a NATO Research Centre
un Centre de Recherche de l'OTAN

PARTNERING FOR MARITIME INNOVATION

Reprint Series NURC-PR-2009-009

Measurements and modelling of high-frequency acoustic scattering by a rough seafloor and sea surface

Alessandra Tesei, Gaetano Canepa, Mario Zampolli

December 2009

Originally published in:

Proceedings of the 3rd International Conference and Exhibition on Underwater Acoustic Measurements: Technologies and Results, 21-26 June, 2009, Nafplion, Greece.

About NURC

Our vision

- To conduct maritime research and develop products in support of NATO's maritime operational and transformational requirements.
- To be the first port of call for NATO's maritime research needs through our own expertise, particularly in the undersea domain, and that of our many partners in research and technology.

One of three research and technology organisations in NATO, NURC conducts maritime research in support of NATO's operational and transformation requirements. Reporting to the Supreme Allied Commander, Transformation and under the guidance of the NATO Conference of National Armaments Directors and the NATO Military Committee, our focus is on the undersea domain and on solutions to maritime security problems.

The Scientific Committee of National Representatives, membership of which is open to all NATO nations, provides scientific guidance to NURC and the Supreme Allied Commander Transformation.

NURC is funded through NATO common funds and respond explicitly to NATO's common requirements. Our plans and operations are extensively and regularly reviewed by outside bodies including peer review of the science and technology, independent national expert oversight, review of proposed deliverables by military user authorities, and independent business process certification.

NOTE: The NURC Reprint series reprints papers and articles published by NURC authors in the open literature as an effort to widely disseminate NURC products. Users should cite the original article where possible.

MEASUREMENTS AND MODELLING OF HIGH-FREQUENCY ACOUSTIC SCATTERING BY A ROUGH SEAFLOOR AND SEA SURFACE

Alessandra Tesei[a], Gaetano Canepa[a], Mario Zampolli[a]

[a]NURC, V.le S. Bartolomeo 400, 19126 La Spezia, Italy

Alessandra Tesei, NURC, V.le S. Bartolomeo 400, 19126 La Spezia, Italy, fax: +390187527331, email: tesei@nurc.nato.int

Abstract: *Acoustic scattering by a rough, possibly dynamic interface is experimentally studied by insonifying the seabed and the sea surface at high frequency at various incident angles. A directional source working at 300 kHz was placed at the top of a 3.5 m high tower deployed on the seabed. A vertical array of 3 omnidirectional hydrophones was suspended from a portable frame, which was deployed in bistatic configuration at a variable range between 30 and 70 m. A selection of the results is presented to evaluate the sea surface and seabed scattering amplitude in the nominal specular reflection direction. Scattering by the sea surface was measured during relatively long periods of time in order to correlate its value with the sea state. Model–data comparison was conducted between the scattering data and a time-domain, three-dimensional rough surface scattering model (BORIS-SSA). Model-based analysis allows for a better understanding of some aspects of high-frequency multipath reverberation in shallow water.*

Keywords: *Environmental Acoustics, High-Frequency Scattering from Rough Boundaries*

1. INTRODUCTION

Multipath reverberation is recognized to be one of major factors that may degrade the performance of new-generation sonar systems, such as high frequency (>100 kHz), very-high-resolution SAS sonars, which are recently operated mainly in shallow water, where environmental constraints (in particular, sound interaction with a rough and dynamic sea surface) are much more severe than in deep water. The impact of multipaths on sonar imaging quality is not fully understood at the present. The main features that a ray propagation model based on pure specular reflection cannot predict are angle and time spread effects, which have been observed to characterize all the multipath arrivals that involve one or more “specular” bounces either on the sea surface or on the seafloor [1,2].

High frequency acoustic forward scattering measurements from rough seafloor and sea surface are presented in this work. The data were collected during the MARES’08 sea trial off the north coast of Elba Island, Italy, in March 2008. A 300 kHz bottom-mounted system was used, which is capable of isolating and measuring ray paths from single interactions with either the seafloor or the sea surface in bistatic configuration.

