Onboard Sea State Estimation Based on Measured Ship Motions

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ABSTRACT
It is possible to obtain estimates of the sea state at the specific position of an advancing vessel by processing measurements of the vessel's wave-induced responses. The analogy to a wave rider buoy is clear, although the situation of an advancing ship is more complex due to forward speed. The paper studies the 'wave buoy analogy', and a large set of full-scale motion measurements is considered. It is shown that the wave buoy analogy gives fairly accurate estimates of sea state parameters when compared to estimates from real wave rider buoys.

KEYWORDS
Sea state estimation; motion measurements; advancing ship; decision support systems.

INTRODUCTION

Sea state parameters, or the directional wave energy spectrum, around a ship are needed on a continuous basis for navigational and operational guidance to a ship's master. The likelihood of parametric roll, for example, depends amongst others on the sea state in which the ship operates. Thus, if the sea state is continuously estimated it is possible to raise a warning if, say, vessel speed or course is in a region where parametric roll can be triggered (Jensen, 2011). The evaluation of a vessel's performance (Hansen and Lützen, 2010) requires also input of the sea state parameters, so onboard wave estimation is highly relevant for any type of monitoring and/or decision support system on ships.

In the literature there are reports (e.g. Iseki and Ohtsu, 2000; Nielsen, 2006, 2008; Pascoal et al., 2007; Tannuri et al., 2003) about the estimation of sea state parameters using measured ship responses (e.g. motion data) where the ship, to make an analogy, acts as a wave rider buoy for which reason the methodology is called the 'wave buoy analogy'. The fundamental input to the wave buoy analogy is a set of response measurements where the individual response basically can be any one as long as a linear (complex-valued) transfer function may be associated to the response. The wave buoy analogy provides a robust alternative to wave radars by utilization of onboard response measurements that are often carried out irrespectively on many of today's navy and commercial vessels. Consequently, the wave buoy analogy is also a relatively inexpensive estimation concept, since the system development is associated to software only.

This study considers sea state estimation from full-scale motion measurements obtained during sea trials conducted by DRDC Atlantic on one of their research vessels. In connection with the sea trials wave measurements were made using traditional wave buoys and the study compares these measurements with those estimated from the measured motion responses of the ship by application of the wave buoy analogy. Particularly, the study investigates how the sea state estimates are influenced by the specific selection of ship motion responses considered. The main objective of the study is to further validate the wave buoy analogy.

CONCEPT AND THEORY – PARAMETRIC MODELLING

Main Principle

The concept of the wave buoy analogy builds on a comparison between measurements of response spectra and calculated ones. On the basis of an error calculation, action is taken to minimize the discrepancy between the measured and the calculated spectra and this procedure is repeated until an acceptable degree of convergence has been reached, see Fig. 1.

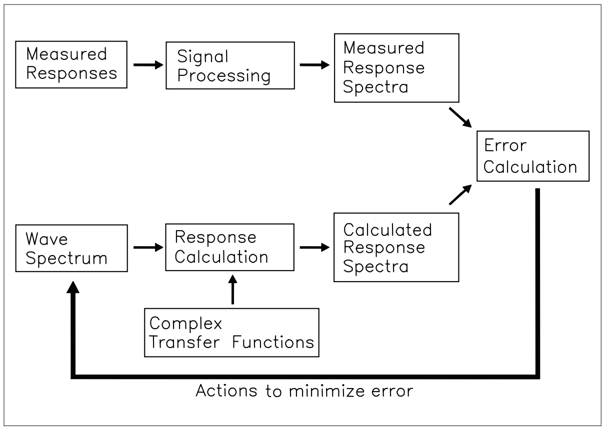

Fig. 1: The fundamental principle of the wave buoy analogy

The iteration problem (Fig. 1) of the wave buoy analogy can be handled by different approaches. Two approaches that have received particular interest are formed by Bayesian modeling and parametric modeling. Bayesian modeling relies on the finding of the discrete spectral components of a frequency-directional wave spectrum, whereas parametric modeling assumes the directional wave spectrum to be formed by a set of parameterized wave spectra with due account for directional spreading. The two approaches should not been seen as competitors but rather as complementary, since each method has its own advantages and disadvantages (e.g. Nielsen, 2006, 2007; Pascoal and Guedes Soares, 2008). It is worth to mention that a third approach building on Kalman filtering has been formulated by Pascoal and Guedes Soares (2009) for response-based wave estimation. However, as reported by the authors, this approach is still in a developing phase and needs further elaboration.

