An evaluation of directional analysis techniques for multidirectional, partially reflected waves
Part 2: application to field data

Evaluation de techniques d'analyse directionnelle pour des vagues multidirectionnelles partiellement réfléchies
Partie II: application à des jeux de données

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ABSTRACT
Based on the findings of a numerical investigation, presented in the Part 1 companion paper, two methods of directional analysis, the maximum likelihood method (MLM) and the Bayesian directional method (BDM) are applied to over 80 field data sets. These cover a wide range of environmental conditions, for which multidirectional, partially reflective sea states exist. The results show that trends similar to those found using the numerical simulations are observed in the field estimates of relative predictions of incident significant wave height, average reflection coefficients, main directions and directional spreading. It is concluded that overall the BDM produces the more accurate results when applied to real sea waves.

RÉSUMÉ
Sur la base des résultats de nos investigations numériques, présentées dans la Partie I associée, deux méthodes d'analyse directionnelle, la méthode du maximum de vraisemblance (MLM) et la méthode directionnelle Bayesienne (BDM), sont appliquées à 80 jeux de données. Cela couvre une large gamme de conditions environnementales, dans lesquelles on trouve des champs de vagues multidirectionnelles partiellement réfléchies. Les résultats montrent que des tendances similaires à celles observées dans les simulations numériques sont obtenues dans les prédictions, pour des hauteurs de vagues incidentes significatives, des coefficients de reflexion moyens, de la direction moyenne et de l'étalement directionnel. Il est montré en conclusion que, partout, la méthode BDM fournit les résultats les plus précis quand on l'applique aux champs de vagues réels.

1 Introduction

The emphasis of this paper is to present the finding of a study of the determination of the true directional spectrum for real, multidirectional, partially reflective sea states. This study has been carried out using data collected from an extensive field measuring programme. Two methods of directional analysis have been used, the Maximum Likelihood method (MLM) and the Bayesian Directional Method (BDM) and their predictive capacities compared, informed by the numerical investigations presented in the Part 1 companion paper. The unique aspect of the paper lies in the investigation of how these techniques can be applied to the analysis of real sea waves for which partial reflection is known to be present.

The initial findings of this study were reported in the IAHR Seminar on multidirectional waves and their interaction with structures by Ilic et al [1]. In the Part 1 companion paper, the theoretical considerations are described concerning the determination of an accurate directional spectrum using spatially distributed arrays. In applying these techniques to field data, another important consideration is the effect of currents. Such currents may comprise tidal and/or wave induced currents. Nakagawa et al [2] investigated the influence of currents on the estimation of directional spectra, finding that these could be significant and could be accounted for by suitable modifications to the wave dispersion equation. Consequently, the influence of currents on the directional spectra derived from the field data are investigated.

Section 2 contains the relevant details of a comprehensive field investigation, in which multidirectional, partially reflective wave fields were measured by three spatially distributed arrays. Sections 3 and 4 present the results from an investigation of over 80 field data sets, covering a wide range of environmental conditions. The results are very clear and were found to follow the same trends discerned from the simulation tests, allowing clear conclusions to be drawn in section 5.

2 Field data

The field measurements took place at, or directly offshore from, an array of eight detached breakwaters at Elmer, West Sussex, UK (see Figure 1). The breakwaters are rubble mound structures constructed of 6–10 tonne syonite blocks. The seaward slope is 1:2. Wave conditions are dominated by locally generated waves, with typical peak frequencies in the range 0.1–0.33 Hz. The tidal range is 5.3/2.9 m on spring and neap tides respectively with inshore tidal currents which rarely exceed 0.7 ms^{-1}. The offshore bathymetry is simple (gradient 1:50), characterised by essentially straight, shore parallel bottom contours.

