

The use of radar for bathymetry assesment

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Abstract

The bottom topography in shallow seas can be observed by air- and spaceborne imaging radar. Bathymetric information derived from radar data is limited in accuracy, but radar has a good spatial coverage. The accuracy can be increased by assimilating the radar imagery into existing or in-situ gathered bathymetric data. The paper reviews the concepts of bathymetry assessment by radar, the radar imaging mechanism, and the possibilities and limitations of the use of radar data in rapid assessment.

1. Introduction

Radar radiation does not penetrate into the sea; on the contrary, all radiation is reflected off the surface. Therefore, only information about the sea surface can be extracted from radar images. Nevertheless, bathymetric features are sometimes expressed in radar images, as was first noticed in airborne radar images of the North Sea in 1969 [6,7]. At the time, the effect was quite unexpected. Since then, the effect has been routinely observed by numerous space and airborne systems, including the SEASAT (L-band, 1978) and ERS-1 (C-band, 1991-1996) radar satellites.

Due to developments in operational earth observation, radar imagery is becoming more easily available these days, the instrument of choice being the Synthetic Aperture Radar (SAR). Therefore, it would seem justified to investigate the possibilities for the use of radar for (rapid) bathymetry assessment. When doing so, it turns out that, although radar certainly has disadvantages with respect to the usual bathymetry mapping techniques, it in fact also has some very special advantages. These are found primarily in synoptic overview, speed, cost reduction, and the ability to survey from a safe distance. Main disadvantage is the fact that the radar produces only partial information, which has to be supplemented by data from other sources.



Figure 1 Radar image from the ERS-1 satellite showing the North Sea and a part of the southwestern Netherlands coast. Most of the structures in the open sea are bottom topography.

This paper aims at discussing some aspects of the use of radar images for bathymetry assessment. The paper first describes, in section 2, the concepts of bathymetry assessment, including the physical processes that lead to the imaging of bathymetric features by radar, the modeling techniques for simulating these radar images, and the use of inversion and assimilation schemes to extract quantitative bathymetric information from radar data. More detailed information on the various elements that play a role is given in section 3, including a review of the instrumentation. Examples of implementation and results are presented in section 4. The paper concludes, in section 5, with a brief summary of the current status of the research.

2. Concepts

2.1. Forward model

The reason that bathymetry can be observed by radar is because the bathymetry influences the sea surface. The amount of backscatter reflected from the sea surface (and thereby its radar image brightness) is proportional to its roughness: the rougher a patch of surface, the brighter it will be in a radar image. It is indeed the changes in sea surface roughness, caused by the sea bottom topography, that result in bathymetric signatures becoming visible in radar images. The way this happens is through a three-step process. First, it is necessary that a water flow is present, such as a tidal current. This current will be modulated by the bathymetry, and the resulting variations in current speed will also be present at the surface. The second step of the process is that these surface current variations influence the surface roughness. The third step is the radar imaging of the surface; as outlined above, the smoother areas will become darker in the image, and the rougher areas brighter.

This whole process can presently be quantitatively modeled, at least with certain approximations. Based on the physics of the problem, algorithms are available that can produce a simulated radar image, given a bathymetry. The radar signatures induced by the bathymetry are strongly dependent on the ambient hydro-meteorological conditions. Shape, location and amount of radar contrast associated with bathymetric features depend, e.g., on current and wind speed and direction. Furthermore, the system parameters of the radar are important, including viewing geometry.

2.2. Inversion

Although it is possible to compute the radar image given the bathymetry, this computation cannot, in fact, be directly inverted. This is due to the complexity of the relation between the magnitude of the radar contrast and the water depth. From a radar image *alone* it is, at least for now, impossible to extract a bathymetry chart. Radar, therefore, will probably never completely replace *in situ* depth measurements by conventional techniques (including sonar). Nevertheless, radar data can be utilized in several ways for bathymetry purposes. Distinction can be made between use in a qualitative and quantitative sense. In the first way, the radar images are interpreted for the presence, shape and location of bathymetric features. This interpretation has to be performed on the basis of knowledge of the forward modeling process, and the actual hydrometeo conditions. For the purpose of this paper, the result of this kind of analysis is denoted as a reconnaissance survey. As was described above,

the relation between the contrasts in the radar image and the bathymetric features such as ridges or slopes is not fixed, but depends on parameters such as current and wind speed and direction. On the basis of modeling, the radar image can be analyzed to yield a more precise geometric location of the bathymetric features.

