Chapter 10

SUMMARY AND CONCLUSIONS

The thesis has shown both the potential as well as the limitations of different techniques for the retrieval of ocean wave parameters from complex SAR data. The study contains theoretical investigations as well as statistical analysis of data. The different parts will be summarized separately in the following sections.

10.1 Theoretical investigations

The first theoretical aspect discussed was a modification of the existing SAR cross spectra integral transform proposed by *Engen and Johnson* [1995], introducing a nonlinear formulation of the RAR modulation in order to avoid negative radar cross sections occurring in the existing linear model. The presented analysis is the first systematic investigation of this phenomenon. It was shown that for the ERS and ENVISAT configuration the effect is tolerable with less than 10% of meaningless cross sections. However, for future spaceborne systems with higher range resolution of up to 2 m, like TerraSAR, or for airborne SAR the effect becomes significant. For the TerraSAR configuration more than 20% of the predicted cross sections are outside the feasible range, if the linear model is used. To solve the problem, an exponential model for the SAR image intensity was proposed, which predicts positive cross sections under all configurations. The model is consistent with the former linear model in so far as both mean and variance of the RAR image are maintained. Based on the new RAR model, an integral transform was derived, which maps an ocean wave spectrum into the corresponding SAR look cross spectrum. Comparisons with the transform introduced in *Engen and Johnson* [1995] showed that the exponential RAR model leads to changes in the fine structure of the simulated cross spectrum, while overall shape and energy levels are maintained.

The second theoretical part was concerned with a first systematic analysis of the distribution of the phase, as well as the real and the imaginary part, of estimated SAR look cross spectra acquired over the ocean. The study was mainly motivated by the need of noise information in the SAR retrieval of ocean wave spectra. The main results of the investigation are:

- A model was proposed for the distribution of the estimated look cross spectrum, which has the coherence as a key parameter. The model provides pdfs for the phase, magnitude as well as the real and imaginary part of the cross spectrum depending on the amount of smoothing applied in the estimation.

- The coherence was factored into two components with the first one describing decorrelation due to SAR data noise, which is dominated by speckle, and the second one representing loss of coherence due to the motion of the sea surface.

- The noise model was applied to optimise the look separation time. It was shown that splitting the total bandwidth into two equal parts is a good choice, if the objective is to maximise the signal to noise ratio of the cross spectrum phase.

Combining the existing integral transforms for the SAR image variance spectrum [*Hasselmann and Hasselmann*, 1991] and the look cross spectrum [*Engen and Johnson*, 1995], a nonlinear model for the cross spectrum coherence was derived, which predicts the coherence of each spectral bin, given a two-dimensional wave spectrum. It was shown that in the linear approximation, decorrelation is due to waves propagating in opposite directions. In the general nonlinear case loss of coherence is caused by the coupling of wave components with different phase speeds in the SAR image formation process.

10.2 Ocean wave damping by sea ice

Damping of ocean waves travelling into sea ice was studied using spaceborne SAR data acquired over the MIZ. Typical imaging artefacts like spiky wave crests and wave refraction were analysed theoretically. It was shown that the observed effects can be explained by damping of the high frequency part of the ocean wave spectrum. A possible increase of the coherence time of the complex reflectivity within sea ice, was shown to have a minor impact for ERS SAR data.

A simple and robust method based on complex SAR data originally developed for wind speed measurements [*Kerbaol et al.*, 1998] was applied to estimate the orbital velocity variance of the sea surface in the open water as well as in the sea ice. The method has the advantage to be relatively insensitive to the RAR modulation, which is in general not accurately known for sea ice. An azimuthal cut-off wavelength estimated from the SAR look cross-correlation function was related to the orbital velocity variance by regression. A linear model was fitted based on simulation of the azimuthal image auto-correlation function using a global data set of two-dimensional ocean wave model spectra.

The orbital velocity variance was used as a parameter to estimate ocean wave damping. A sensitivity analysis for this parameter was carried out using parametric models for wind sea and swell systems. Simple analytical expressions were derived for the contribution of swell and wind sea to the orbital velocity variance depending on wind speed, swell wave height and wavelength.

