On the Imaging of Surface Gravity Waves by Marine Radar: Implications for a Moving Platform

B. LUND, C. O. COLLINS, AND H. C. GRABER

University of Miami, RSMAS
4600 Rickenbacker Causeway
Miami, FL 33149, USA
blund@rsmas.miami.edu

E. TERRILL

UC San Diego, Scripps
9500 Gilman Drive
La Jolla, CA 92093, USA

1. Introduction

This paper studies the retrieval of surface gravity wave and current information from shipborne marine radar data. Access to real-time directional wave spectra and surface current estimates can help improve operational safety on ships (e.g. Iseki and Ohtsu 2000; Tannuri et al. 2003; Nielsen 2006). From a scientific perspective, shipborne wave and current measurements are important for air-sea interaction studies (Donelan et al. 1997). In addition, they provide a unique view of the waves' and currents' spatio-temporal evolution under a wide range of conditions.

Marine X-band radars have long been used to monitor waves and currents from coastal stations, e.g. light houses, or offshore platforms. They operate by transmitting and receiving pulses of microwaves at grazing incidence, typically with HH polarization. The radar pulses interact with the cm-scale sea surface roughness through Bragg scattering. The long surface waves' orbital motion modulates the radar-scattering elements. This leads to the so-called sea clutter in radar images, alternating regions of dark and bright backscatter, in-phase with the surface waves. In addition, tilt modulation and shadowing are important imaging mechanisms (Plant 1986). Finally, micro-breakers are believed to contribute significantly to the backscatter, especially for HH-polarization (Trizna et al. 1991).

The techniques to retrieve wave and surface current information from marine radar data are well-established: the spatio-temporal radar backscatter information is first converted from polar to Cartesian coordinates and then Fourier-transformed. If the waves and winds are favorable, i.e. a minimum significant wave height of ~ 0.5 m and wind speed of ~ 3 m/s (Hatten et al. 1998), the resulting 3-D radar image spectrum shows a set of distinct peaks that are due to the surface gravity waves. Neglecting higher-order and nonlinear contributions, these peaks are located on the linear wave theory's dispersion shell (Young et al. 1985; Borge et al. 1999). In presence of a current, be it from the ocean or due to platform motion, these peaks are shifted in accordance with the dispersion relation's Doppler term. The magnitude and orientation of this shift can then be used to determine the surface current (Senet et al. 2001).

Most marine radar wave studies discussed in the literature were based on data from fixed platforms (e.g. Borge et al. 2004; Reichert and Lund 2007). The few published surface wave results from moving platforms were obtained using the same analysis techniques that were first developed for fixed platforms. To determine the surface current from moving platform data, the known ship motion was simply subtracted from the radar-derived encounter current (i.e. the sum of ship motion and surface current) (Young et al. 1985; Senet et al. 2001).

In recent years, several papers were published that focus on surface wave retrieval from shipborne marine radar data. Stredulinsky and Thornhill (2011) suggest that while radar-based direction and frequency measurements from moving vessels are good, wave height estimates are unreliable. They propose an improved shipboard wave height measurement through fusion of radar data with measured ship motion response data. This technique was adapted by Cifuentes-Lorenzen et al. (2013) who use a laser altimeter to scale the radar-based wave spectra, thus circumventing the traditional approach that is based on the 3-D radar image spectrum's signal-to-noise ratio (SNR) (Ziemer 1995). However, in their comparison of multiple shipboard wave sensors they find that discrepancies increase with ship speed. After performing ship-motion-related aliasing and Doppler corrections, measurements are found to be adequate at ship speeds of 3 m s^{-1} or less, but fail at speeds above 5 m s^{-1}. Serafino et al. (2011) propose a simple georeferencing technique to mitigate the ship-motion-induced aliasing effect. Ludeno et al. (2013) applied this technique to marine radar data from a cruise ship and found good agreement with modeling results. However,

This work was supported by the U.S. Office of Naval Research (ONR) under grants N000140710650, N000140810793, N000140910392, and N000141310288.

their discussion hardly touches on significant wave height, the parameter that other investigators identified to be the most difficult to retrieve from a moving platform. Finally, Bell and Osler (2011) mapped bathymetry using marine radar collected from a moving vessel. Like Serafino et al. (2011), they georeference their data, and, in addition, they propose a technique to reduce the image jitter (i.e. fixed targets drifting in apparent position from image frame to frame). While the jitter reduction helped improve their depth estimates, they found that the remaining jitter in the georeferenced images degraded the higher frequency wave components to such extent that a current fit was no longer possible. (Note that the short waves are most sensitive to the currents, while the long waves are used for depth inversion.)

At the University of Miami, we have collected marine radar data from multiple research vessels as well as a cruise ship. Using traditional wave analysis techniques, we found that errors associated with our shipborne data are significantly larger than the errors we expected from previous fixed-platform experiments. Judging by the aforementioned studies on shipboard marine radar wave retrieval, this finding no longer surprises.

In previous studies, we used shipboard marine radar to determine winds and internal waves (Lund et al. 2012b, 2013). There, ship motion is less of an issue since features are larger and moving much slower. Our current focus has shifted towards surface wave and current retrieval. While the existence of issues with shipboard wave measurements is well-documented, it is our opinion that a thorough discussion of the reasons for the apparent discrepancies between moving and fixed platform data is still lacking in the literature. The present work aims at filling this gap by identifying and addressing challenges that are unique to marine radar wave and surface current retrieval from moving platforms. These challenges include:

- horizontal ship motion and course changes during the radar image acquisition,
- image jitter due to compass or synchronization errors, and
- the dependency of wave and surface current estimates on the analysis position.

