Evaluation of Wave Measurements with an Acoustic Doppler Current Profiler

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Abstract- **Routine monitoring of waves and currents in the nearshore region is of great interest both scientifically and to the general public because of its role in coastline erosion and its impact on recreational activities.**

Historically, the technology for measuring these quantities has required separate instrumentation for each, but within the last year or two, it has been shown that it is possible in shallow water to estimate both the wave height, wave direction, and current from a conventional bottom mounted, upward-looking Acoustic Doppler Current Profiler (ADCP).

Software for converting wave orbital velocity measurements from ADCPs into wave frequency and directional spectra is now becoming commercially available. We have taken the opportunity to evaluate the WAVES software from RD Instruments, USA, by establishing an intercomparison between wave measurements obtained with a permanently deployed 1200 kHz ADCP, an electromagnetic current meter/pressure sensor and a heave/pitch/roll buoy.

We have compared the wave surface elevation and frequency-direction spectra derived from the different measurement/analyze principles and we have analyzed the inherent software limitations due to the measurement principles.

I. INTRODUCTION

DHI Water & Environment (DHI) has a long ranging experience in measuring waves for many applications. The study of multidirectional waves in the open sea and in coastal regions has been the key activity at the Institute since its foundation, whether the objective is an assessment of environmental impact, establishing accurate design criteria for offshore structures or port safety and efficiency.

Besides serving as a direct source of information, the wave measurements are extensively used for calibration and verification of numerical models, which subsequently are used to derive long-term and extreme values for use in design. In this respect, directional wave information is crucial because everything that responds to waves behaves differently in directional waves than in long-crested seas.

Renewed interest in high quality data on crest heights and associated kinematics inspired by seabed subsidence and the appearance of extreme events has focused on improved sensor techniques and monitoring programs.

Traditionally directional wave information has been provided by either an array of bottom mounted pressure gauges or surface mounted directional wave buoys. Both options have serious limitations and are often constrained by complicated and expensive moorings in confined waterways.

Over the years, the possibility of measuring waves from a single bottom-mounted ADCP has been considered. Lately the major manufacturers of these systems have launched software that makes it possible to obtain wave information by studying time series of along beam wave orbital velocities. Height spectrum is calculated by translating velocity spectrum to surface displacement using linear wave theory. Wave direction is estimated from phased differences between the beams.

DHI has taken the opportunity to evaluate the quality of directional wave information obtained by a standard 1200 kHz Workhorse ADCP manufactured by RD Instruments, San Diego, USA. The quality is assessed by comparison to a traditional directional wave gauge sensor based on pressure/velocity measurements and a non-directional surface wave buoy.

II. STANDARD OF COMPARISON

Our standard of comparison was directional wave information provided by analysis of pressure and velocity data recorded with an S4 electromagnetic current meter manufactured by Inter Ocean. Data are processed using DHI Directional Wave Analyses software package (DIWA) which has been especially designed for three-dimensional analysis of wave data acquired by the S4.

The DIWA software processes data recorded in burst mode. Data are retrieved from the S4 current meter using the application software supplied with the instrument.

For many years the S4 in combination with the DIWA software package has served as the key instrument in measuring coastal waves. The quality of the processed data is verified on several occasions and has formed the standard for DHI's wave measurements. We are confident that the directional wave data recorded with an S4 are of a quality that legitimates the use of the data as reference.

III. FIELD MEASUREMENTS

A. *Interocean S4A Electromagnetic Current Meter Setup and Installation*

The S4 was mounted in a stainless steel fixture ballasted with lead bars to compensate for the drag from the S4 mounted near the top (see Fig. 1). Height above seabed was 0.90 m. This fixture is frequently used by DHI and has worked well under similar conditions. The horizontal distance to the ADCP was less than 10 m.

The S4 was configured to collect pressure and velocity data at a rate of 2 Hz. Sampling time (burst time) was 20 minutes thus creating 2400 records every 2 hours.

