1996ESASP.383..303H

APPLICATION OF WAVE SPECTRAL RETRIEVALS FROM ERS-1 SAR WAVE MODE DATA FOR IMPROVED WIND AND WAVE FIELD ANALYSES

P. Heimbach, S. Hasselmann, C. Brüning and K. Hasselmann

Max-Planck-Institut für Meteorologie, Bundesstr. 55, D-20146 Hamburg, Germany
Tel. (+ 49) - 40 - 41 17 33 77, Facs.: (+ 49) - 40 - 41 17 32 98, e-mail: heimbach@dkrz.de

Abstract

This paper focusses on the operational applications of two-dimensional wave spectra retrieved from ERS-1 SAR Wave Mode data. An improved algorithm for retrieving ocean wave spectra from SAR Wave Mode imagette spectra is described and used to assimilate wave data into the WAModel. The assimilation is based on an optimal interpolation method applied to a spectral partitioning representation of the wave spectrum. Information on the wave field is used to correct both the wave and wind field. Finally, first results are presented of a statistical intercomparison between ocean wave spectra derived from ERS-1 SAR Wave Mode spectra and from the WAModel for a 2 1/2 year data set.

1 INTRODUCTION

With the development of the third generation wave model WAM ([15]), which explicitly solves the energy balance equation for the two-dimensional wave variance spectrum, a powerful tool has become available for research and forecasting applications (see also Komen *et al.* [7]). The WAModel has been extensively validated through implementation at operational forecasting centres such as the European Centre for Medium Range Weather Forecasting (ECMWF) and at many research institutions.

However, prior to ERS-1 no data has been available which provided both continuous global coverage and information on the full two-dimensional spectral structure of the wave field. Thus, validation against observations has been restricted to individual field experiments and relatively sparse operational buoy measurements (for an overview see [7]).

Operational assimilation of wave data has so far been implemented only for significant wave height data retrieved from the ERS-1 altimeter (Lionello *et al.* [8]). A single wave parameter, however, is necessarily of limited value in updating the full two-dimensional wave spectrum. Knowledge of the detailed structure of the wave spectrum, on the other hand, is essential not only for reliable wave predicition, but also for many applications, such as shiprouteing and offshore activities, involving the computation of the response of various structures exposed to complex wave forces. A separation of the wave field into windsea and swell components is furthermore required for the development of an advanced wind and wave data assimilation scheme, as outlined below, which attempts to combine wind and wave data in a dynamically consistent simultaneous update of both wind and wave fields.

The operation of the ERS-1 Synthetic Aperture Radar (SAR) in the so-called SAR Wave Mode (SWM) provided for the first time global two-dimensional wave spectral data in near real time. In contrast to the SAR 100 km full-swath mode, which can be operated only during maximally 10 % of the orbit and while in line-of-sight of a ground station, during SWM operation 10 × 6 km snap shot imagettes are collected globally every 200 km along the satellite track. The data are stored on board and transmitted to the ERS ground stations, where they are processed to power spectra, the so called ERS.SWM.UWA Fast Delivery Product (FDP), on a reduced 12 × 12 polar wavenumber grid (for a description see [4]).

The retrieval of ocean wave spectra from the Wave Mode imagette spectra is not straightforward, since the SAR imaging mechanism is strongly nonlinear due to the distortions induced by the wave orbital motions (the velocity bunching mechanism). This leads, among other effects, to a loss of information beyond the so-called azimuthal cut-off, corresponding to wavelengths in the satellite flight direction

Proceedings of the Second ERS Applications Workshop, London, UK, 6–8 December 1995 (ESA SP-383, February 1996)

© European Space Agency • Provided by the NASA Astrophysics Data System

1996ESASP.383..303H

shorter than typically 100m. In addition, ocean wave spectra from satellite SAR images (as presently processed) suffer from a basic 180° frozen-image ambiguity.

Nevertheless, the relation between ocean wave spectra and SAR imagette spectra is basically well understood (see [10] and references therein), and through the derivation of a closed nonlinear integral describing the mapping of an ocean wave spectra into SAR spectrum, Hasselmann and Hasselmann ([11]) were able to develop an efficient inversion algorithm enabling a reliable retrieval of ocean wave spectra from SAR imagette spectra within the computational constraints of real-time operational applications.