Note that the last bullet point pertains to both moving and fixed platforms. However, it is more important for ships where the relative angle between heading and waves underlies regular changes.

This paper is organized as follows: Section 2 gives an overview of our data. Results are presented and discussed in Section 3. In Section 4 we summarize our findings and provide an outlook for future work.

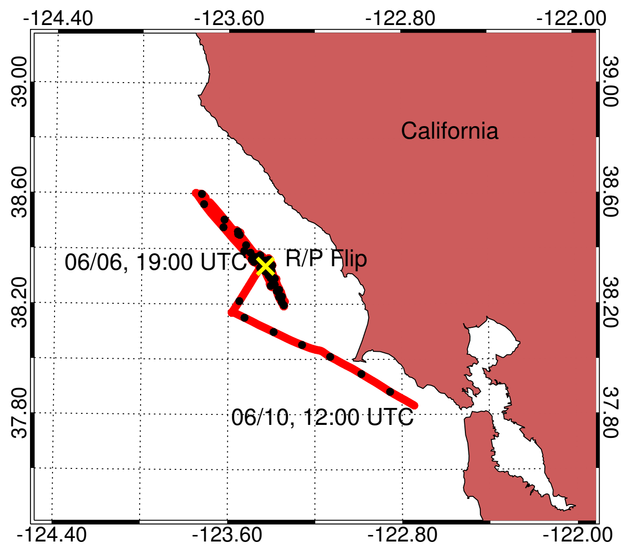

Fig. 2.1. Map of *Sproul*'s track during Hi-Res experiment (red dots). The black dots represent full hours. *Flip*'s position is marked by a yellow cross.

2. Data overview

In this study we analyze marine radar data that were collected during the ONR High Resolution Air-Sea Interaction (Hi-Res) experiment in June 2010. During this experiment, *R/P Flip* and *R/V Sproul*, equipped with a broad range of scientific instruments, were deployed off the coast of California (see Fig. 2.1). The standard Furuno marine X-band radars on *Flip* and *Sproul* were connected to a Wave Monitoring System (WaMoS) radar data acquisition board (Ziemer 1995). WaMoS consists of an analog-digital conversion device, a personal computer for data storage and analysis, and a screen to display results (see Fig. 2.2). The radars were operating at 9.4 GHz with HH polarization and grazing incidence angle. The 8-foot long antennas used here have a horizontal beam width of 0.75° and a repetition frequency of 24 rpm. The radars were set to operate at short pulse mode (here, i.e. a pulse length of 0.07 µs), which results in a range resolution of 10.5 m. Note that a pulse length of 0.07 µs or shorter and an antenna length of 8 foot or longer are a prerequisite for accurate wave and current results. WaMoS was set to collect images over a range from 120 to 3,960 m with a grid size of 7.5 m in range and ~ 0.25° in azimuth. The system stores the logarithmically amplified radar backscatter information at 12-bit image depth, i.e. digitized backscatter intensities range from 0 to 4,095. As is typical for conventional marine radars, the measured backscatter intensities were not radiometrically calibrated.

Fig. 2.3 shows an example radar image from a "typical" ship installation. The sea clutter is clearly visible, with

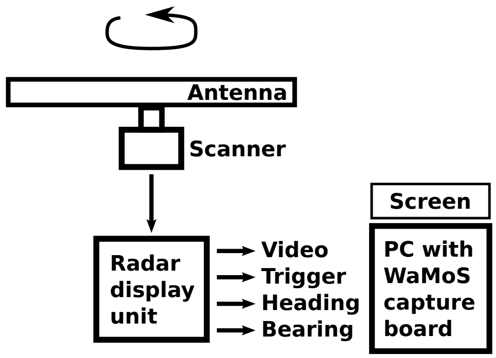

Fig. 2.2. WaMoS hardware components.

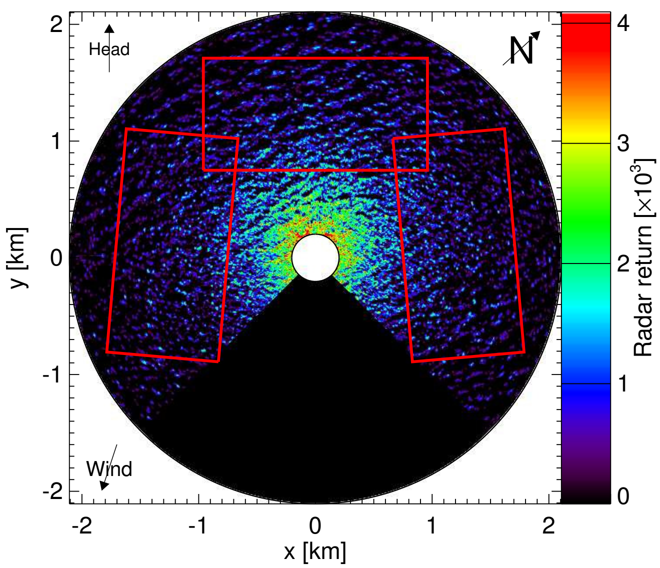

Fig. 2.3. Example of a typical shipborne radar image with wave analysis windows. An aft segment of the sea surface could not be sampled because of the ship mast's shadow.

the dominant waves approaching the ship at a port-side angle (from west-northwest). Traditionally, the wave analysis is carried out in a set of rectangular windows (Borge and Soares 2000). Here, the analysis windows (shown in red) are approximately 2 km^2 in size. They cover the sea surface area where the radar field of view is not obscured by ship superstructures. In this example image, a segment towards the aft is masked by the ship's main mast. The importance of the box position should become evident just by comparing the strength of the wave signal in each of the analysis windows shown in the figure: while the long wave signal in the window towards the bow is well-pronounced, it is considerably weaker both starboard and (to a somewhat lesser extent) port-side.