Fig. 1. S4 Current Meter in its mooring frame.

B. ADCP Hz Set-up and Installation

The ADCP was permanently installed on the Danish west-coast as part of an on-going environmental monitoring program. The program is performed by DHI on behalf of the Danish power distribution company ELSAMPROJEKT A/S, who kindly put the instrument at our disposal for the inter comparison. The west coast of Denmark is known to be subject to severe impact by heavy wave activity from the North Sea.

The ADCP is installed in a pyramidal bottom mount made from marine concrete. The mount features a double-axis gimbal, which keeps the ADCP oriented to vertical. The mooring mount shape - sloping sides and large concrete footprint - were retained to ensure stability and minimize water drag. The weight of the mount was nearly 4000 kg and the height above seabed is 0.85 m.

Fig. 2. ADCP installed in its mooring mount.

The primary purpose of the ADCP is to contribute to the environmental monitoring program by measuring the mean tidal driven current, which runs either south or north with up to 75 cm/sec. In order to use the instrument as a wave gauge the firmware was upgraded according to instructions received from RD Instruments who likewise approved the configuration and setup parameters, which are summarized in Table I.

TABLE I
ADCP CONFIGURATION

Model	: RDI Workhorse Sentinel
Frequency	: 1200 kHz
Firmware	: 16.01
Binsize	: 0.25 m
No. of Bins	: 35
Blanking	: 300
Time per Ping	: 0.5 sec (2 Hz)
Rec. per Burst	: 2048
Burst Duration	: 17 minutes

The depth at the installation site was approximately 7.5 m with up to 1.5 m in tidal variation**.**

C. Datawell Waverider

A traditional Waverider (WR) buoy located roughly 5 km south-east of the WH/S4 at 10 m water depth provided statistical wave information. The WR follows the movement of the water by measuring vertical accelerations but does not provide directional wave information. As the WR wave bursts furthermore are offset by more than 25 minutes from the ADCP bursts, the WR data shall be considered only as redundant information.

IV. DATA RECORDING

The S4 was installed late October 1999 and started to collect data immediately. Due to severe difficulties in upgrading the ADCP to the RDI supplied firmware, the ADCP was not operational until 2 November where a test batch of wave bursts was collected for 14 hours (8 data bursts). Being exclusively for test purpose, the batch was collected without paying attention to temporal coincidence with the S4 data collection schedule.

Time synchronized data collection commenced 11 Nov. and continued as long as the S4 battery life permitted (1 December 1999).

The adverse weather conditions in the autumn/winter 1999 postponed recovery of the S4. The worst storm for centuries swept across Denmark 3 and 4 December and throughout December and January recovery was impossible.

The S4 was eventually recovered 24 January 2000. It was found more than 75 m from its initial deployment position, and it appeared to have suffered severe damage during the storm. Data recovery was only accomplished with great difficulty. Initial analysis of the recovered S4 data revealed that the instrument and its mooring frame apparently overturned around the 10 November – even before the time synchronized data collection started.

This left us with only the test batch of 8 bursts for the comparison. Each burst is displaced 14 minutes relative to the S4 (S4 collects xx00 – xx20 hrs, WH collects xx46 – xx03 hrs). The effect of this time lag on the measurement is, however, negligible considering the nature of the wave climate in the area.

V. DATA PROCESSING

A. S4 Current Meter Analyses

The time series of pressure head and two perpendicular velocity components are analyzed as follows:

- Transformation of pressure head time series to surface elevation time series using a digital FIR filter. The FIR filter comprises the following steps:
  - A 0.02 Hz high-pass filter to remove the hydrostatic pressure and tidal fluctuations.
  - A pressure head to surface elevation transfer function, $H_{p\eta}(f)$ based on Airy wave theory:

    $$H_{p\eta}(f)=\frac{\cosh kh}{\cosh k(z+h)} \qquad (1)$$

    where f is the frequency, k is the wave number, h is the water depth, and $z+h$ is the recorder height above the seabed.
  - A low-pass filter to suppress the transfer function when it increases rapidly with frequency and causes a dramatic amplification of measurement noise.

