INVESTIGATING POSSIBLE BISTATIC CONFIGURATIONS FOR SHIP WAKE IMAGING THROUGH SIMULATION

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Abstract

We consider the context of marine surveillance and ocean imaging with bistatic radar. Since these systems are not yet mainstream and somewhat costly, not much experience has been accumulated yet in the literature and their usefulness is still under debate. We propose an approach to find potentially interesting bistatic configurations that could be used in the future to monitor the ocean, and especially ship wakes. First, we review the important acquisition parameters and how their choice might influence the final image. These considerations are then validated through simulation for frequencies above 1 GHz.

1 Introduction

Increasingly, bistatic and multistatic configurations are brought forward as an alternative to the traditional monostatic configuration. The first purported advantage of these configurations is the possible use of transmitters of opportunity, while the receiver is always passive (thus stealthy). Secondly, the higher number of degrees of liberty is often seen as a way to have a better visibility on the target amid the clutter. However, multistatic configurations are more delicate to use than monostatic systems and can be more costly in some cases. Since those systems are not yet mainstream, not much experience has been accumulated as of today and the benefits of bistatic radar versus monostatic systems are still under debate.

In our case, we consider bistatic radar in the context of marine surveillance and ocean imaging. We are for instance interested in the imaging of ship wakes, since wakes provide useful information on a ship's heading, speed, and dimensions. A way to gain a better insight on this matter is to use simulation tools to determine, *a priori*, how to use bistatic systems and evaluate their pros and cons as opposed to monostatic systems. For this reason, we at the ENSIETA developed a Marine Radar Simulator (MaRS) that enables to simulate raw radar signals for a great deal of bistatic and polarimetric configurations.

The presentation of the MaRS tool and of its implementation will not be the subject of this paper, since we already presented it more thoroughly elsewhere [1,2,3], but we summarize its main properties in part 2 of the paper. We devote section 3 to a few theoretical considerations on the parameters that matter when imaging the sea, and what requirements on, for instance, resolution or polarisation, are needed to satisfactorily observe waves or ship wakes. Note that we did not model the ship itself and leave that for future work. Section 4 exhibits some results we obtained with out simulator. To the best of our knowledge, some of these images have not been simulated nor experimented before, which make them valuable for potential experimenters. Recommendations on future work close the paper.

2 Overview of the simulation tool

The key components of the radar acquisition chain and their interaction as simulated are presented in fig. 1.

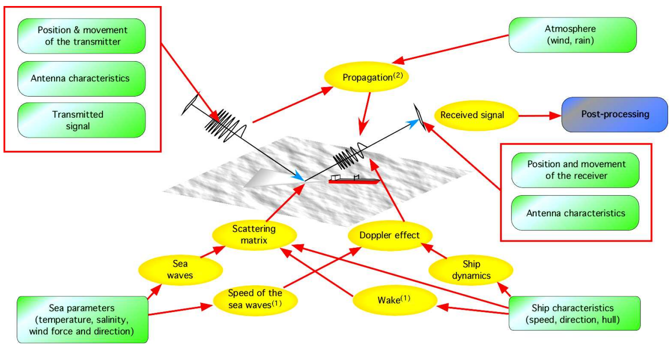

Figure 1: overview of the main elements of the acquisition chain and the environment (1: only partially simulated, 2: not simulated yet). The green boxes are the input parameters, the yellow boxes are the modelled phenomena, and the red arrows show the dependencies.

2.1 Representation of the sea

The sea is represented using a two-scales formulation. The large-scale features (gravity waves) are represented as a digital elevation map (DEM) generated using common sea spectra (Pierson-Moskowitz, Fung & Lee, Elfouhaily). This elevation map evolves with time according to the ocean waves dispersion relation. Small-scale features (capillary waves) are represented statistically through their spectrum.