For our purposes, the marine radar data recorded during Hi-Res have an important advantage over such "typical" installation: both radars were installed with an unobstructed 360°-wide field of view. Such setup, which from our experience is quite unusual, is perfect for our study of the dependency of the radar-based wave and current estimates on the analysis window position. This is because a full radar field of view allows us to consider all possible angles between analysis window and peak wave direction. And, as a side-note, an unobstructed view of the sea surface allows for highly accurate radar-based wind estimates, as shown by Lund et al. (2012a) using the same Hi-Res data set.

3. Results and discussion

In the following, we discuss shipboard wave and current analysis issues that will negatively affect results if not properly addressed. Section 3.1 discusses the influence of horizontal ship motion and course changes on the quality of radar-based wave and current estimates. The issues that we identify here can be mitigated by georeferencing the marine radar data. Section 3.2 discusses the image jitter that results from erroneous (or poorly synchronized) heading information. To resolve this issue, we propose a new antenna heading correction scheme, based on a technique that was first introduced by Bell and Osler (2011). Finally, in section 3.3 we study the dependency of marine radar wave and current results on the analysis window position. While the issues identified in this last section are the most difficult to address, we do propose a technique that may improve radar-based estimates of the significant wave height.

3.1. Horizontal ship motion

Traditionally, the radar backscatter information recorded during each antenna rotation is treated like a spatio-temporal snapshot of the sea surface (e.g. Borge et al. 1999; Senet et al. 2001; Bell and Osler 2011). This means, the data are processed with the assumption that the radar instantaneously scans the sea surface in all directions. The platform is then allowed to move during the "sampling gap" that is equal to the antenna rotation period. Clearly, this assumption is inaccurate: marine radars transmit (horizontally) narrow pulses of microwaves from a steadily rotating antenna. Radar images are built from a sequence of such pulses that cover a full antenna rotation period. For fixed platforms, such as oil rigs or light houses, the errors resulting from this simplification are limited to the time domain. As long as the analysis is limited to windows that cover only a limited section of the radar sweep, meaning that the error will only be a fraction of the antenna rotation period, the "snapshot" simplification has proven to be acceptable.

The issue with moving platforms is, evidently, that they are not stationary during the 1.5 s (or longer) needed for an antenna rotation. For example, a marine radar image recorded from a ship traveling at 6 m s^{-1} will have a maximum mapping error of ~ 10 m. While this error may seem acceptably small given that it is of the order of a single range resolution cell, it is important to remember that we are interested in equally small Doppler shifts when determining the surface currents.

The mapping error resulting from heading changes that occur during an antenna rotation period is even more significant, considering that a 1° heading error leads to a mapping error of ~ 70 m at maximum range. Clearly, for data collected from ships that are undergoing a course change, the "snapshot" assumption will severely impact measurement accuracy. However, even a ship on a steady course will experience slight but constant heading adjustments that may easily exceed 1°, especially in high seas.

In this context, it is important to discuss another issue that arises when fixed-platform techniques are adapted to ships: traditionally, the analysis windows are defined in platform-based coordinates, i.e. on ships they are positioned at a constant angle and range relative to the bow. For Fourier analysis, it is assumed that the radar signal is spatially homogeneous and temporally stationary (Borge et al. 1999). For this assumption to be valid, if analysis windows are fixed in platform space, the ship must assume steady speed and heading over the full period of measurement. If the analysis is based on 64 images, this means a steady course for ~ 1.5 min. Under real-sea conditions this is practically impossible.

In order to overcome the inaccuracies associated with this approach, we chose to forgo the traditional ship-based reference frame and, instead, georeference our radar backscatter data. For each antenna rotation, WaMoS provides us with a single time stamp, compass reading, and GPS position. We collect this information from a sequence of images and then use interpolation techniques to estimate time, heading, and position for every radar pulse (WaMoS was set to record ~ 2000 pulses per rotation). Subsequently, we trilinearly interpolate our georeferenced backscatter data from polar to Cartesian coordinates. Our thus transformed shipborne radar data should behave similar to fixed platform data. In other words, our processing should eliminate the issues raised above. Note that we do not yet consider the ship's pitch and roll. This could be done in the future using a conventional motion pack installed onboard the ship (Hill 2005).

