Report on wave measurements using the Sailbuoy Wave

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Instrument: the Sailbuoy

The Sailbuoy (Figure 1) is an unmanned surface vehicle (USV) manufactured by the Norwegian company Offshore Sensing AS (http://www.sailbuoy.no). It navigates autonomously and uses wind power for propulsion. Data communication and control are in real-time, including data relay, established using the Iridium satellite. The system and operation are user friendly and require limited user input. The Sailbuoy is not dependent on solar power for navigation, which is a great advantage for use in high latitudes. The Sailbuoy is specifically designed for use in Norwegian waters (e.g. North Sea, Barents Sea), for robustness with the ability to survive and operate in very rough environmental conditions (wind, waves, temperature). Sailbuoy is not logistically demanding; it can be easily deployed and retrieved by untrained personnel from light vessels. The physical dimensions are 2 m length, 60 kg displacement and a payload of 15 kg (60 l). It can be fitted with various sensors to be used for a wide variety of ocean applications including near-surface temperature, salinity and oxygen concentration monitoring, and wave measurements. This report summarizes results from a recent deployment of the Offshore Sensing Sailbuoy using a wave sensor, dubbed the Sailbuoy Wave.

The Sailbuoy has proven its endurance and navigation capability through various missions including a transects from Bergen, Norway to Iceland, Bergen to Scotland, a mission north of Svalbard close to the Marginal Ice Zone, and surveys in the northern Gulf of Mexico and off Grand Canaria. For a report on the navigation capability and efficacy we refer to Fer and Peddie (2012), for a report on near-surface temperature, salinity and oxygen concentration measurements see Fer and Peddie (2013), for an application in the northern Gulf of Mexico see Ghani et al. (2014).

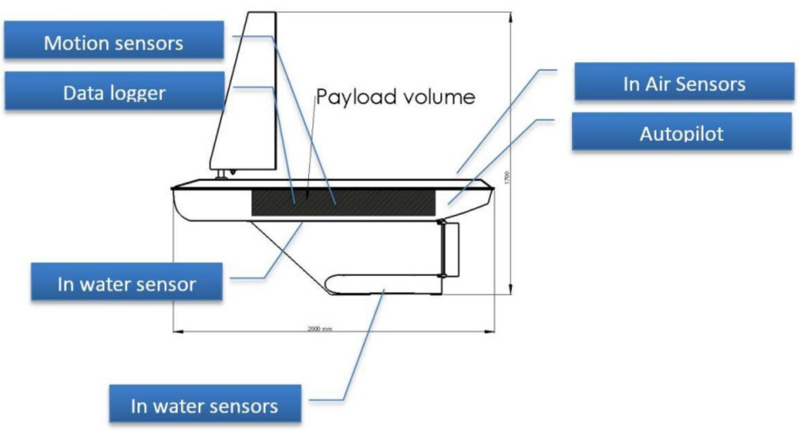

Figure 1. Sketch of the Sailbuoy with major components highlighted.

Deployment

The Offshore Sensing Sailbuoy Wave (SB Wave hereafter) was deployed during the cruise of the research vessel *Håkon Mosby* (cruise number HM2015 623, University of Bergen, Norway), on 30 October 2015, 18:00 UTC, at N56° 32' along the track of the vessel toward the FINO1 platform in the North Sea. On November 2, the SB Wave was inspected when the vessel was returning to Norway. The SB Wave was observed to behave well and was left to continue her mission to the Ekofisk oil field. Ekofisk is in block 2/4 of the Norwegian sector of the North Sea about 320 km southwest of Stavanger.

The SB Wave was equipped with the Datawell MOSE-G1000 wave sensor. This is a 3-dimensional motion sensor based on single GPS and measures the translational motion of the GPS antenna in 3 frequency or period regimes each with its own precision: high frequency motion (1-100 s periods, 1 cm precision), low frequency motion (10-1000 s periods, several cm precision), and GPS position (infinitely long periods, 10 m precision). An indoor version of the sensor was installed in the payload section of the Sailbuoy, and the external GPS antenna was integrated at the rear part of the buoy (Fig 1). The antenna is free from obstructions and is elevated above the deck to mitigate potential signal loss due to wave wash over the Sailbuoy. For details on the MOSE-G1000 we refer to the manufacturer's reference manual (see http://datawell.nl).