For quantitative use, it is necessary to employ an inversion scheme (figure 2). The inversion process can be summarized as an iterative adjustment of the bathymetry to minimize the difference between simulated and measured radar images. From an initial depth chart, a simulated radar image is computed using the forward model and the actual hydrometeo conditions. The differences between the simulated and observed image are used to adjust the depth chart. The procedure is repeated until the simulated results are consistent with the measured image.

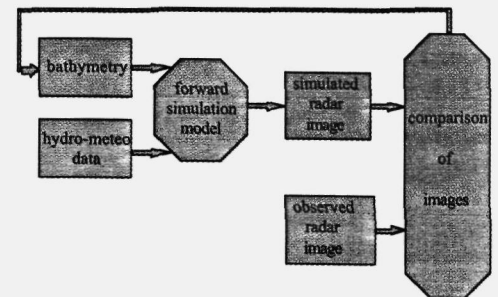


Figure 2 Inversion scheme. From left to right: data input, forward simulation, and comparison of simulated and observed images. The process is repeated until the difference between the images is minimized.

In such an inversion process, the radar data can be combined with bathymetric data from other sources, and the inversion process can thereby be extended to an assimilation scheme [4]. Assimilation of radar data for bathymetry assessment can involve the fusion of data from a range of sensors or data bases. The goal is to optimize the result, in this case bathymetric accuracy, by combining sensor data with different performance aspects. These may include echo soundings, ADCP-measured velocity profiles, existing bathymetric information or depth charts, and space and airborne SAR data. The main advantages for these types of data are: for the sounding and ADCP data their accuracy, for the bathymetry charts their instantaneously availability, and for the radar data their all-weather acquisition capability, extended spatial coverage and possibility for continuous update (for satellite data). Disadvantages are: the sparseness and local confinement of the sounding and ADCP data,

possible obsolescence of the depth chart (depending on the time scales associated with the dynamics of the sea bottom), and the indirect and partial nature of the information in the radar images, plus the fixed orbit of the spaceborne platforms. The use of an assimilation scheme with input from different sensors can lead to more robust results, to more accurate results, and also to cost reduction by lowering the relative contribution of the more expensive types of data.

3. Components

3.1. Instruments

There are various types of radar that can be used to image sea bottom topography. From an aircraft, a "SLAR" (Sideways Looking Airborne Radar) may be utilized. SLAR, however, is becoming replaced by "SAR" (Synthetic Aperture Radar; also for airborne use). The data recorded by a SAR are not in the form of an image right away, but need numerical processing ("SAR processing") first. The advantage of SAR is that the image produced has a constant spatial resolution, whereas a SLAR (or any other type of conventional radar) has a resolution that decreases linearly with distance. For this reason, a SAR can also be operated from a satellite in earth orbit. Indeed, next to airborne SAR, satellite SAR promises to be a suitable instrument for bathymetry applications.

There are two main differences between the use of airborne and of satellite SAR systems. The first difference lies in the scales of the image. A satellite system will in general image a larger area (typically 100 x 100 km), but with less detail (typically 30 x 30 m); an airborne system will image a smaller area (of the order of 10 x 10 km), but with more detail (typically 3 x 3 m resolution). The second difference lies in the scheduling. A satellite will have a fixed orbit, giving it a fixed repeat period for imaging a particular area on the ground. An airborne system can be deployed much more flexibly. Given that the successful imaging of bathymetry depends rather strongly on hydrometeo conditions, and that a satellite needs to be scheduled in advance, satellite imagery typically needs to be collected during a period of time, waiting for a coincidence of favorable hydrometeo conditions with the satellite overpass. An airborne sensor, on the other hand, is typically kept on stand by and is flown once, as soon as the favorable conditions occur. Furthermore, it can be noted that, in general, airborne data is more expensive per square km than satellite data.