In addition, georeferencing has the advantage that aliasing is greatly reduced. Aliasing occurs due to temporal undersampling associated with the radar antenna's slow rotation time. Theoretically, Senet et al. (2001) have shown that the aliasing problem can be overcome through a spectral refolding technique. However, this approach does not come without drawbacks. Fig. 3.1 shows cross sections through 3-D radar image power spectra for (virtual) encounter currents of 1 m s^{-1} and 6 m s^{-1}. In addition to the fundamental mode dispersion relation, higher harmonics represent a significant source of spectral power. The higher harmonics are mostly due to the nonlinearity of the radar imaging mechanism, for example shadowing (Senet et al. 2001). Finally, the group line spectral components that are due to intermodulations between different wave field components contribute significantly to the overall spectral power (Borge et al. 2008). The figure highlights contributions from the fundamental mode and first harmonic, accounting for aliasing, as well as the group line.

Several issues arise in presence of a strong encounter current (i.e. without georeferencing). Firstly, strong currents distort the dispersion lines to such extent that it becomes difficult to distinguish between the different modes (first harmonic, fundamental mode, and group line). In addition, while the group line power is confined to frequencies below 0.5 rad s^{-1} for our small current case, it is shifted to frequencies above 1 rad s^{-1} in case of a strong current. This is problematic in particular for defining the SNR that is used to determine the significant wave height. In the definition given by Borge et al. (2008), the group line contributions and static patterns (due to the backscatter's range and azimuth dependency) are assumed to be limited to the low frequencies and expressly avoided through a frequency threshold. However, for moving platforms, the group line power gets shifted into higher frequencies, artificially reducing the SNR (and thus the significant wave height). Finally, the heavy aliasing associated with a fast-moving vessel will shift wave power into the very-low frequencies. This we would rather avoid since the wave signal would become difficult to distinguish from the static and group line power. To summarize this last point, not correcting for ship motion leads to distorted dispersion shells, complicating the extraction of signal from noise, and thus negatively affecting our wave estimates.

3.2. Image jitter

After the processing discussed in the previous section, assuming that our compass and GPS fixes are accurate, our shipborne radar data should be correctly georeferenced and of similar quality as data from a fixed platform. However, we found that a significant amount of image jitter remained in our data. We explain this either by inaccurate compass measurements or by radar-compass time synchronization errors.

The importance of image jitter was first discussed by Bell and Osler (2011) in the context of shipboard marine radar bathymetry retrieval. While a jittering wave signal is common to all shipboard radars we have used so far, it is unnoticeable for standard navigation applications and has thus been widely ignored. For marine radar wave, current, and bathymetry retrieval, though, the jitter deteriorates results and should not be neglected. As stated above, a seemingly small heading error of 1° leads to significant mapping errors at mid- to far-ranges.

The term image jitter describes the apparent positional drift of fixed targets in the radar image. The problem with open ocean marine radar data is that there are no fixed reference points to help stabilize georeferencing. To resolve this, Bell and Osler (2011) propose using the wave signal in their radar data as a fixed target proxy. To correct their images' heading, they cross-correlate the 2-D spectra of two successive radar frames in terms of bearing.

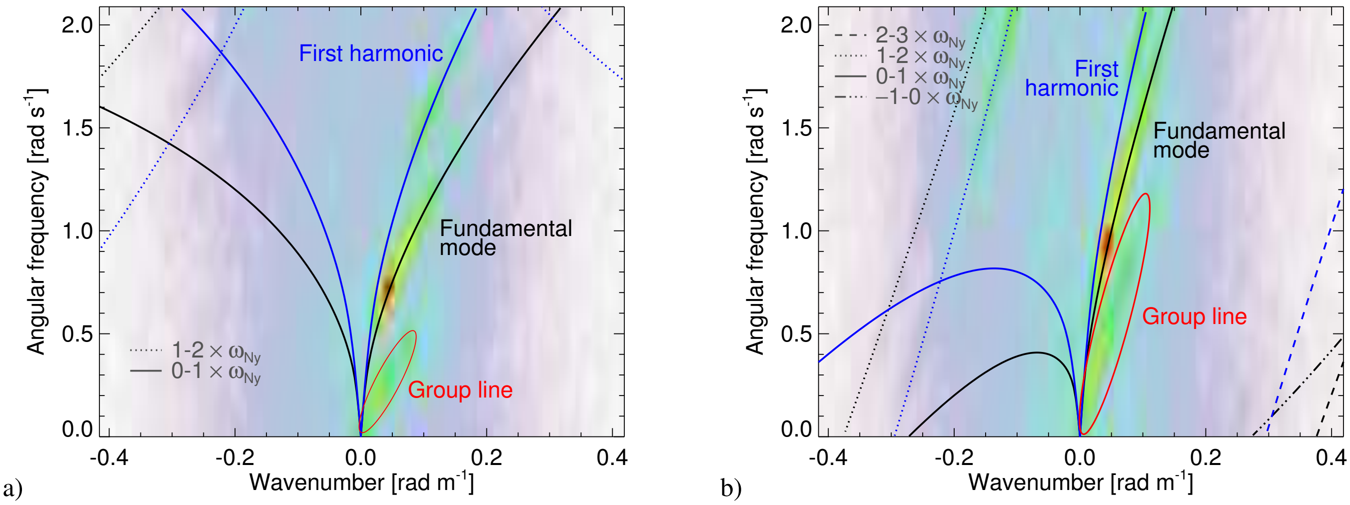

Fig. 3.1. Cross sections through 3-D radar image power spectra for an encounter current of 1 m s^{-1} (a) and 6 m s^{-1} (b). The black lines correspond to the fundamental mode dispersion relation, the blue lines to the first harmonic. Energy due to the group line is marked by red ellipses. The solid lines correspond to spectral coordinates in the range from 0-1 × ω_{Ny}, the dotted/dashed lines correspond to the aliased power associated with higher or lower frequencies.

