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Directional Spectrum Measurements by the Spotter: a new Developed Wave Buoy

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Directional spectrum measurements by the Spotter: a newly developed wave buoy

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Abstract**—** The Spotter is an accurate, low-cost, easily deployable and robust solar powered wave buoy recently developed by Sofar Tecnologies (formerly Spoondrift). Spotter reduces costs and complexity of surface wave and current measurements, which can be useful for academic, military, and commercial research into surface wave and wave-driven dynamics. We performed a series of validation tests and research experiments with the Spoondrift Spotter.
The low-cost and compact Spotter makes it easy to deploy arrays of wave buoys which was previously not feasible (or cost prohibitive) with traditional wave buoys. A well-designed array can provide a direct measurement of the directional wave spectrum, which is not available from a single buoy measurement. To explore this possibility, we performed a series of experiments, where multiple Spotters were deployed in a variety of configurations. The array allowed for the application of plane-wave beamforming techniques to compute wave directional spectra, which were found to compare well with those obtained by conventional methods.

1. Introduction

There is considerable demand for high fidelity, low-cost wave measurements in coastal and oceanic environments for academic, government, commercial, and recreational purposes. Present-day commercial off-the-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.

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 measurements - measurements that can yield tremendous insight into aspects of wave propagation physics that are often overlooked, or restricted to the purvey 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 [1-3] discussed the limitation of single-point measurements in accurate directional wave estimation, together with the improvements afforded by arrays of three or more instruments ([4]) or instruments with multiple degrees of freedom ([5]). Reference [4] further concluded that while a single tri-axial 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 is often lost due to averaging that is inherent to spectral calculation ([6]) An understanding of phenomena such as wave interference, diffraction and extreme waves require deterministic wave measurements ([7]).

Figure 1. The Spotter wave buoy.

To help address the above limitations, Sofar Technologies, Inc. (formerly Spoondrift), in partnership with Integral Consulting Inc. (Integral) and Sandia National Laboratories, have developed the Spotter (Figure 1), 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.

This contribution describes the Spotter wave buoy, developed in support of adaptive tuning of control systems for wave-powered renewable energy installations ([8]) but with broad applicability to a wide variety of wave measurement markets. This contribution can be considered an extension of [9], which primarily focused on data quality evaluation for the Spotter. This paper is organized as follows: Section 2 describes the validity of Spotter measurements during a series of field tests. Section 3 demonstrates the utility of an array of Spotters in estimating the wave directional spectrum. Finally, Section 4 concludes the paper and describes future improvements and ongoing efforts.

2. Experimental validation

At-sea testing was conducted in Half Moon Bay (California) in March 2018. During these tests multiple Spotters were deployed alongside a Datawell DWR-G (Datawell), the current industry standard GPS wave buoy. Given that the Datawell is an established technology, it is treated as the `control' measurement against which Spotter data quality is evaluated. Described in this section are the experimental configurations for the three field tests followed by results from the field test.

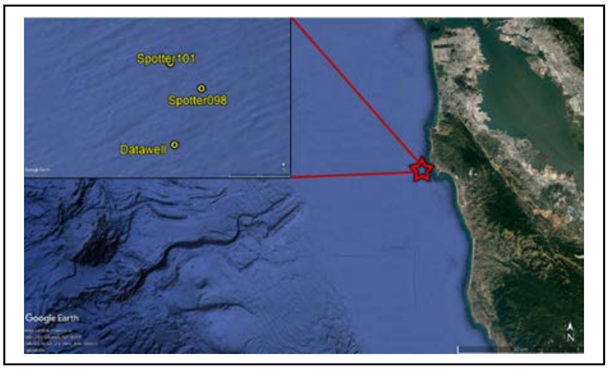

Figure 2. Map of Spotter and Datawell deployment in Half Moon Bay, CA.

