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ESTIMATING UNDERWATER ACOUSTICAL PARAMETERS FROM SPACE-BASED SYNTHETIC APERTURE RADAR IMAGERY

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1. INTRODUCTION

Synthetic aperture radar (SAR) imagery from satellites provides a range of data products that can reveal certain aspects of the underwater acoustical environment. Space-based SAR imagery is available in all weather, day or night and has wide area coverage with swaths up to 500 km across. This availability and coverage gives SAR satellite data the potential to enhance acoustic environmental assessment for naval applications. Rapid processing and dissemination of SAR data has been demonstrated (Henschel, 1998) which further strengthens the case for operational use of space-based SAR.

Acoustic parameters relevant to naval applications are the spectrum and level of underwater ambient noise, acoustical scattering strength at the sea surface and ocean structures such as internal waves and fronts that affect the direction of sound propagation. The SAR data products that can be linked to these acoustical parameters are surface wind fields, ship detections, gravity wave spectra and identification of ocean features.

In this paper we present an overview of the use of space-based SAR data for estimation of underwater acoustical quantities with examples from a recent sea trial.

2. UNDERWATER AMBIENT NOISE

One of the acoustical parameters required for prediction of sonar performance is the underwater ambient noise field. At frequencies above 10 Hz, underwater ambient noise has two primary sources: shipping noise and wind-generated surface noise. The ship detection capabilities of space-based SAR have been described and validated by several researchers (see for example Olsen and Whal (2000), Vachon et al. (2000)). Estimation of surface wind fields from SAR imagery is also a well established technique (Thompson and Beal (2000), Vachon and Dobson, (2000)).

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Remotely sensed winds and shipping density can be combined with information on the propagation environment and geoacoustic properties of the sea bed to estimate the ambient noise field. Hutt (2000) showed that the accuracy of SAR-derived wind fields is adequate for estimation of underwater ambient noise. It was found that winds derived from standard mode RADARSAT-1 imagery yielded ambient noise estimates within 0.6 dB of the measured values. These results were for acoustical frequencies above 200 Hz where wind noise dominates and for deep water (> 1000 m) where acoustical interaction with the sea bed can be neglected.

Preliminary results from a more recent experiment are promising for estimation of ambient noise in shallow water. Figure 1 shows ambient noise measured with an AN/SSQ-53D(2) sonobuoy deployed near 44^o 06.0’N 61^o 08.0’W on the Scotian Shelf on June 10, 2002. The omnidirectional channel of the sonobuoy was averaged over 5-minute intervals and processed to 1/3 octave bands from 10 Hz to 5000 Hz. The measurement period was one hour. In Fig. 1 the measurement curves represent the mean noise level plus and minus one standard deviation.

Mid-way through the ambient noise measurement a Wide 1 mode RADARSAT-1 image was obtained. To retrieve the wind field from the SAR data, a spectral analysis approach (Vachon and Dobson, (2000)) was used to resolve the wind directions but unsatisfactory results were obtained. Then, wind directions from QuickScat were used to guide the RADARSAT-1 wind retrieval. The QuickScat overpass was within one hour of the RADARSAT-1 overpass. The resultant wind field is shown in Fig. 2a. The wind and ship products from the RADARSAT-1 image were then used to estimate the ambient noise shown as a solid curve in Fig. 1.

The noise model used in Fig. 1 was that of Merklinger and Stockhausen (1979) hereafter referred to as the M&S model. This is an empirical model based on the statistical noise analysis of Wenz (1962). The inputs for the M&S model are wind speed and a shipping density parameter. Although acoustical propagation effects and seabed interaction are not taken into account explicitly, an adjustment of 3 dB was added to the wind-generated component of the model in accordance with the recommendation of Piggott (1964). This adjustment accounts for the overall higher noise levels at frequencies above 200 Hz experienced in shallow water. The ship noise parameter in the M&S model was set to 88 dB corresponding to moderate to high shipping density. This value was selected on the basis of the RADARSAT-1 ship detection product which identified 41 ships in the scene of June 10.

More sophisticated models for underwater ambient noise are available (Breeding (1994), Harrison (1996)) which take into account the details of ship location and estimated size, information which is available from SAR imagery. While analysis with these models is on-going, the results obtained with the M&S model are sufficient to demonstrate the concept of using remotely sensed environmental data to estimate ambient noise. Results from this simple model are much better than those obtained from data bases of historical ambient noise levels which are still widely used.

It should also be pointed out that the accuracy of SAR wind and ship data products are complementary to the requirements of noise modelling. This is because ship detection improves as wind speed decreases and the relative accuracy of SAR wind estimates increases as wind speed increases. This is exactly what is required for predicting ambient noise - accurate ship data during low-wind conditions when ship noise dominates and accurate wind speeds when wind noise is dominant.

