PACIFIC EXTREME WIND AND WAVE CONDITIONS OBSERVED BY SYNTHETIC APERTURE RADAR

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It is well known that synthetic aperture radar (SAR) provides information on ocean winds and surface waves. SAR data are of particularly high value in extreme weather conditions, as radar is able to penetrate the clouds providing information on different ocean surface processes.
In this presentation some recent results on SAR observation of extreme wind and ocean wave conditions is summarised. Particular emphasize is put on the investigation of typhoons and extratropical cyclones in the North Pacific.
The study is based on the use of ENVISAT ASAR wide swath images. Wide swath and scansar data are well suited for a detailed investigation of cyclones. Several examples like, e.g., typhoon Talim will be presented, demonstrating that these data provide valuable information on the two dimensional structure of the both the wind and the ocean wave field. Comparisons of the SAR observation with parametric and numerical model data will be discussed. Some limitations of standard imaging models like, e.g., CMOD5 for the use in extreme wind conditions are explained and modifications are proposed.
Finally the study summarizes the capabilities of new high resolution TerraSAR-X mission to be launched in October 2006 with respect to the monitoring of extreme weather conditions. The mission will provide a spatialresolution up to 1 m and has full polarimetric capabilities.

KEY WORDS: Typhoon, SAR, wind field, ocean waves, CMOD

1. INTRODUCTION

Tropical cyclone is the generic term which comprises hurricanes of the Atlantic and Northeast Pacific, typhoons of the Northwest Pacific, and cyclones of the Indian and Southwest Pacific.

Tropical cyclones account for significant fraction of damage, injury and loss of life and are the costliest natural catastrophes. In addition, recent works suggest that global tropical cyclone activity may play an important influence on regional and global climate.

Due to relatively small amount of in situ data available during cyclones, remote sensing techniques take an important role in the retrieval of geophysical information under such conditions. (Katsaros et al. 2000, Du and Vachon).

Radar images, differently from images taken with optical sensors that are dependent on sunlight for illumination, can be used to observe the earth's surface at day and night and in all weather conditions even through cloud coverage. A synthetic aperture radar (SAR) not only records the intensity of the returned signal, but also the phase history of the backscattered radar signal and is processed to high spatial resolution (~30 meter) images.

In this study both the ocean wave field and the wind field as observed in tropical cyclones with spaceborne SAR are analysed. The work aims at the improvement of the prediction of the cyclone track, intensity and sea state as well as the achievement of a better understanding of the radar return under extreme wind and wave conditions.

This paper focuses on the illustrative case study of typhoon Talim acquired by ENVISAT ASAR over the NW Pacific when the typhoon was at category 4 stage of the Saffir Simpson scale (Fig.1).

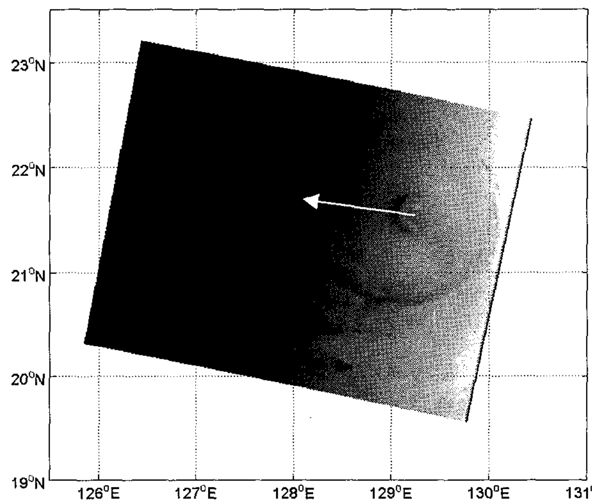

Figure 1. ASAR Image of typhoon Talim, Aug. 30, 2005 01:24 UTC. The arrow refers to the travel direction of movement of the typhoon

2. TYPHOON TALIM

Typhoon Talim was building strength in the western Pacific Ocean in late August as it bore down on Taiwan and mainland China (fig. 2). The name of the typhoon comes from the "Tagalog" term *Talim,* which means 'sharpness'.

