

## **Wind Retrieval using Marine Radars**

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### **LONG-TERM GOALS**

Within the High Resolution Air-Sea Interaction (HiRes) DRI the NATO Undersea Research Center (NURC) wants to develop and validate methodologies to retrieve wind field parameters from X-band marine radar. The main parameters NURC will focus on are the mean surface wind vector as well as the wind gusts in vicinity of the measurement platform (within 2000 m). In contrast to traditional wind measurements marine radar retrieved winds are not influenced by the blockage and shadowing of the platform itself. Therefore, we expect marine radars to be an ideal solution to measure winds operationally from large platforms and ships. As the wind information is an important parameter in the marine radar wave measurement and the wave modelling, we anticipate our wind information will help to improve the measuring and modelling activities of phase-resolved surface wave fields undertaken within HiRes.

### **OBJECTIVES**

The scientific objective is to develop a methodology to retrieve surface wind speed and direction using X-band marine radar data. We also aim at developing an algorithm, which requires simple and as little as possible calibration. The validation and limitation of the different developed methodologies will be investigated using the measurements acquired during the HiRes experiment in June 2010 by RV Flip and RV Sproul. In contrast to conventional wind measurements from ships and platforms, the radar retrieved wind vectors will not be affected by wind shadowing and blocking as well as turbulence due to the platform and sensor mounting structures. A further objective is to develop a methodology to detect and quantify wind gusts with marine radar imagery within 2000 to 4000 m of the platform, which aims toward a short time forecast of wind gusts/variability at the measurement platform. The validation as well as limitation of the developed methodologies will be investigated utilizing the measurements obtained during the HiRes experiment in June 2010 from RV Flip and RV Sproul.

### **APPROACH**

In the following we introduce the approaches developed for retrieving information on the wind direction, wind speed and wind gusts from marine radar image sequences. We have identified three

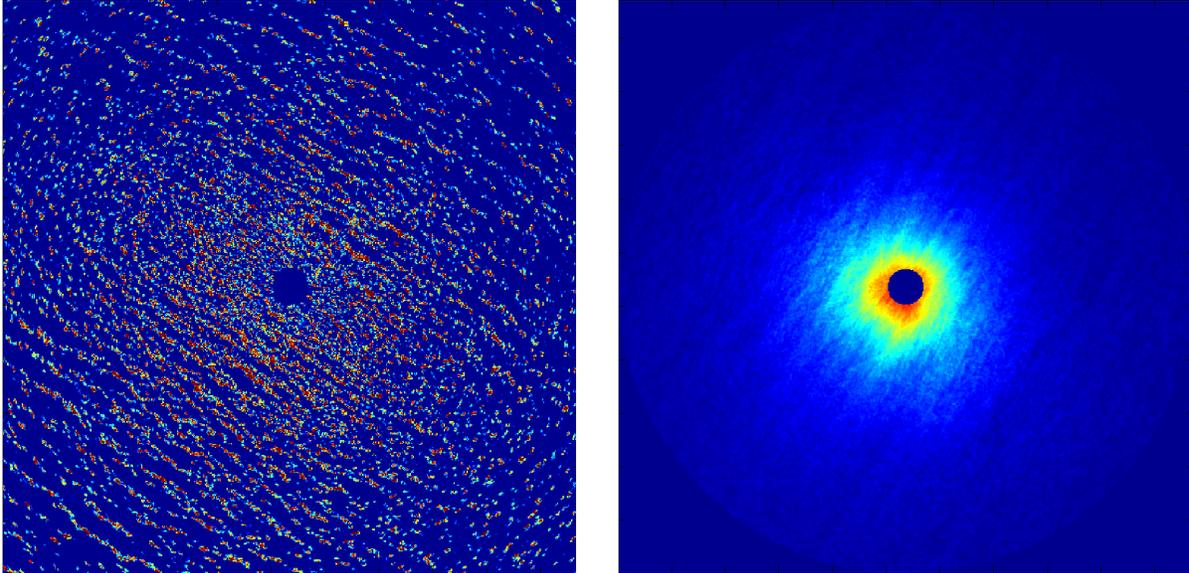
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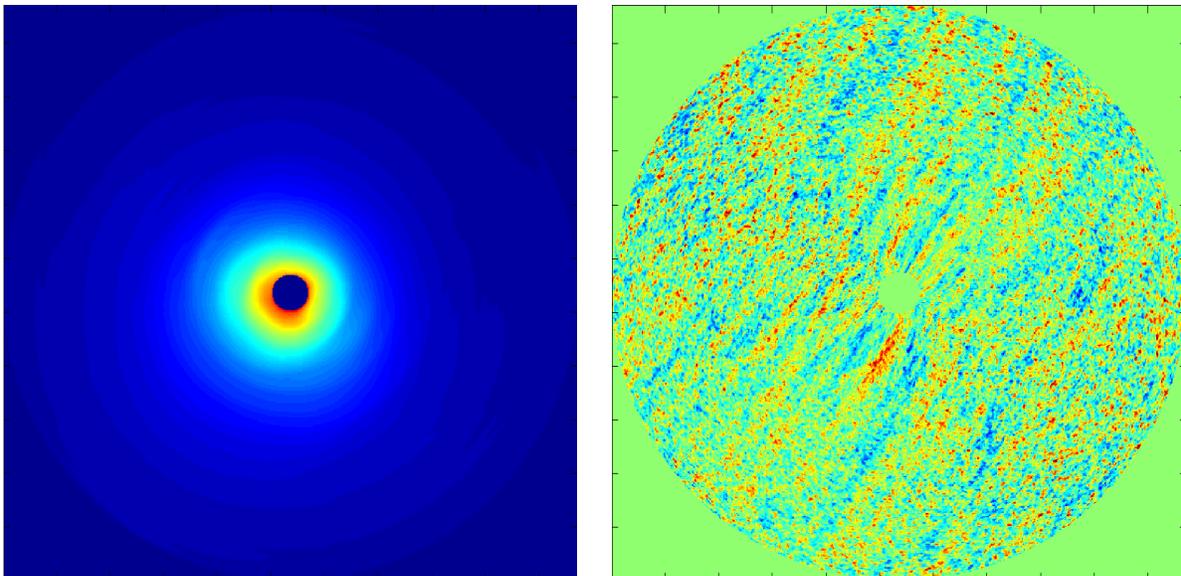
artifacts in marine radar images, which are suited to infer the mean wind directions. In the following we will discuss the artifacts as well as the approaches we developed to estimate the wind direction.



