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Short communication

# Note on wave parameters from moored wave buoys

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#### Abstract

For decades, the accelerometer wave buoy has been a preferred choice for offshore wave measurements. Although these measurements are accurate and robust, there are some issues of practical character that need to be inspected before using such measurements for detailed timeseries investigations. Here three potential sources of inaccuracies are outlined which can appear due to improper mooring, limited high-frequency resolution or overly simple procedures for attaching measurement times (time stamps) to the measurements. The last two of these apply to all types of single-point wave-measuring devices.

An example of a wave-height series is given, in which part of the observed variation seems to be induced by the mooring. It is argued that unexpected semi-tidal modulations in measured wave-height can be an indication of a mooring that is too rigid. By truncating observed wave spectra from a deep-water location, it is demonstrated how the high-frequency cut-off limit of a wave measurement influences the most commonly used wave parameters. It is observed that the accuracy of common wave parameters remains acceptable up to a cut-off limit in the range of 0.30–0.35 Hz if the spectra above the cut-off frequency are replaced by a prognostic  $f^{-5}$  tail. Finally it is noted that the procedure of connecting time stamps to wave measurements can in some cases introduce an artificial time-lag compared to the real-time sea state. © 2008 Elsevier Ltd. All rights reserved.

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## 1. Introduction

There are many different methods used to measure local wave characteristics, but the moored accelerometer buoy seems to be one of the most popular choices worldwide [30]. One good property of this measuring technique is that it measures the actual surface movement and does not imply any theoretical approximations in order to transform particle or pressure fluctuations, measured at some elevation in the water column, into wave movement at the surface. Another strength of this method is that the sea surface is always well defined, even in rough conditions where sea spray or air bubbles can compromise the accuracy of e.g. acoustic surface tracking devices [30].

In the literature single-point wave measurements are either labeled Lagrangian (particle following) or Eulerian (fixed to one location in space). The main difference is that a Lagrangian device, such as a buoy, measures the orbital periods and heights of the passing waves whereas an Eulerian device measures the spatial profile of the waves as they pass a fixed point. The first measurement type has a clear link between a measured orbital period and a single frequency in the wave spectrum, whereas the second one distributes some energy from the same wave into higher harmonics if the wave is steep [13,25]. The spatial asymmetry of the waves, often referred to in the literature as non-linearity of the waves, is not as well resolved in Lagrangian measurements [15,17,24] as in Eulerian measurements. Usually there is also a need to filter out low-frequency components of Lagrangian data [25]. The effects of the Lagrangian path on wave parameters can be reduced by analytical methods [16] but the influence on integral wave parameters, such as mean wave period and wave-height, is negligible [17]. Another concern is that the mooring might steer the buoy around the peaks of high short-crested waves and thus artificially reduce the measured heights of single waves [1].

Overall it can be said that the moored buoy is an ideal robust measuring device to measure the linear characteristics of the passing waves [12,13], whereas the non-linear characteristics of the waves are not as well represented [6,15,24,30].

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Fig. 1. Location of the wave buoys on the Faroese Shelf. Vertical and horizontal axes give longitude and latitude relative to north and east, respectively. Background colors indicate bottom depth in m.

Here we will mention three issues of more practical character that can be important in detailed investigations of waveparameter series derived from an accelerometer wave buoy.

The first issue is the possible influence from the buoy mooring on the measurements; the second issue is the effect of the limitation of high-frequency resolution on wave parameters, and the third issue relates to the association of time stamps to the wave measurements.

#### 2. Mooring influence

Wave buoys, can in principle, be operated with a wide range of different moorings, but experience has shown that some mooring types are to be preferred [3]. A description of how a recommended mooring influences wave measurements is given by Joosten [12,13], which emphasizes sufficient elasticity in the mooring, especially for directional measurements.

The main factors that are important in determining the mooring setup are depth, current and buoy size [3]; but in some cases, the largest expected wave-height may also play a role [11]. However, circumstances like ship traffic, fishery, limited deployment facilities and financial restrictions etc., may result in deviations from the recommended mooring type.