To remove the jitter from our data, we decided to follow Bell and Osler's approach and exploit the wave signal. However, there is an important difference between our and their technique: they made the simplifying assumption that their ship is a static platform within the time period required for a single antenna rotation period. In fact, even after their correction they observed a remaining small jitter in the bearing and position of fixed targets, and suggested that their "snapshot" assumption may be to blame. As discussed above, we chose to georeference each individual radar pulse. This made it possible for us to develop an iterative scheme that allows the complete removal of image jitter. Essentially, we determine the image jitter from image to image, use that information to correct our heading estimate for each pulse, and repeat this process until the remaining jitter falls below an acceptable threshold.

Fig. 3.2 gives an example of the antenna heading correction results for ~ 90 s of data, covering 64 consecutive antenna rotations. The data were recorded from *Sproul* on June 10, 2010. The mean absolute image jitter for the first iteration was found to be ~ 0.38°. After the first correction the jitter was reduced to ~ 0.05°, and after ten iterations it was less than 0.001°. The maximum heading error between two consecutive radar frames is 1.84°. At the two extremes, around t = 56 s, pulse headings are 2.86° apart, which at maximum range corresponds to a mapping error of ~ 200 m.

We would like to conclude this section with the following remarks. Firstly, for our wave-based antenna heading correction scheme to be successful, as for the subsequent Fourier analysis, the wave field conditions of spatial homogeneity and temporal stationarity must be met. This is because the correction assumes all changes in the wave direction to be artifacts, even if they are true. However, for the short analysis periods, of the order of 1 min, considered here, we think that this assumption generally holds. Secondly, our heading correction scheme faces one challenge that we haven't yet resolved satisfactorily: how to correct the radar image sequence's start orientation? In our example, we used the mean heading error to correct the start orientation, but this does not come without risks. Through our heading correction scheme, we found that WaMoS frequently experiences data flow gaps that lead to biases in the mean error. In such case, which is not straight-forward to identify, using the mean error to correct the sequence's start orientation will introduce a new error that is likely to add variability to our wave and current estimates. To conclude, for reliable shipboard wave and current measurements, it is very important to take accurate heading and GPS measurements, and to ensure that these measurements are precisely time synchronized with the radar data.

3.3. Dependency on analysis window position

In the following, we use data collected from *Flip* to investigate the marine radar surface wave and current parameters' dependency on range and azimuth. The strength of the surface wave signal in marine radar images strongly depends on the angle between antenna look direction and waves as well as on range. The dependency of marine radar surface wave estimates on antenna heading was first investigated by Reichert (1994). However, to our knowledge, no parameterization to address this dependency has been proposed in the literature. Here, we propose a new correction scheme that we expect will improve shipboard radar wave estimates.

Ideally, to address this dependency, the wave analysis

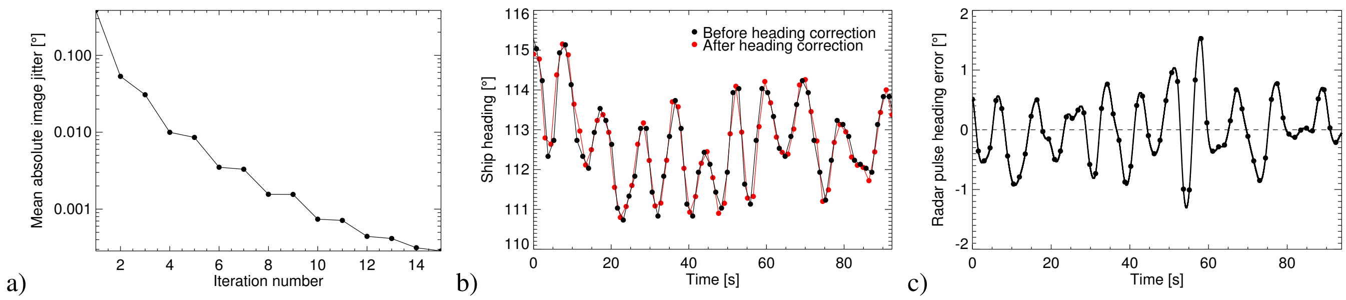

Fig. 3.2. Example of antenna heading correction results for a ~ 90 s period covering 64 consecutive antenna rotations. Data were collected from *Sproul* on June 10, 2010. (a) Mean absolute image jitter for fifteen heading-correction iterations. (b) Radar image heading before (black) and after (red) correction. (c) Time series of the pre-correction pulse-by-pulse heading error with black dots marking the start of a new image.

windows must be distributed evenly over the whole image, covering all directions. Averaging the results from all windows to produce a single estimate would then mitigate the issues related to this dependency. However, on ships the radar field of view is typically partially obstructed by superstructures, e.g. the mast, limiting the area that can be used for wave retrieval. If not properly addressed, this will result in an increased variability or error associated with the wave parameters, especially in the case of regular course changes.