**Figure 1:** *On the left hand side an individual marine radar image is depicted as collected by the radar system. The right hand side shows the image after integration in time.*

1. As already mentioned in literature (Trizna and Carlson, 1996; Dankert and Horstmann, 2007) a dependence of the mean radar cross section on wind direction is observed in radar images. However, it has not yet been shown, that this dependence is strong enough to infer accurate wind directions. In general the radar cross section is larger for wind blowing towards the radar than for the other directions. To enhance this artifact the radar image sequences have to be integrated over time (e.g. 64 radar images, which correspond to approximately 100 s), which significantly reduce the noise in the radar image due to speckle and in addition removes non static patterns such as ocean surface waves (Figure 1). Utilizing these radar imagery we search for the upwind peak utilizing the following methods.
  - a. Upwind Peak method (UP-method): Search for the maximum range distance to a preselected intensity level. The intensity level is selected by searching for the maximum radar cross section, which can be measured over the entire azimuth of the integrated and smoothed radar image sequence.
  - b. Azimuth Dependence method (AD-method): Search of the upwind peak by fitting the mean azimuthal dependence of the radar backscatter.
  - c. Ramp Differential method (RD-method): Within the RD-method the integrated radar image is additionally smoothed by a 2D Gaussian filter. Then the upwind peak is found by integrating the mean filtered image over range and then searching for the maximum change of radar cross section along azimuth. The wind direction is inbetween the 2 maxima and therefore relieving a  $180^\circ$  directional ambiguity. The directional ambiguity can be resolved by considering one of the above methods or by retrieving the mean radar cross section within  $\pm 45^\circ$  of the range integrated radar cross section were the maximum of the two is in up wind direction.