Presently, there are a number of satellite SARs in operation. These include ESA's ERS-2 (successor to ERS-1), Japan's JERS-1 and the Canadian

RADARSAT. In the past, ERS-1 has produced useful data. Concerning airborne SAR, several systems are nowadays available for (semi-)operational use throughout the world. Many offer a choice of radar frequency and/or polarization, some are even multi-frequency or multi-polarization.

3.2. Details of the forward model

The first of the three steps of the forward modeling is the calculation of surface currents. Flow models have the bathymetry as a boundary condition at the bottom, and are typically driven by much larger-scale flow models that provide, e.g., a tidal and wind-driven current averaged over the entire area of interest. When the bottom topography is one dimensional, as in the case of parallel long-crested sand waves, a simple model suffices. Such parallel sand waves are found, for example, in front of the Dutch coast. In such a simple model the component of the surface current perpendicular to the sand wave crests can be approximated by simple flux conservation law, while the component parallel to the crests is constant. When the sea bottom topography is more complicated, however, more sophisticated two dimensional flow models are needed, or, in order to relate the surface current to the depth-averaged current, even three dimensional ones. The comparison of the simulated results with radar images requires flow data on a extremely fine grid (ERS-1 image comparison leads to 12.5 m) and the flow model must pass the assimilation loop not once but a (large) number of times. These requirements constrain the flow model complexity since there is only a limited computer capacity available.

The second step of the modeling describes the influence of the current, and in particular the current variations associated with the bathymetry, on the surface roughness. This description is in terms of the wave directional spectrum. The spectrum needs to be described over a very large range of wavelengths, from tens or hundreds of meters down to centimeters. Among the short (centimetric) waves are the so-called "Bragg" waves, which are in first instance responsible for the radar backscatter; these are in turn modulated by the longer waves upon which they ride. The modeling is of a perturbation/relaxation type. Starting with the equilibrium wave spectrum, the local changes in wavelength and amplitude of each wave in the spectrum due to the variations in current are computed. Again, this is done on the basis of conservation laws: conservation of apparent frequency and conservation of wave action. The conservation of apparent frequency yields the wavelengths of the waves as they are subject to the current variations while traveling on the water surface; the

conservation of action yields the wave amplitudes. This leads to a wave spectrum away from equilibrium. The evolution of the wave spectrum in time is then computed as a relaxation back toward its equilibrium. In this way, a wave spectrum is computed on each location of the surface [1,3,8,9,11,12].

The third step of the modeling is the computation of the radar backscattering from the local wave spectrum. The simplest model for this is the Bragg scattering model. In this model, the radar backscattering is simply proportional to the spectral value at the Bragg wavelength in the radar look direction. More sophisticated models average the local Bragg scattering contributions over all tilts that occur due to the long waves; as a further refinement they may also include contributions of specular reflection, which occurs when the water surface is locally tilted so much as to be aligned perpendicular to the radar. These types of models are called two-scale and composite models, respectively [10]. A different approach is also possible, computing the backscatter from the basic Maxwell equations of electromagnetics, resulting in so-called Kirchhoff-type models [e.g., 5]; in order to get practical results, however, rather strong approximations need to be applied.

The various backscatter models have their advantages and disadvantages. The Bragg model is simplest and fastest, and often quite accurate. The two-scale and composite models in addition give polarization dependence. The Kirchhoff-type models are more accurate for steep incidence angles, but not very simple to compute.

3.3. Assimilation/inversion scheme

An assimilation scheme as outlined in section 2.2 can be implemented on the basis of a cost function that has to be minimized. The cost function quantifies the difference between simulated and observed image. Such a cost function can, e.g., be defined as the sum of the squared differences between model predictions and measurements at all positions. Different weights may be assigned to all of the input data, to reflect their reliability [2,4].