2.2 Ship wakes

The elevation of the Kelvin waves induced by the ship hull is obtained by assuming that the Mitchell thin-ship theory holds, using the SWPE model as proposed by Tuck [4] (note that we used a much cruder model in [1]). This model allows for using a 3D representation of a ship obtained through a CAD program (as in figure 2). Then, we deduce the Kelvin waves elevations at each point of the sea surface as a function of the ship velocity. We also have a first approximation of the turbulent wake left by the ship: we locate the points that lie within the turbulent wake on the DEM and reduce the small-scale roughness spectrum. The location of those points is obtained using an empirical relationship [5], which gives the breadth of the turbulent wake at a given distance from the ship as a function of the ship's length and beam.

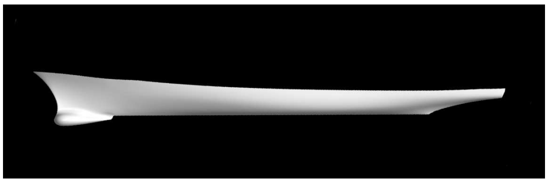

Figure 2: the DTMB 5415 hull used in the simulations provided in this paper

2.3 Transmitter, receiver and signal

The transmitter (X) and the receiver (R) are then positioned within the scene. Various antenna gain patterns can be used (rectangular & elliptic apertures, or custom gain pattern loaded by the user). The modulation is also left free to the user, even if we only used linear chirps so far.

2.4 Computing the received signal

For each transmitted pulse, the position of X and R evolves freely with time. The trajectory can be eventually noisy to see how this influences SAR focusing. The contribution of each facet of the DEM as given by the polarimetric and bistatic radar equation is then computed using a raytracing scheme. The contribution of specular points is computed using the Kirchhoff Approximation and the diffuse component is obtained using the Small Perturbations model in the local frame associated to a tile. The models work for frequencies above 1 GHz and assumes incoherent diffusion (in space) but a short correlation (in time).

The outputs of MaRS are twofold. First and foremost, a raw temporal signal is delivered, which can then be fed to post-processing tools such as a synthetic aperture processor. This raw signal is obtained by adding the elementary returns of each facet, with the adequate Doppler shift, attenuation, and a random de-phasing which comes from the fact the reflection on each facet is incoherent. However, the simulator can also output reflectivity maps of the surface, which gives an interesting indication on the potential visibility of specific features.

3 *A priori* theoretical considerations

The size of the variable space influencing the final received image is extremely high (see figure 1 for a review of these variables). Therefore, it would be hard to perform a brutal series of tests with variables such as the frequency varying one by one. We first begin by selecting a few configurations that might be interesting from *a priori* considerations. The following outlines what parameters are important and how their choice can influence on the final image quality.

3.1 Radar design choices

There are design choices than will have a direct influence on the visibility of desirable features on the image, such as the carrier frequency, the polarization, the required resolution, etc. Those are often fixed beforehand when the radar system is conceived. When imaging the sea, the ability to measure variations of heights is of much less importance than the ability to distinguish waves by using shadows and/or the difference of contrast between one side and the other. These shadows or variations of intensity allow for retrieving the spatial frequency of the waves, which in turn is linked to environmental parameters such as the wind speed and direction, as well as the depth of the water zone being considered. Therefore, we feel the contrast is the first parameter that should be optimized.

Polarization: Some polarizations are known to be better than others for sea imaging. For monostatic radars, for instance, HH polarization is considered to be better than VV polarization, since it yields a better contrast between steep and moderate slopes. This helps to see the waves. This comes from the fact that specular returns will tend to be comparatively higher than diffuse returns. Cross-polarization is still not used very often, even if it has been argued that cross-polarized radars could yield a better contrast to observe ship wakes, since they allow for a better contrast in average incident angles. Our simulator indeed confirms these claims for monostatic radars and suggests that they are also true in the bistatic case in most of the viewing configurations.