The mooring can influence the measured waves either by the buoy being dragged through crests or dodging around them [1]. This artificial effect of the mooring on the measurements is hard to quantify. The mooring-induced error can take the form of crest clipping, and in severe cases, full submersion of the buoy. Even if wave clipping has occurred on such a scale that averaged wave parameters are affected, it is still very hard to recognize this problem directly from the measurements. In extreme cases, the mooring constraint can result in flat spots in real-time data coverage, if the buoy and its antenna are fully submerged. If the data communication is not affected, or if the measurements are only stored onboard and transmitted later, no flat spots will be present in the data and the detection of the submersion problem is not straightforward. In such cases, one intuitive way to inspect the data is to investigate the possibility of a systematic undershoot in some wave parameter in situations where the mooring is most likely to induce crest clipping or full buoy submersion. The influence from an improper mooring is expected to be most evident in heavy seas, high tides or when the currents are strong. If possible, the buoy measurements can be validated against some other wave measurements, without the same mooring issues, in the vicinity of the buoy site [22], or to a modeled hindcast for the area [2,20].

Operational wave measurements have been conducted at offshore locations around the Faroe Islands since 1979 [4]. The original setup consisted of four non-directional Waverider buoys, labeled WV-1 (East), WV-2 (West), WV-3 (North) and WV-4 (South), see Fig. 1 and Table 1. These buoys have for most of this period been operated by the Office of Public Works in the Faroe Islands. The original deployment to the south of the islands (WV-4) was abandoned in 1988, but a cooperation of oil companies has been operating a directional Waverider slightly east of the original position (WVD-4) since 1999 [9,10].

In a resent study of all available waverider data from the Faroese shelf, we concluded that the operational wave measurement program, contained measurements influenced by the moorings [22]. One side effect of the improper mooring was that an apparently artificial semi-tidal variation was observed in the measured wave-height time-series. One example is given in Fig. 2. In the first plot of Fig. 2 the measured wave-height (solid line) is seen to have mainly semi-diurnal variation (12.4-hour period) until the 15th, after which a quarter-diurnal variation (6.2-hour period) seems to be superimposed on the semidiurnal variation, creating twin-peaked maxima. Comparing the variations seen in the wave-height against the modeled depth averaged current at this location (Fig. 2), it is observed that the wave-height is largest close to slack-currents times and has local minima near peak currents. When looking at waveheights predicted by a state-of-the-art wave model (Fig. 2 top), including the effect of non-stationary currents, it is seen that

Table 1
Information related to the wave measurements and the tidal current at the deployment sites

Buoy Id	Position (Lat Long)	Depth (m)	Duration	M2 (m/s) major/minor	M4 (m/s) major/minor	Max (m/s)	Compliant material
WV-1	61°48'N, 6°13'W	100	1980-	0.400/0.126	0.009/0.006	1.0	None
WV-2	61°52'N, 7°32'W	130	1981-	0.311/0.240	0.006/0.002	0.7	None
WV-3	62°30'N, 6°50'W	100	1979–	0.509/0.172	0.009/0.002	1.2	None
WV-4	61°13'N, 6°29'W	130	1979-1988	0.677/0.329	0.032/0.001	1.4	None
WVD-4	61°18'N, 6°17'W	240	1999–	0.330/0.037	_/_	0.6	Rubber cord

The information related to the buoys is taken from [8]. All estimates of the tidal constituents M2 and M4 and maximum measured current strength are from [7], except for the WVD-4 site where the tidal information is based on a numerical model [28].



Fig. 2. First plot: measured and modeled wave-height at WV-1 in September 2000. Second plot: measured and modeled wave period. Third plot: absolute current strength derived from [28]. Last plot: directions (degrees clockwise from north) of tidal current, wind and waves.

this model captures neither the semi-diurnal nor quarter-diurnal variations observed at this location, in spite of the fact that this model could recreate most of the current influence observed simultaneously at WVD-4 [21].

The physics behind this quarter-diurnal or semi-tidal variation are thought to be as follows. During maximum current, which usually occurs twice during the period of the M2 tidal cycle, the drag forces on the mooring system are increased, inflicting less buoyancy and higher risk of wave clipping than is the case in slack currents. A mooring without sufficient flexibility can therefore lead to a semi-tidal period variation

(half of the M2 period) in the measured wave-height where the recorded wave-height is reduced in strong currents.

The arguments that wave clipping did occur at these sites, and that the semi-tidal variation in  $H_{m0}$  was not due to wave current interactions, are given below.