4. Applications and results

4.1. Reconnaissance survey

In qualitative use, the foremost aspect of a radar is the synoptic overview it provides of a large area. This can be used to assess information about previously unknown areas, or to quickly detect changes in the bathymetry when such an overview is compared with a previous image or map. A radar image can thus be used for a preliminary survey

leading to information about the occurrence of the type of bathymetric features as sand banks or shoals, sand waves, and channels.

Areas of particular interest can be identified with such a reconnaissance survey. If, consequently, a comprehensive survey is favored, this information can be used to optimize the gathering of *in situ* data. In this way, the *in situ* measurement capacity can be deployed in an economical way. Such an approach can lead to considerable cost reduction, possibly as high as a factor of ten [4]. In addition, radar bathymetry assessment can lead to a reduction in measuring time. In military applications sometimes the cost factor is less important than the ability to deliver results fast. In a reconnaissance phase, radar images are a valuable information source that can be used for rapid assessment; in this context, one can also think of using (recent) spaceborne data that are available from archives.

4.2. Quantitative survey

For a quantitative analysis, the inversion/assimilation process needs an initial depth map (section 2.2). For this, an existing bathymetric chart may be used, such as a digitized Admiralty Chart. The assimilation of an old Admiralty Chart with a recent radar image will lead to an updated bathymetric chart, with an accuracy depending on the deviations between the two and the quality of the radar image.

It is also possible to extract a map from a radar image with the help of a number of bathymetric cross-cuts through the image. A limited number of ship soundings are needed to determine large scale depth variations and to adjust model parameters. The cross-cuts help to locally "calibrate" the radar contrasts to the bathymetry. In this way, radar data can be applied to substantially reduce the *in situ* measurement effort by ships. For example, while a ship would conventionally need to survey a block by covering it with cross-cuts 50 meter apart, the same result may be obtained by having the ship measure cross-cuts 500 meter apart, and combining these measurements with a radar image. Inversion of the radar image using the 500 m-separated cross-cuts can yield a bathymetric map with similar depth accuracy. Accuracies achieved in this way depend on the complexity of the area, on the spacing of the *in-situ* cross-cuts, and, of course, on the quality of the input data. With a 500 m spacing, accuracies of better than 30 cm have been claimed, going down below 10 cm with closer spacing [4]. Experiments show that a bathymetry with curved or forked channels results in lower accuracies than a smooth sea floor or straight channels. Cost reductions that can be attained depend strongly on the situation, but a factor of three has been reported in a specific case [4].

4.3. Military context

In case of a rising conflict, radar observations can be used in several stages. First, they can be used in a reconnaissance survey. The achieved accuracy will not match that of the conventional method of (multi beam) echo sounding, but it is faster and there is no need for a vessel on location. A satellite can be used, or, when higher spatial resolution is needed, also an airborne radar: with the latter it is in principle possible to observe from a considerable distance by making use of a low grazing angle, enabling reconnaissance without violating a country's territory. When there is a need for more accurate and quantitative bathymetric information, the SAR images can be assimilated in existing depth charts. Ultimately, an even higher accuracy can be obtained by assimilation of *in situ* gathered data and radar data into a comprehensive survey. These methods make for a gradual refinement of the bathymetry assessment.

4.4. Limitations

Limitations on the use of radar images are imposed by water depth, hydrometeorological conditions, image positioning, and the radar image noise.

Concerning depth limitations, the technique only works in relatively shallow seas; typically, features of a few meters height are detectable down to a few tens of meters depth. Given optimal conditions, such features would still be detectable at considerably greater depth, while larger features or a faster current would in principle still further extend that depth range.

The hydrometeorological conditions impose rather strict limitations on the imaging of the bathymetry.