Frequency: X band is the most often used frequency in marine radar; on the other hand L band has been shown to be an interesting choice since it makes some features of Kelvin wakes visible. This comes from the fact that some wavelengths of the Kelvin wake can enter into Bragg resonance at those frequencies, which will then be responsible for well-documented bright lines forming a cone of about a dozen degrees centred on the main axis of the wake. Besides, this band is also used by GPS and Galileo systems, although the expected resolution that can be attained with GPS is much lower since the modulation is done on a smaller band than dedicated radar systems. Lower frequencies also yield lower reflectivities in the diffuse zone. This has the combined advantage of both maximizing contrast and yielding a lesser developed speckle.

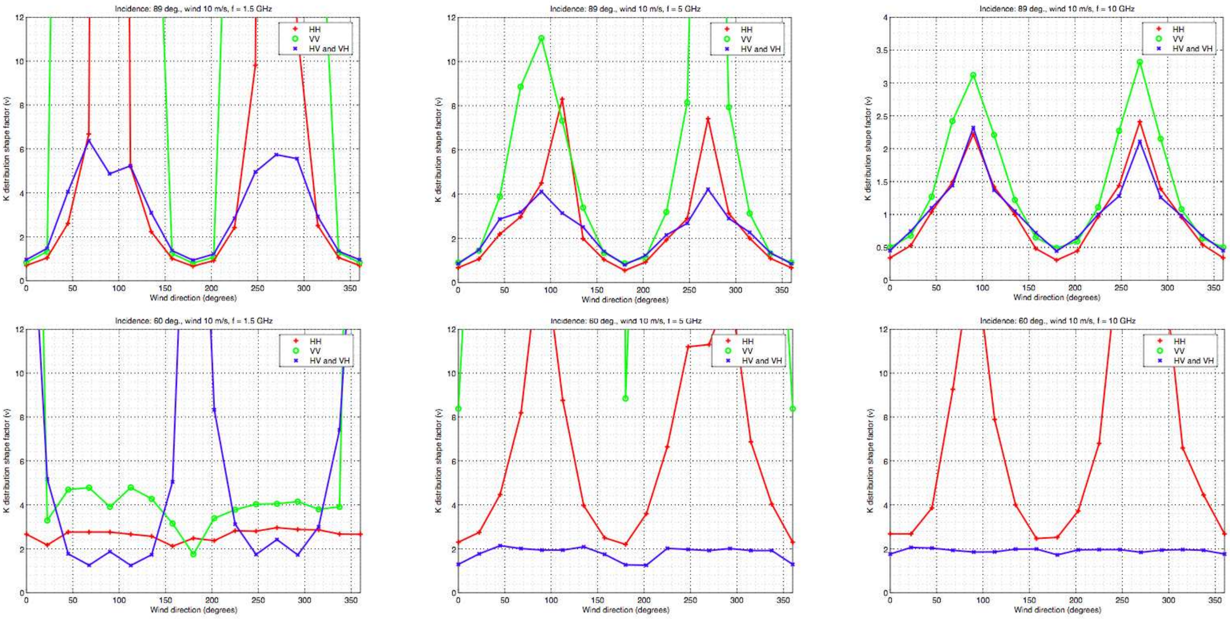

Figure 4: shape factors ν of the speckle in our simulated monostatic SAR images as a function of the wind direction in degrees, assuming it follows a K distribution, for a 89º incidence (top row) and a 60º incidence (bottom row).

Resolution requirements: depending on what is to be observed, these requirements are not the same. With resolutions currently available with radar satellites (about 30 m, since multilook imaging is used), the dark turbulent wake is commonly visible, as is the border of the Kelvin wake cone, which appears as a bright line. Distinguishing the actual wave system of the Kelvin wake is much harder. To see it, two factors have to be considered. First, the ground resolution must be compatible with the wavelength of the Kelvin waves. For instance, a ship going at U = 10 knots generates transverse waves in the ship direction with a wavelength equal to $2\pi U^2/g$ = 17.2 m, thus the ground resolution must be at least in the 8.5 to 9 m range (for the image to be sampled at the Nyquist rate).