Independently of the estimation approach, the study of data from an advancing ship means that the so-called triple-valued function problem needs to be considered. This problem stems from the transformation of encounter frequencies into true wave frequencies which is made difficult due to the Doppler effect. In the literature, some studies are restricted to FPSO vessels, (e.g. Tannuri et al., 2003; Simos et al., 2010; and Pascoal et al., 2007) which means that the triple-valued function problem is avoided. Iseki and Ohtsu (2000) showed how to include response measurements from an advancing ship, and the present study deals with sea state estimation from a ship *with* forward speed. In the remaining part of this section, the fundamental theory of the wave buoy analogy will be briefly outlined, when parametric modeling (e.g. Nielsen, 2006; Tannuri et al., 2003; Pascoal et al., 2007) is applied. The details can be found in the mentioned literature.

Governing Equations

The governing equation system of the wave buoy analogy origins from the electric filter analogy (St. Denis and Pierson, 1953), which assumes linearity between the response spectrum $S_{ij}(\omega_e)$ of the ith and jth responses and the directional wave spectrum $E(\omega_e,\theta)$

$$S_{ij}(\omega_e) = \int_{-\pi}^{\pi} \Phi_i(\omega_e,\theta)\overline{\Phi_j(\omega_e,\theta)}E(\omega_e,\theta)d\theta \quad (1)$$

where ω_e and θ are the encounter wave frequency and the relative wave heading, respectively. The left-hand side is the measured cross (response) spectrum whereas the right-hand side is the calculated cross spectrum using the estimated wave spectrum $E(\omega_e,\theta)$ and the response amplitude operators (RAOs) in terms of complex-valued transfer functions $\Phi(\omega_e,\theta)$. The bar denotes the complex conjugate. The measured cross spectra, i.e. the left-hand side of Eq. (1), are obtained by cross-spectral analysis, and in the present model multivariate autoregressive modeling is applied (Neumaier and Schneider, 2001; Nielsen, 2006).

In this study, the on-site wave spectrum is obtained by parametric modeling which means that the complete frequency-directional spectrum is estimated through an optimization problem derived from Eq. (1). The solution to the problem is a set of (optimized) wave parameters that, together with a parameterized wave spectrum, characterize the sea state. The parameterized directional wave spectrum is chosen to be a fifteen-parameter tri-modal spectrum that allows for mixed sea such as wind and swell, since the spectrum is a summation of three base spectra. Basically, the spectrum is similar to the ten-parameter spectrum suggested by Hogben and Cobb (1986), although they consider a summation of only two parameterized five-parameter spectra. The applied parametric expression reads

$$E(\omega,\theta)=\frac{1}{4}\sum_{i=1}^{3}\frac{\left(\frac{4\lambda_i+1}{4}\omega_{p,i}^4\right)^{\lambda_i}}{\Gamma(\lambda_i)}\frac{H_{s,i}^2}{\omega^{4\lambda_i+1}}A(s_i)\cdot \cos^{2s_i}\left(\frac{\theta-\theta_{mean,i}}{2}\right)\exp\left[-\frac{4\lambda_i+1}{4}\left(\frac{\omega_{p,i}}{\omega}\right)^4\right] \tag{2}$$

with H_s being the significant wave height, λ is the shape parameter of the spectrum, θ_{mean} is the mean relative wave direction, ω_p is the angular peak frequency, and s represents the spreading parameter. The constant $A(s)$ is introduced to normalize the area under the $\cos^{2s}$ curve. The constant is given by

$$A(s)=\frac{2^{2s-1}\Gamma^2(s+1)}{\pi\Gamma(2s+1)} \tag{3}$$

where Γ denotes the Gamma function. It should be noted that the spreading parameter(s) s is not included in the optimization, which means that a total of twelve parameters are to be optimized. The spreading parameter is modeled as a function of wave frequency and as function of the principal parameter s_{max}, cf. Goda (2000)

$$s=\begin{cases}\mathrm{ceil}\left[(\omega/\omega_p)^5 s_{max}\right] \ , & \omega\le\omega_p\\ \mathrm{ceil}\left[(\omega/\omega_p)^{-2.5} s_{max}\right] \ , & \omega>\omega_p\end{cases} \tag{4}$$

where s_{max} = 25 in this analysis, as this value characterizes wind waves and/or swells with a short decay distance, cf. Goda (2000), which is assumed to be applicable for the given environmental conditions and geographical area. In Eq. (4), 'ceil' rounds towards plus infinity and is a numerical technique introduced to stabilize the optimization.