In the case of sea surface scattering, variability with time was measured through high-ping-rate, long-term monitoring. By pointing the sonar to the sea surface at normal incidence in monostatic configuration, it was also possible to use the same system to measure the wave height at a high ping rate and with the spatial resolution of about 6 cm. This resolution is substantially better compared to what can be obtained by a wave rider buoy or a static pressure sensor, and is only one order of magnitude larger than the sonar wavelength (equal to 5 mm). Wave height measurements were alternated to scattering measurements of the sea surface in order to be able to correlate the two datasets.

The acoustic datasets were correlated to environmental ground truth measurements, such as bathymetric swath measurements, geophysical measurements of the seabed, sea surface and seafloor large-scale (waves) and small-scale (surface ripples) measurements, CTD (conductivity-temperature-depth), wind and sea currents.

Model–data comparison was conducted between the scattering data and a time-domain, three-dimensional rough surface scattering model (BORIS-SSA). Model-based analysis allows for a better understanding of some aspects of high-frequency multipath reverberation in shallow water and is a prerequisite to high-frequency acoustic propagation and reverberation modeling in coastal waters. The data acquired have been used for model-data comparison against simulations obtained with the BORIS-SSA modelling tool. BORIS-SSA is a full 3-D time-domain model that simulates the echo received by an interface of known roughness and reflection coefficient, given the source pulse and the beam pattern and position of transmitter and receiver [3-5]. The surface scattering component is calculated using either the Kirchhoff approximation or a second/fourth order small slope approximation (SSA).

2. EXPERIMENTAL SET-UP

The experimental set-up was designed to collect acoustic scattering measurements from rough static and dynamic surfaces.

The Biodola bay at Elba Island is characterized by a wide area of relatively flat, homogeneous, fine sandy seabed. Sand ripples are ~3-4 cm high (peak to peak), have spatial period around 20-25 cm, and are mainly oriented with a heading of about 130^o North, and with an angle of about 20^o with respect to the transmission axis of the sonar. These values were provided by divers. The sediment was classified as very fine sand, with compressional speed $c_{p,sed}$ = 1770 m/s, density ρ_{sed} = 2100 kg/m^3, as derived from the analysis of a core. Figure 1(a) shows the photo of typical sand ripple structure in the measurement area; a compass indicates the North. All the selected measurements were collected under isospeed conditions: water sound speed c_w = 1507 m/s; water density ρ_w = 1040 g/m^3.

During the day when the data presented here were collected, weather conditions were good, with sea state 1. Figure 1(b) shows a photo of the sea surface. As estimated in the following, the roughness is characterized by a swell of small amplitude (hardly detectable from the photo) on which mid- and small-scale wavelets are superimposed. The main direction of the wind remained constant, blowing from 135^o North with an average speed of 4 m/s.

In order to conduct scattering measurements from a fixed location, a directional source was placed at the top of a 3.5 m high tower deployed on the seabed. The transmitter was coupled with a backscattering hydrophone in quasi monostatic configuration. The sonar was rigidly connected to a rotation motor to tune its pan and tilt orientations, which were monitored by a motion reference unit (MRU).

The transmitter frequency is 300 kHz with 60 kHz bandwidth at -3 dB. Its beamwidth at -3 dB is approximately 60^o on the horizontal plane and 0.7^o on the vertical plane. A vertical array of 3 omnidirectional hydrophones (40 cm spacing) was suspended from a portable frame, which was deployed in bistatic configuration at a variable range between 30 and 70 m. From a rubber boat, it was possible to adjust the receiver height at a number of equally-spaced, fixed positions through an adjustment line connected to the receiver frame by a sliding and blocking mechanism. Changing the range and depth of the receive array enabled the receiver to be positioned at the nominal specular reflection direction once a certain sonar incident angle was selected. The system was connected to the NURC's Coastal Research Vessel (CRV) Leonardo. The transmit/receive system was calibrated and identified using a 1ms LPM (linear period modulation) pulse in the bandwidth 270-330 kHz. For acoustic scattering measurements a 10 ms LPM pulse was used. While most of the parameters can be considered stable along the short period of measurement (1 minute), there are two exceptions: the Tx/Rx distance and the sea surface roughness. In post-processing, the scattered echoes are aligned with respect to the direct arrival in order to compensate for the receive array motion due to the sea waves action on the portable frame. The variability of the Tx/Rx distance is included in the simulations. Matched-filtering was applied to data and simulation to improve the signal-to-noise ratio and the time resolution.