After a couple of trial sections and performance testing, the Sailbuoy was directed to the way point WP1 to keep station and conduct wave measurements. On 14 November, the Sailbuoy was directed to WP2, closer to a nearby bottom-anchored conventional wave buoy (Waverider). The position and measurement periods are summarized in Table 1. The mission is shown together with WP and Waverider positions in Figure 3. The Sailbuoy was recovered on 20 November 2015.

Figure 2. Picture taken on 2 November 2015 showing the SW Wave. The wave sensor's GPS antenna is marked by an arrow.

Table 1. Measurement positions and duration.

	Position (Latitude ; Longitude)	Measurement Period (2015, UTC)
WP1	56° 45.0000′ N ; 3° 9.0000′ E	7 November 0000– 14 November 1000
WP2	56° 38.1194′ N ; 3° 11.9346′ E	14 November 1200– 20 November 0930
Waverider	56° 32.9187′ N ; 3° 6.2286′ E	Entire mission

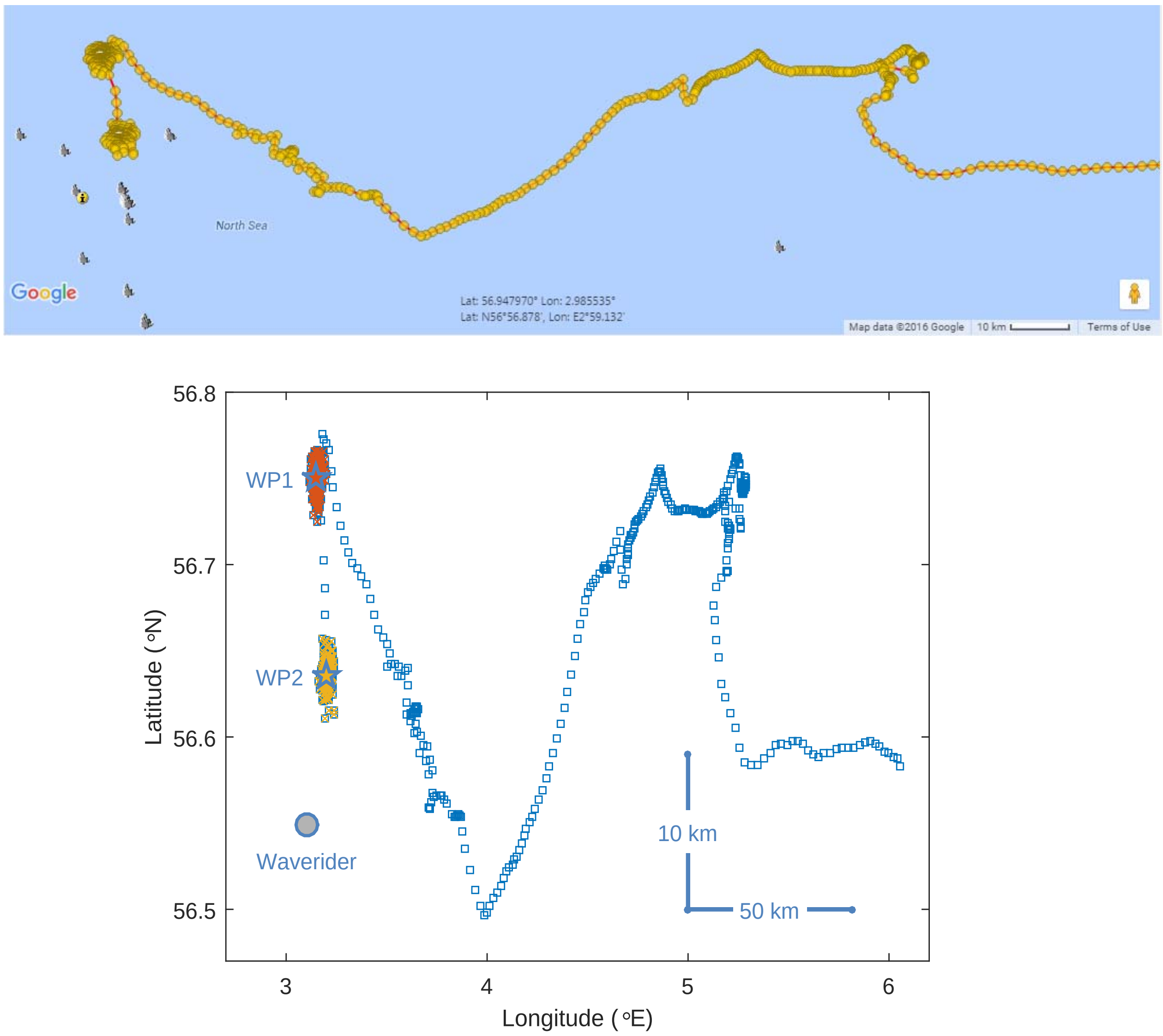

Figure 3. Map showing the mission of SB Wave together with the waypoints WP1 and WP2 and station keeping around them. The bullet marks the position of the Waverider buoy, approximately 10 km south of WP2.

