Global ENVISAT ASAR and coastal TerraSAR X Measurements of Sea State for validation of Ocean Wave Models

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Introduction

Satellite Synthetic Aperture Radar (SAR) images are acquired independent of light and weather conditions on a global scale. Figure 1 shows an example of a 5 km x 10 km ERS SAR wave mode image, reprocessed from SAR raw data at DLR and its respective image spectrum.

At weather centers SAR data are used to improve the two dimensional wave spectrum from a wave model by a nonlinear SAR ocean wave retrieval schemes.
In the present paper new algorithms to derive sea state parameters from globally available SAR wave mode data are briefly introduced, significant wave height (SWH) is derived and used to investigate severe storms and compiled to global statistics. The empirical algorithm CWAVE is extended from use for ERS SAR data (Schulz-Stellenfleth et al., 2007) to ENVISAT ASAR wave mode images (Li et al, 2009).

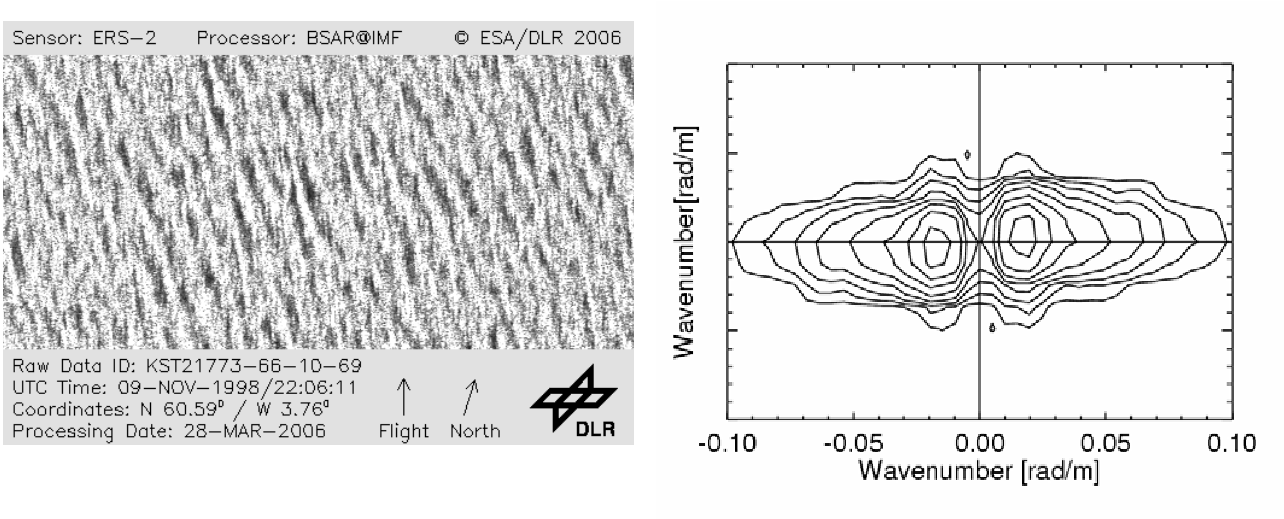

Figure 1: SAR wave mode image and respective image spectrum, acquired on Nov 9, 1998 over the North Sea near the Shiehallion accident

SAR measurements of integral ocean wave parameters like significant wave height (SWH) and mean period (TM) are compared to buoy and altimeter data, to ECMWF and DWD model results and are validated by SWH measurements from crossing altimeter tracks. ENVISAT ASAR SWH measurements from SAR show a scatter index of 24 % in comparison to buoy measurements, 16 % scatter index when compared to ECMWF data and 18 % to DWD data. Thus the CWAVE SAR SWH measurements show about the same quality as altimeter measurements. As SAR is a right looking instrument situated on the same satellite as the altimeter, on ground the SAR data are acquired on a parallel track around 300km off the nadir measuring altimeter sub-satellite track.

We use these double tracks to investigate severe storms and to compile global statistics in comparison to ECMWF and DWD model results. ERS data are available since November 1991 and ENVISAT data since March 2002. With the continuation of data from Sentinel 1 to be launched 2011 first investigations on wave climate statistics (or at least decadal variability) become possible.

For validation of high resolution coastal models and the investigation of refraction and wave breaking new datasets have become available to the science community from the TerraSAR X satellite. The new X-band (3 cm radar wave length) radar satellite TerraSAR-X (TSX) was launched in June 2007. Images with a resolution as good as 1 meter are available to the scientific community since December 2007, for data access see information on the TSX science web page at www.dlr.de .

TerraSAR-X images of the sea surface are used to measure the wind field and sea state to high resolution and are thus well suited to investigate the variability of the wind and ocean wave field in coastal areas and around offshore platforms.

While for the globally measuring ESA satellites ERS and ENVISAT usually only ocean waves from around 100 meter wave length are directly observable (depending on environmental conditions and wave travel direction in respect to the satellite antenna), see figure 1, on TSX images for the first time ocean waves can be observed from space in semi enclosed seas and on large lakes. In addition to measuring the two dimensional spectra, properties of individual wave trains can be observed.

Figure 2 shows a TAX Spotlight image as an example of shoaling swell entering the Bight of Melbourne at Port Philipp. Wave refraction, wave current interaction and wave breaking can be observed, a detailed description of the scene is given in Brusch et al, (2009).
TSX image scheduling times (for scientists) of only a day allows to easily acquire images of forecasted storm systems. Due to power limitations of the TSX satellite global ocean wave statistics cannot be acquired though by TSX.