The actual optimization problem is established by minimizing the difference between the left- and the right-hand side of Eq. (1), with the wave spectrum $E(\omega,\theta)$ given by Eq. (2). The implementation of the problem is, however, not straight forward due to the triple-valued function problem that must be taken into account for advancing ships. Moreover, the present model considers an energy conservation requiring the 0^{th} order spectral moment of the left- and right-hand side to be identical. Finally, constraints are set for the relationship between significant wave height and zero-crossing period, and it is also taken into account that wave estimations between two consecutive time instants cannot vary too much, leaving out details and further argumentation.

FULL-SCALE MOTION MEASUREMENTS

Sea Trials

In the following, sea states will be estimated on the basis of motion measurements obtained during sea trials. The sea trials have been conducted by DRDC Atlantic in Nov./Dec. 2008 using the Canadian Navy research ship CFAV Quest (Fig. 2). The principle particulars of Quest are shown in Table 1. A complete description of the sea trials is given in Stredulinsky (2010) but it is noteworthy that in this analysis consideration is given to 16 sets of trials comprising a total of 96 runs each of approximately 25 minutes duration. During all runs, motion measurements were recorded together with information about the on-site sea state obtained by three wave rider buoys. The motion measurements were taken approximately 250 km southeast of Halifax, cf. Fig. 3, in close vicinity to the MEDS (Marine Environmental Data Service) moored buoy at Station C44137; the other two wave buoys were a TRIAXYS™ and a Triaxys MINI™ deployed in a drifting mode. The motion measurements were obtained by the DRDC Ship Motion package (Brunt, 2003) which was installed at the ship center-of-gravity (COG). The ship motion signals were digitized using a laptop computer with a LabView data acquisition card sampling at 20 Hz. Time histories recorded from the motion package included the roll angle, roll rate, pitch angle, pitch rate, yaw rate and longitudinal, lateral, and vertical accelerations and data was stored to file every 20 minutes.

Table 1: Principle particulars of CFAV Quest.

Displacement	2305 t
Length between perpendiculars	71.6 m
Beam	12.8 m
Draft	4.8 m
Block coefficient	0.509
Metacentric height	0.31 m

Fig. 2: The Canadian Navy research ship CFAV Quest.

For each set of trials, six runs were conducted so that six different relative wave headings were experienced. The run pattern of trial no. 1 is seen in Fig. 4, where run 1 corresponds to head sea, run 2 to following sea, run 3 to starboard bow, run 4 to port quarter, run 5 to port beam, and run 6 corresponds to starboard beam. All other trials had ("relative") run patterns similar to that of trial no. 1, although the absolute heading would not be the same.

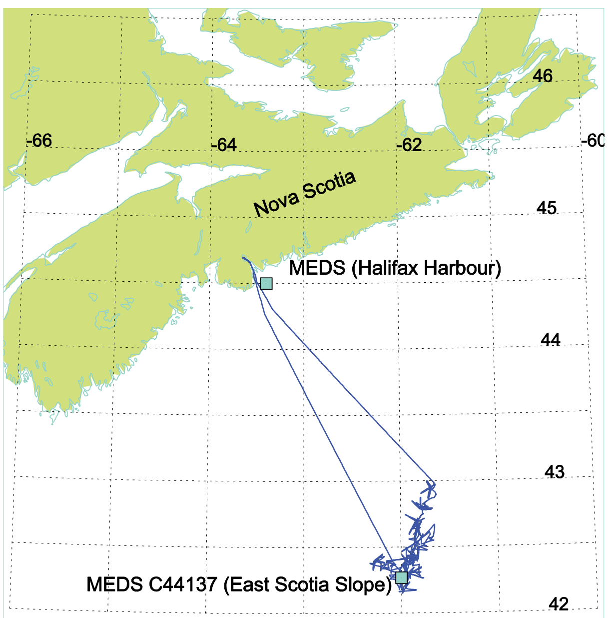

Fig. 3: Voyage map of sea trials.