The original inversion algorithm has been validated (see [3]) and has recently been improved ([13] and [14]), as shortly summarized in the following section. Section 3 describes the assimilation of ocean wave spectra retrieved from SWM imagette spectra in the WAModel. It is shown that measurements of the wave field yield also corrections of the wind field which drives the waves. To reduce the computational requirements in accordance with the restrictions of operational applications, the detailed two-dimensional spectral information is projected onto a smaller set of spectral parameters by partitioning the wave spectrum into a number of individual wave systems. Each wave system, obtained through a modified form of Gerling's partitioning technique ([5]), is characterized by a mean energy, frequency and propagation direction . Finally, in section 4 first results from a statistical intercomparison between ocean wave spectra retrieved from SWM spectra and from the WAModel over a 2 1/2 year period are presented. Despite good overall agreement, small but systematic discrepancies are revealed when the spectra are partitioned into windsea and swell systems. The seasonal and regional stratification of the data provides a useful climatological sea state data base.

2 The retrieval of ocean wave spectra from SAR imagette spectra

The inversion of the closed nonlinear spectral transform relation defining the mapping of an ocean wave spectrum into a SAR image spectrum is carried out iteratively (Hasselmann and Hasselmann ([11]). A SAR spectrum is first computed, using the forwards transformation relation, from a first guess spectrum obtained from a model. The input spectrum is then iteratively modified until a cost function representing the error between the simulated and observed SAR spectra is minimized. The cost function penalises not only the error between observed and simulated SAR spectrum, but also the deviation of the modified wave spectrum from the first-guess spectrum. This has the effect of inserting information from the first guess wave spectrum where information from the SAR spectrum is lacking, namely in resolving the 180° ambiguity and at high wavenumbers beyond the azimuthal cut-off. An important feature of the retrieval algorithm is that the retrieved wave spectra can be calibrated internally, independent of the instrument calibration, using the observed level of the clutter-noise spectrum in the high wavenumber domain beyond the wave spectral signal (see [1]).

Although the original method of Hasselmann and Hasselmann yielded generally reliable retrievals, occasional deficiencies were observed:

(i) The azimuthal cut-off wavelengths were sometimes too high, the inverion algorithm being unable to adjust the input spectra to reproduce the observed cut-off.

(ii) The spectra occasionally exhibited discontinuities in the transitional region connecting the low wavenumber part of the spectrum, which had been modified by the SAR data, and the high wavenumber region beyond the cut-off, in which the original first-guess spectral form was retained.

(iii) In a few cases in which the retrieved spectrum differed significantly from the first-guess spectrum, the simulated and observed SAR spectra also showed larger discrepancies. This was due to the fact that the retrieved spectrum was not allowed to adjust completely freely, but was partially constrained by the first-guess spectrum.

(iv) Finally, the simulated SAR spectra tended to have sharper azimuthal cut-offs than the observed SAR spectra. This was attributed to the smoothing incurred in the SAR spectra of the ESA Fast Delivery Product, which were represented on a 12 × 12 polar (log) wavenumber grid. This last effect was corrected by introducing a similar smoothing filter in computing the simulated SAR image spectra at each iteration step of the cost function minimisation.

To resolve the first three shortcomings, two modifications where introduced into the retrieval algorithm ([13]).

1. A third term was added to the cost function explicitly penalizing errors in the cut-off wavenumber. To accomodate this term, the overall energy level of the wave spectrum was adjusted,

© European Space Agency • Provided by the NASA Astrophysics Data System

in addition to the energy distribution itself. This affects the wave spectrum also in the high wavenumber region of the spectrum beyond the azimuthal cut-off, where no direct SAR information is available. However, the approach is justified by the fact that the high-wavenumber part of the spectrum contributes significantly to the rms orbital velocity, which determines the cut-off.