Two different types of equipment were deployed for the wave measurements. Their locations are given in Figure 1. An array of six pressure transducers over an area of 60 × 16 m was deployed offshore to measure directional waves approaching the shoreline. Data were collected every 3 hours for 12 minutes

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with a sampling frequency of 2 Hz. The development and field application of this wave recording system (WRS) is fully described in Bird [3]. A star array of four surface piercing wave resistance staffs was deployed in the lee of breakwater 3 to give directional information inshore after waves were refracted and diffracted. This device is known as the inshore wave climate monitor (IWCM). The development and field application of the IWCM is fully described in Chadwick et al [4]. Two additional independent wave probes were deployed, one in the gap between breakwaters 3 and 4 and another one shoreward of the gap. They and the IWCM collected data every 3 hours for 17 minutes with a sampling frequency of 4 Hz but were only operational for approximately half the tidal cycle. Additionally an array of 6 pressure transducers was deployed in the front of breakwater 4 to measure reflection for a period of two months in Spring 1994. The WRS was deployed from September 1993 until January 1995 and measurements were taken continuously for a year. Table 1 contains a summary of the data collected during the field measurements at Elmer. Figure 2 shows the IWCM at the Elmer site under moderate wave conditions at high tide and Figure 3 shows the WRS seaward of breakwater 4 at low tide. Further details of the field work may be found in Chadwick et al [5].

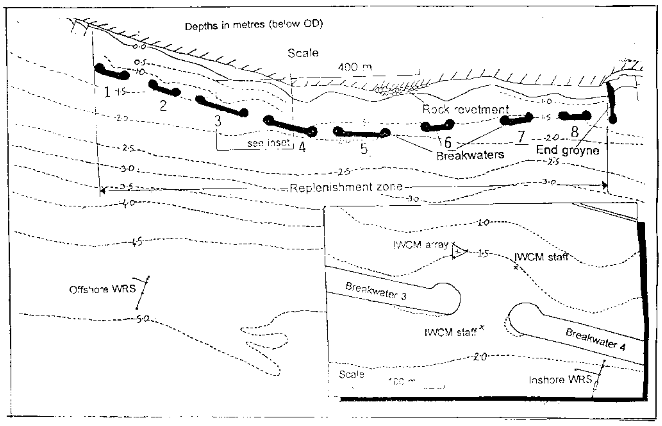

Fig. 1. Location plan for the Elmer Breakwaters site.

Fig. 2. Photograph of the IWCM measuring diffracted waves at high tide.

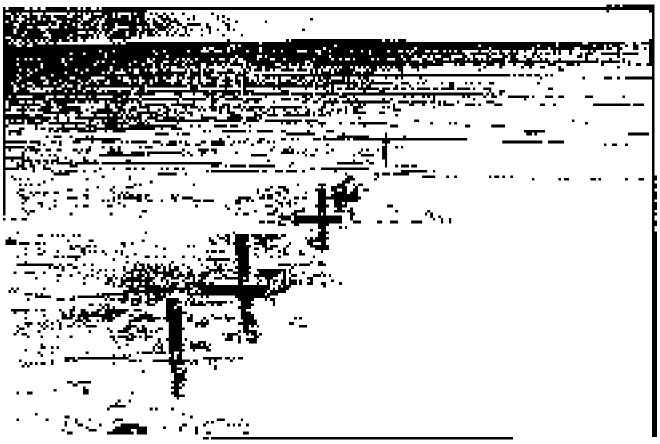

Fig. 3. Photograph of the WRS located seaward of breakwater 4 at low tide.

Table 1 Field data summary.

Deployment period	Location	Equipment	No of records collected
June-Aug 1992	Seaward of breakwater 4	WRS 2	586
June-Aug 1992	Inshore of breakwater 3	IWCM	296
Sept 1993-Jan 1995	Offshore	WRS 2	2,776
Oct 1993-Dec 1994	Inshore of breakwaters 3 and 4	IWCM and Satellites	1,550
Feb - Apr 1994	Seaward of breakwater 4	WRS 1	364

3 Directional analysis of offshore field data

3.1 *Offshore data selection*

Forty two data sets were selected. These data sets were classified into three groups by referring to frequency shape, narrow frequency spectra, bimodal spectra and broad frequency spectra. The main directions for the selected data was from the south (almost normal incidence to the breakwaters) or slightly south-west with only five data sets having a main direction from the south-east. Prior to the directional analysis, spectral analysis was performed in the same way as was carried out on the numerically simulated data, described in the Part 1 companion paper. All the data sets were analysed using the case 1 spectral analysis and 18 of these were re-analysed using the case 2 spectral analysis.