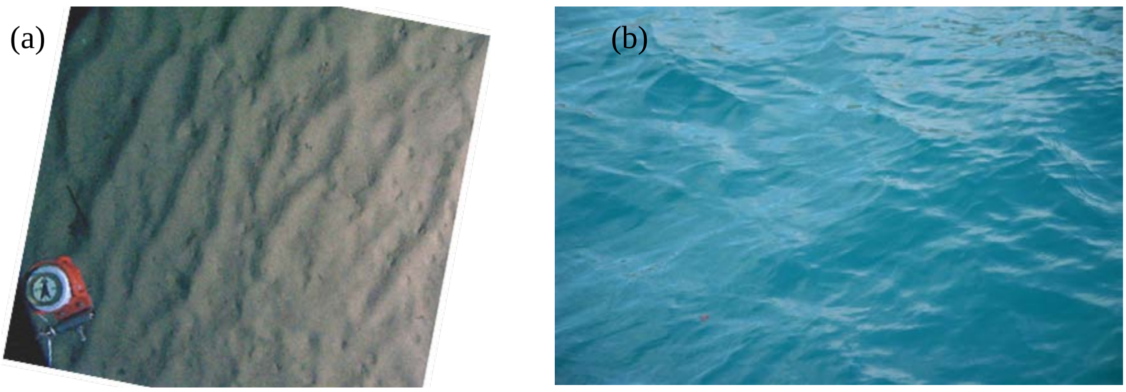

Fig.1: (a) Photo of the seabed in the measurement area. (b) Photo of the sea surface.

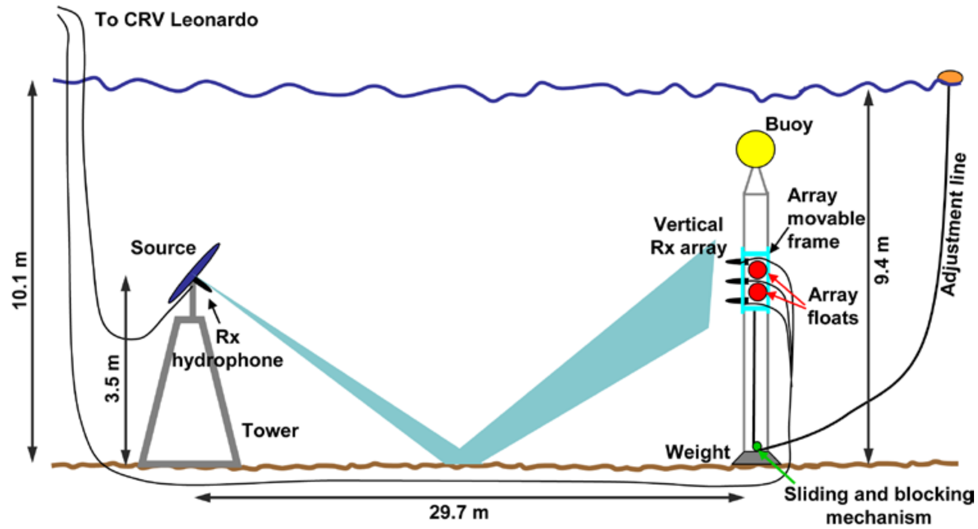

Fig.2: Experimental set-up (side view). Drawing not to scale.

The presented results were obtained under the following conditions (see Fig.2): the water depth was 10.1 m at the transmitter and 9.4 m at the receiver (29.7 m away), with a smooth up-slope of 1.3^o.