- Spectral analysis to obtain auto-spectra of surface elevation and velocities and co-spectra of pairs of signal combinations.

- Directional wave analysis using the Maximum Entropy Method (MEM), [1].

B. ADCP Analyses

The ADCP current measurements have been analyzed by applying specialized software (*WavesMon*) developed and patented by RD Instruments. The wave parameters have been determined by applying the velocity measurements derived from the four beams. The surface elevation spectrum, $S_\eta(f)$ is determined by the following expression:

$$\sum_{n=1}^{4} S_V(\mathrm{f},\boldsymbol{x}_n,z)=T^2(\mathrm{f},z,\mathrm{h})S_\eta(\mathrm{f})+S_N(\mathrm{f}) \qquad (2)$$

where $S_v(f,\boldsymbol{x}_n,z)$ denotes the spectrum of velocity measured by the n^{th} acoustic beam at a height z above the bottom, $S_N(f)$ is the spectrum of the Doppler velocity error, [3], and $T(f,z,h)$ is a transfer function. T is derived from Airy wave theory and information on the ADCP geometry. Three levels of velocity measurements were used in a least square fitting methodology to obtain the surface elevation spectrum.

The directional surface elevation spectrum is determined by the iterative version of Capon's Maximum Likelihood Method (IMLM), [4]. The method is described in more detail in [4] and [2].

The surface elevation spectrum is also determined based on echo-ranging (or surface tracking), which determines the location of the water surface at a rate of 2 Hz, see e.g. [2].

The WavesMon software generates text files with directional surface elevation (3D) and surface elevation (2D) spectra based on velocity measurements, and surface elevation (2D) spectra based on echo-ranging measurements. Wave parameters (significant wave height, H_s, peak period, T_p and peak wave direction α_{peak}) are calculated and stored in log files. It is noted that the peak wave direction, α_{peak}, is taken as the direction of the maximum peak of the directional surface elevation spectrum. Therefore, this is a very uncertain parameter, which depends significantly on the analysis method (smoothing and number of degrees of freedom). In the present study the peak wave direction is defined as the wave direction with the highest energy content irrespective of frequency (see the next section, Fig. 4).

VI. RESULTS

Based on:

- S4 derived 3D directional surface elevation spectrum,
- ADCP derived 3D directional surface elevation spectrum based on velocity measurements
- ADCP derived 2D surface elevation spectrum based on velocity measurements
- ADCP derived 2D surface elevation spectrum based on echo-ranging

the following statistical wave parameters have been derived for each data burst:

- Significant wave height H_{m0}: Calculated as $4\sqrt{m_0}$, m_0 being the zero'th moment of the surface elevation density spectrum
- Wave Peak Period T_p: Wave period corresponding to wave frequency of maximum energy density
- Wave period T_{01}: Wave period calculated from surface elevation density spectrum as $T_{01} = m_0/m_1$, m_1 being the first spectral moment
- Wave period T_{02}: Wave period calculated from surface elevation density spectrum as $T_{02} = \sqrt{m_0/m_2}$, m_2 being the second spectral moment
- Mean wave direct*ion* $!_{\text{mean}}$: The mean of the directions from which the waves approach. Direction is relative to geographical North
- *Peak wave direction* $!_{\text{peak}}$: Wave direction with the highest relative energy content accumulated over all frequencies.

In addition WavesMon computes H_{m0}, T_p and $!_{\text{peak}}$ on the basis of velocity spectra, and H_{m0} on the basis of echo-ranging spectra. These computations are confirmed by our calculations. The remaining parameters are computed by DHI as derivatives from the WavesMon generated 2D and 3D spectra files.