2. When investigating the integrated radar images, streak like features are visible in the image, which are well aligned with the wind direction. We have developed two approaches for estimating the orientation of these streaks. Therefore, we utilized the integrated images as mentioned above and removed in addition a 2D ramp, which describes the mean range and azimuth behavior of the radar cross section. This ramp was obtained by azimuthal and range smoothing of the integrated radar image (Figure 2 left hand side). To further enhance the signal over the entire range the backscatter is normalized with respect to range resulting in a feature enhanced image (Figure 2 right hand side). To find the orientation of these streaks we developed the following methods.
- a. Fast Fourier Transformation method (FFT-method): Estimate the orientation of streaks by transformation of the integrated ramp removed image in the wave number domain (by FFT) and search for the direction to the main energy in the resulting power spectra corresponding to wave numbers corresponding to scales between 30 and 400 m. The corresponding wind direction is perpendicular to this direction and relieves a  $180^\circ$  directional ambiguity, which can be resolved following the methodologies introduced above. Similar to the method used in SAR wind direction retrieval (Lehner et al. 1998).
  - b. Radom Transform method (RT-method): Estimate the orientation of streaks by a RT (Horstmann et al., 2011), which projects the integrated and ramp removed subimages to a single line and repeats this process for various rotation directions of the subimage. The direction for the maximum contrast in the Radon transform image is in direction of the surface streaks and therefore the surface wind direction with a  $180^\circ$  directional ambiguity. See also SAR wind direction retrieval (Wackerman et al. 2003).

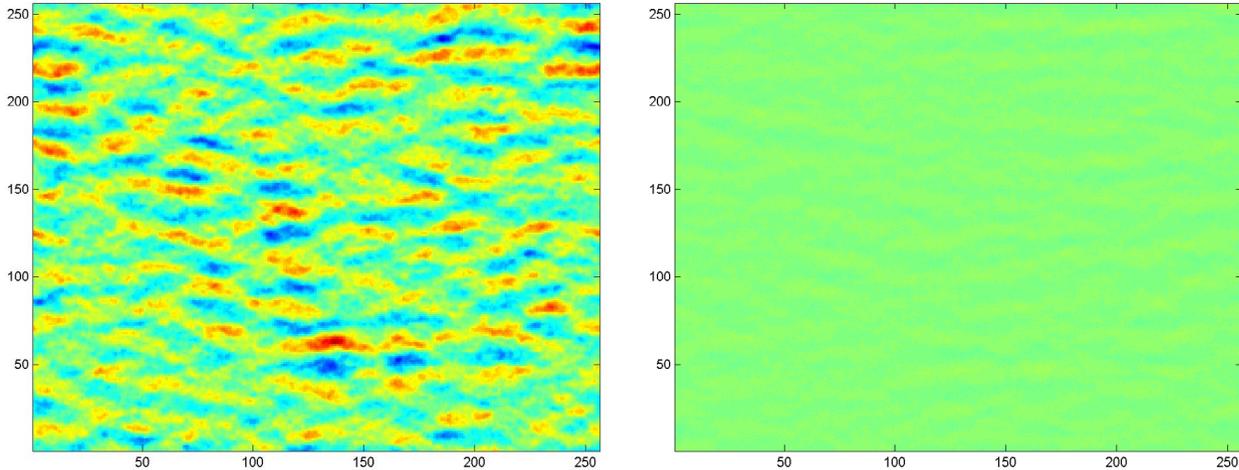


***Figure 2: The left hand side depicts the the 2D ramp resulting from the marine radar image sequence. Subtracting the 2D ramp and normalization of the image results in the right hand side image.***

3. When investigating image sequences from integrated radar images we observed motion of radar backscatter patterns in wind direction, which are most likely the imprints of wind gusts on the ocean surface. We have developed two algorithms to estimate the direction of the movement of these patterns. Both methods analyze the movement between two consecutive integrated and smoothed images and are described below.
  - a. Optical Flow method (OP-method): The OP-method is defined as the “flow” of intensity values within an image sequence. As in radar images the radar backscatter depends on range, meaning the radar backscatter as well as the variance of the backscatter decrease with range, a normalization of the images has to be undertaken. In addition there is a spatial constrain, as the intensity changes that are to be evaluated must be within the evaluated pixel neighborhood. Therefore, the image resolution must be resized considering the maximum feature speed to be resolved under consideration of radar resolution and image time step. By analyzing the optical flow in x and y directions, the complete flow field is obtained. The mean direction of the flow field results in the surface wind direction.
  - b. Normalized Cross-Correlation method (NCC-method): The NCC-method matches corresponding radar backscatter patterns between two consecutive images. Due to the high computational costs the matching points search has to be limited in consideration of maximum feature speed and size. As wind gusts are larger features the radar image resolution is decreased by a factor of 5. The mean wind direction results from the mean direction of the movements of the features resolved by the NCC-method. A similar method was previously utilized to remove the 180° directional ambiguity in SAR wave retrieval (Engen and Johnson, 1995).

We have observed a strong dependency of the measured radar backscatter intensity on wind speed and direction. This has also been observed previously by other investigators (Lee et al., 1995). For the marine radar wind speed retrieval we have developed four approaches, with the major intention of high accuracy and simple and low level of calibration effort.