- The original mooring setup used on the Faroese shelf included rubber cords [4] but, due to operational difficulties, the mooring was later simplified and deployed without any compliant material [8]. The use of a rubber cord is stressed by the manufacturer [3,12,13] so some degree of mooring influence on the measurements must be expected when the mooring deviates from the recommended arrangement.
- Comparison of time-series and statistics measured from wave buoys on the Faroese shelf, deployed with the simplified mooring, against satellite data and long-term hindcasts for the area, indicates that the recorded waveheight is clipped in severe storms [2].
- According to linear wave theory [18] wave-height variations are expected due to local currents, but the magnitude of this variation observed with buoys utilizing simplified moorings are at times too large to be explained by wave-current interaction alone [22].
- The presence of a higher-harmonic or semi-tidal variation in the recorded wave-height is unexpected according to linear wave theory [22,27] and cannot be a direct effect, as the size of the higher-harmonic tidal component (M4) is negligible at these sites compared to the dominant tidal constituent (M2) at these sites (Table 1).
- This semi-tidal variation occurs due to reduced measured wave-height when the currents are strong (Fig. 2), which indicates that the mooring might restrict the buoy movement.
- The semi-tidal variation is only observed at sites where the simplified mooring has been used (WV-1 and WV-3), and is not observed at WVD-4 where a 30-meter rubber cord is used in the mooring design.
- In a recent high resolution wave hindcast for the Faroese shelf [21], the influence of the tidal currents on the waveheight at WVD-4 was well resolved by the model, but at the same time the model could not recreate the size of the semidiurnal  $H_{m0}$  variation observed at WV-1; nor the quarterdiurnal variation observed in the measurements (Fig. 2 top).

It must, nevertheless, be noted, in respect to the semi-tidal variation, that this variation is only observable in some periods at the sites using the simplified mooring. It seems as if small variations in the mooring setup and the deployment position (water depth) between different deployments at the same site determine whether the quarter-diurnal variation is present or not in the measured wave series. In those deployments where the quarter-diurnal variation is present, the variation is not continuously observable, but tends to be clearer in steady sea conditions of low wave-height (e.g. Fig. 2).

It must also be noted that the quarter-diurnal variation is never observed at WV-2 in spite of the fact that the simplified mooring is used at this site. This apparent contradiction can to a certain degree be explained by the argument stated above, namely, that it is the variation in the tidal current strength, and not direction of the current that induces the semi-tidal variation in the wave-height. At the deployment sites the semi-diurnal tidal constituent M2 is dominant, and the variation in current strength in shorter time spans is therefore usually dominated by the semi-diurnal contribution, which varies according to the length of the major and minor axes of the M2 ellipse. From Table 1 it can be seen that the semi-diurnal ellipse is much more circular at WV-2 than the semi-diurnal ellipses at the other locations. It should therefore be expected that the level of wave clipping occurring at WV-2 would not have the same clear quarter-diurnal pattern seen at the other locations. Another important factor, which can explain why the quarter-diurnal variation is missing at WV-2, is that the currents are not as strong at WV-2 compared to the other sites using the simplified mooring (Table 1).

A similar example is reported in data from the Sylt-Rømø Bigth [26,27], where an unanticipated semi-tidal variation was found in the measured wave-height series, that was not captured by a wave model covering the area. In this case the deployment was also located in an area with strong currents, and the measurements were made by a floater (small wave buoy).

As mentioned previously the semi-diurnal M2 tidal constituent is dominant at all the deployment sites but, due to the artificial effect of the mooring, the quarter-diurnal M4 constituent, which otherwise is negligible at the site (Table 1), becomes important in the power spectra of the significant waveheight (Fig. 3). If such semi-tidal components are found to be overrepresented in the spectra of the wave-height series from some other site, this could then indicate that there might be a mooring influence on the measured data.

No similar quarter-diurnal influence is obvious in power spectra or time-series of measured peak wave period  $T_p$ , and the quarter-diurnal variation in  $T_{m02}$  is, if present, usually not as clear as the corresponding variation in  $H_{m0}$  [22]. The fact that the wave-height was the wave parameter most affected by the overly restrictive mooring is in accordance with the expectations of Wolf and Prandle [31].

To summarize, an overly restrictive mooring will, in locations with moderate-to-strong currents that are oscillating in strength (have oval tidal ellipse), most likely induce the following characteristics:

 wave-height modulations frequently occur with half the period of the dominant tidal component in the area. A fast test is to check the power spectra of the time-series for semitidal peaks.



Fig. 3. Power spectrum of the entire wave-height series measured east of the Faroe Islands in the year 2002. The peaks at 6.2 and 12.4 hours correspond to the tidal constituents M4 and M2, respectively (see Table 1).