3.2 *Effects of tidal currents on the directional estimates*

The directional analysis methods used for the field data did not originally allow for the effect of tidal currents. One reason for this was that such currents were not measured. However, as pointed out in section 1, Nakagawa et al have shown that these can have a significant influence on the directional spreading function in the presence of a following or adverse current. At the chosen field site, the main wave directions are largely normal to the direction of the tidal currents. Hence, the wavelength and pressure attenuation factors are largely unaffected for the main direction. However, due to directional spreading, effects will exist for wave angles other than the main direction. At the chosen field site, tidal currents rarely exceed 0.7 m/s on a spring tide and the measurement depth at the offshore location rarely exceeded 8m. Based on these conditions, the effects of the tidal currents on the computed wavelengths and pressure attenuation factors were calculated for a range of wave frequencies, assuming a depth of 8m, an angle of 45^o between a tidal current (of magnitude 0.5 m/s) and the wave direction (there is very little wave energy at larger angles). The percentage differences between the still water case and the current case were all less than 5% for wave frequencies less than 0.167 Hz and these differences were all less than the change in frequency between each frequency bin for the case 1 spectral analysis case (smallest delta f). It was therefore concluded that the results would be largely unaffected by the presence of currents for wave frequencies less than 0.167. Additionally, given that the actual currents were not measured, any corrections introduced to account for them would have to be based on astronomical predictions using chart data. Such estimates would not be very accurate and lend little to the analysis of the results. However, as a final check, some of the derived directional spectra were re-analysed assuming the presence of a 0.5 m/s current orthogonal to the main direction. The results of this analysis are given in 3.7.

3.3 *Results for main direction*

Both methods predicted almost the same direction. The percentage difference between the BDM and MLM is summarised in Table 2. The percentage difference between the BDM and MLM is larger than for the simulated data. The average percentage is almost the same for case 1 and case 2 spectral analysis, but the maximum difference decreases for case 2, as was found using the numerically simulated data.

Table 2. Percentage difference between the BDM and MLM direction estimates.

BDM/MLM	overall		T<6 sec		T>6 sec	
percentage	**case 1**	**case 2**	**case 1**	**case 2**	**case 1**	**case 2**
min	-9.186		-9.186		-3.565	
max	18.202		13.686		18.20	
abs min	0.152		0.878		0.152	
average	3.764		2.858		4.382	
			18 selected data files			
min	-1.723	-9.312	-1.723	-9.312	-0.630	-4.447
max	10.733	6.364	10.733	2.88	7.811	6.365
abs min	0.152	0.236	0.878	0.236	0.152	0.480
average	2.421	-0.405	3.109	-3.329	1.870	1.933

3.4 *Results for directional spreading*

The largest difference between the BDM and MLM was found for directional spreading. The BDM generally predicts a narrower directional distribution than the MLM. The summary of the comparison in given in Table 3. The largest difference is observed for case 2 when the MLM constantly produces a larger directional spread, as was found for the simulated data..

Table 3 Percentage difference between the BDM and MLM directional spreading estimates.

BDM/MLM	**overall**		**T<6 sec**		**T>6 sec**	
percentage	**case 1**	**case 2**	**case 1**	**case 2**	**case 1**	**case 2**
min	-35.628		-22.887		-35.628	
max	13.424		13.424		-8.122	
abs min	0.423		0.423		8.122	
average	-16.418		-9.184		-21.350	
			18 selected data files			
min	-26.431	-39.367	-22.887	-26.675	-26.431	-39.367
max	13.424	-15.002	13.424	-15.002	-8.122	-21.484
abs min	5.211	15.002	5.211	15.002	8.122	21.484
average	-13.380	-26.790	-10.177	-22.566	-15.943	-30.169

3.5 *Results for incident significant wave height*

The MLM estimates are generally smaller than the estimates obtained using the BDM and using the case 2 spectral analysis increases the significant wave height. Table 4 summarises the percentage differences. These results show the same trends as was found from the numerically simulated data. However the percentage differences between the BDM and MLM increases.