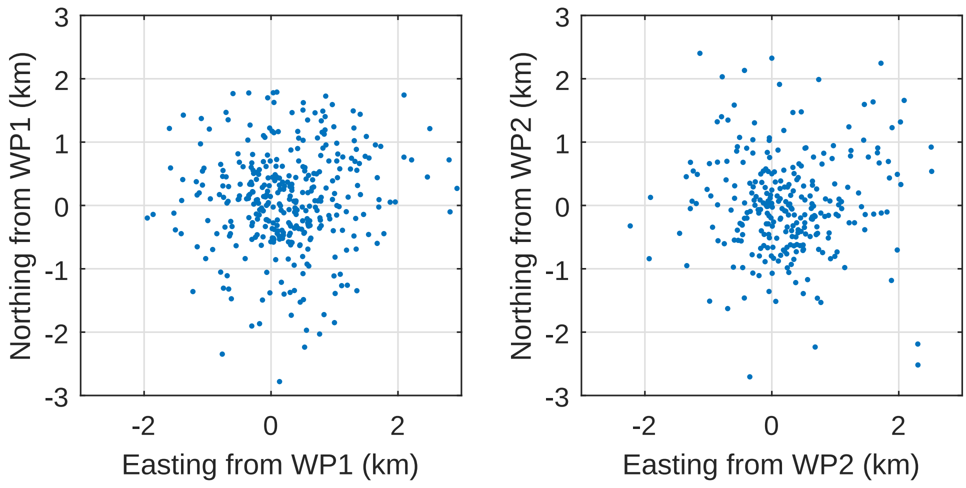

Figure 4. Distance from the waypoints, WP1 and WP2.

The Sailbuoy was successful in station keeping and maintained a position within ±2 km of the WPs (Figure 4).

Data acquisition details

The MOSE-G1000 sensor was set to sample at 2 Hz. The internal logging included the high-frequency (HF) string comprising of the horizontal and vertical displacements and a data quality flag. Furthermore, every 10 s the position, together with horizontal dilution of precision (HDOP) and vertical dilution of precision (VDOP), were logged. The sensor was initialized by power (82 mA), and a new data file was written every 30 minutes, logging data for 25 minutes (3000 data points). The sensor was left on continuously, thanks to the short duration of the experiment. Only between 2 November 1500 UTC and 5 November 1400 UTC the sensor was deliberately turned off when the buoy was in transit. It is trivial to assign a duty cycle, for example, whereby the sensor is powered on and off, sampling 20 minutes data at desired intervals (1 hour, 3 hours etc.). While the entire raw data field was logged internally, the data were also transferred to the Sailbuoy for data reduction and relay of wave parameters via satellite. The first 125 data points (of 3000; approximately 1 minute) were excluded to avoid a possible contamination by filter effects or file book-keeping.

There are, therefore, two data sets: 1) full resolution, raw sensor data for post processing using various methods to infer wave parameters, and 2) twice-hourly real-time relayed data including time, position and key wave parameters inferred onboard from a zero-crossing analysis of typically 2875 data points.

Measurements: satellite relay

The internal processing of 2875 data points every 30 minutes follows the following steps:

i) detect individual waves using zero crossing of the vertical displacement record (retain every second zero crossing to define a complete wave- this is loosely referred to as the number of zero crossings),
ii) calculate wave height and wave period for each individual wave
iii) sort the wave heights (book-keeping the corresponding periods),
iv) calculate the significant wave height (H_s, average of the largest 1/3rd sorted wave heights) and the maximum wave height (H_{max}), and
v) calculate mean zero-crossing period (T_0, mean period of all the waves in the record), and the significant period (T_s, average period of the waves used to define H_s).

In addition to these parameters, the total number of data points, the number of bad data points (quality flag bad from the sensor) and a sensor on/off flag are sent. Figure 5 shows the internally processed data (no cleaning or filtering is applied) including the significant and maximum wave height and zero-crossing period and the significant period. The durations of the WP1 and WP2 stations are indicated. The measurement period covers from quiescent periods with H_s on the order 1 m, as well as energetic periods with H_s exceeding 5 m with maximum waves in excess of 10 m.