3.2 Operational choices

Operational choices really concern the viewing configuration (that is, the position of both the transmitter and the receiver, the incidence angle, etc), so as to maximize the visibility expectation of some desirable features.

Resolution: The distance resolution on the ground Δr_g increases with the incidence angle θ:

$$\Delta r_g = \frac{\Delta r}{\sin\theta} \qquad (1)$$

where Δr is the resolution on the distance axis. This suggests the use of large incidence angles to maximize the resolution. Also, the slope of the waves mostly influences the reflectivity of the swell and the wake. This slope varies with the wind speed and direction (for the swell), the ship velocity and the hull shape (for the wake), and also with the viewing configuration. As seen earlier, it is desirable to have a good contrast for the waves, so that their spatial frequency can be estimated in the best possible way. Again, this can suggest the use of low grazing angles to maximize shadows.

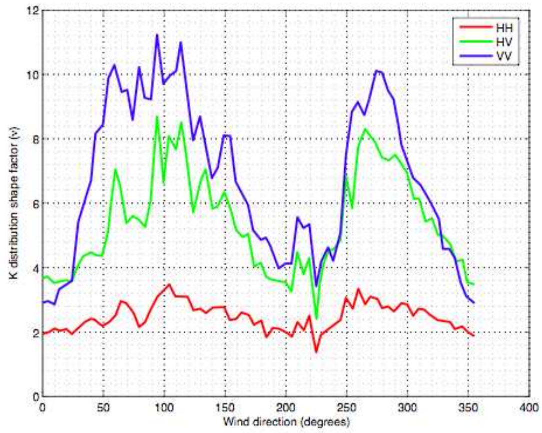

Figure 3: real-world measures of the clutter shape factor ν as a function of the wind direction (degrees) assuming a K distribution, quoted from [6]. Incidence 55-65°, X band.

Clutter and observation configuration: The last concern is about clutter mitigation. Our simulations as well as real experimental data show a strong dependency between *i)* the incidence angle and *ii)* the clutter type and the angle between the boresight direction of the radar and the wind direction. If the clutter is, for instance, K-distributed, the measured amplitude a will have the following probability distribution:

$$p(a) = \frac{2b}{\Gamma(\nu)}\left(\frac{ba}{2}\right)^{\nu} K_{\nu-1}(ba) \qquad (2)$$

where b is a scale factor, ν a shape factor, Γ the Gamma function and K_ν a modified Bessel function of the third kind of order ν (the higher ν, the more Rayleigh-like the clutter). Figures 3 and 4 exhibit this dependency. Figure 3 shows experimental measures obtained using the Ingara SAR platform [6] at 10 GHz for incidences going from 55 to 65 degrees. The ν/wind direction dependency is correlated to the relation between the reflectivity of the sea and the wind direction, that is, the reflectivity is highest when looking in the upwind direction (see fig. 5) and the clutter spikiest in that direction. In our simulations (figure 4), the shape factor is sometimes overrated as compared to those of [6] and indeed, when ν was too large, the Weibull-distribution was better suited than the K-distribution. Notice also the dependence of the shape factor to the incidence: the speckle becomes more Rayleigh or Weibull-like as the incidence angle becomes smaller or the wind speed higher.

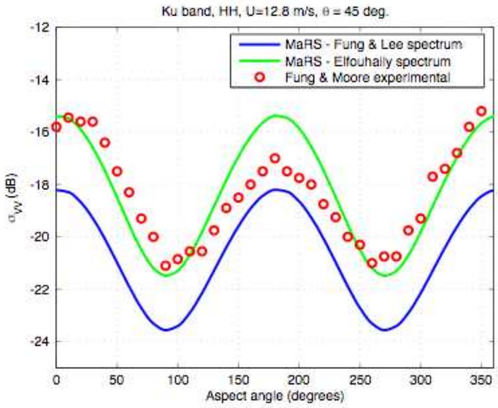

Figure 5: evolution of the NRCS of the sea as a function of the wind aspect angle. Comparison between MaRS and experimental measurements quoted after [7] at 14 GHz. VV measures show a similar trend.