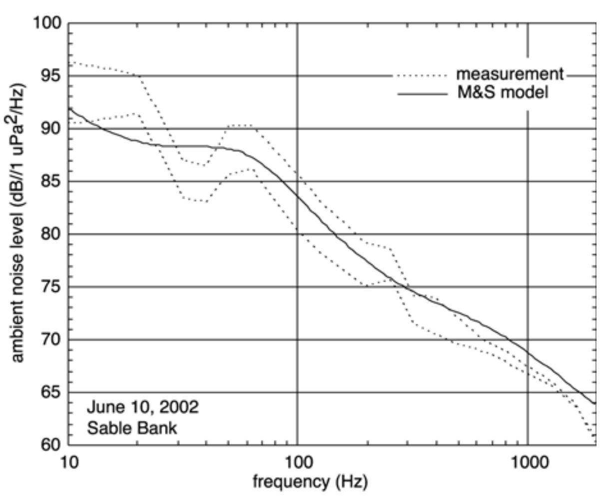

Figure 1 Ambient noise measured on Sable Bank June 10, 2002, compared to M&S model prediction based on RADARSAT-1 wind and ship data.

3. SEA SURFACE ACOUSTICAL SCATTER

The probability of detecting a target with an active sonar is a function of the signal-to-noise ratio of the target return. The noise background is due to the ambient noise field and reverberation from the sonar pulse. The target return is determined by the amount of energy transmitted to the target and back to the sonar receiver. The reverberation level and target return are determined by the acoustical backscatter and forward scatter coefficients of the sea surface. Expressed in decibels of non-dimensional ratios, these quantities are referred to as the surface backscatter strength (SBS) and forward scatter loss (FSL), respectively.

The SBS and FSL are the result of the complex interaction of underwater acoustical waves with the air-sea interface. Generally, as winds and seas increase, a layer of air bubbles forms below the sea surface which enhances acoustic backscatter and reduces forward scatter (increases FSL).

To estimate SBS we use the model of Gauss, Fialkowski and Wurmser (2002) which employs a wind-dependent power-law surface roughness spectrum and a semi-empirical expression for the bubble contribution to the scatter strength which is also wind-dependent. The wind field from the RADARSAT-1 image of June 10, 2002, shown in Fig. 2a, was used to compute the SBS over the image scene as shown in Fig. 2b. Figure 2c shows FSL computed using the model of Eller (1984). Both surface scatter parameters are functions of the acoustic frequency and the angle between the propagation direction of the acoustic wave and the sea surface (grazing angle). The example plots of SBS and FSL are for a frequency of 1500 Hz and grazing angle of 10^{o}.

While *in situ* measurements of SBS and FSL are not available to validate the values shown in Figs. 2b and 2c, these examples show that operationally-relevant surface scatter products can be obtained from SAR wind fields. The spatial resolution of the surface scatter products is high enough to be useful for range-dependent sonar performance prediction.

4. OCEAN SURFACE WAVES FROM SAR

Ocean surface waves are relevant to underwater acoustics in that they are the primary source of noise at frequencies below 10 Hz and they have an important impact on acoustical scattering at the sea-air interface. For example, the concentration of air bubbles with depth near the sea surface depends upon the direction of the wind relative to the direction of surface waves and the amplitude and direction of swell. Therefore, models for sea surface scatter could likely be improved if information on surface wave spectra were included.

The ability of SAR to image ocean surface wave fields is dependent on the spatial resolution of the SAR, the height and length of the surface waves, the wave propagation direction relative to the SAR look direction, and the platform range-to-velocity ratio. These factors, through the orbital motion of the wave field, introduce a non-linear azimuthal (along-track) cut-off that severely limits the SAR's.