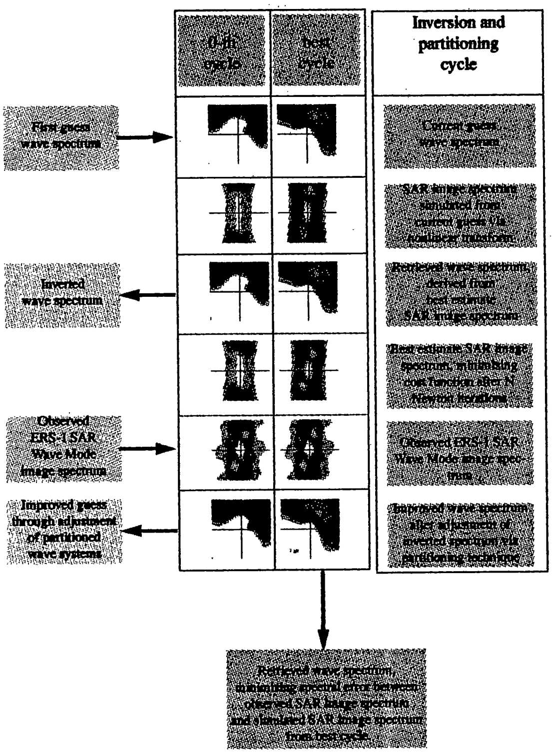

Figure 1: Different steps in the retrieval algorithm, illustrating the iterative improvement of the simulated SAR image spectrum

2. To achieve a smooth transition across the cut-off region, the wave spectrum was decomposed into a number of wave systems, using a modified version of Gerling's partitioning scheme (described briefly in section 3). After cross-assigning the individual first guess and inverted wave systems, the first guess wave systems were adjusted to the systems inferred from the inverted spectrum by modifiying the characteristic mean wave-system parameters (significant wave height, mean frequency and mean propagation direction) by a suitable rotation and rescaling in frequency and energy. A modified input (second guess) spectrum was then reconstructed by superimposing the adjusted wave systems of the original first guess spectrum. Occasionally, a low-wavenumber wave system was found in the SAR-inverted wave spectrum which had no counter-part in the first guess. Such wave systems, indicating swell which the model failed to predict, were simply superimposed onto the modified input spectrum. The modified spectrum now served as an improved input spectrum in a subsequent inversion cycle, the whole procedure being repeated several times if necessary.

   The additional iteration loop on the input spectrum allowed the final retrieval to decouple from the original first guess spectrum, thus leading to a closer agreement between observed and final simulated SAR image spectrum.

   However, it was found that repeated application of the inversion cycle using the iteratively improved input spectrum ultimately leads – in combination with the spectral partitioning scheme – to a gradual broadening of the spectrum and a divergence of the simulated and observed SAR spectra. Thus the iteration on the input spectrum was terminated at the iteration cycle yielding the smallest error between the simulated and observed SAR spectra.

The different steps of the modified retrieval algorithm are illustrated in Figure 1. The figure demonstrates also, for the example chosen, the improvement in the agreement between the best estimate and observed SAR image spectra which can be achieved by iterating the input spectrum.

3 Assimilation of SAR wave data using an optimal interpolation scheme

Existing wave data assimilation schemes have been developed so far only for significant wave heights H_s derived from the ERS-1 altimeter (altimeter wave heights have been or are available also from other satellites such as SEASAT, GEOSAT or TOPEX/POSEIDON, but not in real time, as required for operational applications). In the scheme of Lionello *et al.* ([8]), which has been implemented operationally for global wave forecasts at ECMWF, a set of H_s-values obtained within a given observational time interval is optimally interpolated to all model grid points which lie within a correlation length from the observed data points. The updated model wave field is then obtained by adjusting the total energies of the model wave spectra to agree with the analysed H_s field. At the same time, the frequency scales of the spectra are adjusted, using

© European Space Agency • Provided by the NASA Astrophysics Data System

1996ESASP.383..303H

1996ESASP.383..303H

either fetch and duration laws, in the case of windseas, or the condition that the mean wave slopes remain unchanged, in the case of swell.

The optimal interpolation method of Lionello *et al.* ([8]) can be readily generalized to wave spectral data derived from ERS-1 SWM spectra using the retrieval algorithm described in the previous section. For this purpose, both the WAMmodel and SAR-retrieved wave spectra are partitioned into their individual wave systems ([12], [13]), each of which is characterized by three mean parameters: significant wave height H_s, mean frequency $\bar{f}$ and mean propagation direction $\bar{\theta}$. This represents a significant reduction of the full two-dimensional spectral information to a manageable data set amenable to operational data assimilation. Conveniently, the wave system parameters at the locations of the SAR observations are already computed in the process of the retrieval. However, the partitioning is also carried out at all other model gridpoints within a correlation length scale of the observation points.

