III, S. D. Howden, D. Dodd, and N. L. Guinasso Jr., 2010: Wave heights during Hurricane Katrina: An evaluation of PPP and PPK measurements of the vertical displacement of the GPS antenna. J. Atmos. Oceanic Technol., 27, 1760–1768, https://doi.org/10.1175/2010JTECHO761.1.
- Benoit, M., P. Frigaard, and H. A. Schäffer, 1997: Analysing multidirectional wave spectra: A tentative classification of available methods. *Proc. Seminar on Multidirectional Waves and their Interaction with Structures*, San Francisco, CA, National Research Council of Canada, 131–158.
- deVries, J. J., J. Waldron, and V. Cunningham, 2003: Field tests of the new Datawell DWR-G GPS wave buoy. *Sea Technol.*, 44 (12), 50–55.

- Donelan, M., A. Babanin, E. Sanina, and D. Chalikov, 2015: A comparison of methods for estimating directional spectra of surface waves. J. Geophys. Res. Oceans, 120, 5040–5053, https://doi.org/10.1002/2015JC010808.
- Drazen, D., C. Merrill, S. Gregory, A. Fullerton, E. Terrill, and T. de Paolo, 2016: Interpretation of in-situ ocean environmental measurements. *Proc. 31st Symp. on Naval Hydrodynamics*, Monterey, CA, Office of Naval Research and Stanford University.
- Electronic Industries Association, 1979: EIA standard RS-274: Interchangeable variable block data format for positioning, contouring, and contouring/positioning numerically controlled machines. Electronic Industries Association Tech. Rep., 30 pp.
- Forristall, G. Z., and K. C. Ewans, 1998: Worldwide measurements of directional wave spreading. J. Atmos. Oceanic Technol., 15, 440–469, https://doi.org/10.1175/1520-0426(1998)015<0440: WMODWS>2.0.CO;2.
- Gemmrich, J., J. Thomson, W. E. Rogers, A. Pleskachevsky, and S. Lehner, 2016: Spatial characteristics of ocean surface waves. *Ocean Dyn.*, 66, 1025–1035, https://doi.org/10.1007/ s10236-016-0967-6.
- Gerling, T. W., 1992: Partitioning sequences and arrays of directional ocean wave spectra into component wave systems. J. Atmos. Oceanic Technol., 9, 444–458, https://doi.org/ 10.1175/1520-0426(1992)009<0444:PSAAOD>2.0.CO;2.
- Hals, J., J. Falnes, and T. Moan, 2011: A comparison of selected strategies for adaptive control of wave energy converters. *J. Offshore Mech. Arct. Eng.*, **133**, 031101, https://doi.org/ 10.1115/1.4002735.
- Hasselmann, K., and Coauthors, 1973: Measurement of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Deutches Hydrographisches Institut Rep., 95 pp.
- Herbers, T. H. C., P. F. Jessen, T. T. Janssen, D. B. Colbert, and J. H. MacMahan, 2012: Observing ocean surface waves with GPS-tracked buoys. J. Atmos. Oceanic Technol., 29, 944–959, https://doi.org/10.1175/JTECH-D-11-00128.1.
- Hunt, J. N., 1979: Direct solution of wave dispersion equation. J. Waterw. Port Coastal Ocean Div., 105, 457–459.
- Iwanaka, Y., T. Kasai, T. Murayama, M. Harigae, I. Yamaguchi, H. Nakanish, H. Suko, and H. Igawa, 2005: Abreast of the waves: Moored-sea sensor to measure height and direction. *GPS World*, Vol. 16, No. 5, 16–27.
- Joodaki, G., H. Nahavandchi, and K. Cheng, 2013: Ocean wave measurement using GPS buoys. J. Geod. Sci., 3, 163–172, https://doi.org/10.2478/jogs-2013-0023.
- Krogstad, H. E., S. F. Barstow, S. E. Assen, and I. Rodriguez, 1999: Some recent developments in wave buoy measurement technology. *Coastal Eng.*, 37, 309–329, https://doi.org/ 10.1016/S0378-3839(99)00031-9.
- Li, G., G. Weiss, M. Mueller, S. Townley, and M. R. Belmont, 2012: Wave energy converter control by wave prediction and

dynamic programming. *Renewable Energy*, **48**, 392–403, https://doi.org/10.1016/j.renene.2012.05.003.

- Longuet-Higgins, M. S., D. E. Cartwright, and N. D. Smith, 1963: Observations of the directional spectrum of sea waves using the motions of a floating buoy. *Ocean Wave Spectra*, Prentice-Hall, 111–136.
- McIntyre, S. A., 2013: Wave and current observations in a tidal inlet using GPS drifter buoys. Ph.D. thesis, Naval Postgraduate School, 99 pp.
- Mitsuyasu, H., F. Tasai, T. Suhara, S. Mizuno, M. Ohkusu, T. Honda, and K. Rikiishi, 1975: Observations of the directional spectrum of ocean waves using a cloverleaf buoy. J. Phys. Oceanogr., 5, 750–760, https://doi.org/10.1175/ 1520-0485(1975)005<0750:OOTDSO>2.0.CO;2.
- Naaijen, P., and R. Huijsmans, 2008: Real time wave forecasting for real time ship motion prediction. *Proc. 26th Int. Offshore Mechanics and Arctic Engineering*, Estoril, Portugal, American Society of Mechanical Engineers, 607–614, https://doi.org/ 10.1115/OMAE2008-57804.
- National Data Buoy Center, 1996: Nondirectional and directional wave data analysis procedures. National Data Buoy Center Tech. Doc. 96-01, 37 pp.
- Pierson, W. J., and L. Moskowitz, 1964: A proposed spectral form for fully developed wind seas based on the similarity theory of S. A. Kitaigorodskii. J. Geophys. Res., 69, 5181–5190, https:// doi.org/10.1029/JZ069i024p05181.
- Ringwood, J. V., 2016: Control optimization and parametric design. Numerical Modelling of Wave Energy Converters: State-of-the-Art Techniques for Single Devices and Arrays, M. Folley, Ed., Elsevier, 229–252.
- Terrill, E., 2012: X-band observations of waves, algorithm development, and validation high resolution wave-airsea interaction DRI. Office of Naval Research Rep., 11 pp.
- —, and T. de Paolo, 2016: Development, testing and quality control of the Scripps Miniature Wave Buoy. *Regional Marine Instrument Centre Coordination Meeting*, Gulfport, MS, Joint Technical Commission for Oceanography and Marine Meteorology.
- Thomson, J., J. B. Girton, R. Jha, and A. Trapani, 2018: Measurements of directional wave spectra and wind stress from a Wave Glider autonomous surface vehicle. J. Atmos. Oceanic Technol., 35, 347–363, https://doi.org/10.1175/ JTECH-D-17-0091.1.
- Wilson, D., G. Bacelli, R. G. Coe, D. L. Bull, O. Abdelkhalik, U. A. Korde, and R. D. Robinett III, 2016: A comparison of WEC control strategies. Sandia National Laboratories Tech. Rep. SAND2016-4293, 98 pp.
- Young, I. R., 1994: On the measurement of directional wave spectra. *Appl. Ocean Res.*, 16, 283–294, https://doi.org/10.1016/ 0141-1187(94)90017-5.