Ocean wave length of the spectral peak has been measured on TSX data for waves from 10 meters spectral peak wave length onwards, shorter than the observation of around 60 meters for range travelling waves on images of the ERS and ENVISAT satellites.

Thus using TSX images the fetch laws of wave generation are directly observable in a JONSWAP-from-Space type of experiment (G. Diaz et al, 2009). Refraction of shoaling waves can be investigated and from the changing wave length and direction the underwater topography can be derived.

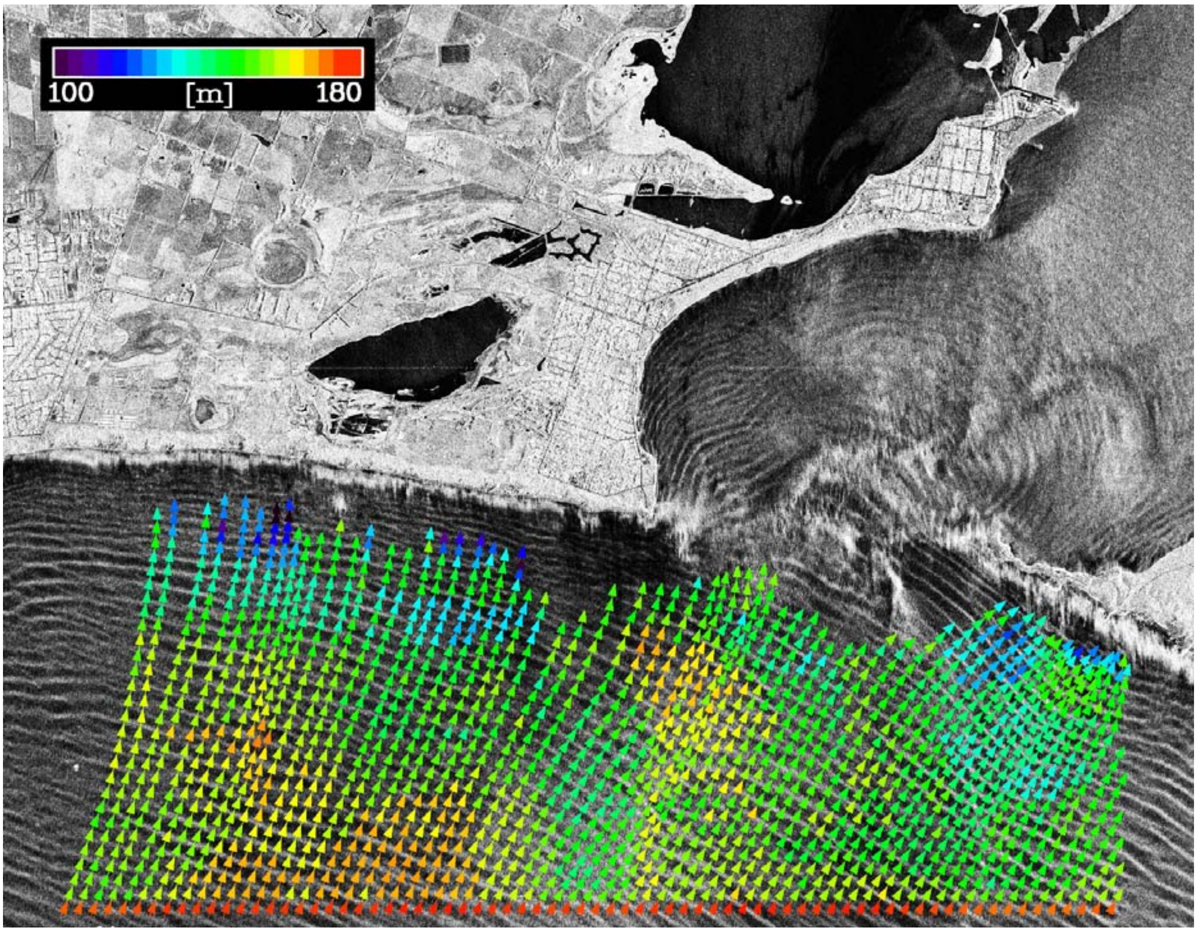

Figure 2 TerraSAR 5 km x 10 km TSX Spotlight image acquired over Port Philippon March 17, 2008, 19:45 UTC showing shoaling waves at the entrance to the Bight of Melbourne, colour coded is the change in ocean wave length

In the following we give an overview of the new possibilities arising from globally available SAR measurements of SWH since 1991 and the new high resolution data from TSX in coastal areas.

2. Data Set Description for global Sea State Measurements from ERS and ENVISAT

Assimilation of SWH from altimeter data into the WAM model has been performed by Lionello and Günther (1984) and is now in operational use at the ECMWF, DWD and the French Met Office. Impact on wave forecast is, e.g., discussed in Janssen et al 2007. Up to now independent measurements of SWH from SAR were not available though and can now be provided by the CWAVE algorithm.