To explain this expected deterioration of our wave estimates, note that the wave signal is much more pronounced in the up- than the downwave direction (compare Fig. 2.3). Let us consider a typical scenario where a 90°-wide section of the radar field of view towards the stern is blocked by superstructures and three analysis windows are placed such that one points towards the bow and two in the port and starboard directions, respectively. Now, if the ship travels first upwave and then downwave – something that is not unusual on a research vessel, as Fig. 2.1 illustrates –, the radar-based significant wave height will show an artificial decrease, unless some correction scheme is implemented. As this example should make clear, the wave (and current) results' dependency on azimuth is especially important for open ocean situations (where some section of the radar field of view is masked). This is because at coastal stations, waves generally travel towards shore. Consequently, the dependency on the analysis window position is difficult to observe and investigate, which may be the reason why this issue has received so little attention in the literature.

Fig. 3.3 illustrates the analysis window setup for this investigation. We chose to study three ranges, and, for each range, twelve directions covering the full radar field of view. The different box sizes were chosen such that each box roughly covers the same range of wave directions. As a result, the analysis window size increases from near- to far-range with edge lengths of 480 m, 960 m, and 1,920 m, respectively. Here, we'll be looking at a 6.5-hour period of data collected from *Flip* on June 14, 2013. During this period,

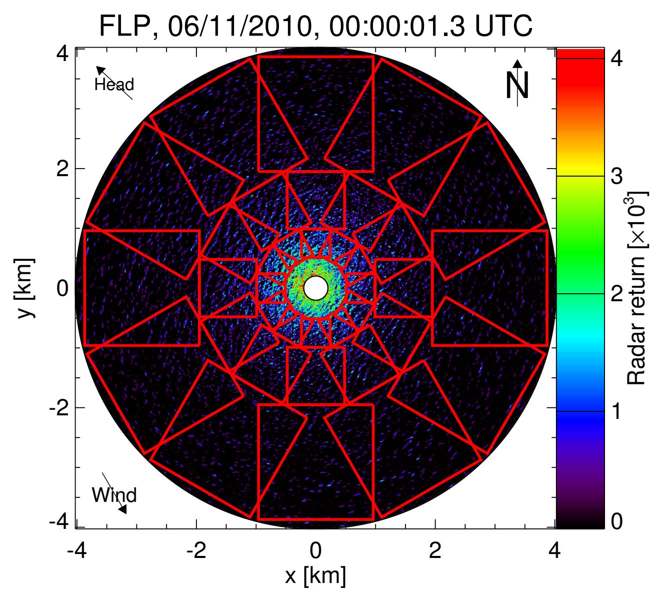

Fig. 3.3. Analysis window setup for study. At each range increment, 12 slightly overlapping windows are set to sample wave and current conditions, covering all antenna look directions.

the wind speed and wave height were constantly increasing, from 9.3 to 14.0 m s^{-1} and from 2.1 to 3.2 m, respectively.

The results in Fig. 3.4 give the mean SNR, peak wave period, and peak wave direction as a function of the relative angle between analysis windows and waves for the first hour of our analysis. The vertical lines mark the upwave, crosswave, and downwave directions. The red, green, and blue points correspond to the near-, mid-, and far-range results, respectively. The figure prompts a number of observations.

- The SNR has a dominant peak upwave, a second peak that is much smaller downwave, and a trough in the two crosswave directions. In part, this can be explained by the imaging mechanism: the surface roughness elements that are responsible for the backscatter are concentrated on the forward face of the wave, and thus more (less) prominent as the radar looks upwave (downwave) (e.g. Plant 1989). The crosswave trough can be explained by the fact that the Bragg waves (and micro-breakers) are mostly oriented in wind direction (e.g. Lund et al. 2012b). Also, SNR is fairly independent of range.

- The peak wave period's dependency on the box positions shows some similarity with that of the SNR: it has two peaks up- and downwave (the latter smaller), and troughs crosswave. However, there is also a significant dependency on range, with near-range peak periods up to ~ 1.5 s shorter than the far-range ones. The range dependency has a relatively straight-forward explanation: shadowing by the wave crests (visible as pixels with zero intensity in our radar images) is much more pronounced in the far than in the near range. The stronger the shadowing effect, the more the short waves are suppressed and the long waves enhanced. As a result, the peak period appears to increase from near- to far-range. The dependency on the angle between analysis windows and peak wave direction is due to the fact that for each box position, the waves that are traveling towards the box are favored. This concept is easy to understand if one imagines a radar first looking perpendicular to the wave crests (upwave) and then parallel (crosswave). Clearly, the radar's imaging capability is best in the former and greatly compromised in the latter case. Finally, note that while, to first order, the peak wave period's azimuth dependency must be interpreted as an artifact induced by the radar imaging mechanism, to some extent, it also reflects the wave field's directional variability.

- The peak wave direction has a clear (if small, note the axis range) dependency on the box orientation relative to the waves. As with the peak wave period, this behavior can be explained by the fact that each box "favors" the waves that are traveling towards it. Like the SNR, the peak wave direction shows no evident dependency on range.