Transfer Functions of the Ship

The complex-valued transfer functions have been calculated using the in-house code SHIPMO7 (McTaggart, 1997) at DRDC Atlantic. SHIPMO7 is to a large extent a classical strip theory code (Salvesen et al., 1970), but the code includes appendage and viscous forces and it uses an iterative procedure to obtain the roll amplitude and effective linearized damping for the prescribed sea conditions. Other details of the code, including additional references to verification studies of SHIPMO7, can be found in Stredulinsky and Thornhill (2011).

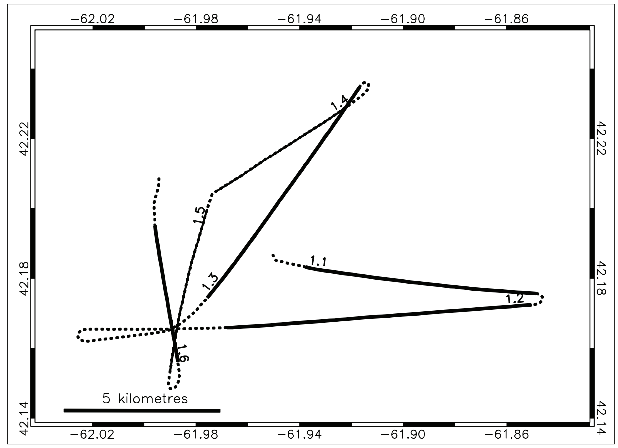

Fig. 4: Run pattern of trial no. 1.

Selecting Responses for Sea State Estimation

Typically, it is considered as a good compromise to include three responses at a time (Nielsen, 2006), when sea state estimation is carried out on the basis of Eq. (1). If fewer responses are used there may be a lack of "information", whereas more than three responses increases the computational time significantly. The specific selection of which three responses to include in the estimation analysis forms a general problem. In this analysis 8 combinations, or sets, of three responses have been formed from the motion measurements recorded. The considered sets are:

Set 1: {roll angle, pitch angle, vertical acc.}

Set 2: {roll angle, pitch angle, horizontal acc.}

Set 3: {roll angle, pitch rate, vertical acc.}

Set 4: {roll angle, pitch rate, horizontal acc.}

Set 5: {roll rate, pitch angle, vertical acc.}

Set 6: {roll rate, pitch angle, horizontal acc.}

Set 7: {roll rate, pitch rate, vertical acc.}

Set 8: {roll rate, pitch rate, horizontal acc.}

SEA STATE ESTIMATION

Results

The analysis of data has been conducted as a post-voyage process and the results of the wave buoy analogy (WBA) are given in Figs. 5-7 that show the significant wave height, H_s, the zero-crossing period, T_z, and the absolute mean wave direction, v, respectively. For the individual wave parameter, the "true" value, obtained as the mean value of the three wave rider buoys (MEDS, TRIAXYS, Triaxys MINI), is included in the figures with legend 'DRDC'. The estimated significant wave heights of the three wave rider buoys shows in some cases more than a plus/minus 15% scatter compared to the mean value. Similarly, a difference of more than plus/minus 1 second is observed for the crossing period, whereas the mean wave direction between the buoys differs more than plus/minus 40 deg. in some cases. The corresponding scatter bands have been included in Figs. 5-7.

Two outcomes of the wave buoy analogy are presented in Figs. 5-7: The results corresponding to the wave estimations obtained by use of Set 2 of the motion measurements, and the results achieved when all the estimations obtained in the individual runs by Sets 1 to 8 are averaged.

Discussion

Based on Figs. 5-7 it is seen that the results of the wave buoy analogy compare reasonably well with the mean estimates by the wave rider buoys for nearly all runs. Since the "true" wave parameters are known, as a result of the deployment of real wave rider buoys in the sea trial area, it is easy to select the set of motion measurements that leads to the most accurate sea state parameters, when the wave buoy analogy is applied for wave estimation. In this way, Set 2 of the motion measurements has been selected. The selection has been based on a combined root-mean-square difference calculation considering all wave parameters (H_s, T_z, v).

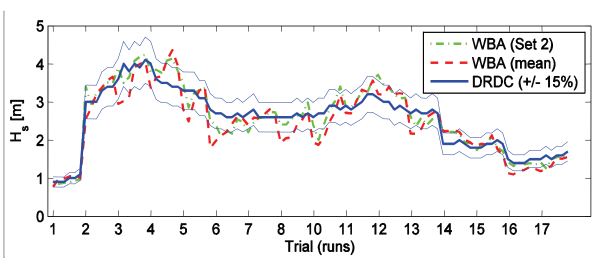

Fig. 5: Estimates of significant wave height by wave buoy analogy (WBA) and wave rider buoys (DRDC).