2.1. ERS-1 and 2, ASAR global SAR and Altimeter data

The Synthetic Aperture Radar (SAR) onboard the European Satellite ERS-1,2 is operated in wave mode over the global oceans, whenever no image mode data acquisition is requested. For ERS the processed dataset contains daily between 1300 and 1500 images of 5 km (azimuth direction) by 10 km (range direction) size acquired over the global ocean (Lehner et al. 2000). Data from ENVISAT wave mode together with collocated ECMWF WAM wave spectra were downloaded from the CERSAT server at IFREMER and will soon be provided on ESAs GLOBWAVE server..

In the scope of the Wave Atlas Project, ESA provided a two-year wave mode dataset of ERS-2 SAR raw data mainly collected during 1999 and 2000. The data were reprocessed to single-look-complex (SLC) images at DLR using the BSAR processor. ENVISAT Wave Mode images collocated to EMWF WAM model data were made available by ESA for this study for the time frame of Nov 2006 to May 2007.

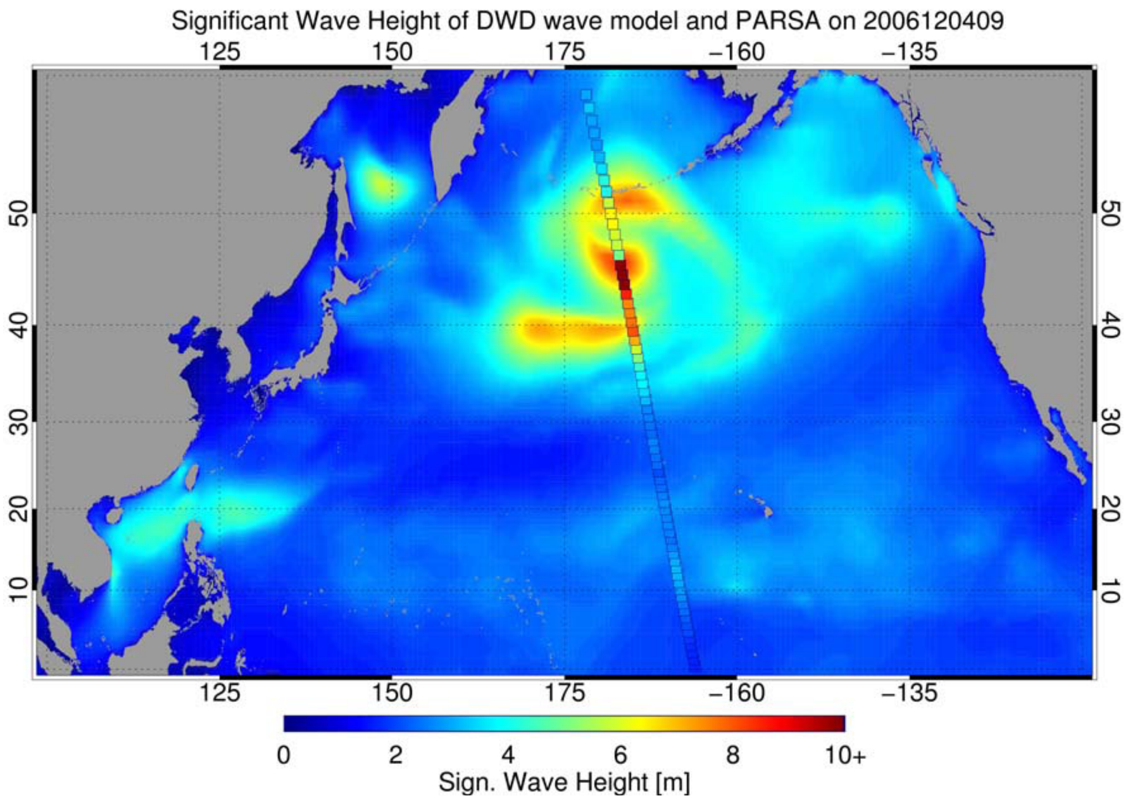

Fig. 3 SWH derived by the PARSA algorithm from ENVISAT ASAR wave mode data, colour coded squares give the SWH derived by nonlinear inversion PARSA on an orbit acquired on Dec, 4, 2006. The background shows SWH from DWD model data in the same colour scale .

2.2. Ocean Wave Model Data used in the Validation Study

The numerical wave model used here for comparison to the SAR data is the WAM model, a third generation model (WAMDI group 1998, and description of cycle 4, Guenther *et al.*, 1992), in which the wave spectrum is computed by integration of the energy balance equation.

For the case studies performed with ERS SAR data (available since November 1991) model results from the second reanalysis ERA-40 (www.ecmwf.int/research/era/) are used for comparison. DWD WAM model results at a spatial and temporal resolution of 0.75 degree grid and 3 hours respectively are stored at DWD since 2006 and are used for comparison to ENVISAT CWAVE results..

3. Measurements of Wind Field and Sea State from SAR

While the wind field on a global scale is usually measured by scatterometer using CMOD 4 or its update CMOD 5 (Hersbach et al. 2003), the same algorithm together with information on wind direction has been used on SAR images (e.g. Lehner et al, 1998). Some attempts have been made as well to derive the global wind field from SAR wave mode data (Horstmann et al., 2004). The wave mode images are usually small for derivation of wind direction, especially as the wind streaks detected on SAR images and used for directional information are less present on the open ocean

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SWH is usually measured by altimeter data. Due to the high resolution of SAR imagery several methods were developed to infer the full two dimensional spectrum from SAR images. Up to now only algorithms using additional information from a first guess or yielding limited information on some inner part of the spectrum are available, new development like CWAVE make as well the measurement of SWH and mean period possible. In the following some recent developments are described.