Table 4 Percentage differences between BDM and MLM significant wave height estimates.

BDM/MLM	**overall**		**T<6 sec**		**T>6 sec**	
percentage	**case 1**	**case 2**	**case 1**	**case 2**	**case 1**	**case 2**
min	-9.193		-5.362		-9.193	
max	28.066		20.293		28.066	
abs min	0.270		0.270		1.263	
average	7.270		2.540		10.495	
			18 selected data files			
min	-9.193	-18.61	-4.954	-1.191	-9.193	-18.612
max	22.684	20.255	4.669	11.017	22.685	20.255
abs min	0.27	0.11	0.27	0.11	1.263	1.159
average	3.837	5.792	1.804	5.446	5.464	6.069

3.6 *Results for reflection coefficient*

The MLM estimates are generally higher than the estimates obtained using the BDM and using the case 2 spectral analysis reduces the reflection coefficient. These results show the same trends as was found from the numerically simulated data, but the differences are again higher. This is shown in Table 5.

Table 5 Percentage difference between the BDM and MLM reflection coefficient estimates.

BDM/MLM	**overall**		**T<6 sec**		**T>6 sec**	
percentage	**case 1**	**case 2**	**case 1**	**case 2**	**case 1**	**case 2**
min	-61.569		-52.347		-61.569	
max	22.033		22.033		-25.009	
abs min	4.163		4.163		25.009	
average	-35.087		-18.461		-46.422	
			18 selected data files			
min	-55.107	-75.225	-52.347	-74.667	-55.107	-75.225
max	22.033	-38.079	22.033	-44.366	-25.009	-38.079
abs min	8.506	38.079	8.506	44.365	25.009	38.079
average	-35.051	-59.893	-27.935	-60.178	-40.743	-59.666

An example of the frequency dependent reflection coefficient is given in Figure 4. The MLM estimates are higher for the lower frequencies, but also higher than expected for higher frequencies where a certain amount of energy was expected to be dissipated in breaking. In the case of the BDM, the reflection varies quite strongly with frequency.

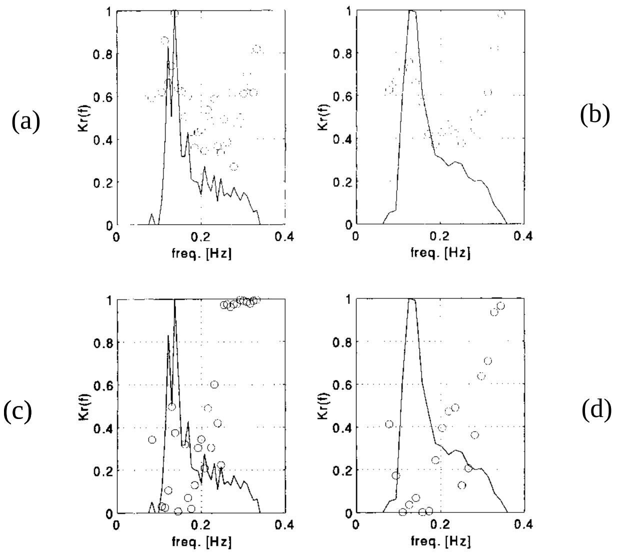

Fig. 4. Example frequency dependent reflection coefficient estimates for the offshore data. Circles are for reflection coefficients. Solid line represents wave energy over frequency. (a) MLM case 1 spectral analysis, (b) MLM case 2 spectral analysis, (c) BDM case 1 spectral analysis, (d) BDM case 2 spectral analysis.

3.7 *Discussion of results for offshore data sets*

The differences between the BDM and MLM are larger than in the case of the simulated data. The reflection coefficient was frequency independent for the simulated data but this is not the case for the field data where the reflection coefficient is frequency dependent. As was shown for the simulated data, both methods' estimates are also correlated to the direction of the incoming waves and reflection.