Fig. 3.5 shows the corresponding results for the surface current speed and direction. The surface current results show some limited dependency on orientation and range, however, the relationships are more difficult to interpret than those for the waves. For both current speed and direction, the near-range results show outliers in the crosswave directions. This may be an artifact since the wave signal in the cross-wave directions is poorly defined. However, it could also be due to the fact that in each window the waves are "weighted" differently (refer to discussion above). As shown by Stewart and Joy (1974), the radar-based surface currents correspond

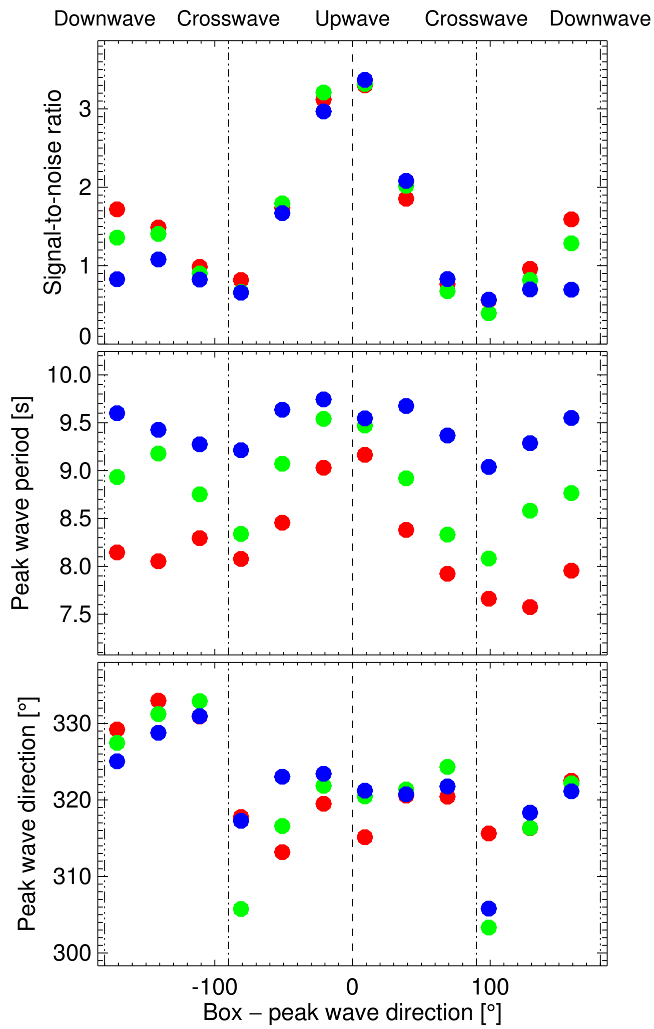

Fig. 3.4. 1-h mean of signal-to-noise ratio, peak wave period, and peak wave direction for all analysis windows. Results are plotted based on the difference angle between analysis window and the overall mean peak wave direction. Near-range results are shown in red, mid-range results in green, and far-range results in blue.

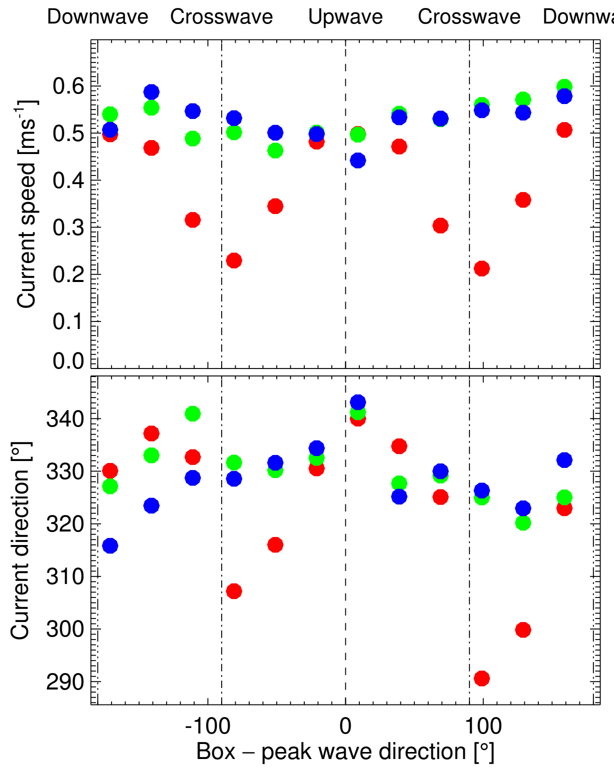

Fig. 3.5. 1-h mean of current speed and direction for all analysis windows. Results are plotted based on the difference angle between analysis window and the overall mean peak wave direction. Near-range results are shown in red, mid-range results in green, and far-range results in blue.

to the average current from the surface to a depth of the order of $(2k)^{-1}$, where k is the wavenumber of the sampled ocean wave. The mean depth at which a marine radar samples the surface current thus depends on the given vertical current profile and on the wavenumber coordinates chosen for the current fit. Assuming a wind-driven current with a logarithmic profile, long waves can be expected to experience a smaller Doppler shift than short waves. In addition, waves that propagate in a direction that is perpendicular to the current will not at all be Doppler shifted. Further research is required for more conclusive results.