To establish a correspondence between observed and modelled wave systems, and between modelled or observed wave systems at different locations, a suitable cross-assignment criterion must be introduced. This is based on a dimensionless distance between the wave systems, defined in the three-dimensional phase space of the model parameters. Observed wave systems which cannot be assigned to a modelled system are introduced as additional wave systems into the updated wave field. However, model wave systems for which no counterpart is found in the SAR retrievals are not deleted from the updated wave field. In this case it is assumed that the SAR was unable to observe the wave system because of low signal-to-noise levels, azimuthal cut-off limitations or other instrumental contamination problems.

Having cross-assigned the observed and model wave systems, updated fields of wave system parameters can now be constructed by standard optimal interpolation. The updated full wave spectrum at each model grid point is recovered by superimposing the corrected wave systems. Gaps are filled by parabolic interpolation.

Corrections in the wave field can be used to infer errors in the driving wind field. For this purpose, the wave systems can be separated into windsea and swell. In practice, it is found useful to introduce also a third wave system class representing mixed windsea and swell. This occurs mainly in turning wind situations in which the usual criterion for a pure windsea is not satisfied, but the wave system is nevertheless still being influenced by the wind. Wave systems are regarded as pure windsea if the component of the wind velocity in the mean propagation direction of the wave system is greater than 1.3 times the phase velocity of the wave system (defined in terms of the mean wave system frequency). The remaining components are then either pure swell or mixed windsea/swell systems. The wind field can now be correc-

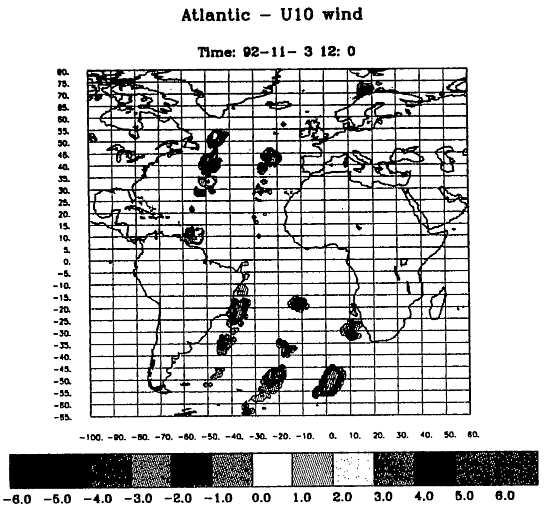

Figure 2: Wind field corrections for a 6 hour assimilation window

ted using the corrected mean wave parameters of the windsea systems. Applying empirical power law relationships for the dependency of the windsea spectral scale parameters on duration or fetch (see [9] and [8]), the duration or fetch dependency can be eliminated to express the local wind speed directly as a function of the total energy (or significant wave height) and mean frequency of the windsea. Since these parameters are updated by the wave data assimilation scheme, one obtains also a corrected wind field. Figure 2 shows as example wind field corrections for the Atlantic inferred from SAR data obtained during a six-hour observation window on November 3, 1992. In a final step the corrected and first guess wind field can be subjected to a further optimal interpolation analysis to yield a best estimate wind field.

4 Statistical intercomparison between SWM-derived and WAModel spectra

The improved retrieval algorithm described in Section 2 has been applied to derive spectral wave parameters from the ERS-1 SWM data for the 2 1/2 year

© European Space Agency • Provided by the NASA Astrophysics Data System

1996ESASP.383..303H

period July 1992 - December 1994 (additional data after this period are currently being processed). Continual long term time series of spectral wave parameters with global coverage are valuable both for research and for the establishment of a global wave climatology. Approximately 1 000 spectra per day were processed, of which about 5 % had to be rejected due to poor signal-to-noise ratio. For another roughly 15 % a reliable inversion failed. The remaining spectra were subjected to various intercomparisons with model spectra computed operationally with the WAModel on a global 3° × 3° grid at ECMWF. In addition to standard integral parameters such as the total significant wave height and wave period, the characteristic parameters of individual wave systems were intercompared both globally and on a regional and seasonal basis. While the spectrally averaged parameters showed good general agreement, the intercomparison of individual wave systems indicated small but systematic discrepancies.