On the following figures, results from the measurements taken on 2 November 1999 at 20.00 hrs. are shown. It is noted that a time lag of 14 minutes is present between the ADCP measurements and the S4 measurements.

Fig. 3 shows the derived surface elevation spectra from the S4 current meter and two spectra derived from the ADCP. The spectrum denoted "ADCP Velocity" is based on the velocity measurements and the spectrum denoted “ADCP Surf. Track” is based on echo-ranging. The spectra are very comparable. The cut-off frequency for the S4 current meter is approximately 0.33 Hz (3 s). This frequency corresponds to an amplification of the pressure head by a factor of 15 to obtain the surface elevation. This amplification is considered as a maximum amplification in order not to include too much instrument noise in the data. It is seen that the ADCP is capable of measuring waves with periods less than three seconds. The actual frequency cut-off is 0.55 Hz (1.8 s).

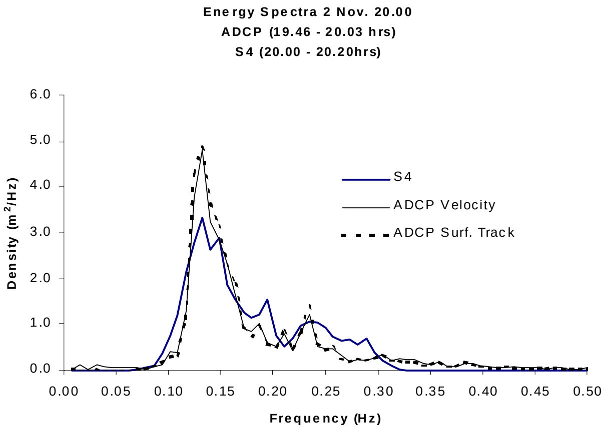

Fig. 3. Surface elevation spectra on 2 Nov 2000 at 20.00 hrs.

Fig. 4 shows the directional distributions for the S4 current meter and the ADCP. The figure shows the relative energy as a function of the wave direction. The MEM analysis of the S4 measurements yields a much smoother directional distribution than the IMLM analysis of the ADCP measurements. This may be explained by the different analysis methods, and one of the characteristics of the IMLM method is that it sharpens the directional distribution and reduces sidelobes, [2]. This effect is seen for all the analyzed time series.

The effect is seen even more clearly on the 3D surface elevation spectra shown in Figs. 5 and 6. Fig. 5 shows the 3D spectrum for the S4 current meter and Fig. 4 shows the corresponding spectrum for the ADCP. For the ADCP IMLM analysis, the peaks are much higher and sharper than for the S4 MEM analysis. However, the significant wave heights computed for the two spectra are identical (see Table II).

In [1] a comparison between the MEM and MLM directional analysis methods is given. Numerical simulations, physical model tests, and field measurements were analyzed. Generally, the paper shows that the MEM consistently resolves directional seas better than the MLM for both unimodal as well as bimodal seas. It should be noted that both methods require that the wave field is spatially homogeneous, hence effects from diffraction, refraction, and reflection may influence on the results (due to phase locking). Reference [1] shows that in such cases both methods become inaccurate with the MLM being the least accurate.

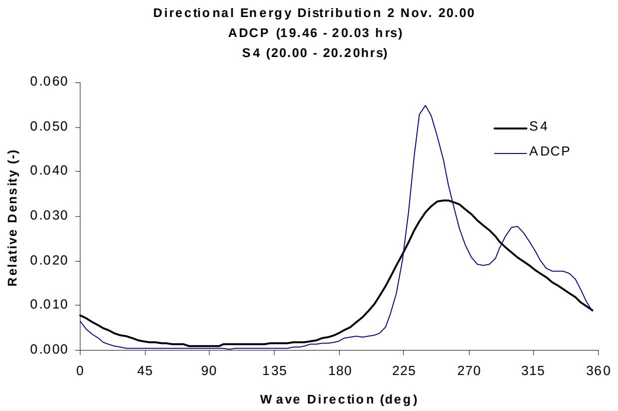

Fig. 4. Wave directional distributions.