1. The simplest method considers the mean radar cross section of 64 radar images and fits a polynomial function to this dependency.
2. To improve the performance of the method above in case of limited azimuthal coverage we only consider the mean radar cross section at cross wind direction ( $\pm 5^\circ$ ) in dependence of wind speed, which will allow the method to work for azimuth coverage as low as  $180^\circ$ .
3. Another approach followed is utilizing the UP-method and measure the distance to the pre selected intensity level. The resulting wind speed is given by  $u = ra(I)$ , where  $a(I)$  is conversion number in dependence of the pre selected intensity level  $I$ , which is obtained from an empiric polynomial calibration function.
4. Instead of searching in the UP-method for the maximum range to the pre selected intensity level the minimum distance is selected. As in 3. an empiric polynomial calibration function is obtained. This approach avoids having to have the full azimuthal coverage of the radar as the upwind direction does not have to be within the acquired radar image.



***Figure 3: Dispersion filtering to remove ocean surface waves from marine radar imagery. The left hand side depicts a simulated surface wave image. The right hand side shows the image after applying the dispersion relation filter.***

The above methodologies are limited to a single wind vector from the entire radar image and have to be calibrated for wind speed retrieval. However, the OF- and NCC-method have the potential to obtain the surface movement of wind gusts patterns in space and time in a range of approx. 2000 to 4000 m of the radar origin. For detecting the wind induced patterns the wave information has to be carefully removed from the marine radar image sequences. Previously, the radar image sequence was integrated in time, which reduced/removed most of the wave information. However, typically 1 to 2 minutes of data had to be integrated and some wave information was still contained in the radar image sequence. To reduce the number of images needed for the temporal integration the wave information can be removed by additionally filtering via the dispersion relation of ocean surface gravity waves (Senet et al., 2001; Nieto Borge et al., 2004). Therefore, the data are transferred into the wave number frequency domain where all the energy located on the dispersion shell, which is defined by the dispersion relation of linear surface waves, is replaced by the mean energy of the corresponding wave number and the spectra is retransformation into the spatial temporal domain. In Figure 3 we show the described filtering process utilizing a simulated wave field image. It can be seen that most of the waves have been removed by this filter. These developments are ongoing.

## **WORK COMPLETED**

We have completed developing the algorithms to retrieve the mean wind direction from marine radar images. All of the algorithms have been applied to the marine radar data collected from RV FLIP during the HiRes experiment in June 2010 and were validated to the co-located in situ data. The resulting statistical parameters are listed in Table I. We have investigated the dependency of the methods on wind speeds as well as on limited azimuthal coverage and have started to apply the methods to the data acquired by RV Sproul during the HiRes experiment. The later will enable us to validate the performance of the methods on moving vessels, which is in particular important to consider when using the methodologies based on wind streaks and wind gusts, as in addition to the standard processing the geolocation of the data has to be considered.

**Table I: Main statistical parameters of the radar wind direction retrieval algorithms. The validation was performed utilizing radar and in situ data collected at RV Flip during the HiRes experiment in June 2010.**

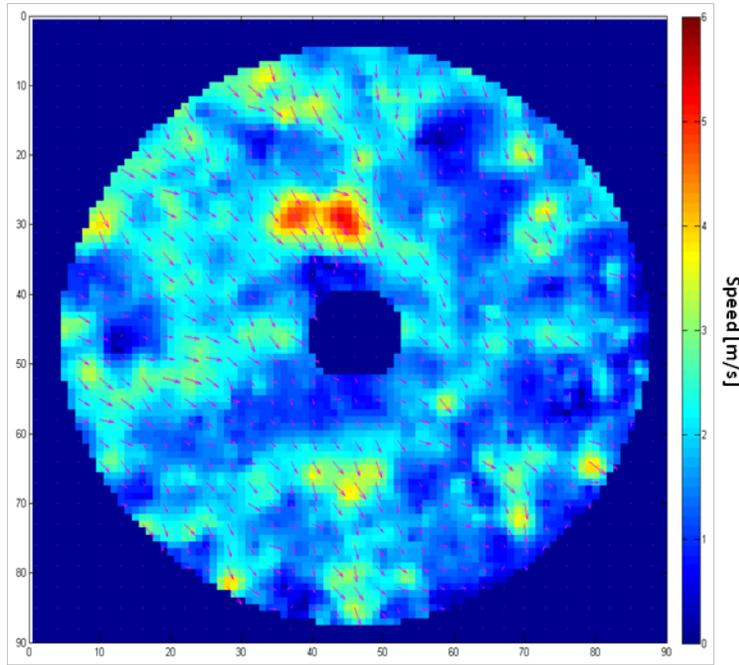
Method	Root mean square error [°]	Standard deviation [°]	Bias [°]
Upwind Peak method	14.5	14.5	0
Azimuth Dependence method	6.4	6.2	-1.5
Ramp Differential method	6.5	6.2	-1.2
Fast Fourier Transformation method	9.9	9.9	0.4
Radom Transform method	9.7	9.4	2.1
Optical Flow method	7.5	7.1	-2.4
Normalized Cross-Correlation method	26.3	24.9	-8.9