The method was applied to ERS SAR scenes acquired over the Weddell and the Greenland Sea. It was shown that the estimated attenuation rates are consistent with measurements obtained in earlier field campaigns in the Greenland and Bering Sea.

In a second step a more sophisticated SAR inversion scheme for the MIZ was presented, which yields estimates for the two-dimensional ocean wave spectrum in front of, and behind the sea ice boundary, as well as a two-dimensional filter function characterising the sea ice impact on the ocean waves. The scheme makes use of first guess information taken from an ocean wave model. It was shown that the method provides results consistent with the cut-off estimation technique.

10.3 Statistical analysis of complex imagettes

A global data set of reprocessed ERS-2 wave mode raw data enabled the application of the cross spectrum technique on a statistical basis for the first time. A comparison with two-dimensional wave spectra computed with the WAM model run at the ECMWF showed good agreement of wave propagation directions, except for cases with very low signal to noise ratios. The analysis confirmed the theoretical finding, that the cross spectrum phase noise is increasing with decreasing spectral energy in the respective image variance spectrum.

The distribution of the cross spectrum phase showed a good agreement with the ocean wave phase speeds expected within the linear wave theory. Explanations for the small deviations observed were given.

Apart from the new phase information contained in the cross spectra, the reprocessed data allowed to make use of the full image information, which was not possible with the former standard wave mode product available from ESA. To detect image patterns associated with phenomena like wind rolls, rain cells, biological or anthropogenic surface films or sea ice, which spoil SAR wave measurements, an inhomogeneity test was proposed. The test checks the shift invariance of the image spectrum and is thus able to detect phenomena not associated with ocean waves, as well as strongly inhomogeneous ocean wave fields, which should not be used for wave spectra estimation. It was shown that the majority of inhomogeneous cases occurring in the open ocean is associated with very low wind speeds.

10.4 PARSA wave retrieval scheme

A new scheme for the retrieval of two-dimensional wave spectra from complex SAR data was presented. The partition rescale and shift algorithm (PARSA), which extends the MPI retrieval scheme [*Hasselmann et al.*, 1996], has the SAR cross spectrum and some prior ocean wave spectrum, e.g. taken from a numerical wave model, as input.

The scheme is based on explicit models for measurement errors, uncertainties in the forward model and errors in the prior spectrum. The model for measurement errors is based on the noise analysis performed in the theoretical part. It was shown that in the case of ERS or ENVISAT wave mode data, errors occurring in the estimation of the cross spectrum are relevant mainly for longer swell. To take into account errors in the SAR imaging model, two parameters describing uncertainties in the overall energy level and the cut-off wavelength of the simulated cross spectra were introduced as additional optimisation variables.

The PARSA scheme was tested using synthetic data. The test proved the ability of the method to measure wave spectra under the presence of different error sources, and to provide the respective error statistics of the retrieved parameters. Furthermore, the explicit use of the phase information provided by cross spectra was demonstrated.

The PARSA scheme was applied to a data set of 15000 reprocessed complex ERS-2 cross spectra acquired in August and September 1996. The main conclusions to be drawn from the retrievals are as follows:

- The WAM model tends to have lower wave heights for strong wind seas than the PARSA retrieval. There is some indication that this observation has to do with a possible underestimation of wind speeds on the southern hemisphere by the numerical model.

- For longer waves the WAM model tends to predict slightly shorter mean wavelength than measured by the PARSA retrieval.
- In particular for spectra with several swell systems like, e.g. frequently observed in the central Pacific, the imaginary part of the cross spectrum helps to resolve ambiguities in the wave propagation direction.

The PARSA scheme has thus shown its ability to make use of the additional information contained in SAR cross spectra, at the same time keeping consistent with the prior wave model spectra. It is therefore regarded as an ideal tool for wave model assimilation using the new ENVISAT ASAR wave mode data.