- Less pronounced semi-tidal variation in wave periods.
- When the semi-tidal variations occur in the wave-height, the maximum recorded wave-height will be observed close to slack currents, while the lowest wave-height will be observed when the currents are strong.

Finding sequences in a long time-series, where the influence of the semi-tidal period is significant, can be done using a wavelet procedure similar to the one suggested by Torrence and Compo [29]. As wavelet analyses are scale-dependent and  $H_{m0}$  variations generally are largest over longer periods, the clearest results are therefore obtained if the  $H_{m0}$  series is de-trended before applying the wavelet procedures.

Above we have only mentioned that a restrictive mooring might increase the level of wave clipping. Another effect that a mooring might have on wave measurements is given in [19], where an unexpected low-frequency peak appears in the recorded wave spectrum. Here it is argued that highspeed currents can cause large horizontal displacements and tilting of the buoys, and as the buoys try to adjust to their initial horizontal orientation, this additional acceleration may be misinterpreted as a change in wave-height.

#### 3. Limited high-frequency resolution

The dimensions and the measuring apparatus of a wave buoy invoke a high-frequency limitation on what the buoy can accurately measure. For this reason, the measured wave spectrum will only contain frequencies up to a systemdependent upper frequency limit  $f_{\text{high}}$ . The missing highfrequency information of the measured wave spectrum above  $f_{\text{high}}$  could be recreated to some extent by adding a prognostic  $f^{-5}$  tail before integrated wave parameters are calculated. This prognostic  $f^{-5}$  tail is usually a valid assumption for the higher frequencies as these typically are in equilibrium with the forcing wind speed [23]. Such padding procedures are nevertheless not default in most systems, so wave parameters



Fig. 4. Averaged spectra from WVD-4 (solid line) and equivalent Pierson–Moskowitz spectra (dashed line) and JONSWAP type spectra (dot-dashed line).

are usually calculated from a wave spectrum with missing highfrequency information. Wave parameters such as  $H_{m0}$  and  $T_p$ are not sensitive to the upper tail of the wave spectrum, but there are other widely used wave parameters such as average wave periods which, by definition, are more sensitive to the energy content in the higher frequencies [30].

In order to represent the frequencies above the model resolution most operational wave models add  $f^{-5}$  tails to the spectra, before computing integrated wave parameters. Comparing results from wave models to buoy data must therefore be done with care, as the buoy's high-frequency limit,  $f_{\text{high}}$ , might affect the validated parameters [14]. If modeled spectra are available, the artificial impact of the missing high-frequency spectral tail in the measured wave parameters can be counteracted by using modeled wave parameters that are calculated with the same high-frequency limit as that of the buoy [5].

In order to understand the effect of the high-frequency limit on different wave parameters, wave data from a Waverider located south of the Faroe Islands (WVD-4 in Fig. 1 and Table 1) were investigated. From this site a time-series of measured wave spectra, spanning from 10/2-1999 to 13/2-2004, were available. After removal of measurement errors and outliers 17,196 wave spectra were available. This directional Waverider is located in deep water (Table 1) and the distance to land is some 20 km. The buoy site is relatively unsheltered (Fig. 1) and the weather climate is generally quite windy. At this site the average sea state is clearly influenced by swells, as can be seen from the amount of low-frequency energy in the averaged spectrum in Fig. 4.

In the following, all available data from this site are used to quantify how different values of  $f_{high}$  affect different wave parameters. The statistics from these investigations can, to some extent, serve as an indicator of the  $f_{high}$ -dependence in wave parameters from buoys located in different settings. It should, nevertheless, be expected that buoy wave data from deep-water sites with milder wind and wave climate, or sites more influenced by fetch limitations, will have a different Table 2

Wave-parameter statistics from the deep-water buoy south of the Faroe Islands (WVD-4)

	Mean	Std	Max	Min
$H_{m0}$ (m)	2.90	1.48	14.11	0.48
$T_p$ (s)	10.59	2.51	22.22	3.33
$T_{m-10}$ (s)	8.59	1.77	17.12	3.71
$T_{m01}$ (s)	7.34	1.61	15.57	2.80
$T_{m02}$ (s)	6.44	1.45	14.17	2.43

Std gives the standard deviation of the parameter value, max the largest recorded value and min the smallest recorded value.

dependence of  $f_{high}$  than the trend observed here, as such sites are expected to have a proportionally larger part of their average energy content in the higher frequencies than the present site.