The transmitter and the hydrophone, located in quasi-monostatic configuration, were also used to measure the wave height at high ping rate and with a relatively high spatial resolution. Wave height measurements were alternated to scattering measurements of the sea surface in order to be able to correlate the two datasets. The sonar was pointed to the sea surface at normal incidence and a burst of 50 μs was sent each 40 ms. Wave height was measured from the time of arrival of the echo from the surface with respect to the transmission time. As the wave displacement was estimated from the first arrival of the surface echo, its spatial resolution was approximately the minimum width of the sonar footprint on the sea surface, which was about 6 cm in the geometrical configuration selected. This resolution is only one order of magnitude bigger than the sonar wavelength (equal to 5 mm). Figure 3(a)-(c) shows the wave displacement vs. time acquired by a Seabird static pressure sensor, a Teledyne RDI ADCP1200, mounted such one of its transducers pointed to the sea surface at normal incidence, and the 300-kHz acoustic system described above, respectively. Also the two former instruments were mounted at the top of the 3.5m high tower. The data samples in Fig. 3(b) and (c) are synchronized; the data in (a) were recorded in the same day under the same weather conditions. The capability of the proposed acoustic system to catch higher frequency components is evident. In Fig. 4(a) the nondirectional spectrum of the time series plotted in Fig. 3(c) is computed in the bandwidth 0.1-5 Hz, and the corresponding wave height is estimated versus range (Fig. 4(b)) through the simplified characteristic equation linking time frequency f and spatial wavelength λ of the waves:

$$f = \frac{1}{2\pi}\sqrt{gk\tanh(kH)}\,, \tag{1}$$

where g is the acceleration of gravity, k the wavenumber ($k = 2\pi/\lambda$) and H the water depth. This estimate can be used to feed scattering, reverberation and propagation modeling tools working under the condition of rough sea surface.

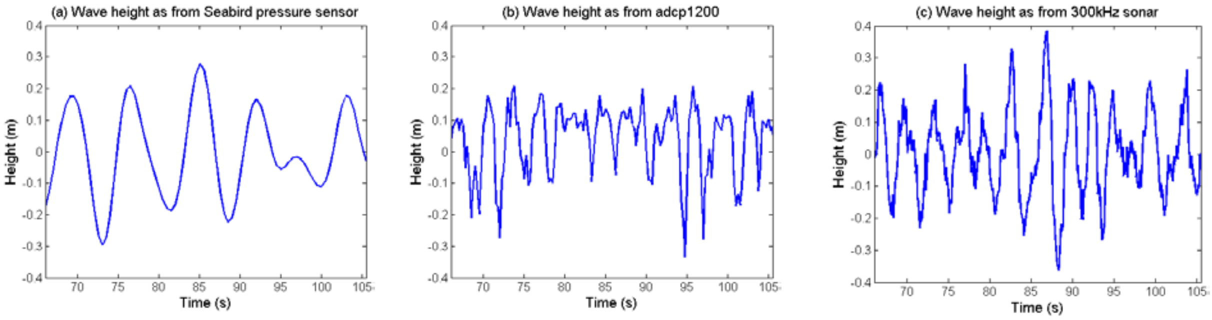

Fig.3: Wave height vs. time (40 sec) as from (a) pressure sensor, (b) ADCP, (c) 300-kHz sonar. The capability to catch high-frequency components of the surface roughness significantly increases from (a) to (c).

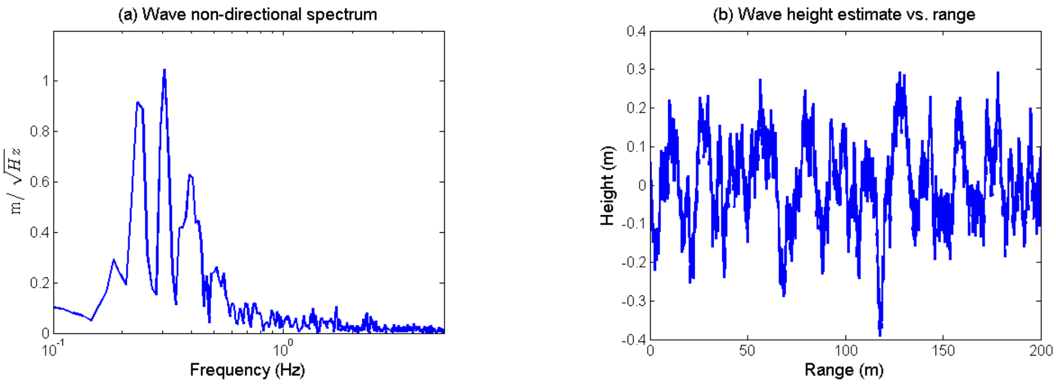

Fig.4: (a) Non directional spectrum of time series in Fig. 3(c); (b) wave height vs. range.