Example directional distributions for both methods are given in Figure 5 which also illustrates the effect of reducing the segment length.

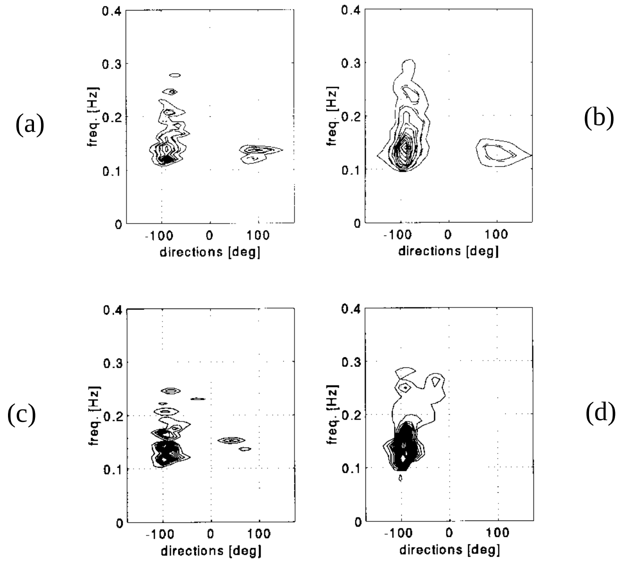

Fig. 5. Example contour plots of offshore directional distributions. Solid lines, contours at 10% intervals of the peak value, dashed line 5%. (a) MLM case 1 spectral analysis, (b) MLM case 2 spectral analysis, (c) BDM case 1 spectral analysis, (d) BDM case 2 spectral analysis.

Figure 6 shows the effect of introducing an assumed current of 0.5 m/s, orthogonal to the main direction, for two test cases. As was postulated in section 3.2, the effects on the directional distribution are negligible.

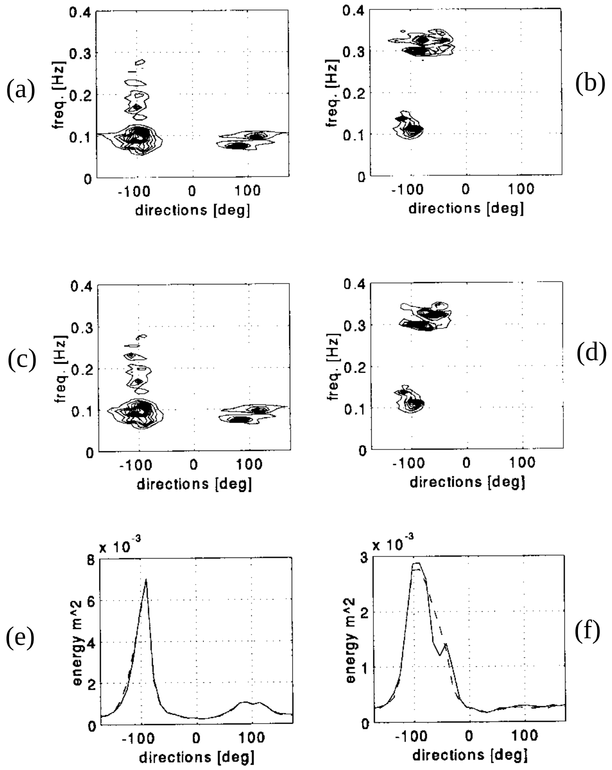

Fig. 6. Example plots of offshore directional distributions without and with currents for two data sets. (a) and (b) MLM without currents, (c) and (d) MLM with 0.5 m/s current. Solid lines, contours at 10% intervals of the peak values. (e) and (f) 2D-directional distributions, solid lines without currents, dashed lines with currents.

4 Directional analysis of inshore field data

4.1 *Inshore data selection*

Forty two data sets were selected corresponding to the offshore data sets. These wave measurements were collected inshore of the breakwaters using the IWCM and therefore the only wave reflections present were those from the beach face. This is a very interesting case to study as the nature of the reflection is more complex than from a structure. Only one case for the spectral analysis was considered as shown in Table 6.