Many wave parameters are derived from moments of the wave spectrum. Given a wave spectrum where E(f) gives the variance density at frequency f, the spectral moment  $m_n$  is given as:

$$m_n = \int_0^\infty f^n E(f) \mathrm{d}f, \quad n = -1, 0, 1, 2....$$

The parameters that will be inspected here are  $H_{m0}$ ,  $T_{m-10}$ ,  $T_{m01}$  and  $T_{m02}$ . The definitions of these parameters are:

$$H_{m0} = 4\sqrt{m_0}, \qquad T_{m-10} = \frac{m_{-1}}{m_0},$$
  
 $T_{m01} = \frac{m_0}{m_1} \quad \text{and} \quad T_{m02} = \sqrt{\frac{m_0}{m_2}}.$ 

Statistical information related to the values of these wave parameters and  $T_p$ , derived from the individual 17,196 wave spectra recorded at WVD-4, are given in Table 2.

The Waverider used for these investigations has a high-frequency limit of  $f_{\text{high}} = 0.58$  Hz. And an  $f^{-5}$  tail is padded to the measured spectra above  $f_{\text{high}}$  in order to recreate the 'true' wave spectra. That is, we have assumed that

$$E(f) = E(f_{\text{high}}) \frac{f_{\text{high}}^5}{f^5}, \text{ for } f > f_{\text{high}}$$

Let us assume that we have a set of *N* wave parameters labeled *x*, derived from the complete wave spectrum (that is  $f^{-5}$  prognostic tail added above 0.58 Hz) and *N* parameters labeled *y*, derived from wave spectra with some high-frequency limit (that is, no energy above  $f_{\text{high}}$ ). The relation between these two time-series is in the following given by the mean difference, also known as bias:

Bias 
$$=$$
  $\frac{1}{N} \sum_{i=1}^{N} (y_i - x_i) = \overline{y} - \overline{x}$ 

where  $\overline{x}$  and  $\overline{y}$  represent the mean values of the two series, and the scatter index or normalized root-mean-square error:

$$ScI = \frac{1}{\overline{x}} \sqrt{\frac{\sum_{i=1}^{N} (y_i - x_i)^2}{N}}$$

Table 3

Statistics of wave parameters calculated from spectra with different high-frequency limits, compared with the wave parameters calculated from the complete wave spectra

		Cut-off frequency f <sub>high</sub> (Hz)										
		0.58	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15	0.10
$H_{m0}$ (m)	Bi	0.00	-0.01	-0.01	-0.01	-0.02	-0.03	-0.05	-0.09	-0.17	-0.39	-1.16
	Sc	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.03	0.07	0.15	0.44
$T_{m-10}$ (s)	Bi	0.03	0.04	0.06	0.08	0.12	0.17	0.26	0.42	0.72	1.39	3.49
	Sc	0.00	0.01	0.01	0.01	0.02	0.03	0.04	0.06	0.10	0.18	0.44
<i>T<sub>m01</sub></i> (s)	Bi	0.13	0.15	0.20	0.26	0.35	0.47	0.64	0.92	1.37	2.24	4.50
	Sc	0.02	0.02	0.03	0.04	0.05	0.07	0.10	0.14	0.20	0.32	0.64
$T_{m02}$ (s)	Bi	0.30	0.34	0.43	0.53	0.66	0.84	1.08	1.43	1.98	2.96	5.31
	Sc	0.05	0.06	0.07	0.09	0.11	0.14	0.18	0.24	0.32	0.48	0.85

Bi is bias and Sc is scatter index.

Statistics from comparison of wave parameters derived from the full wave spectrum to parameters derived from wave spectra with different values of  $f_{high}$  are given in Table 3.

It is clear that the effect of the missing high-frequency tail on wave-height is insignificant for all reasonable values of  $f_{\text{high}}$ , while the influence on the different mean wave periods is more pronounced, especially  $T_{m02}$ .

Let us say that we can accept a measured wave parameter series where the bias induced by  $f_{high}$  on the parameter is less than 5%. When we compare Tables 2 and 3, it becomes apparent that the  $H_{m0}$  and  $T_{m-10}$  measurements at this site would be acceptable with  $f_{high} = 0.25$  Hz, while  $T_{m01}$  and  $T_{m02}$  would require a  $f_{high} = 0.40$  Hz and  $f_{high} = 0.58$  Hz, respectively.