Considering the wind speed retrieval all methods have been applied to the marine radar data acquired from the RV Flip during the HiRes experiment in June 2010 and have been validated using the *in situ* data available. The resulting statistical parameters are listed in Table II. We have also investigated the performance of the algorithms with respect to wind speed and limited azimuthal coverage. The application of the methodologies to the data collected by RV Sproul during the HiRes experiment are ongoing.

**Table II: Main statistical parameters of the radar wind speed retrieval algorithms. The validation was performed utilizing radar and in situ data collected at RV Flip during the HiRes experiment in June 2010.**

Method	Root mean square error [m/s]	Standard deviation [m/s]	Bias [m/s]
Range method	0.60	0.60	0.01
Intensity method	0.42	0.42	0.01
Cross wind method	0.44	0.44	0.02

Considering the motion of wind gusts in space and time we have performed some preliminary studies. Figure 4 depicts a vector field of movements detected via the OF-method from an image sequence collected by RV Flip during the HiRes experiment. The maximum radar range shown is 2000 m and the data were collected at a mean wind speed of 14.5 m/s at a wind direction of 340° measured at 30 m height. However, the removal of the seastae from the radar data is not yet sufficient and further development of proper removal of the wave information within the radar images is ongoing.



**Figure 3: Estimate of speed and direction of wind gust patterns extracted from a radar image sequence acquired during the HiRes experiment in June 2010. Speeds are given in m/s and represent the surface pattern speeds.**

## RESULTS

Validation of the different methodologies to retrieve wind directions from marine radar image sequences have shown that if the entire azimuth of the image is available the best suited methods are the AD-method, RD-method, OF-method. However, in case of limited azimuthal coverage less than  $\sim 320^\circ$ , such as in case of coastal setups or radar shadows aboard vessels, the RD-method will not work. Investigating the wind direction retrieval performance with respect to wind speed showed an increase in error with decrease of wind speed for the OF-method. At this point we believe the best methodology is based on the AD-method, however, most likely a merged approach of different methodologies will provide a higher certainty of wind direction estimates.

Concerning the validation of wind speed retrieval all methodologies show good results. However, all the methods require a calibration phase to estimate the conversion function. In case of limited azimuthal coverage we only consider the mean radar cross section at cross wind direction ( $\pm 5^\circ$ ) in dependence of wind speed, which will allow the method to work for azimuth coverage as low as  $180^\circ$  with still a very high accuracy.

We have shown that marine radars are suitable for retrieving a mean surface wind estimate with an accuracy of less than  $7^\circ$  in wind direction and 0.5 m/s in wind speed, which are similar to the estimates of standard *in situ* instruments. However, in contrast to *in situ* measurements, the radar measurements are not affected by their installation platform, which often induce blockage, shadowing and turbulence and therefore better suited for taking wind measurements from large vessels or platforms.

## IMPACT/APPLICATIONS

Due to the high accuracy of the mean surface wind measurements ( $7^\circ$  in direction and 0.5 m/s in speed) obtained from the marine radar system and the mentioned advantages to standard *in situ* measurements in particular from large vessels, the methodology has the potential to be utilized for operational wind measurements on large vessels.

It is also likely that the wind information obtained from marine radar imagery can be utilized to improve the marine radar retrieved significant wave heights. In particular we believe it should be attempted to develop a methodology to calibrate the marine radar significant wave heights utilizing the radar winds instead of external wave height information.

## RELATED PROJECTS

There are no ongoing related projects that are closely identified with this project.

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- Horstmann, J., Raul Vicen-Bueno and Matthew Coffin, "Reading The Ocean With Marine Radars", *Defence Global*, pp. 58-60, may 2011.