Two Spotters and a Datawell were deployed in Half Moon Bay, California, offshore of Pillar Point (Figure 2), between March 12 and March 30, 2018. The Spotters deployed in this test belonged to the first commercial version of the buoys, and sampled at 2.5 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 spring time 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 due to snagging of the mooring line by a vessel, occured on March 23. Therefore, data from the two Spotters and Datawell are analyzed for intercomparison between March 12-22, 2018, with the Datawell representing the control measurement.

Vertical power spectra and bulk statistics are computed over the time period March 12-22, 2018. Bulk statistics (significant wave height, peak period, mean direction and directional spread) were computed over 30 minute intervals which results in a total of 72 spectral samples used in the spectral computations.

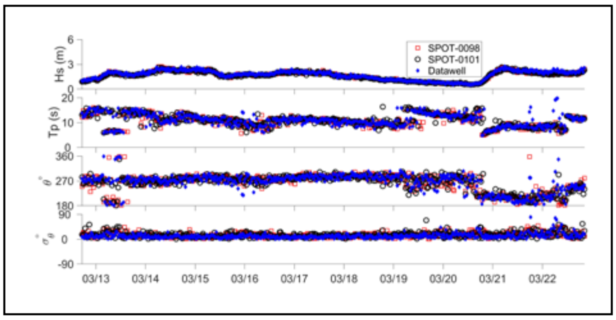

Figure 3. Comparison of significant wave height (top), peak period (second from top), peak direction (third from top) and directional spread (bottom) for two Spotter wave buoys and a Datawell, deployed in Half Moon Bay, CA, in March 2018

Bulk statistics (significant wave height, peak period, mean direction and directional spread) were computed over 30 minute intervals, and shown in Figure 3 for the Spotter buoys and the Datawell. Consistency between various buoy measurements is seen, lending confidence to computations of bulk statistics by the numerous buoys. The 10-day duration of the wave record reflects multiple swells arriving from different directions, with different peak periods. The Spotter-derived significant wave height was 4.8% lower than that measured by the Datawell 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.

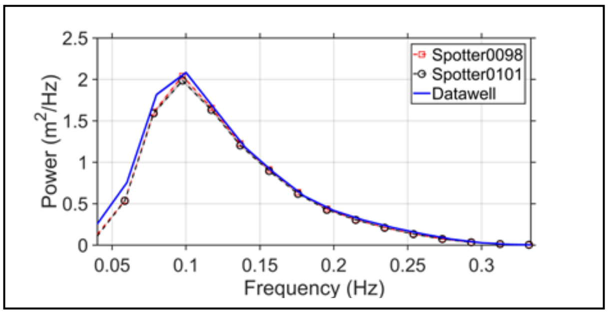

Figure 4. Comparison of Spotter bulk statistics to that measured by a Datawell DWR-G4 in Half Moon Bay, CA in March 2018.

Figure 4 compares vertical displacement power spectra for the Spotter wave buoys compared to that computed from the Datawell displacement measurements. 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 34,000 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).

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 non-stationary, and wave statistics can be expected to evolve over the ten-day measurement period. Therefore, while the spectrum is not representative of realistic wave conditions, it remains a useful means of instrument inter-comparison to evaluate signal quality.

3. Plane Wave Beamforming of Three-Buoy Array

The directional wave spectrum provides an estimate of the angular distribution of wave energy. This quantity is typically computed using the lower Fourier moments of the wave directional spectrum, calculated using standard methods such as those found in [10] and [11]. A fundamental limitation of this method is that it attempts to make estimates of the wave directional spectrum using single point measurements. The resulting estimates of the directional spreading function has been found to be higher than that obtained using spatially diverse wave measurements ([4]).

The availability of simultaneous wave measurements from a three-element array of wave buoys allows for the application of coherent array processing techniques ([12]) to estimate the wave directional spectrum. The basic principle of directional estimation using an array measurement is illustrated in Fig. 5. Here, a plane wave impinges upon a linear array of sensors. For a given angle of incidence, the signal received on each channel of the array is offset by a wavenumber-dependant phase relative to that received on neighbouring elements.