3. EXPERIMENTAL RESULTS OF ACOUSTIC SCATTERING AND MODEL-DATA COMPARISON

A selection of single-bounce scattering measurements in bistatic configurations are presented in this section along with corresponding model-data comparison results.

Figure 5 shows a time domain comparison of forward scattering from the sea surface. An example of experimental time aligned data is given in Fig. 5(a) and (b). The results shown are relative to 40 pings registered at a single receiver position (4.05 m of altitude). The sea surface arrivals are poorly aligned and also change in shape because the sea surface is changing in height and shape, ping after ping. Figures 5(c) and (d) show the corresponding results of BORIS-SSA simulations after matched filtering and realignment (to remove the receiver horizontal displacement which was included in the simulation), which agree well with the experimental data. Only surface scattering (second order SSA) is used in this case. The differences between real data and simulations are caused by the presence of noise in the experimental data and by the distribution of the arrival times, the experimental pings being more concentrated around the central arrival. The latter difference is probably caused by the imperfect sea surface model (especially for long and medium wavelengths).

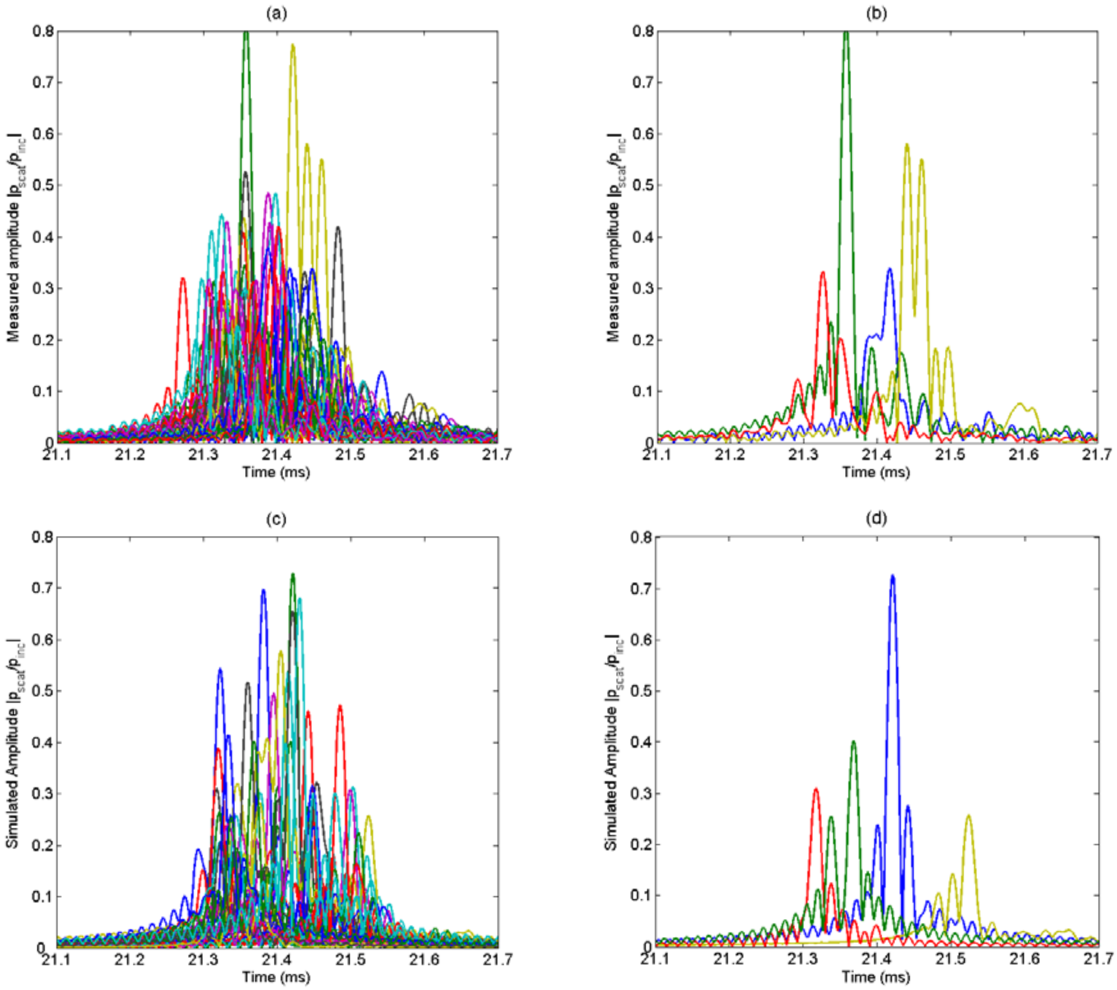

Fig.5: (a) Measured scattering amplitude from the sea surface in specular reflection direction at -22° (40 pings); (b) few pings extracted from (a); (c) simulated scattering amplitude from the sea surface (40 pings); (d) few simulated pings extracted from (c).