Table 6. *L/S* values for the inshore field data.

Case No	S (s)	Limits of L/S Lower f (Hz)	Highest f (Hz)	df	Degrees of freedom	95% confidence limits
1	256	0.54	1.27	0.0078	28	0.63-1.8

4.2 *Results for the main directions*

The agreement between the BDM and the MLM direction estimates is excellent, the percentage differences between the BDM and MLM being given in Table 7. The maximum and minimum values are smaller than in the case of offshore data and the average difference is only 0.41 %.

Table 7 Percentage differences between the BDM and MLM parameters for the inshore data

BDM/MLM percentage	significant wave height		main direction		directional spreading		reflection coefficient	
	u=2.0	u=20.0	u=2.0	u=20.0	u=2.0	u=20.0	u=2.0	u=20.0
min	1.04	-11.56	7.65	-6.41	-35.36	-24.24	-74.22	-57.88
max	23.71	4.07	2.13	7.34	15.02	38.46	-24.73	72.90
abs min	1.04	0.08	0.03	0.26	0.34	0.02	24.73	0.01
average	9.33	-1.75	-1.81	0.57	-13.10	4.87	-53.79	-3.49

4.3 *Results for the directional spreading*

The difference between the BDM and the MLM directional spreading estimates is also given in Table 7. The values are very similar to the values obtained in the case of the offshore data sets. However the BDM does not produce narrower directional spread for all inshore field data.

4.4 *Results for Incident significant wave height*

The estimates obtained using the MLM are generally lower than those obtained by the BDM. The percentage difference between the BDM and MLM is given in Table 7. The differences are smaller than in the case of the offshore field data which can be related to the presence of less reflection.

4.5 *Results for reflection coefficient*

Those derived using the MLM have higher values than those estimated by the BDM. The coefficients derived from the MLM results are in the range from 0.3 to 0.75 whereas the coefficients derived from the BDM results are in the range 0.08 to 0.55. A summary of the percentage differences are given in Table 7. The average differences when the BDM with u = 20 was used are very similar to the differences for the offshore data. However, when the hyperparameter was changed to u = 2.0, the differences increase, most noticeably in the estimation of the reflection coefficient.

4.6 *Discussion of results for the inshore data sets*

In general the differences between the BDM and the MLM estimates are similar to the differences between the BDM and the MLM estimates offshore even though the values are slightly smaller. The example directional distribution plots given in Figure 7 illustrate typical results in which the BDM introduces less directional spread than does the MLM, but is seen to produce different results depending on the value of the hyperparameter u. Frequency dependent reflection is shown in Figure 8, in which the MLM predicts higher reflection coefficients than does the BDM.

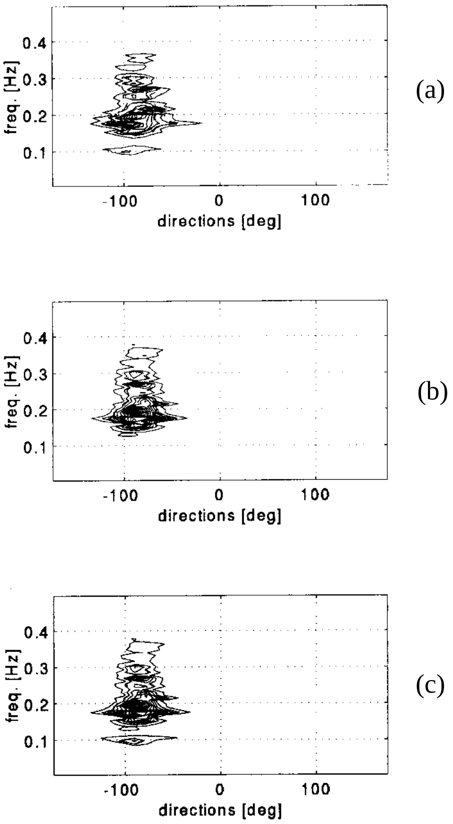

Fig. 7. Example contour plots of the directional distributions for the inshore data. (a) MLM estimate. (b) BDM estimate with u = 20. (c) BDM estimate with u = 2.