For peak wave period, direction, and surface currents, similar dependencies are observed throughout the whole 6.5-hour period. In the following, we focus on the SNR (significant wave height), which for many practical purposes is the most important surface wave parameter. Fig. 3.6 shows the SNR's evolution with time, where each line represents a range-averaged ~ 1-hour average. As mentioned before, the wave height steadily increased during our analysis period. Therefore, it should not come as a surprise that also the SNR for all box−wave angles increased with time. Aside from the increase in magnitude, the SNR's azimuthal dependency

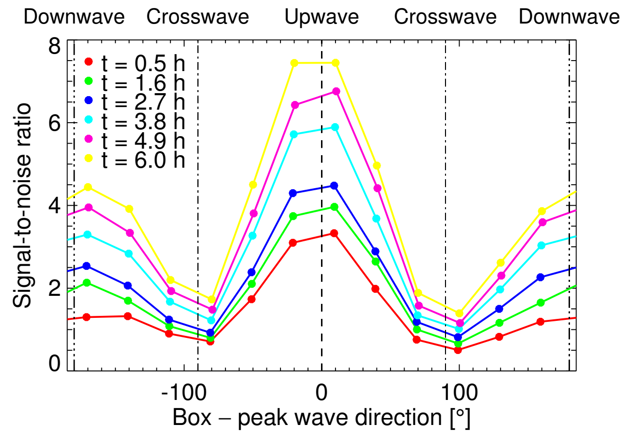

Fig. 3.6. 1-h mean signal-to-noise ratio, averaged over all ranges, as a function of the difference angle between analysis window and the overall hourly mean peak wave direction. The results shown here cover a ~ 6 h period during which the significant wave height was steadily increasing.

keeps the same characteristics as observed above (compare Fig. 3.4). Note that the SNR can be up to four (two) times larger for an analysis window that is positioned upwave as opposed to crosswave (downwave). This finding strengthens the above claim that a course change is liable to heavily deteriorate our radar-based wave height estimates. However, we believe that this error could be corrected by least-squares fitting an empirical function (e.g. a Fourier series) to the relationships observed here. The fitted functions could then easily be used to estimate an SNR (significant wave height) that is independent of the given box−wave angle.

4. Summary and outlook

This paper investigates the reasons and proposes solutions for the apparent poor performance of shipborne marine radar surface wave and current estimates relative to fixed platform data. In particular, previous investigators found shipboard marine radar significant wave height estimates to be unreliable, and proposed an alternative technique that scales the radar-based wave spectra using measurements from a conventional ship motion pack or laser altimeter (Stredulinsky and Thornhill 2011; Cifuentes-Lorenzen et al. 2013). Bell and Osler (2011) introduced an antenna heading correction technique with the goal of improving shipboard radar results. However, while marine radar wave estimates from moving vessels have received increasing attention in recent years, we found that a thorough discussion of the reasons for the apparent discrepancies between fixed and moving platform results was still lacking in the literature. We hope that this work helps fill this gap, and that the solutions we propose to address the identified issues will eventually allow shipboard marine radar wave and current estimates that are of comparable quality as those from fixed platforms.

Traditionally, the wave analysis is carried out in windows that are fixed in platform-based coordinates. The ship motion is then treated as a current that must be subtracted from the measured encounter current to obtain an estimate of the real ocean current (Young et al. 1985; Senet et al. 2001). To simplify the data processing, the traditional approach assumes that the ship is static during the time required for one antenna rotation. Here, we identified three reasons why this traditional approach negatively affects shipboard radar measurements.

- Making the simplifying assumptions that the ship is static over the 1.5 s required to build a radar image and that the ship course is steady over the full 1.5-min-long analysis period, results in significant mapping errors. This is especially the case if the ship is traveling fast, is operating in heavy seas, where holding a steady course is practically impossible, or undergoes frequent course changes. The errors resulting from this simplification can be eliminated by georeferencing each radar pulse, accounting for the horizontal ship motion and heading changes that occur during a radar sweep. Georeferencing also helps mitigate issues associated with the aliasing problem.

- Even after properly georeferencing our radar data, we found that a considerable image jitter remained. To remove this jitter, we developed a new iterative technique that exploits the surface wave signal, as first proposed by Bell and Osler (2011).

- Marine radar wave and current estimates show a strong dependency on the position of the analysis box in range and relative to the peak wave direction. If the radar has an unobstructed field of view, this issue can be mitigated by evenly distributing the analysis windows over all directions. However, typically, a significant section of the radar field of view is masked by ship superstructures. In this case, assuming that the analysis windows are defined in a ship-based reference frame, every heading change will modify the radar-based wave and current estimates, thus increasing the error. Here, we propose a new technique that corrects the SNR (significant wave height) by fitting an empirical function to its dependency on the box−wave angle.

While we found that the proposed solutions significantly improve shipboard marine radar wave and current estimates, several issues require further study. To begin with, we still need to find a reliable technique to estimate our radar image sequence's true orientation after performing the jitter correction (i.e. automatically identify gaps in the WaMoS data flow before correcting for the mean heading error). In the end, a slight error is bound to remain, which is why accurate and well-synchronized heading and GPS measurements are of utmost importance to achieve high quality wave and current estimates.

The dependency of our wave and current estimates on the analysis window position is the most difficult problem to address. While we do propose a correction scheme for SNR (significant wave height), which is the parameter that may be of greatest practical use and has faced the most criticism, this work is far from complete. In particular, we need to find ways of correcting for the dependency of peak wave period and direction on the box position. In the future, we will attempt to achieve this through modifications of the so-called modulation transfer function, that, so far, considers solely the wavenumber (Borge et al. 2004). The difficulties encountered here, lead to the following conclusion: if at all possible, a shipboard wave radar should be setup such that it has an unobstructed view of the sea surface. If this condition is met, high quality wave and current estimates can be obtained either by distributing the analysis windows evenly over all directions, or by simply analyzing the whole radar image covering all possible antenna look directions. Finally, our findings regarding the radar-based surface current estimates suggest that more work is required to improve our understanding of their physical meaning.

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