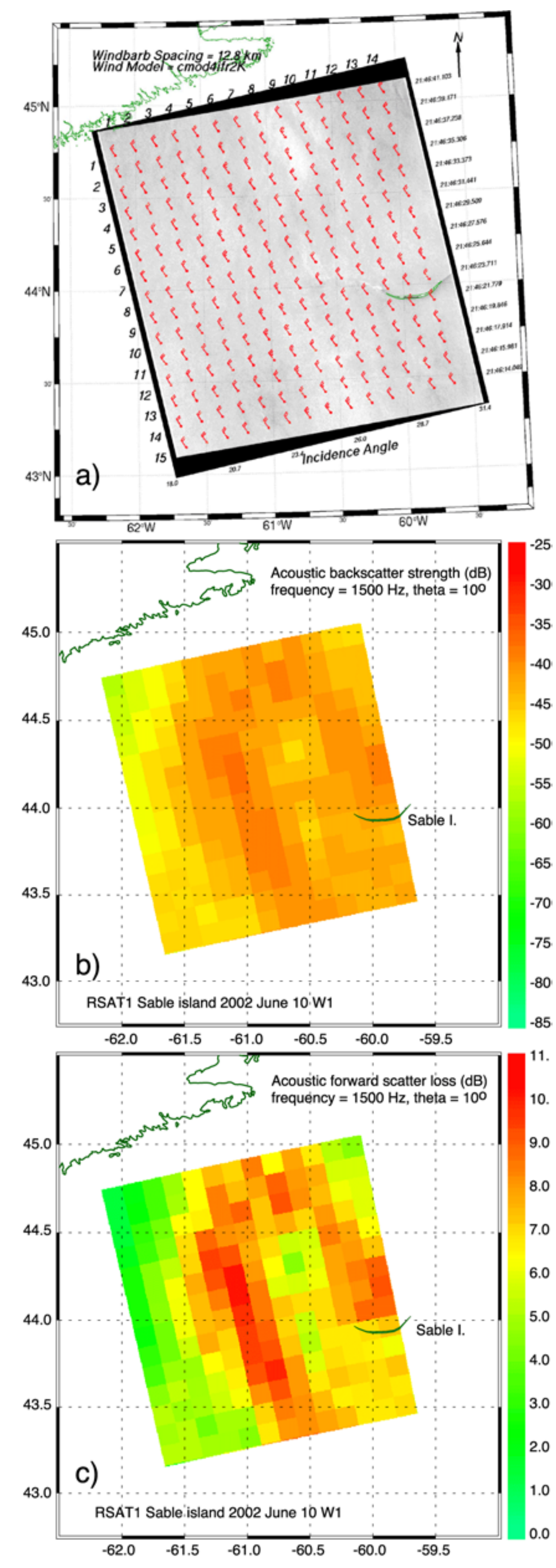

Figure 2 RADARSAT-1 wind field (a), derived acoustic backscatter strength (b), acoustic forward scatter loss (c). Scatter quantities calculated for acoustic frequency 1500 Hz and grazing angle 10^{o}.

ability to detect ocean waves. The cut-off becomes more severe for steeper waves that are travelling in the azimuthal direction. Furthermore, the range-to-velocity ratio for RADARSAT-1 is large, which is not favourable for ocean wave observation. Nevertheless, long waves (swell) are often observed in

RADARSAT-1 imagery and attempts to extract ocean wave information using non-linear optimization techniques can produce useful ocean wave information (e.g., Dowd et al., 2001). The results are strongly dependent upon the wave conditions

5. OCEAN STRUCTURES

The ability to predict the propagation of underwater sound is critical to predicting sonar performance. Sound propagation is controlled by spatial variations of the sound speed. Since sound speed is proportional to water temperature to first order, knowledge of the water temperature field is required in order to predict sound propagation. Over the past decade, numerical ocean forecasting or “operational oceanography” has exploited data from remote sensing satellites to produce forecasts of the thermal and density structure of the ocean (see Hutt, 2002).

Space-based SAR has an important role to play in augmenting operational ocean forecasts which often do not have the spatial resolution to accurately localize ocean fronts. Combining SAR imagery, with its high spatial resolution and ability to see through clouds, with infrared and visible imagery can provide highly accurate ocean feature detection and localization. This idea has been promoted by N. Stapleton of QinetiQ (Hutt, 2002).

Sub-surface oscillations of the stratified water column are known as internal waves. They are frequently observed at shelf edges in the summer as a result of tidal flow over the bottom topography. Internal waves can have a great impact on the propagation of underwater sound in the surface duct and can significantly affect the performance of sonar systems. Internal waves cannot be represented by most ocean models yet their surface manifestation can be easily seen in SAR imagery.

Small (1999) has demonstrated that the SAR backscatter signature of internal waves can be used to infer it’s surface current field which suggests that it may be feasible to use the remotely sensed SAR backscatter ratio, along with estimates of the width and spacing of internal waves packets, to model their depth structure. Such a capability would be extremely valuable for remote sensing of these important ocean structures and for estimating their effect on underwater acoustics.

6. CONCLUSIONS

We have presented an overview of space-based SAR capability to provide information about the underwater acoustic environment. The ability of SAR to provide accurate surface wind fields can be used to estimate the surface backscatter strength and forward scatter loss. When the SAR wind product is combined with ship detections the underwater ambient noise field can be estimated. The surface scattering parameters and ambient noise are required to predict the performance of naval sonar.

The characteristics of SAR wind and ship products are complementary to the requirements of noise modelling. Ship detection improves as wind speed decreases and the relative accuracy of SAR wind estimates increases as wind speed increases. Promising agreement has been obtained between measured ambient noise and model output based on SAR products for both deep and shallow water.

The high spatial resolution of SAR imagery allows acoustical quantities to be estimated continuously across the image scene which enables range-dependent acoustical predictions to be made. Swath widths up to 500 kilometres across and the ability to provide data day or night and through clouds make space-based SAR a potential contributor to operational assessment of the underwater acoustical environment.

Further research is required to exploit SAR imagery for fusion with other data sources to provide enhanced ocean feature analyses and for quantitative interpretation of internal waves.

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