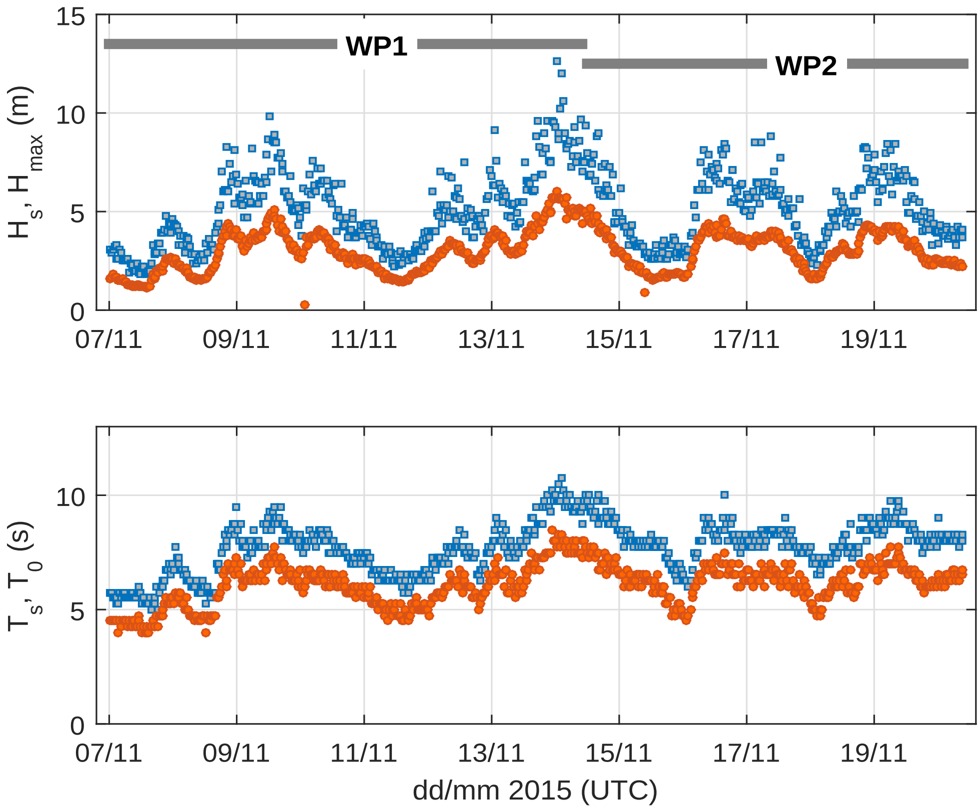

Figure 5. Time series of wave parameters relayed by Iridium; internal processed using the zero-crossing method.

The data return is very good, despite the large waves. In each segment, there are approximately between 200 and 300 zero crossings (individual waves). When H_s is less than approximately 3 m, there are no erroneous data points. Such bad data are expected, for example, when seawater covers the GPS antenna, which may happen at high seas. Even when the maximum wave height is about 10 m, the number of bad data returns is on the order 100, that is less than 3% of the segment length. This small amount of data loss has negligible (unquantified) influence on the resulting wave parameter estimates.