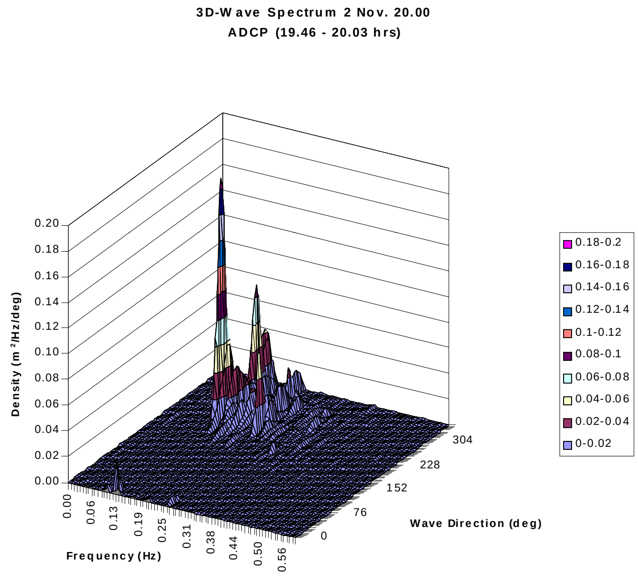

Fig. 5. Three dimensional wave spectrum based on ADCP measurements.

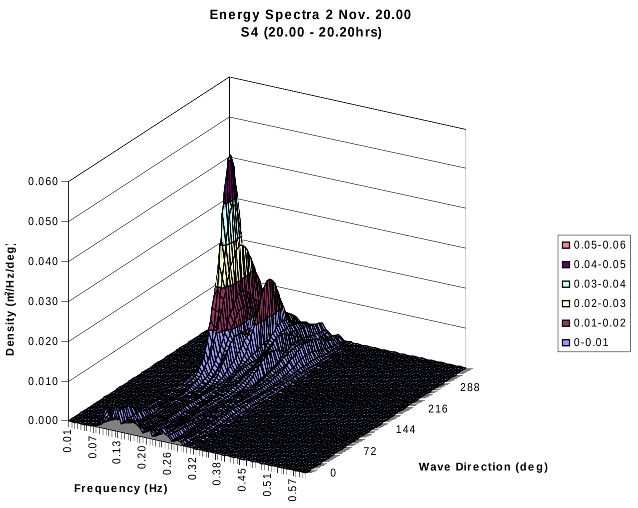

Fig. 6. Three dimensional wave spectrum based on S4 measurements.

Tables II through IV show a comparison between basic statistical parameters for the eight time series considered in the present analysis. The tables are visualized in Figs. 7 through 9. Table II shows a comparison of the significant wave height, H_{m0}, (including H_{m0} computed by WavesMon), Table III shows the spectral period, T_{02}, while Table IV gives a comparison between the obtained wave directions for the two instruments. Tables II and III also include the wave parameters from the Waverider for comparison. In general, the significant wave heights obtained by the ADCP correspond very well to the wave heights derived from the S4 current meter. In most cases, the difference is less than five per cent.

TABLE II
COMPARISON BETWEEN SIGNIFICANT WAVE HEIGHTS, H_{m0}

Time	H_{m0} (m)				
	S4	ADCP Velocity	ADCP Surface Tr.	Wave Rider	WMon
2 Nov 16.00	1.81	1.77	1.74	1.8	1.8
2 Nov 18.00	1.79	1.94	1.95	1.8	1.9
2 Nov 20.00	2.09	2.08	2.09	1.9	2.1
2 Nov 22.00	1.94	1.82	1.80	1.8	1.8
3 Nov 00.00	1.87	1.86	1.88	1.9	1.9
3 Nov 02.00	1.88	1.85	1.92	1.7	1.8
3 Nov 04.00	1.79	1.96	2.01	1.8	2.0
3 Nov 06.00	1.89	1.91	1.93	1.9	1.9