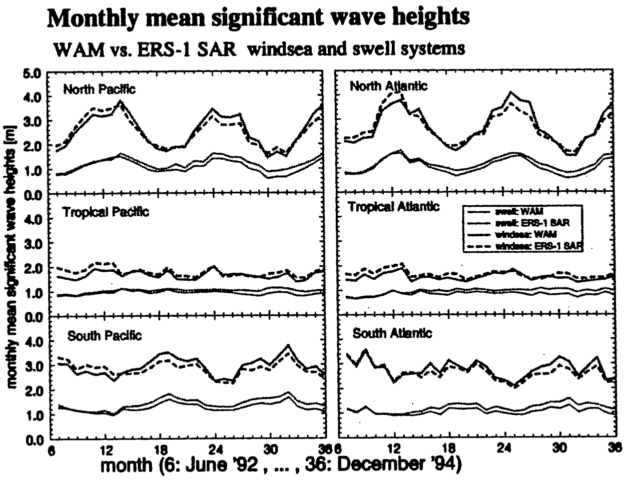

Figure 4: Time series of monthly mean H_s of windsea and swell systems for different ocean basins. Curves for WAM and for ERS-1 SAR retrievals are depicted.

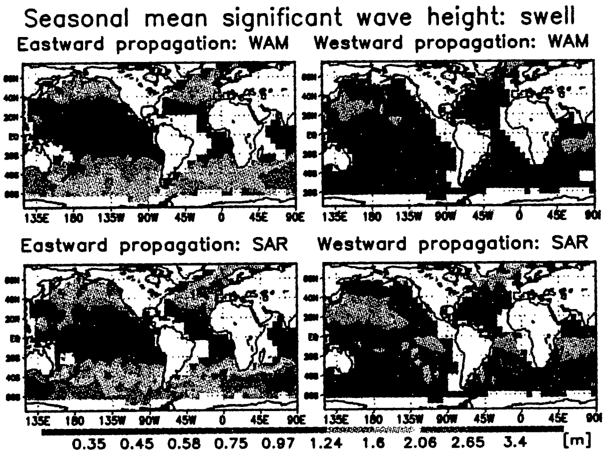

Figure 3: Seasonal mean significant wave heights of swell systems travelling to the East (left panel) or West (right panel) for the period Sept. to Nov. 1994.

Figure 3 depicts as example the average significant wave height of swell systems travelling to the East (left panel) or West (right panel) for (northern-hemisphere) Autumn 1994. The influence of the trade winds is clearly seen in the tropical wave systems travelling to the West, Note also the large swell systems emerging from the regions of high wave activity in the Southern Ocean. Figure 4 shows the corresponding time series of windsea and swell for the North, Tropical and South Pacific and Atlantic in the two propagation directions for the full 2 1/2 year period. The systematic deviations between model and observed wave heights cannot be attributed to erroneous input wind fields alone: the WAModel tends to overpredict the wave height for windsea systems, whereas swell is underpredicted. The data indicate a slightly too strong dissipation source term in the WAModel at low frequencies and a somewhat too strong wind input source function. However, more detailed investigations, including analyses of individual events, are needed to clearly identify the causes of the discrepancies.

5 Conclusions

Detailed knowledge of the two-dimensional wave spectrum is necessary for many applications, including wave prediction, wave research, ship routeing, offshore activities, the construction of reliable wave climatologies and, ultimately, an improved understanding of air-sea interaction processes and the development of coupled atmosphere-wave-ocean models. The synthetic aperture radar is at present the only instrument capable of providing such data continuously and with global coverage.

However, to reliably retrieve ocean wave spectra from observed SAR image spectra, the nonlinear image distortion due orbital motion effects must be taken into account. This problem has been successfully solved by an improved retrieval algorithm

© European Space Agency • Provided by the NASA Astrophysics Data System

1996ESASP.383..303H

based on an efficient inversion of a closed nonlinear forwards transformation relation. The application of the algorithm in an optimal interpolation assimilation scheme yields not only an update of the global two-dimensional wave spectral field, but provides also corrections of the driving wind field.