At maximum intensity, Talim was a category 4 storm, just under super typhoon intensity with a maximum sustained wind speed of 230 *Km/h* and a minimum pressure of 926 *hPa.*

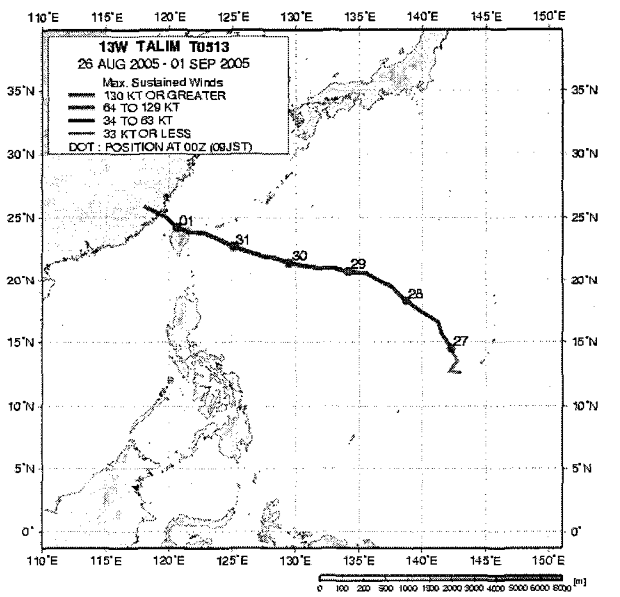

Figure 2 Storm track of typhoon Talim (from JWTC)

3. WIND SPEED RETRIEVAL

SAR provides a useful complement to support traditional wind observations and numerical modeling and offers the potential for 100 m high resolution spatial measurements of the wind field over the ocean.

To compute wind fields over the ocean by SAR, the normalized radar cross section (NRCS), referred to as Sigma0 (σ^0), has to be derived from the image. σ^0 is independent of satellite type, and therefore can be used to identify the radar properties of objects like the roughness of the sea surface. Extraction of such calibrated data from the pixel intensity in the image requires several satellite sensor, product and scene specific operations to achieve a calibrated SAR image.

SAR backscatter from the ocean surface is dependent on the small scale roughness, which in turn is strongly dependent on the local wind field. Therefore the backscatter can be used as a measure for the local wind. SAR ocean surface wind retrieval is a two-step process. In the first step, wind directions are estimated from wind induced streaks and in the second, the wind speeds are derived from the normalized radar cross section (NRCS), (Lehner 1998).

The SAR wind speed retrieval is based on the C-band scatterometer (SCAT) model usually the CMOD4, which gives the empirical relation between the vertical (VV) polarized NRCS, the wind vector and the incidence angle. CMOD4 is used by ESA as the standard wind retrieval model for the ERS scatterometer. As it was only tuned to wind speeds up to 15m/sec this algorithm should thus not be extrapolated to much higher wind speeds (Stoffelen 1997). For hurricane cases CMOD5, which has been retuned for high wind speeds is used (Hersbach, 2003).

In figure 3 we show the wind speed for typhoon Talim derived by CMOD 5. Superimposed on the calibrated 400 x 400 km SAR image is the measured wind field.

SAR images of typhoons show in addition to the wind streaks, which are used to determine wind direction many additional features due to severe rain and ice clouds. We therefore chose the approach to evaluate wind directions through a visual inspection of the streak visible in the SAR image followed by an two dimensional interpolation of directions over the complete swath.

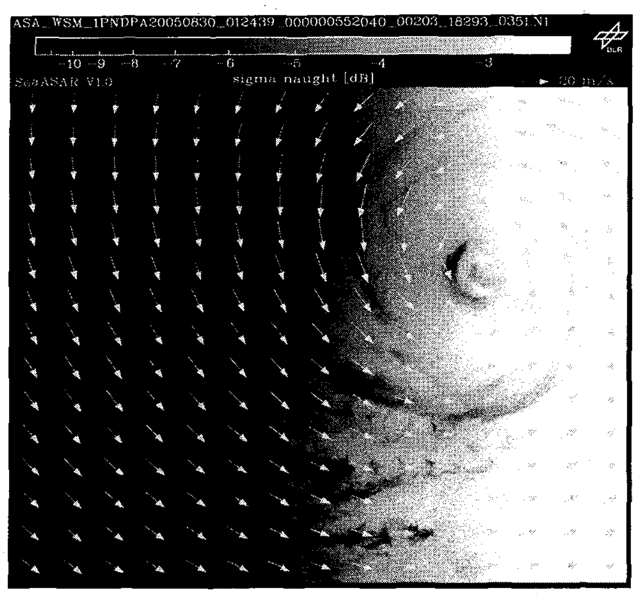

Figure 3 Wind Speed and Direction derived from the 400 x 400 km ENVISAT ASAR image of typhoon Talim

Using this field of directions and by application of CMOD 5 wind speed is derived. In the case of Talim a maximum wind speed of about 30 m/sec is measured from the ASAR image.