3.1 Nonlinear SAR inversion

Ocean wave information is traditionally derived from SAR by a nonlinear inversion using first guess information from a numerical wave model (like WAM) together with the SAR image spectrum, e.g., as in the MPI algorithm, (Hasselmann and Hasselmann, 1991).
A major point of criticism of first guess algorithms is of course the dependency of the results on this first guess. Still for case studies major differences between model and SAR measurement can be inferred, see e.g. figure 3 showing a North Pacific Storm for December 4, 2006.

This MPI approach has been extended to complex SAR image data and the related cross spectrum (Engen and Johnsson, 2000) in the so called PARSA algorithm, (Schulz-Stellenfleth *et al.*, 2005). The PARSA algorithm yields the full two dimensional ocean wave spectrum as a final result.

Further validation by buoy data and intercomparison to other algorithms is given in Li et al (2008). This paper shows that results from models and measurements agree well up to a sea

state of 4 meters. Usually due to smoothing in the models the inversion algorithm will yield SAR measurements with higher SWH especially in severe storms.
To derive information on individual wave properties from ERS SAR images, an algorithm making joint use of the image data and the cross spectrum was developed by Schulz-Stellenfleth and Lehner (2005).

3.2 Emprirical algorithm CWAVE
In addition to inversion methods, algorithms have been developed, to derive information on integral wave parameters like SWH from SAR images without the use of first guess information, e.g., called the CWAVE algorithm (Schulz-Stellenfleth *et al.*, 2007). This empirical algorithm is based on a quadratic function with 22 input parameters. These parameters include the radar cross section, the image variance, and 20 parameters computed from the SAR image variance spectrum. The proper quadratic function is obtained by fitting to the training dataset based on a stepwise regression method. The algorithm has been validated against buoy and altimeter data. The validation between SAR results and in situ data shows a root mean square error (RMSE) of 0.61 m in SWH.
An extension of the algorithm has been retuned to be used with ENVISAT ASAR data, called CWAVE_ENV, a validation yielding a scatter index of 24 % in comparison to buoy data is given in Li et al. (2009).

The standard ESA ENVISAT ASAR wave mode product, which will in near future be available on the ESA GLOBWAVE server, is concerned with the derivation of spectral energy density in some inner part of the ocean wave spectrum. The area over which wave height is derived varies for each spectrum, dependent on ocean wave travel direction and environmental parameters. Therefore, although this ESA product is often called swell product, it rather gives the energy contained in the inner part of the spectrum with such wave lengths as visible on the SAR images. These visible ocean waves are usually waves longer than 100 meters, but are not the ocean wave swell and the respective wave height measured (e.g. H12), correlates badly with swell wave height of ocean wave models..

Thus, while conventional SAR algorithms do not allow the generation of independent measurements of integrated wave parameters like significant wave height, this is possible by use of the CWAVE algorithm. Results from this algorithm can further be taken for independent model validation and compilation of global statistics just like altimeter measurements.

4. Example of SWH in Severe Storms and Derivation of global SWH Statistics from SAR

Figure 3 shows the SWH for a severe storm that occurred over the North Central Pacific on December 4, 2006 with significant wave height exceeding 10 meters and wind speed exceeding 20 meters per second.. Figure 3 shows the DWD SWH for 09:00 UTC in the background, SAR measurements are superimposed as coloured squares. From the SAR data the highest SWH occurring in the storm is estimated to be over 11 meters. Further discussion of SAR measurements of storm cases is given in the paper of Li et al. (2008 and.2009).

Significant wave height and zero up-crossing wave periods as derived from ASAR wave mode data using the CWAVE_ENV empirical algorithm are compiled into a global wave atlas.