4 Towards a useful bistatic configuration: some selected results

The broad principles coming from the considerations stated above suggest using large incidence angles, if possible. Coastal radars can do that; yet monostatic coastal radars have poor azimuthal resolutions at large distances; consider for instance the case of a radar with a 0.5° aperture; the resolution at 10 nm is 162 meters; this could theoretically be increased by the use of an hybrid coastal/airborne bistatic configuration, so that synthetic aperture radar could be performed and better resolutions attained.

To give an idea of the kind of images we obtain, we present a set of images simulated in a classic, SAR configuration (figure 6), as well as the hybrid coastal/airborne configuration mentioned before (figure 7). The parameters are summarized in table 1. In the second configuration, the contrast is the one attained with coastal radar due to the high grazing angle of the transmitter, but on the other hand, the resolution is the one obtained with synthetic aperture systems and is much higher. On the other hand, a drawback of this configuration is the difficulty to put it into operational use since the coastal radar must be servoed to the aircraft so that the antennas aim at the same point; also, aircraft do not have a 24/7 disponibility (but this is also true for monostatic SAR as well).

Parameter	**Value**
Frequency	10 GHz
PRF	222 Hz
Modulation	60 MHz
Pulse length	0.3 µs
Wind speed	10 m/s
Wind direction	30°
Ship speed	4.5 m/s

Table 1: parameters used in the simulation

5 Conclusions and future prospects

It is early to categorically reject or argue in favor of one particular configuration, since too many parameters are involved. This paper is by no means an exhaustive catalogue of all possible configurations. However, some basic principles can be stated, which could help to increase the quality of the images. In the context of ocean and ship wake imaging, it is interesting to maximize the contrast of the image so that waves are more visible. This suggests using configurations where at least one antenna aims with a small grazing angle. If possible, the looking direction should be perpendicular to the wind direction in order to reduce speckle. This can also be achieved by choosing the appropriate polarization (HH or cross-polarized) and by lowering the frequency. The choice of a particular configuration should ideally be validated through experiments but since those are costly and unwieldy, simulation is an alternate way to investigate the use of radars for marine imaging. Finally, there is hope that simulation could be used to investigate the influence of environmental and observation parameters on the shape of speckle.

Acknowledgements

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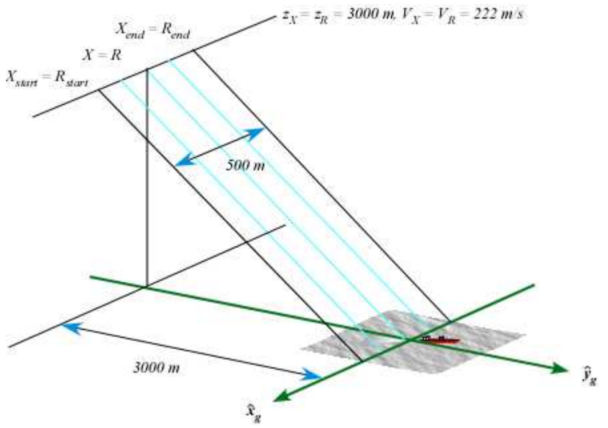

Figure 6: classical SAR configuration

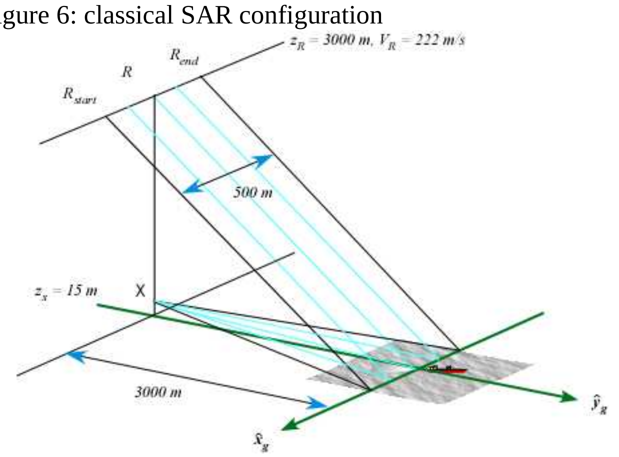

Figure 7: hybrid coastal/airborne bistatic SAR; the two antennas are focussed on the same point at each instant.