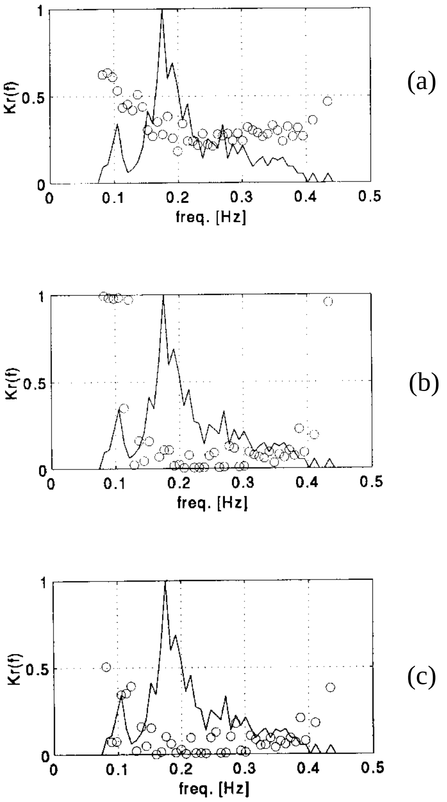

Fig. 8. Example frequency dependent reflection coefficient estimates for the inshore data. Circles are for reflection coefficients. Solid line represents wave energy over frequency. (a) MLM estimate, (b) BDM estimate with u = 20, (c) BDM estimate with u = 2.

5 Conclusions

The analysis of the field data sets measured offshore showed that the trend of differences between the MLM and BDM in estimating the main direction, the directional spreading, the incident significant wave height and the reflection coefficient, was the same as for the numerically simulated data. However the differences were larger in the case of the field data. The MLM gave lower estimates of the incident wave height and related to this higher estimates of the reflection coefficients. Comparing the field results to the numerical simulation results, it appears that the BDM produces the most reliable results overall.

The analysis of the field data sets measured inshore showed that both methods predicted reflection from the beach in the front of the breakwater. The reflection estimates obtained by the BDM were the lower and consequently the incident wave heights were lower using the MLM. The predicted main directions using the BDM and MLM were very similar. The BDM estimates were also found to be sensitive to the (arbitrarily) chosen value of the hyperparameter u. Both methods succeed in producing estimates in an environment outside their theoretical domain of application, where non-linear processes, wave induced currents and reflection are present.

Acknowledgements

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References

1. ILIC, S., CHADWICK, A.J., DAVIDSON, M., BIRD, P.,A.,B., HUNTLEY, D.,A., 1997. Directional analysis of partially reflected waves. *27th IAHR Congress San Francisco August 1997, Canadian Hydraulics Centre, Ottawa, Canada.* pp. 323–336.
2. NAKAGAWA, Y., TSURUYA, H., HASHIMOTO., N, 1996. The effects of currents on estimations of directional wave spectra. *Proc. 25th Conf. on Coastal Eng., ASCE, New York, pp. 30–42.*
3. BIRD, P.,A.,B., 1993. Measurement and analysis of sea waves near a reflective structure. *PhD Thesis, University of Plymouth.*
4. CHADWICK, A.J., POPE, D.J., BORGES, J., ILIC, S, 1995. Shoreline directional wave spectra Part 1. An investigation of spectral and directional analysis techniques. *Proc. Instn Civ.Engnrs Wat. Marit. & Energy, 1995, 112, Sept., 198–208.*
5. Chadwick A J, Fleming C, Simm J, Bullock G N, 1994. Performance Evaluation of Offshore Breakwaters - a Field and Computational Study, *Proceedings Coastal Dynamics 94 Barcelona, Spain, Feb. International Conference on the Role of Large Scale Experiments in Coastal Research, American Society of Civil Engineers, Sept 1994, 950 - 961.*