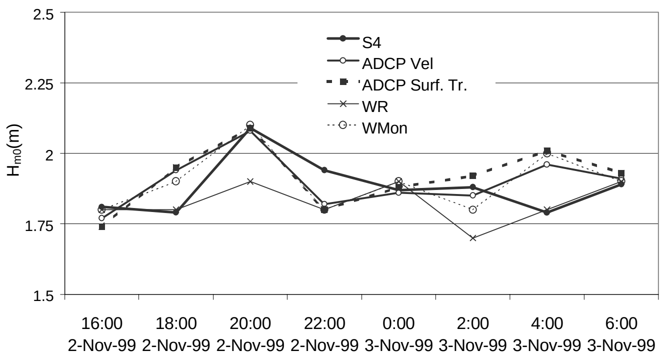

Fig. 7. Time series of significant wave height, H_{m0}.

Table III shows a comparison between the spectral period, T_{02}, derived from the four surface elevation spectra. The periods correspond reasonably well, however with the ADCP derived periods being slightly smaller than the S4 derived periods. This difference is caused by the fact that the present configuration, the S4 current meter has a cut-off frequency corresponding to 3 s. while the ADCP measures waves with periods less than 3 s.

TABLE III
COMPARISON BETWEEN SPECTRAL WAVE PERIODS, T_{02}

Time	T_{02} (s)			
	S4	ADCP Velocity	ADCP Surface Track	Wave Rider
2 Nov 16.00	5.5	5.4	5.3	4.7
2 Nov 18.00	5.4	4.7	4.9	4.7
2 Nov 20.00	5.5	5.0	5.1	4.9
2 Nov 22.00	5.7	4.7	4.9	4.8
3 Nov 00.00	5.7	5.1	5.2	5.1
3 Nov 02.00	5.4	4.9	5.1	4.7
3 Nov 04.00	5.5	5.1	5.2	4.8
3 Nov 06.00	5.6	4.9	5.0	5.0

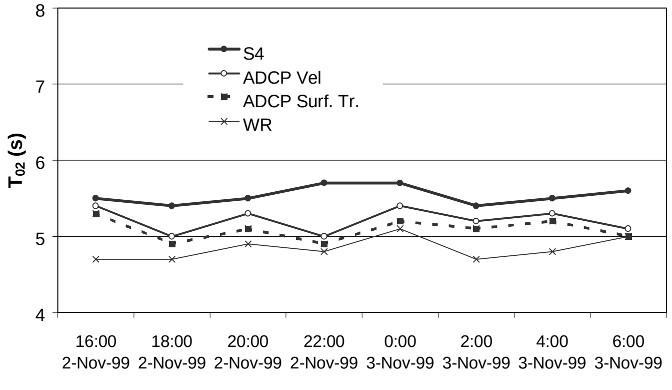

Fig.8. Time series of spectral wave periods, T_{02}.

Table IV shows the obtained mean wave directions, $!_{mean}$, and the peak wave directions, $!_{peak}$, from the two different analyses of the two instruments. The peak wave direction computed by WavesMon is also showed. The mean wave directions are very similar for the measurements from the two instruments, while a larger variation is seen on the peak directions computed for the S4 and the ADCP. This is expected, because the peak direction is a single value while the mean direction is a more robust quantity (just like T_{02} is a more robust quantity than T_p). The differences are caused by the more narrow directional distribution of the IMLM method, which in many cases yields distributions with two or more peaks.

The difference in computing methods accounts for the large variation between peak direction computed by WavesMon and the peak direction derived from the S4 and ADCP measurements. While the latter is computed as the direction with the highest accumulated energy over all frequencies, the former is simply taken as the direction of the maximum peak of the directional surface elevation spectrum.