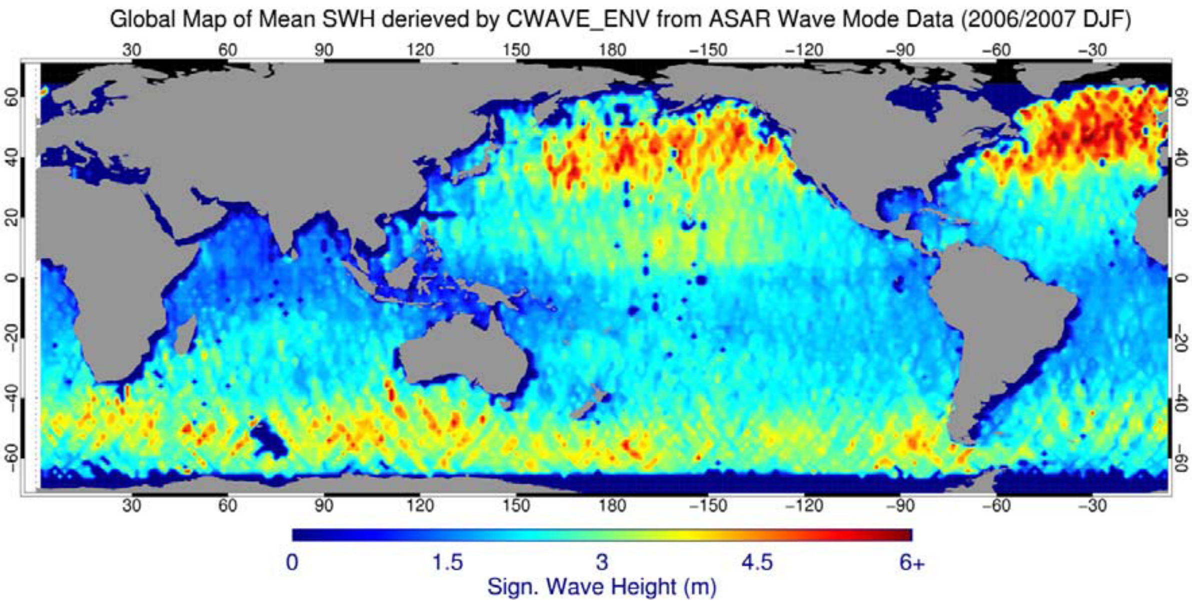

Figure 4 Mean significant wave height in 1.5 by1.5 degree boxes retrieved from ASAR wave mode data in winter season of 2006 / 2007 DJF

First results are given in Li et al, (2008), figure 4 shows as an example the global statistics of mean significant wave height derived by the CWAVE_ENV algorithm during the winter of 2006 and 2007. An extensive analysis of the full ERS and ENVISAT ASAR dataset that is available since 1991 and 2002 respectively in comparison to altimeter and model statistics remains to be done.

5. Coastal Ocean Wave Measurements from TerraSAR-X images

For investigation of rapidly changing wave fields in coastal areas data from TerraSAR-X (TSX), a high resolution right looking radar satellite, launched on June 15, 2007 are very suitable. TSX carries an X-band SAR sensor, that can be operated in different modes (coverage and resolution) and has quad polarization and dual receive antenna mode used for along track interferometry (ATI) experimental acquisitions. Additionally TSX supports the reception of along track interferometric radar data for the generation of current maps and quad polarisation. Information on how to order data can be found on the TerraSAR-X science web page.

The sensor is operating in the following modes, see figure 5:

- the "Spotlight" mode with 5 km x 10 km scenes at a resolution of 1-2 meters
- the "Stripmap"mode with 30 km wide strips at a resolution of 3.3 meters
- the "ScanSAR" mode with 100 km wide strips at a resolution of 16 meters.

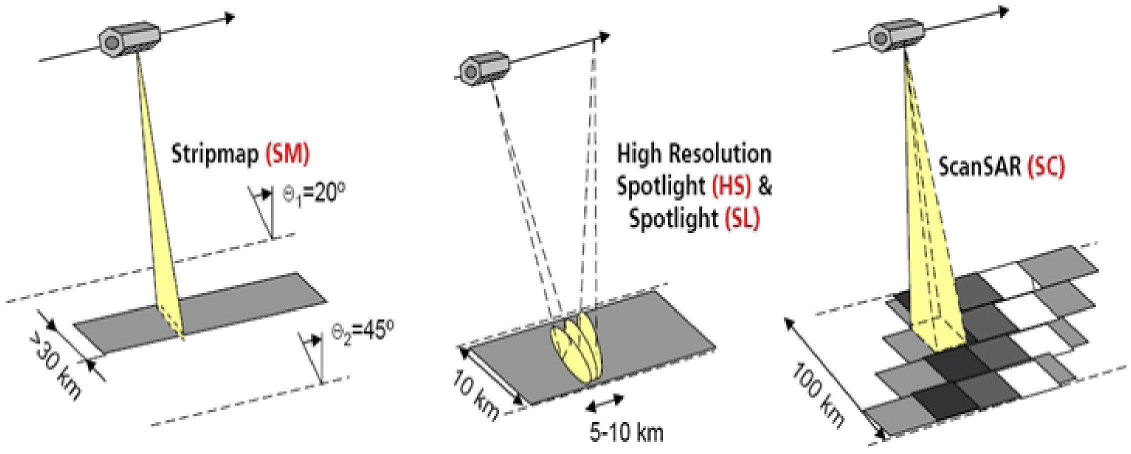

Figure 5 TerraSAR- X imaging modes

Figure 6 demonstrates the coverage of the different modes over the Azores islands. While from ScanSAR an overview of the mesoscale the wind field can be derived, details on the ocean wave field especially on wave refraction can be measured on the Stripmap and Spotlight TSX images. The case of wave refraction around Terceira island is further described in the upcoming special issue on TSX in IEEE TGARS by Li et al..

Figure 7 shows a comparison of a two dimensional ocean wave spectrum from a marine radar WAMOS and the TSX stripmap derived image spectrum. As up to now only intensity data are used. Wave direction for the WAMOS wave spectrum is coming from, the TSX spectrum shows two peaks The instrument is mounted on the North Sea island Heligoland

Figure 8 shows a case study of a swell refraction case acquired over Duck Pier. The data were used to infer underwater topography (Brusch et al 2010).