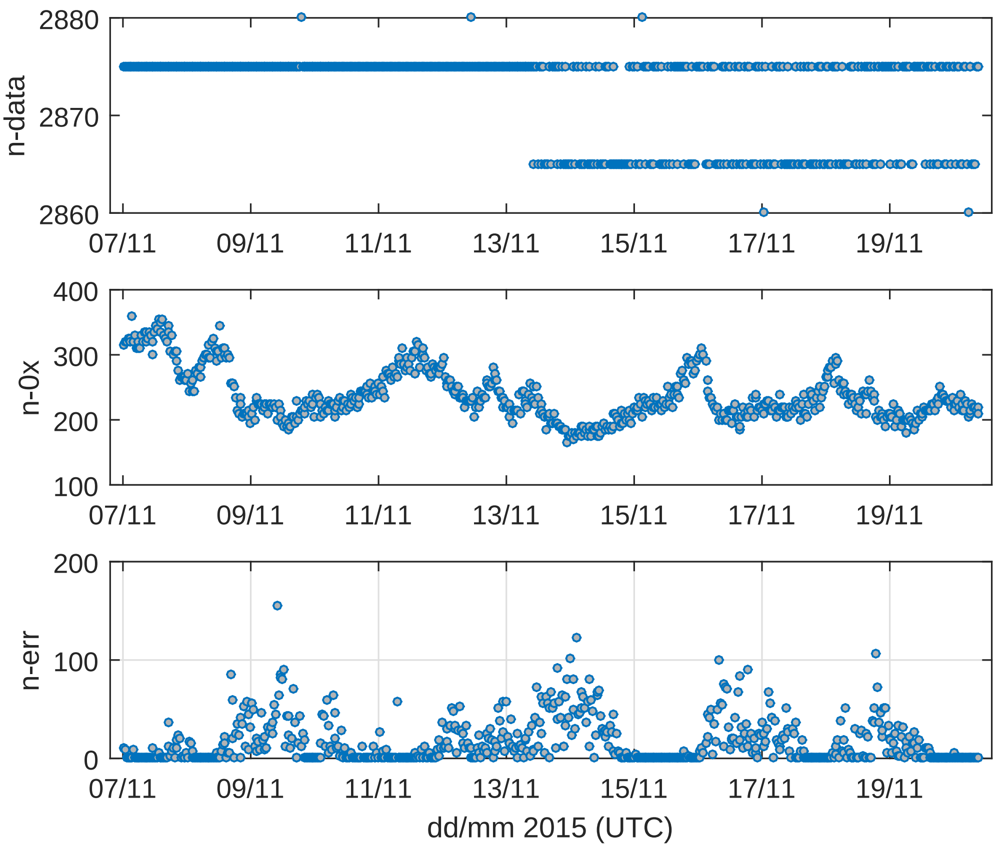

Figure 6. Time series of number of data points (n-data), number of zero crossings (n-0x), and number of bad data points (n-err) for each 24-min record analyzed internally by the Sailbuoy. The panels cover the same period as in Figure 5.

Measurements: post-processed raw data

Raw data downloaded from the instrument are further analyzed for more accurate estimates of the wave parameters, using spectral analysis. Spectral analysis results are compared to internally-processed zero-crossing results to show-case the accuracy of the real time data relayed by the Sailbuoy.

The spectral analysis of the 2-Hz sampled horizontal and vertical displacement data is made using the DIWASP toolbox (Directional Wave Spetra Toolbox, v1.4 for Matlab). The direct Fourier Transform Method (DFTM) is used with a frequency resolution of 0.01 Hz in the range 0.05 to 1 Hz, and a direction resolution of 2°. From the analysis, the significant wave height, H_s, peak period, T_p, direction of spectral peak, D_{Tp} and the dominant direction, D_p are extracted.