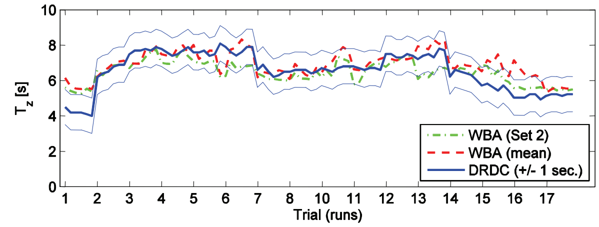

Fig. 6: Estimates of zero-crossing period by wave buoy analogy (WBA) and wave rider buoys (DRDC).

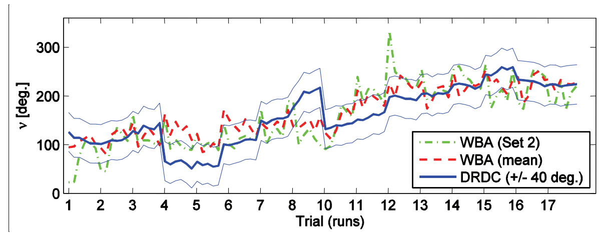

Fig. 7: Estimates of the mean (absolute) wave direction by wave buoy analogy (WBA) and wave rider buoys (DRDC).

It is clear that such a selection is possible only because the "true" wave parameters are known. Under normal operational conditions, considering any type of vessel at an arbitrary position in the ocean, the wave parameters are unknown and the selection of the best set of responses must be based on other means. Until recently, no research has studied the development of approaches that can be used to select – automatically – the most sensible set of responses for particular operational conditions, when the wave buoy analogy is used for wave estimation. However, Lajic (2010) and Lajic et al. (2010) have developed ideas that can be useful for the specific purpose. The ideas have been derived within the field of control theory, and preliminary results indicate that an automatical selection of a set of responses is possible. In the future it will be of interest to study this topic further and to apply and elaborate on the approaches (Lajic, 2010; Lajic et al. 2010) using, e.g. the set of full-scale data studied in this paper.

As an alternative to select one specific set of motion measurements it is interesting to note (Figs. 5-7) that the mean value, formed by the average of the 8 sets of responses, provides also a fair estimate of the individual wave parameter for all runs. The standard deviation on the significant wave height of the 8 sets are seen in Fig. 8. The spreading is normalised with the mean value of the wave rider buoys and is seen to be less than 30 percent in all runs. Thus, it is a reasonable option to consider the 8 sets all together. However, the disadvantage of this approach is the increased computational time, which would be an issue for real-time onboard sea state estimation. On the other hand, for the specific implementation of the wave buoy analogy, using parametric modelling, it takes approximately 10 minutes to obtain the sea state estimate of one run using all 8 sets of motion measurements (intel® CORE™ i5, 2.40 GHz). Consequently, it would be feasible to update the sea state estimate at a reasonable time interval.

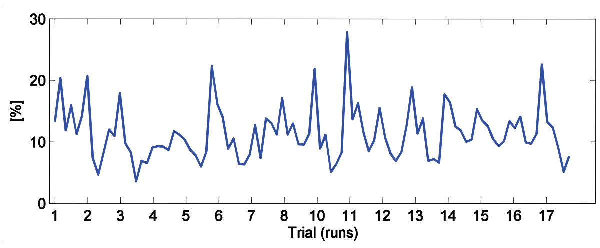

Fig. 8: The relative spreading on significant wave height using the 8 different sets of measurements.

Although mixed-sea conditions can be estimated by the wave buoy analogy, the present analysis lacks a detailed study of the agreement of the actual distribution of wave energy with frequency and direction. This choice has been made due to space limitations. However, not only integrated wave parameters but the complete distribution of wave energy must be correct for decision support systems to give reliable guidance with respect to critical wave-induced events. A more comprehensive study of the considered data should therefore be made.