4. REMAINING PROBLEMS FOR WIND SPEED MEASUREMENTS

For the image of Talim the eye of the typhoon is situated in the near range of the image. CMOD 5 saturates though, depending on incidence angle at high wind speeds blowing towards the SAR antenna (Horstmann, 2005).

Above 25 m/sec CMOD 5 shows saturation effects, which could be due to the general saturation of the drag coefficient as suggested in (Donelan et al. 2004). Another possibility is that CMOD 5 is tuned to the coarser resolution of the scatterometer, this may be improved by further investigations of the relation between σ^0 at high resolution by aircraft experiments. New aircraft measurements using the IWRAP radar system are investigated to improve wind speed algorithms for tropical cyclone cases.

The wind speed derived from SAR images is strongly dependent on measured direction and incidence angle and is additionally influenced by rain. L band radar due to its longer radar wavelength should be better suited to measure extreme wind speeds in a robust manner.

5. WAVELENGTH AND DIRECTION OF BOUNDARY LAYER ROLLS FOR INFORMATION OF MIXED BOUNDARY LAYER DEPTH

Additional information can be derived from the wind streaks that are visible on SAR images, that are ranging in wavelengths from 600 to 2,000 meters.

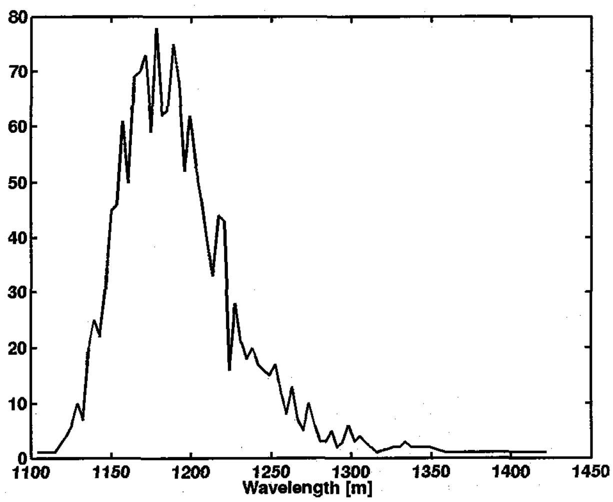

Figure 4. Histogram of roll vortices lengths of typhoon Talim, see Fig.2

This variation in sea surface roughness is explained by change in surface wind speed due to the formation of boundary layer rolls (Young 2002). The direction of these streaks can thus be used not only to derive the wind direction, but in addition the wavelength is taken to be a measure of roll size and thus mixed layer depth.

To determine wavelength and direction from the SAR image a 2-dimensional spectral analysis is performed.

For the example of the SAR image of Talim is divided into sub areas of 12.5 km and on each sub scene the image spectrum is calculated by two dimensional FFT. Length of the wind rolls is determined by finding the maximum of spectral energy for wavelength between 600m and 1600m. Figure 4 is a histogram of the wave length of wind rolls found for all sub areas of the image of Talim.

The main length of the roll vortices shown in Fig. 4 is between 1150 and 1200 m. Longer wavelengths are measure only when image features due to rain cells are prominent on the image and thus contaminate the image of the roll vortices.

In comparison to wavelength of the rolls measured in other tropical cyclones these are longer than measured for other hurricane images, investigated before, were the usual roll size was measured to be between 600 and 800 m, e.g. in Ivan, Floyd at a Cat 3 stage (Lehner 2000).

As the roll size is a measure of the boundary layer depth with an aspect ratio of horizontal to vertical roll size of about 2.4 (Ralph Foster, pers. com) a first preliminary conclusion is, that in a Cat 4 or higher tropical cyclone the boundary layer is deeper with moisture being transported up higher into the hurricane thus reinforcing the circulation.

6. SEA STATE IN TERMS OF WAVELENGTH AND DIRECTION

SAR images show features due to ocean waves, usually waves longer than 100 m are imaged depending on travel direction. Figure 5 shows the wave length and direction of the ocean waves as observed on the ASAR images of typhoons Talim. Wavelength is colorcoded, red referring to 300 to 350 m, direction is given by the black line in the sub area.