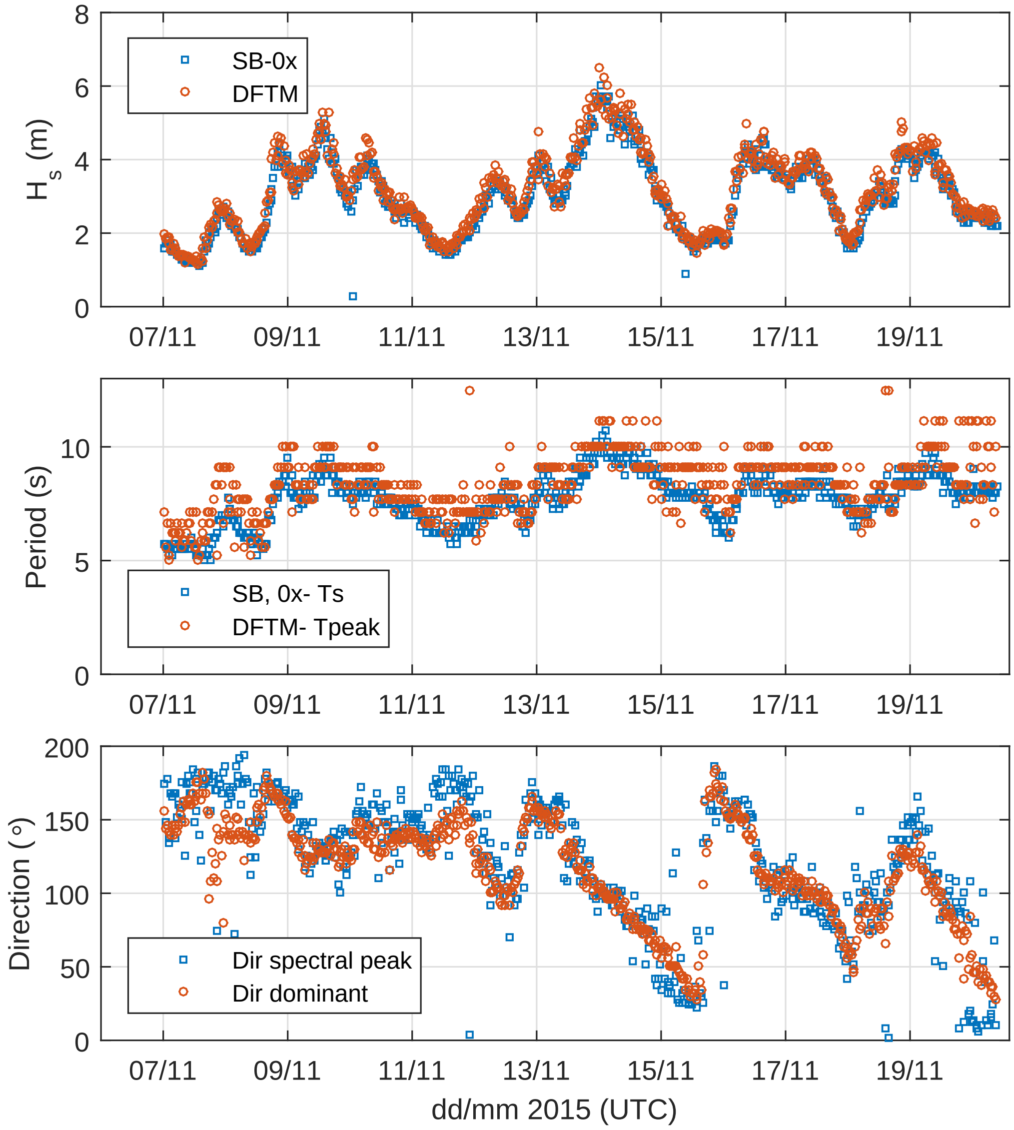

Figure 7. Results from the post-processing of the raw data using DFTM compared to the wave parameter estimated from internal processing using the zero-crossing method.

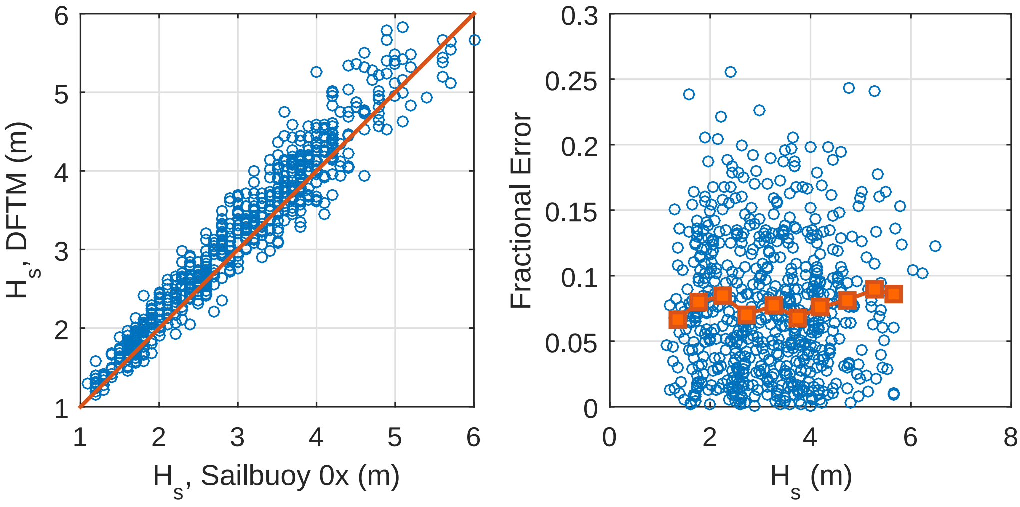

Figure 8. (left) Scatter plot of significant wave height inferred from post processing (DFTM) and internal processing (zero crossing, Sailbuoy 0x). A perfect agreement would lie on the red line. (right) Fractional absolute error (when DFTM estimate is true) as a function of H_s. Also shown are the average errors averaged in 0.5-m wide H_s bins (red).

A detailed comparison of significant wave height values inferred from the spectral analysis and the internal processing using the zero crossing method is shown in Figure 8. The agreement is very good, lending confidence on the real-time values relayed by the Sailbuoy. One would expect increased error for increasing H_s, for example, because of increased number of bad data points or failure to detect individual waves by the zero-crossing method. However, the fractional error, averaged in H_s bins do not show a significant trend.