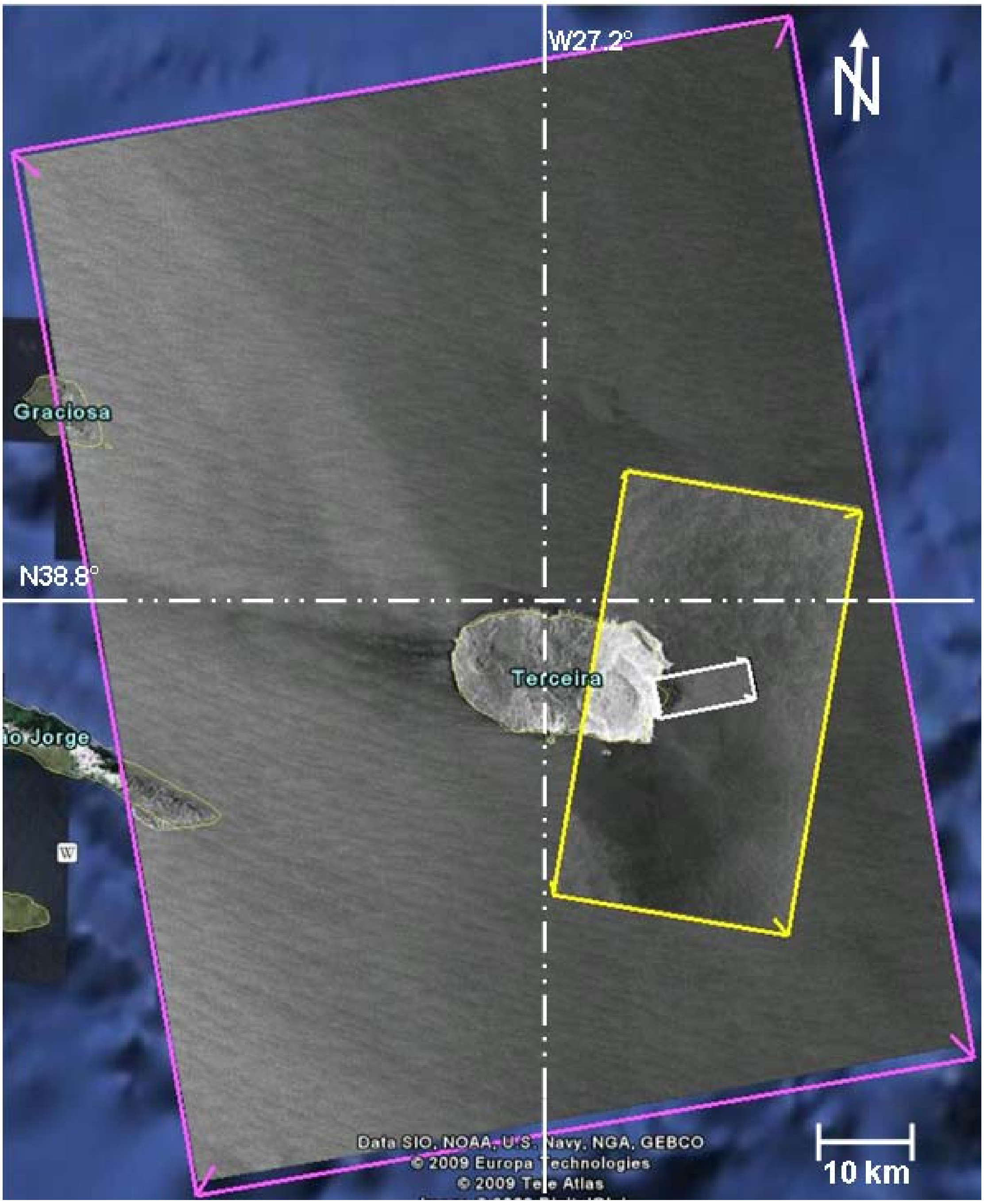

Figure 6: the three main modes of TSX acquired over the Azores (on three different dates), the pink frame is the Sscan SAR (100 km), yellow the Stripmap (30 km) and white the Spotlight image (5km x 10 km).