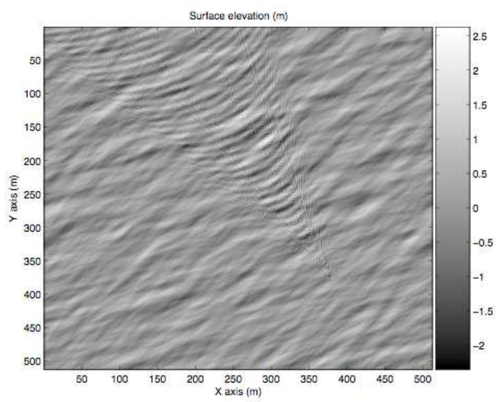

Figure 8: surface used in the simulations (sea state 4-5, DTMB 5415 hull at a 4.5 m/s velocity)

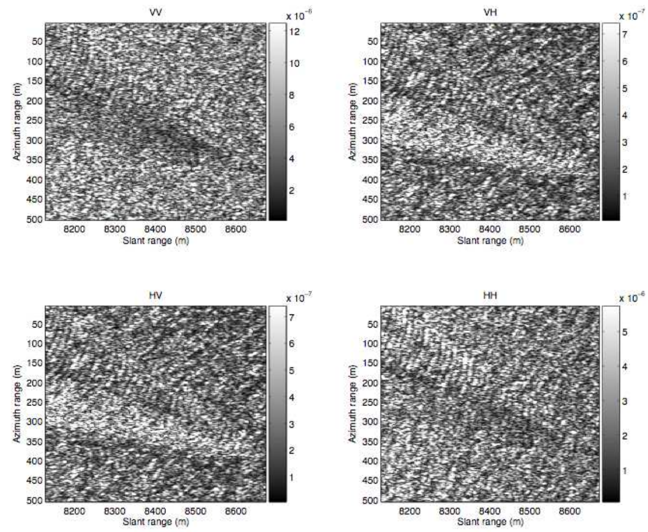

Figure 9: results for the SAR configuration. Note the high contrast on cross-polarized channels. Ocean waves are not very distinguishable, however, due to the low contrast.

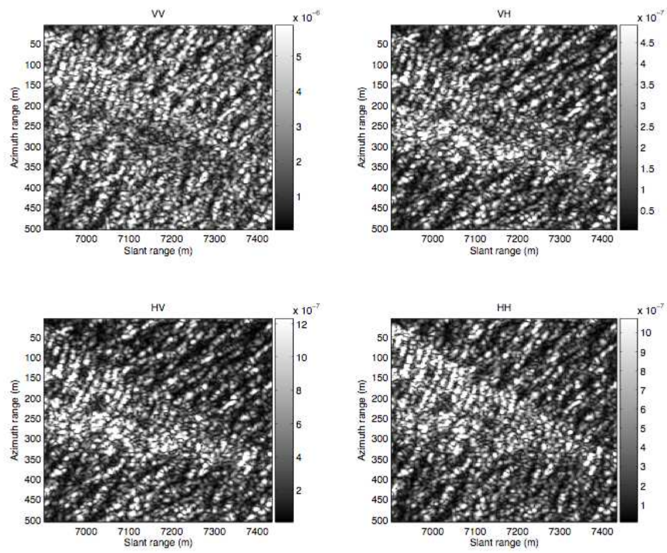

Figure 10: results with the bistatic SAR configuration. Notice the high contrast of the image and the nice resolution.