Ocean waves of wave length 250 to 300 m can be observed, with wavelength increasing, as the swell travels away from the typhoon center. In the areas where the ASAR image is shown instead of the image spectral measurements, the signal to noise ratio was too low to detect a peak in the SAR image spectrum. This happens mainly in areas, where wind and waves travel against each other.

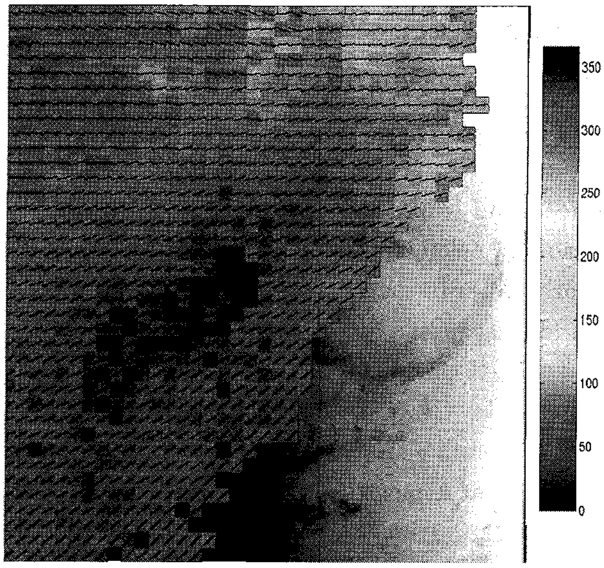

Figure 5. Ocean wave lengths and direction of hurricane Talim

7. CONCLUSION AND OUTLOOK

The analysis showed that ENVISAT ASAR typhoon images can be used to infer information on structure, sea state and the sea surface roughness from the intensity image.

Use of CMOD 5 instead of CMOD 4 leads to better estimates of wind speed in the regime above 15 m/sec. Further retuning of the algorithms using new aircraft data is under investigation. For C band rain and saturation effects severely limit the possibilities to measure tropical cyclone wind speeds, especially, when the eye of the cyclone is situated in the near range of the SAR image.

Even on the coarse resolution of ASAR wide swath images ocean waves can be observed and their wave length and direction can be measured. This can be used to validate and improve high resolution ocean wave models.

8. REFERENCES

M.A. Donelan, , B.K. Haus, N. Reul, W.J. Plant, M. Stiassnie, H.C. Graber, O.B. Brown, and E.S. Saltzman, , 2004, On the limiting aerodynamic roughness of the ocean in very strong winds. *Geophysical Research Letters* 31(18):LI8306, doi:10.1029/2004GL019460.

H. Hersbach, 2003 "CMOD5 an improved geophysical model function for ERS C-band scatterometry," *Internal report, European Centre for Medium- Range Weather Forecast.*

K.B. Katsaros, P.W. Vachon, P.G. Black, P.P. Dodge, and E.W. Uhlhorn, 2000., Wind fields from SAR: *Could they improve our understanding of storm dynamics? Johns Hopkins APL Technical Digest*, 21(1):86-93.

S. Lehner, J. Horstmann, W. Koch and W. Rosenthal, *Mesoscale wind measurements using recalibrated ERS SAR images*, J Geophys. Res., vol03, pp. 7847-7856, 1998

S. Lehner, 2000, Analysis of Synthetic Aperture Radar (SAR) Images of Hurricanes, *8th International Conference on Remote Sensing for Marine and Coastal Environments*, 17-19 May, 2005 Halifax, Nova Scotia, Canada.

S. Lehner, A. Repucci,, J. Schulz - Stellenfleth,: *Validation of Parametric Hurricane Models by ENVISAT ASAR,* in: Proc. SEASAR 2006, 6 pages, 2006.

J. Horstmann, D. R. Thompson, F. Monaldo, S. Iris, H. C. Graber, Can synthetic aperture radars be used to estimate hurricane force winds? Geophysical Research Letters, VOL. 32, L22801, doi:10.1029/2005GL023992

Stoffelen, Ad and David Anderson, 1997, *"Scatterometer Data Interpretation: Transfer Function Estimation and Validation", J. Geoph. Res.*, 102(C3), 5767-5780.

Young, G.S., D.A.R. Kristovich, M.R. Hjelmfelt, and R.C. Foster, 2002, *Rolls, streets, waves, and more: A review of quasi-two-dimensional structures in the atmospheric boundary layer. Bulletin of the American Meteorological Society*, 83:997-1001.