The sea surface variability is simulated taking into account three wavelength scales. BORIS-SSA is used to produce stochastic realizations of small patches of sea surfaces that lie on a horizontal plane (2x2 m). These patches take into account the small and medium scale roughness by adding two surfaces together: (a) an isotropic Gaussian power law spectral density stochastic surface with rms height of 2 cm and correlation length of 33 cm (aimed to simulate coastal isotropic wave); and (b) a Gaussian power law spectral density stochastic surface translated in the wind direction, with rms height of 0.5 mm and wave correlation length of 1 cm (to simulate wind generated capillary wave) [5]. This surface model is preferred to other well established sea surface models (such as the Pierson-Moskowitz models included in BORIS-SSA) because it takes into account small scale roughness. This small patch is added to a large scale roughness (wavelength of the order of tens of meters) wave generated using a Gaussian power law spectral density stochastic surface translated in the wave direction, with rms height of 113 cm and wave correlation length of 16 m (these parameters are estimated from Figs. 3(c) and 4(b)).

Figure 6 shows measured and simulated specular reflection returns from the seabed acquired at a grazing angle of 12.4°, which is much lower than the critical angle, estimated here as 31.6°. The BORIS-SSA simulations are obtained using a seabed roughness model consisting of (a) a directional Gaussian power law spectral density stochastic surface with