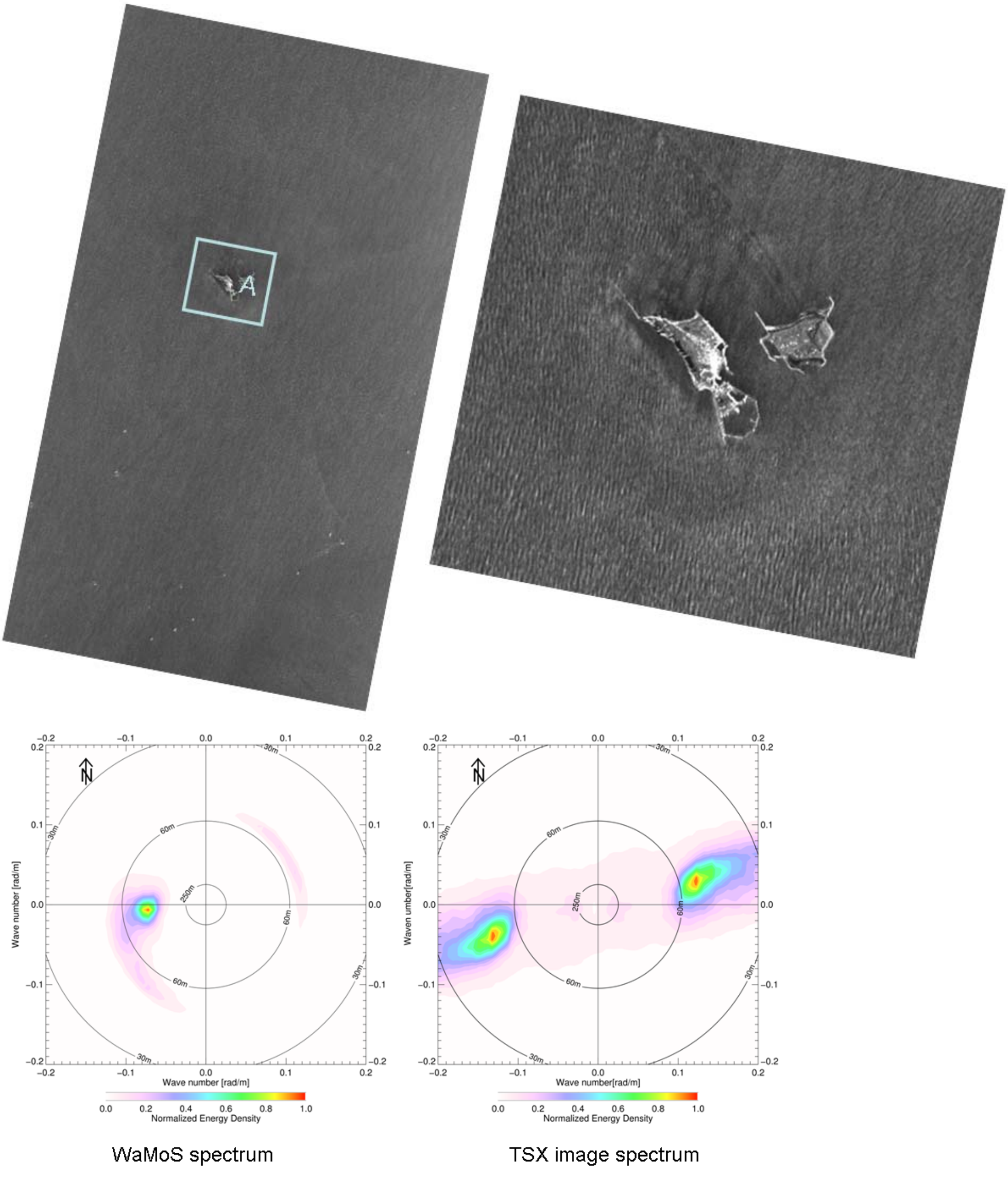

Figure 7: A (30 km x 100 km) stripmap TSX image and the subscene A of the North Sea island Heligoland from November 28, 2008 at 5:50 UTC. On the island a WAMOS radar is mounted. A comparison of the WAMOS and the TSX image spectrum is given. Wave direction of WAMOS spectra is coming from