As mentioned previously it is possible to add a prognostic  $f^{-5}$  tail to a measured wave spectrum that has a high-frequency limit  $f_{\text{high}}$ . This procedure is, of course, not generally applicable for all frequencies of the wave spectra, as the lower frequencies do not follow the equilibrium  $f^{-5}$  tail suggested by Phillips [23].

In order to understand how suitable it is to apply the prognostic  $f^{-5}$  tail, we compared parameters derived from spectra, where the frequencies above  $f_{high}$  were substituted by an  $f^{-5}$ -tail, compared against wave parameters derived from the original full spectrum. These results are given in Table 4.

From Table 4 it is clear that too low a cut-off frequency,  $f_{\rm high}$ , combined with a prognostic  $f^{-5}$  tail, results in underestimation of the energy in the high-frequency part of the spectrum, as this induces negative bias in wave-height and positive bias in the wave periods. By comparing the levels of bias and scatter index in Tables 3 and 4, it is clear that addition of the prognostic tail makes it possible to have a relatively low cut-off frequency,  $f_{\rm high}$ , while maintaining the same level of measurement accuracy as a measurement made with high  $f_{\rm high}$  and no prognostic tail. This effect is clearest in  $T_{m02}$  where the addition of the prognostic tail enables measurements with  $f_{\rm high}$  between 0.30–0.35 Hz to have the same level of accuracy as measurements made with  $f_{\rm high} = 0.58$  Hz and no prognostic tail.

Here we have looked at the influence of the missing high frequencies in an area that, on average, is swell-dominated. The influence of the cut-off frequency on different wave parameters is dependent upon the shape of the given spectrum. As a test of how the average sea state at this location corresponds to known spectral types, all the measured spectra at WVD-4 were combined to generate one average spectrum (Fig. 4). The energy content of this spectrum was then used to generate a equivalent Pierson-Moskowitz spectra and a JONSWAP type spectra (Fig. 4). For instance if we look at artificial bias introduced by  $f_{\text{high}} = 0.58$  Hz onto the  $T_{m02}$  value of the averaged spectrum, it corresponds to some 4%, whereas the artificial error introduced by  $f_{high}$  is in the range of 2%-3% in the equivalent Pierson-Moskowitz and JONSWAP spectra. At a first glance one might expect that the effect of a cut-off frequency was less pronounced in a swell-dominated spectrum compared to a wind-sea spectrum, but due to the  $f^2$  term in the second momentum, the influence of  $f_{high}$  on  $T_{m02}$  is in fact larger when applied on the average spectrum compared to the other equivalent spectra. This therefore indicates that the statistics in Tables 3 and 4 are representative only for buoy deployments in similar settings, which are deep-water and swell-dominated.

In a recent wave model validation study [21] the model seemed to give quite different  $T_{m02}$  wave period biases when compared to wave buoy data from the area. After some inspection (derivation of Table 3) it was concluded that this difference was not caused by the model, but was rather an artifact due to not taking into account the different  $f_{high}$  values of the individual buoys.

#### 4. Time stamps

In order to determine the sea state from a point wave recorder, e.g. a wave buoy, it is necessary to record and analyze a time segment of some length. This time segment or data burst can have various lengths depending upon the operational setup preferred by the operator.

The sample length influences the level of random variation of wave parameters, with more random variation from a sample containing fewer waves. In Tucker and Pitt [30] it is estimated that a 1024 s sample length of a representative sea state gives rise to random variations of 5%–6% in  $H_{m0}$ , whereas a sample of three time this length would have approximately 2%–3% random variation. In order to measure wave parameters with constant-level of random variations, some buoy systems can be set up to measure a fixed number of waves. The drawback Table 4

Statistics of wave parameters calculated from spectra with padded  $f^{-5}$  above a high-frequency limit  $f_{high}$ , compared with the wave parameters calculated from the original wave spectra

		Cut-off frequency $f_{high}$ (Hz)										
		0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15	0.10	
$H_{m0}$ (m)	Bi	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.02	-0.05	-0.14	-0.60	
	Sc	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.07	0.25	
$T_{m-10}$ (s)	Bi	0.00	0.00	0.01	0.02	0.04	0.07	0.13	0.26	0.55	1.64	
	Sc	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.05	0.09	0.24	
$T_{m01}$ (s)	Bi	-0.01	0.00	0.03	0.07	0.12	0.19	0.31	0.52	0.93	2.09	
	Sc	0.01	0.01	0.01	0.02	0.03	0.04	0.06	0.10	0.16	0.33	
$T_{m02}$ (s)	Bi	-0.03	0.00	0.05	0.12	0.20	0.31	0.49	0.76	1.23	2.40	
	Sc	0.02	0.02	0.03	0.04	0.05	0.07	0.10	0.15	0.23	0.41	

Bi is bias and Sc is scatter index.

of this type of measurements is the potentially large variation in sample length and storage rates (time interval between consecutive measurements).