The statistical analysis of 2 1/2 years of ERS-1 data yields good overall agreement of the ERS-1 retrievals with the WAModel computations with respect to net significant wave height. However, small but systematic discrepancies between the modelled and retrieved wave heights for windsea and swell systems suggest that the WAModel physics can still be improved. The information contained in the ERS-1 spectral retrievals needs to be investigated in greater detail to identify the origins of the deviations found in this first exploratory statistical analysis.

Acknowledgements

This work is a contribution to the ESA pilot project PP2-D1 "Derivation and assimilation of ERS-1 wind and wave data" which is coordinated by Werner Alpers, Institut für Meereskunde, Universität Hamburg. Björn Hansen from ECMWF kindly provided the collocated WAModel spectra. We are also gratefull to R. Brokopf and C. Bennefeld for their assistance.

References

[1] Alpers, W. and K. Hasselmann, 1982: Spectral signal-to-clutter and thermal noise properties of ocean wave imaging synthetic aperture radars. *Int. J. Remote Sensing* **3**, 423-446.

[2] Bauer, E., S. Hasselmann, K. Hasselmann and H. C. Graber, 1992: Validation and assimilation of Seasat altimeter wave heights using the WAM wave model. *J. Geophys. Res.* **C97**, 12671- 1268

[3] Brüning, C., S. Hasselmann, K. Hasselmann, S. Lehner, T. Gerling, 1994: First evaluation of ERS-1 synthetic aperture radar wave mode data. *GAOS* Vol 2, pp. 61-98.

[4] ERS USER HANDBOOK, esa SP-1148, 1993

[5] Gerling, T.W., 1992: Partitioning sequences and arrays of directional wave spectra into component wave systems. *J. Atmos. Ocean. Techn.* **9**, 444-458.

[6] Hansen,B., C. Brüning and C. Staabs, 1994: Global comparison of significant wave heights derived from ERS-1 SAR wave mode, ERS-1 altimeter and TOPEX altimeter data. in: *Space at the Service of our Environment, Proceedings of the Second ERS-1 Symposium, Hamburg, Germany, 11-14 October 1993.* ESA SP - 361, 1994

[7] G.J. Komen, L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann und P.A.E.M. Janssen: Dynamics and modelling of ocean waves, Cambridge University Press, Cambridge, UK, 1994, 560. pp.

[8] Lionello, P., H. Günther and P.A.E.M. Janssen, 1992: Assimilation of altimeter data in a global third generation wave model. *J. Geophys. Res.* **C97**, 14453-14474.

[9] Hasselmann, K., D.B.Ross, P. Müller and W. Sell, 1976: A Parametric Wave Prediction Model. *J. Phys. Ocean.* **6**, 199-228.

[10] Hasselmann, K., R.K. Raney, W.J. Plant, W. Alpers, R.A. Shuchman, D.R. Lyzenga, C.L. Rufenach and M.J. Tucker, 1985: Theory of synthetic aperture radar ocean imaging. A MARSEN view. *J. Geophys. Res.* **C90**, 4659-4686.

[11] Hasselmann, K., S.Hasselmann, 1991: On the nonlinear mapping of an ocean wave spectrum into a synthetic aperture radar image spectrum and its inversion. *J. Geoph. Res.* **96** 10713- 10729

[12] Hasselmann, S., C. Brüning and P. Lionello, 1994: Towards a generalized optimal interpolation method for the assimilation of ERS-1 SAR retrieved wave spectra in a wave model. *Space at the Service of our Environment, Proceedings of the Second ERS-1 Symposium, Hamburg, Germany, October 1993.* ESA SP - 361.

[13] Hasselmann, S., C. Brüning, K. Hasselmann and P. Heimbach, An improved algorithm for the retrieval of ocean wave spectra from SAR image spectra, submitted to *J. Geoph. Res.*

[14] Hasselmann, S., C. Bennefeld and P. Heimbach, 1996: Algorithm for retrieving ocean wave spectra from SAR image spectra, Technical Report of the *German Climate Computer Centre, DKRZ*, in preparation

[15] WAMDI group, 1988: The WAM model - a third generation ocean wave prediction model. *J. Phys. Oceanogr.* **18**, 1775-1810.

© European Space Agency • Provided by the NASA Astrophysics Data System