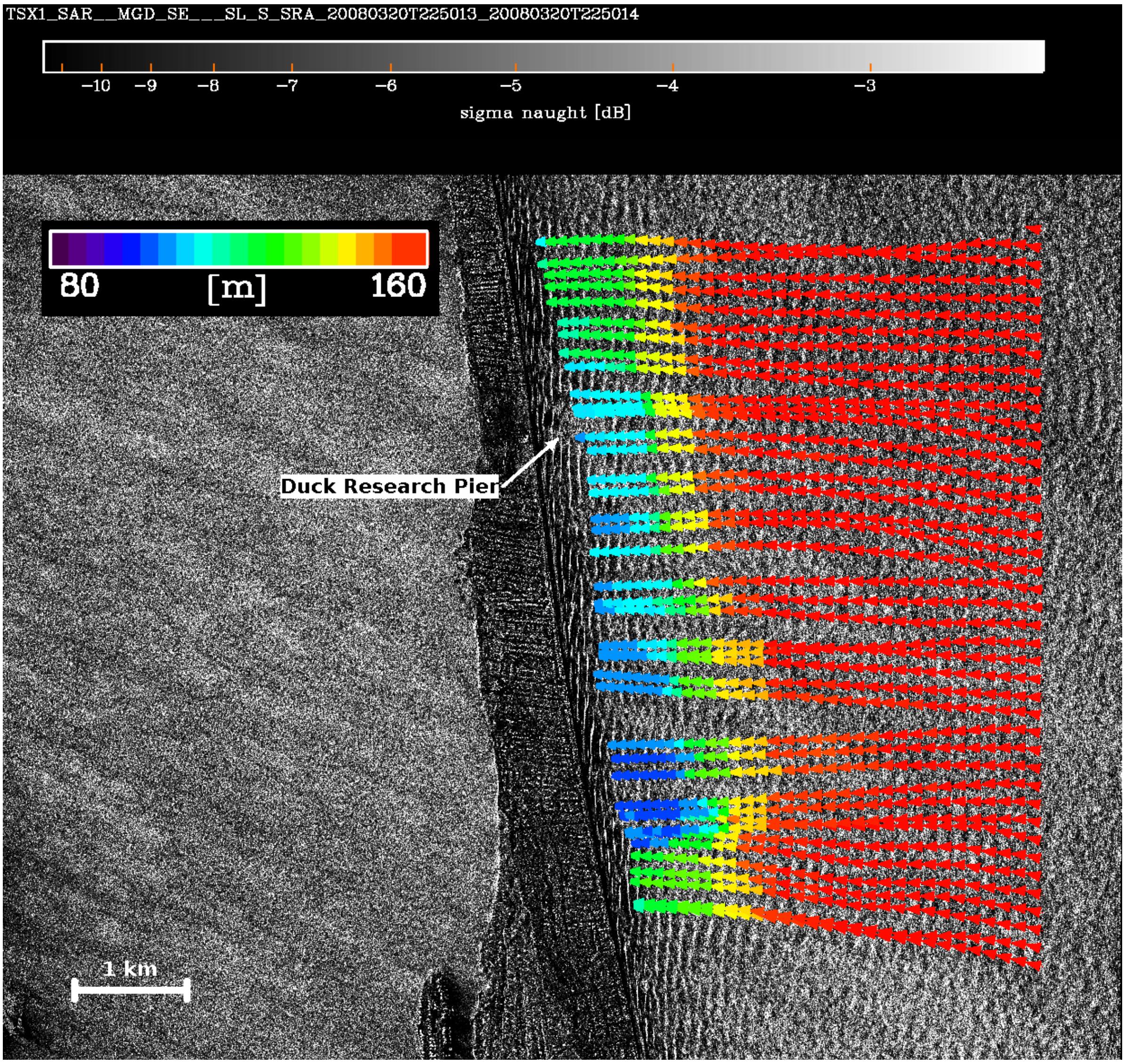

Fig 8: Swell refraction at Duck Pier, imaged by a TSX Spotlight image, acquired on March 20, 2008

Conclusions

The paper gives a summary of recent developments regarding sea state measurements from SAR data, details can be inferred from the respective literature.

A new empirical algorithm CWAVE that yields SWH from global SAR wave mode data has been developed, that gives a scatter index of around 20 per cent when compared to buoy data and crossovers of altimeter orbits.

This empirical algorithm CWAVE does not use wave model spectra as an input. As the SAR is a right looking instrument and altimeter data are nadir measurements, two measurement tracks around 300km apart are available. This makes cross validation and development of joint assimilation schemes possible.

High resolution coastal ocean wave measurements have been demonstrated using the new high resolution radar satellite TSX. New X band algorithms for wind field and sea state measurements are under development.

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References

S. Caires and A. Sterl, 2003, Validation of ocean wind and wave data using triple collocation, Journal of Geophysical Research, 108, doi: 10.1029/2002JC001491.

G. Diaz, S. Lehner, F.Ocampo-Torres, X. Li, S. Brusch , 2009, Wind and wave observations off the south Pacific coast of Mexico using TerraSAR-X imagery, IJRS, in print

G. Engen and H. Johnson, 2000, SAR-ocean wave inversion using image cross spectra, IEEE Transactions Geoscience and Remote Sensing, 33 (4), 329-360.

H. Günther, S. Hasselmann and P. Janssen, 1992, The WAModel cycle 4 (revised version). Technical report, Deutsches Klimarechenzentrum (DKRZ), Hamburg, Germany. Technical Report 4.

K. Hasselmann and S. Hasselmann, 1991, On the nonlinear mapping of an ocean wave spectrum into a synthetic aperture radar image spectrum and its inversion, Journal of Geophysical Research, 96, 10713-10729.

J. Horstmann., S. Lehner, H. Schiller, 2003, Global wind speed retrieval from SAR, IEEE Transactions Geoscience and Remote Sensing, 41(10), 2277-228

P. Janssen, B. Hanssen, and J-R. Bidlot, 1997, Verification of the ECMWF Wave Forecasting System against Buoy and Altimeter Data. Weather Forecasting, 12, 763–784.

S. Lehner, J. Schulz-Stellenfleth, J.B. Schättler, and H. Breit, J. Horstmann, 2000, Wind and wave measurements using complex ERS-2 wave mode data, IEEE Transactions Geoscience and Remote Sensing, 38 (5), 2246-2257.

X-M. LI, S. LEHNER, M. HE, 2008, Ocean Wave Measurements based on Satellite Synthetic Aperture Radar (SAR) and Numerical Wave Model (WAM) Data-- Extreme Sea State and Cross Sea Analysis, Int. Journ of Rem. Sens., Vol. 29:21,pp 6403 — 6416

X-M. LI, Th. KOENIG, J. SCHULZ-STELLENFLETH, S. LEHNER, 2009, Validation and intercomparison of ocean wave spectra retrieval scheme using ASAR wave mode data, Int. Journ of Rem. Sens., accepted

X.-M. Li , S. Lehner and Th. Bruns, 2009, Ocean Wave Integral Parameter Measurements Using ENVISAT ASAR Wave Mode Data, acceptedX. Li, S. Lehner, W.Rosenthal, 2009, Investigation of Ocean Surface Wave Refraction   Using TerraSAR X Data IEEE, TGARSS, in print

J. Schulz-Stellenfleth and S. Lehner, 2004, Measurement of 2-D Sea Surface Elevation Fields using Complex Synthetic Aperture Radar Data, IEEE Transactions Geoscience and Remote Sensing, 42(6), 1149-1160.

J. Schulz-Stellenfleth, S. Lehner, and D. Hoja, 2005, A parametric scheme for the retrieval of two-dimensional ocean wave spectra from synthetic aperture radar look cross spectra, Journal of Geophysical Research, 110, doi: 10.1029/2004JC002822.

J. Schulz-Stellenfleth, T. König and S. Lehner, 2007, An empirical approach for the retrieval of integral ocean wave parameters from synthetic aperture radar data, Journal of Geophysical Research, 112, doi: 10.1029/2006JC003970.

WAMDI Group, 1988, The WAM model a third generation ocean wave prediction model, Journal of Physics Oceanography, 18,1775-1810.