Because wave parameters from a point measurement cannot be measured in real time, as they are based on a preceding measured data sample, it can be important to know the setup of the time tags (point in time connected to each measurement by the buoy). Some systems set the time tag equal to the completion time of the preceding data burst, but the optimal choice of time tag, seen from the perspective of detailed comparison to real-time wave-parameter variations, would be to use the midpoint time of the preceding data burst.

One relevant example is given in Fig. 5, where a measurement setup with sample lengths fixed to 1024 zerocrossing waves is used. This setup resulted in storage sequences and sample lengths ranging from two to six hours. In Fig. 5 a measured  $H_{1/3}$  series (dashed line) is compared to hindcasted  $H_{m0}$  values (solid line) [21]. The vertical bars correspond to the start and end times of the individual recorded wave sample series but, as argued above, the mean time of each data sample is used to generate the curve. From the figure it is clear that the lag between model and reality would be artificially reduced if the start time stamp (left corners of the vertical bars) were used instead of the midpoint times. In Fig. 5 it can be seen that the sample length varies with the sea state, being longer in heavy seas. The reason for the extremely long sample lengths after the peak of the storm is partly due to a swell-dominated sea state (long wave periods), but this is also caused by decreased data coverage in this period. Data coverage is here used to describe how much of the recorded wave-field is transmitted correctly to land. If data coverage is low it takes correspondingly longer time before the required number of zeros-crossing waves are recorded.

If the sample length is small, which is usually the case, the precise definition of the time stamps is not an important issue; but for long sample lengths this can, as exemplified in Fig. 5, introduce an unwanted time delay in measured wave data compared to their real-time values. Another drawback of long data samples is that the underlying assumption of a stationary sea state during the recording interval is not fulfilled in periods with fast wave development. One such example is seen in Fig. 5



Fig. 5. Predicted  $H_{m0}$  wave-height from a numerical model (full line) and measured  $H_{1/3}$  wave-height (dashed line) at WVD-4, spanning from 0:00 hours on the 7th of September to 0:00 hours on the 9th of September 2000. Horizontal lines give the duration of the underlying data samples.

after the peak of the storm, where the wave-height is reduced by almost 2 m during one of the sample intervals.

Using long sample intervals that do not overlap imposes a reduction in the time resolution of the wave parameter timeseries, and the resulting uneven storing rates can complicate subsequent parameter analysis somewhat.

### 5. Conclusion

It is argued that unexplainable semi-tidal modulations observed in measured wave-height by an accelerometer wave buoy can be an indication of a too restrictive mooring.

Investigations of wave spectra from a deep-water wave buoy are investigated in order to exemplify the effect of the highfrequency cut-off on different wave parameters. It is seen that the wave-height is quite robust with respect to the highfrequency cut-off, whereas mean wave periods are much more dependent upon the higher frequencies. If it is possible to add a prognostic  $f^{-5}$  tail to the measured wave spectrum, the dependency of the mean wave periods upon the high-frequency cut-off is significantly reduced. Point wave measurements require a measured time-series (data burst) of some length in order to produce reliable estimates of the sea state. Therefore the time stamps connected to a point wave measurement do, in some cases, need to be compensated for the length of the data burst in order to eliminate artificial time delays introduced into the measured wave parameters compared to the real-time sea state.