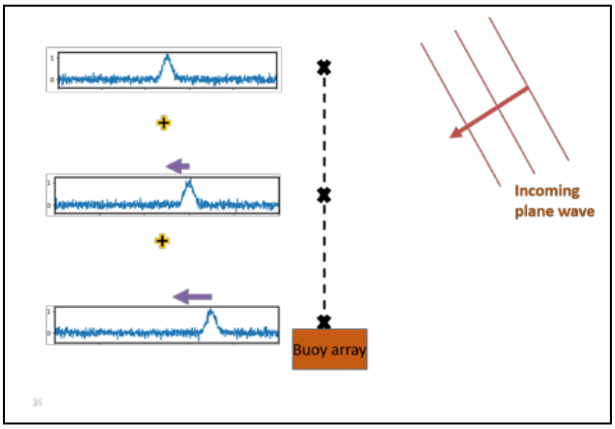

Figure 5. Schematic of beamforming principle. Displacement measurements across the array are delayed and summed, where the delay is representative of the angle of arrival of an incoming plane wave.

Plane-wave beamforming [13] acts by phase-shifting the signal on each channel, followed by coherently summing over the array. The larger the number of array channels, the greater the array gain, and better the suppression of incoherent random noise, while reinforcing a coherent signal. A wave buoy makes three measurements on each sensor (velocity or displacement on three axes). The coherent delay-and-sum approach when applied to tri-axial displacement measurements across the wave buoys array is shown to lead to directional wave spectra that is comparable to that obtained using traditional techniques.

The technique for bearing estimation calculation involves segmenting the time series into discrete one second-long segments. 1024-point Fast Fourier Transforms (FFTs) are computed on each 1 s data segment, and plane-wave beamforming applied in the frequency domain following the methods outlined by [13]. This method yields wave angles of arrival for each time segment, estimates of which are then averaged across the wave record to obtain the directional spectrum.

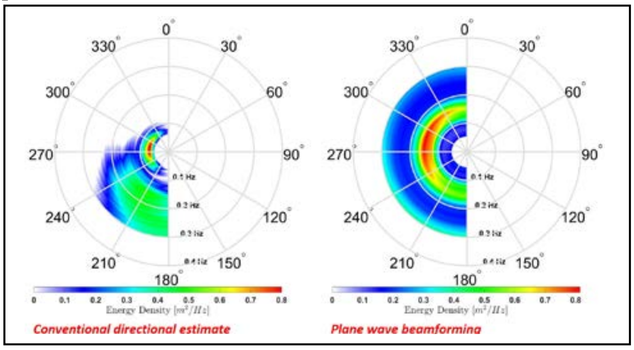

Figure 6. Comparison of directional spectra obtained using conventional maximum likelihood techniques (left) and plane-wave beamforming (right).

Figure 6 shows the wave directional spectra obtained using conventional directional estimation techniques and that obtained using plane-wave beamforming. The peak angle of arrival of the impinging swell is seen to be identical in both cases (approximately 270º), but the directional distribution around this angle is seem to be considerably broader than that obtained using conventional techniques. This is likely a function of array spacing, resulting in sidelobe contamination of the beamforming estimate. Closer spacing of the array elements is likely to remove these sidelobes.

4. Conclusion

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 documented in recent literature ([14]) 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. 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^o and 1^o, respectively. The slight differences are expected due to spacing of buoys up to 100 m during the Half Moon Bay tests which leads to statistical variability from directional spreading and small-scale random wave motions.

Finally, the low-cost and ease of deployment of the Spotter allowed for the application of coherent array processing to determine the directional spectrum of the incoming wave field. These techniques, typically found in fields such as sonar and radar signal processing, offer the possibility of highly refined wave directional estimates. Further evaluation of the potential of these techniques is ongoing, particularly with regard to appropriate spacing of array elements to resolve a wide range of wavelengths.

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