TABLE IV
COMPARISON BETWEEN WAVE DIRECTIONS

Time	$!_{mean}$ (deg N)		$!_{peak}$ (deg N)		
	S4	ADCP	S4	ADCP	WMon
2 Nov 16.00	257	254	232	232	234
2 Nov 18.00	272	261	236	236	250
2 Nov 20.00	272	267	252	236	238
2 Nov 22.00	278	261	260	244	242
3 Nov 00.00	279	273	248	244	310
3 Nov 02.00	275	281	248	308	310
3 Nov 04.00	279	258	252	240	226
Nov 06.00	278	277	236	248	250

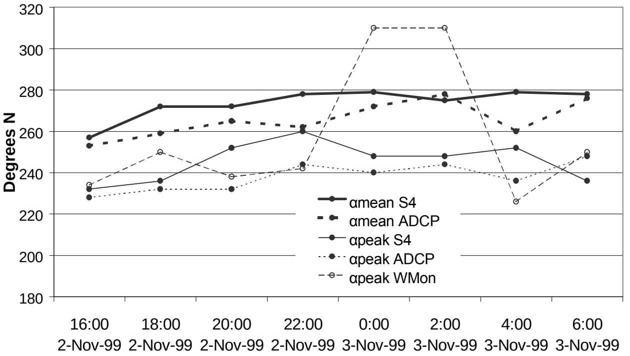

Fig. 9. Time series of Mean Wave Direction ($!_{mean}$) and Peak Direction ($!_{peak}$)

VII. SUMMARY

We have compared statistical wave parameters derived from measurements with an ADCP with the corresponding parameters derived from an S4 electromagnetic current meter and found that the values compare reasonably well. The most part of the differences we have encountered can be explained by differences in processing techniques each having its advantages and disadvantages.

The difference in processing technique is distinct in the directional distribution of the wave energy. The ADCP uses the IMLM analyses, which provide a narrower directional width than the MEM analyses used with the S4 data. Despite this, the differences between S4 derived statistical wave parameters and the corresponding parameters derived from the ADCP measurements are insignificant (generally within 5%).

The peak wave direction, $!_{peak}$, computed by WavesMon show considerable fluctuations due to the inherent computation method. Rather than determining $!_{peak}$ as the direction with the highest accumulated energy over frequency, the software simply takes the direction of the maximum peak. This explains the fluctuations in the peak direction computed by WavesMon.

It is evident that the ADCP has the capability to measure waves with higher frequency than the S4, which is limited in its frequency response because of the frequency dependent attenuation with depth. In the present comparison, this is reflected in the higher ADCP cut-off frequency, which results in smaller ADCP derived spectral periods, $T_{02.}$ The improved frequency response is one of the ADCP's major advantages compared to the S4 although the ADCP frequency response is likely to decline – to a lesser extent - since the beam separation can become a significant fraction of the wavelength in deeper water.

VIII. CONCLUSIONS

The comparison – though based on a limited amount of data – has shown that the ADCP is a useable instrument for measuring wave parameters without compromising the instrument's current measuring capability.

The statistical wave parameters computed by WavesMon are confirmed by our calculations, but we find, however, that parameters such as Tp (peak period) and α_{peak} (peak direction) are inexpedient for most hydraulic applications. The corresponding spectrum derived values T_{02} and α_{mean} are more robust and less sensitive to differences in analysis method.

Our comparison has not substantiated that the ADCP estimates wave parameters neither more nor less accurate than the S4. It is, however, undisputed, that given the conditions, the ADCP is capable of measuring waves with higher frequencies than the S4.

Objectives of further research could be to collect data over a prolonged period in order to check the ADCPs response to more varying wave conditions than we experienced. Also the response of ADCPs with lower frequency in deeper water is an obvious topic for further research.

ACKNOWLEDGMENT

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