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#### References

- Allender J, Audunson T, Barstow SF, Bjerken S, Krogstad HE, Steinbakke P, et al. The wadic project — A comprehensive fieldevaluation of directional wave instrumentation. Ocean Engineering 1989; 16:505–36.
- [2] Ceccacci A, Cardone VJ. AES40 North Atlantic hindcast vs. Faroe Islands buoys comparative analysis. 2001. Cos Cob, CT, USA, Oceanweather Inc.
- [3] Datawell. Datawell Waverider Reference Manual. 1-137. 2006. Datawell BV Labratory for Instrumentation.
- [4] Davidsen E, Hansen B. The Faroese wave-measuring and currentmeasuring project. Coastal Engineering 1981;5:111–23.
- [5] Dykes JD, Hsu LH, Rogers WE. SWAN evaluation in the Northern Gulf of Mexico. In: 7'th international workshop on wave hindcasting and forecasting. 2003.
- [6] Forristall GZ. Wave crest distributions: Observations and second-order theory. Journal of Physical Oceanography 2000;30:1931–43.
- [7] Hansen B, Larsen KMH. Traditional current meter observations in Faroese offshore waters 1977–1994. Torshavn, Faroe Islands, Fiskiransóknarstovan. 1999.
- [8] Heinesen SP. Faroese wave measurements A review of methods and use since early 1970'ies. 2001. Sp/f Data Quality.
- [9] Heinesen SP. GEM Faroewave Q/A, Quality assurance of faroese wave data 1979–2000. 1-77. 2001. Sp/f Data Quality.

- [10] Heinesen SP. FOIB Southwv project final data Q/A report, Data Period 10'th February 1999-18'th February 2004. 1-27. 2004. Sp/f Data Quality.
- [11] Humphery JD. Operational experiences with waverider buoys and their moorings. 145. Institute of Oceanographic Sciences. 1982.
- [12] Joosten HP. Directional wave buoys and their elastic mooring. International Ocean Systems 2006;10(4).
- [13] Joosten HP. Wave buoys and their elastic mooring. International Ocean Systems 2006;10(3).
- [14] Laing AK. An introduction to ocean waves. Guide to wave analysis and forecasting. World Meteorological Organization 1998;1–14.
- [15] Longuet-Higgins MS. Eulerian and Lagrangian aspects of surface-waves. Journal of Fluid Mechanics 1986;173:683–707.
- [16] Magnusson AK, Donelan MA, Drennan WM. On estimating extremes in an evolving wave field. Coastal Engineering 1999;36:147–63.
- [17] Magnusson AK, Nidermayer A, Jenkins AD, Nieto-Borge JC. Extreme wave statistics from time-series data. WP2, 1-6. 8-10-2003. In: Proceedings of MAXWAVE final meeting. 8-10-2003.
- [18] Mei CC. The applied dynamics of ocean surface waves. Singapore: World Scientific Publishing; 1989.
- [19] Moghimi S, Gayer G, Gunther H, Shafieefar M. Application of third generation shallow water wave models in a tidal environment. Ocean Dynamics 2005;55:10–27.
- [20] Niclasen B, Simonsen K. Validation of ECMWF analysis wave data for the area around the Faroe Islands. Societas Scientiarum Færoensis; 2007.
- [21] Niclasen BA. An operational wave model for the Faroe Shelf. 1-127. Ph.D. thesis. University of the Faroe Islands; 2006.
- [22] Niclasen BA, Simonsen K. Inspection of possible mooring related problems in wave data from the shelf of Faroe Islands. 2005:04. 2005. Torshavn, University of the Faroe Islands. NVDrit.
- [23] Phillips OM. The equilibrium range in the spectrum of wind-generated waves. Journal of Fluid Mechanics 1958;4:426–33.
- [24] Prevosto M, Krogstad HE, Robin A. Probability distributions for maximum wave and crest heights. Coastal Engineering 2000;40:329–60.
- [25] Rademakers PJ. Waverider wavestaff comparison. Ocean Engineering 1993;20:187–93.
- [26] Schneggenburger C. Spectral wave modelling with nonlinear dissipation. 1-117. Ph.D. thesis. University of Hamburg; 1998.
- [27] Schneggenburger C, Gunther H, Rosenthal W. Spectral wave modelling with non-linear dissipation: Validation and applications in a coastal tidal environment. Coastal Engineering 2000;41:201–35.
- [28] Simonsen K. Tides and tidal simulation in the area around the Faroe Islands. 166. 1999. Bergen, Nansen Environmental and Remote Sensing Center.
- [29] Torrence C, Compo GP. A practical guide to wavelet analysis. Bulletin of the American Meteorological Society 1998;79:61–78.
- [30] Tucker MJ, Pitt EG. Waves in ocean engineering. Elsevier Science; 2001.
- [31] Wolf J, Prandle D. Some observations of wave-current interaction. Coastal Engineering 1999;37:471–85.