Comparison to Waverider measurements

The independent wave measurements obtained for the Waverider instruments located nearby give ground-truth for the wave measurements conducted by the Sailbuoy. Sailbuoy WP1 is approximately 20 km away from the Waverider position whereas WP2 is at 10 km. The following is a detailed comparison between the two data sets. Figure 9 shows the time series of H_s measured by the two instruments. To quantify various measures of agreement, the Waverider measurements are first interpolated to the Sailbuoy time stamps, giving 634 measurement points. The scatter plot of the resulting Hs data is given in Figure 10. Apart from a few outliers, the agreement is typically within ±0.5 m, with scatter slightly increasing with increasing wave heights.

Linear correlation coefficient is 0.97 (r^2 = 0.94). When analyzed separately, measurements from WP1 and WP2, respectively 20 km ad 10 km from the Waverider, give results statistically identical with r = 0.97 and r = 0.96, respectively. See Table 2 for a detailed comparison.

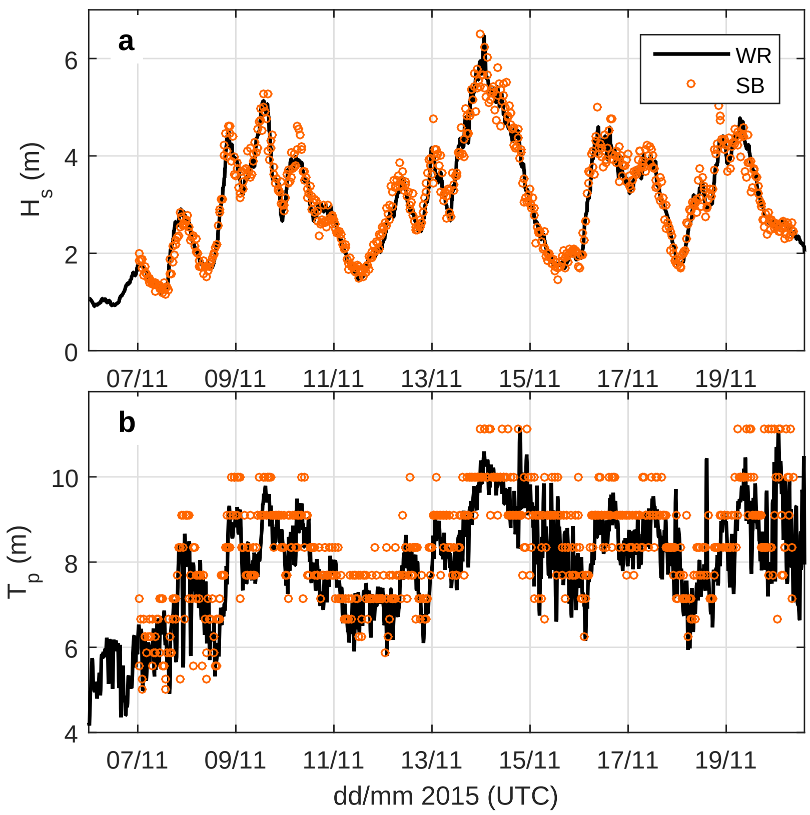

Figure 9. Times series of H_s and peak period, T_p, comparison of the Waverider data (black) and the Sailbuoy data (red).

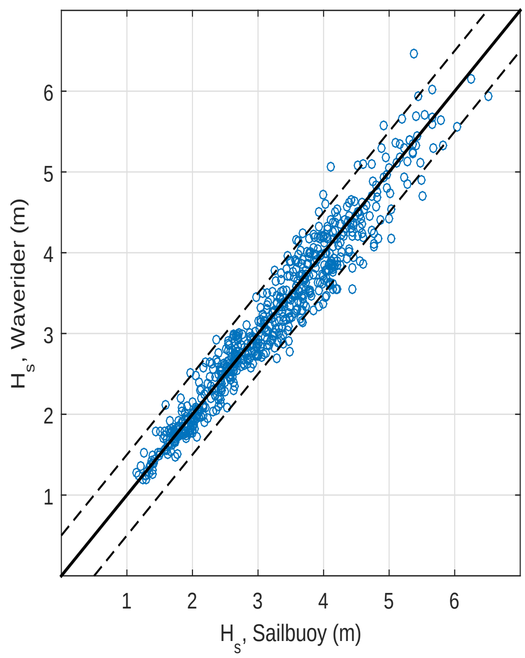

Figure 10. Scatter plot of H_s measured by the Sailbuoy and the Waverider. The diagonals show excellent (solid) agreement and agreement to within ±0.5 m (dashed).