CONCLUSIONS

It has been shown that the wave buoy analogy can be used to obtain sea state parameters at the position of an advancing ship. In the paper, full-scale motion measurements from sea trials conducted by DRDC Atlantic were studied. The agreement between estimates of wave parameters by the wave buoy analogy and and by real wave rider buoys was good. More detailed comparisons of the frequency-directional distribution of energy lacks and should be carried out also in the future.

REFERENCES

Brunt, E. (2003). Motion Sensor Acquisition System, DRDC Atlantic TM 2003-139, Defence R&D Canada – Atlantic.

Goda, Y. (2000). *Random Seas and Design of Maritime Structures*, Advanced Series on Ocean Engineering, Vol. 15, World Scientific.

Iseki, T. and Ohtsu, K. (2000). Bayesian estimation of directional wave spectra based on ship motions, *Control Engineering Practice*, Vol. 12, pp. 25-30.

Hansen, S.V. and Lützen, M. (2010). Performance Monitoring and Ship Modelling by the Bond Graph Method, *Proc. 11th PRADS*, Rio de Janeiro, Brazil.

Hogben, N. and Cobb, F.C., (1986). Parametric Modelling of Directional Wave Spectra, *Proc. 18th Offshore Technology Conference*, Houston, TX, USA.

Jensen, J.J. (2011). Probability of Parametric Roll in Random Seaways, *In: Fossen and Nijmeijer (Eds.), Chap. 4*, Parametric Resonance and Dynamical Systems, Springer.

Lajic, Z. (2010). *Fault-tolerant Onboard Monitoring and Decision Support Systems*, Ph.D. thesis, Dept. Mech. Engineering, Technical University of Denmark.

Lajic, Z., Nielsen, U.D. and Blanke, M. (2010). Fault Isolation and Quality Assessment for Shipboard Monitoring, *Proc. 29th OMAE conference*, Shanghai, China.

McTaggart, K. (1997). An updated strip theory program for predicting motions and sea loads in waves, Technical Report DREA TM96/243, Defence Research Establishment Atlantic.

Neumaier, A. and Schneider, T. (2001). Estimation of Parameters and Eigenmodes of Multivariate Autoregressive Models, *ACM Transactions on Mathematical Software*, vol. 27, pp 27-57.

Nielsen, U.D. (2006). Estimations of on-site directional wave spectra from measured ship responses, *Marine Structures*, Vol. 19, pp. 33-69.

Nielsen, U.D. (2007). Response-based estimation of sea state parameters – influence of filtering, *Ocean Engineering*, Vol. 34, pp. 1797-1810.

Nielsen, U.D. (2008). Introducing two hyperparameters in Bayesian estimation of wave spectra, *Probabilistic Engineering Mechanics*, Vol. 23, pp. 84-94.

Pascoal, R., Guedes Soares, C. and Sørensen, A.J. (2007). Ocean wave spectral estimation using vessel wave frequency motions, *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 129, pp. 90-96.

Pascoal, R. and Guedes Soares, C. (2008). Non-parametric wave spectral estimation using vessel motions, *Applied Ocean Research*, Vol. 30, pp. 46-53.

Pascoal, R. and Guedes Soares, C. (2009). Kalman filtering of vessel motion for ocean wave directional spectrum estimation, *Ocean Engineering*, Vol. 36, pp. 477-488.

Salvesen, N, Tuck. E. and Faltinsen, O. (1970). Ship Motions and Sea Loads, *Trans. SNAME*, Vol. 78, pp. 250-287.

Simos, A.N., Tannuri, E.A., Sparano, J.V., and Matos, V.L.F. (2010). Estimating wave spectra from the motions of moored vessels: Experimental validation, *Applied Ocean Research*, Vol. 32, pp. 191-208.

St. Denis, M. and Pierson, W.J. (1953). On the Motions of Ships in Confused Seas, *Trans. SNAME*, Vol 61, pp 280-332.

Stredulinsky, D.C. (2010). Quest Q319 Sea Trial Summary and Wave Fusion Analysis, DRDC Atlantic TM 2010-051, Defence R&D Canada – Atlantic.

Stredulinsky, D.C. and Thornhill, E. (2011). Ship Motion and Wave Radar Data Fusion for Shipboard Wave Measurement, *Journal of Ship Research*, (to be published).

Tannuri, E.A., Sparano, J.V., Simos, A.N. and Da Cruz, J.J.. (2003). Estimating directional wave spectrum based on stationary ship motion measurements, *Applied Ocean Research*, Vol. 25, pp. 243-261.