When the wind speed is too low, the sea surface will be too smooth to produce radar backscatter, and all radar measurements are precluded. When, on the other hand, the wind speed is too high, the bathymetry contrasts are drowned in the background of waves, white caps and radar image noise. In practice, wind speeds between 2 and 8 m/s seem to be optimal, though this also depends on the radar frequency used. The second requirement is the existence of an overall current through the area of interest. No fixed minimum for the current speed can be specified; the higher the current, the easier the bathymetry can be measured (i.e., the smaller the features and the larger the depth range); typical figures are a few tens of cm/s. In practice, a current is often present in shallow waters in the form of a tidal current. In contrast to the wind, the time of favorable current can be known beforehand on the basis of the tidal cycle; this limitation need therefore not severely limit practical applicability. Apart from the aspects of wind and current, the bathymetry has to compete with a number of other atmospheric and

maritime features that can produce contrasts in the radar image. These include, e.g., ocean waves, slicks, ships and their wakes, fronts, and internal waves. (Some of these features can be found in figure 1.) If any of these features happen to be present, it is possible that they (locally) preclude the use of the radar data for bathymetry purposes; this may also be expected in case a strong thermocline is present.

For the assimilation of satellite or airborne radar imagery with in-situ data, accurate geopositioning of the radar data is a necessity. The positional accuracy of space-measured SAR imagery is of the order some 100 m. For airborne data this can be of the same order, based on GPS (higher for differential or military GPS). This is not accurate enough for assimilation, and therefore ground control points need to be used. The number of ground control points required depends on the quality of the SAR image.

The fourth limitation is imposed by the, unavoidably present, radar image noise (or "speckle"). The occurrence of the speckle precludes detection of the weaker bathymetric contrasts, and is the main cause for the operational limitations on depth range and hydrometeo conditions. The speckle noise level can be reduced, but generally at the expense of spatial resolution.

Some of these limitations can be partly overcome by performing multi-temporal analysis [2]. By making use of more than one radar image of the same scene, the chance on optimal hydro-meteorological conditions is increased, true bathymetric signatures are more easily distinguished from other maritime features, and the impact of noise is diminished.

The rather indirect way in which the bathymetric features are expressed at the sea surface, combined with the speckle noise and the limited spatial resolution, gives rise to the fact that small objects on the sea bottom are not readily imaged. It is not expected that objects like containers or small ship wrecks will be reliably imaged by radar. If one needs to find objects like these, conventional surveys will still be needed. However, radar images are able to indicate those areas that are dynamic, where sunken objects can be expected to become covered or re-exposed.

5. Present research

The research efforts of the past twenty years have come far in understanding and describing the radar bathymetry imaging mechanism, and in delineating the boundaries for practical applications. On the one hand, it is on the basis of this work that the use of radar for bathymetry purposes can now begin to enter the operational domain. On the other hand, certainly a number of problems still perseveres. Most of the physical models used are merely approximations, at

times close to their limits of validity. In general, the modeling is characterized by the use of *ad hoc* parameters for black box descriptions of low-level physical processes. (This approach is of course in itself not at all unsuitable for practical purposes.) The most outstanding questions that are still open at the moment, and have a consequence for practical use, pertain to the shape of the equilibrium gravity-capillary directional wave spectrum, and to the rate by which deviations from equilibrium in this wave spectrum decay. Furthermore, several processes that are probably under most circumstances of minor consequence are not taken into account in the modeling so far, such as the role of wave breaking. Also, no proper model has yet been implemented to describe the radar imaging under very low grazing angles (< 80 degrees), precluding the quantitative use of surface-based radar data for bathymetry as yet.

Extensions and improvements of the models and their numerical implementations are subjects of current research. Other current developments are aimed at recognition and exclusion of non-bathymetric features from the SAR images, at improved techniques for the inversion and assimilation of the radar data, and at obtaining better quality radar images. The latter aspect concerns improvement of the image quality by applying dedicated SAR processing for bathymetry purposes, as opposed to the usual standardized processing (the same for all scenes, either over land or over water) [13]. As these developments will be finding their way into the operational process, the role of radar in bathymetry applications can be expected to be constantly further consolidated.

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