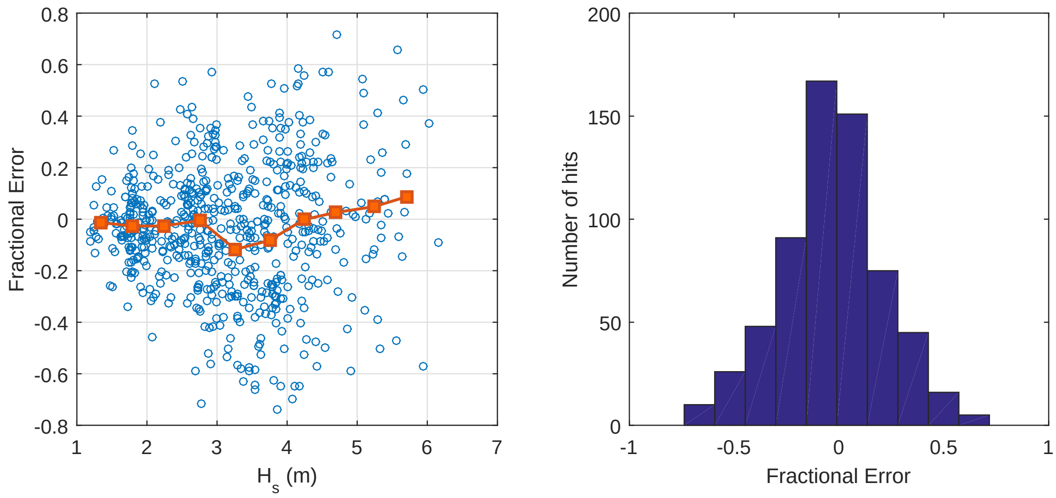

Figure 11. Fractional (signed) error relative to the Waverider measurements, and its histogram. The red data points in the left panel are the error averaged in 0.5-m wide H_s bins.

A detailed analysis of the two time series is made as follows. We define the deviation between the two time series as $d = x_1 - x_2$ where index 1 refers to the Waverider H_s (assumed the "true" value) and index 2 to H_s measured by the Sailbuoy. Normalized deviation is $d_n = d/x_1$, whereas absolute deviation is $|d|$. The following statistical parameters are calculated:

Mean signed difference (= bias)	:	MSD = $\langle d \rangle$
Mean absolute error	:	MAE = $\langle \|d\|. \rangle$
Mean percent error	:	MPE = $\langle d_n \rangle \times 100$
Mean percent absolute error	:	MPAE = $\langle \|d_n\| \rangle \times 100$
Root-mean-square error	:	RMSE=$\langle d^2 \rangle^{1/2}$

where $\langle . \rangle$ indicates mean over the samples. The results are summarized in Table 2.

Table 2. Overview of the statistical parameters on comparison of Waveride and Sailbouy H_s measurements. Here n is the number of samples and r is the correlation coefficient.

Subset	*n*	*r*	MSD (m)	MAE (m)	RMSE (m)	MPE (%)	MPAE (%)
All	634	0.97	-0.03	0.19	0.25	-1.2	6.2
WP1	353	0.98	-0.04	0.20	0.25	-1.4	6.5
WP2	277	0.96	-0.02	0.18	0.24	-0.8	5.8

Summary and Conclusion

A data set was collected between 7 and 20 November 2015, near the Ekofisk oil field in the North Sea. For sensor intercomparison and data validation, the measurement position was co-located (10 to 20 km) with a bottom-anchored Waverider buoy. The measurement period covers from quiescent periods with significant wave height (H_s) on the order 1 m to energetic periods with H_s reaching 6 m with maximum wave heights in excess of 10 m. The peak period of the wave spectrum was approximately 5 s for the H_s on the order 1 m, and 10-12 s for H_s exceeding 5 m.

The Sailbuoy delivered two data sets: i) twice-hourly real-time relayed wave parameters processed on board using a zero-crossing analysis, ii) full resolution, raw sensor data for post processing using spectral methods to infer wave parameters. First, the two data sets are analysed and compared to showcase the accuracy of the real time data relayed by the Sailbuoy. The agreement is very good with a fractional error less than 10%, and without a significant trend when binned in H_s. Next, the wave measurements from the Sailbuoy are compared with the Waverider measurements. The agreement between the two data sets is excellent with a linear correlation coefficient of 0.97, a bias of 3 cm, a root-mean squared error of 25 cm, and a mean percent absolute error of 6%. We conclude that the Sailbuoy is a suitable platform for wave measurements delivering reliable real time data as well as accurate post-processed data.

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