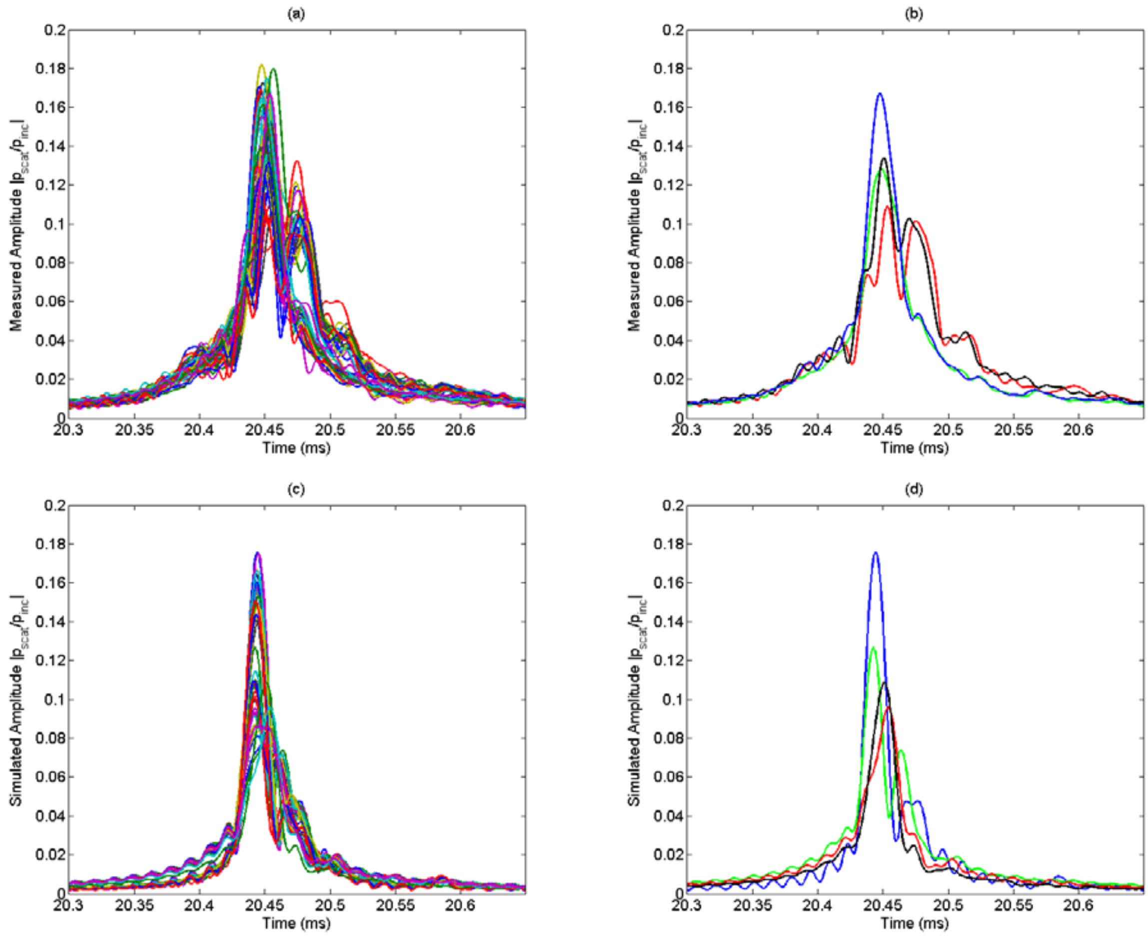

Fig.6: (a) Measured scattering amplitude from the seafloor in specular reflection direction at 12.4° (40 pings); (b) few pings extracted from (a); (c) simulated scattering amplitude from the seafloor (40 pings); (d) few simulated pings extracted from (c).

the same orientation as the sand ripples, rms height of 1.1 cm and correlation length of 25 cm; and (b) a Gaussian power law spectral density stochastic surface aimed to simulate the grain size, with rms height of 0.5 mm and wave correlation length of 3.3 cm. During this experiment the transmitter was randomly tilted ping to ping within a range of ±1° around the nominal grazing angle. The model (Fig. 6(c) and (d)) takes this system variability into account, as well as the variability in the transmit/receive distance. The peaks of the scattering amplitude in Fig. 6(a) and (b) are much lower than the theoretical reflection coefficient expected for a perfectly flat interface, due to the surface roughness (sand ripples and micro-roughness), which allows both penetration into the sediment and scattering. Fig. 6 shows a lower variability with respect to Fig. 5 because of the stationary state of the seafloor roughness.

4. CONCLUSIONS

An experimental system used to measure high frequency scattering from rough interfaces is presented. The spreading of sound bouncing off the sea surface and the seafloor is such, that the maximum amplitude of the respective echoes are much lower than what one would expect from the theoretical reflection coefficient from perfectly flat interfaces.

Using BORIS-SSA, it is possible to confirm what one would expect from physical considerations: the main causes of time of arrival variability, time dispersion and amplitude variability appear to be the roughness of the interface. Variability of the boundary height, slope and fine scale roughness limits the applicability of simple flat interface specular-reflection ray approximation in such cases. The simulations presented here take into account the variability of the boundary parameters, which improves the model-data agreement. The large-scale roughness mostly influences the time of arrival, the variability of the peak shape and the dispersion of the energy in other directions than the specular one. The small and medium-scale roughness mostly influences the (maximum) amplitude and the single ping time dispersion. Scattering measurements from the seabed could not involve the same level of variability but confirmed the good agreement with simulations in terms of echo shape and time spreading.

The same experimental acoustic system was used in monostatic configuration to obtain relatively high-resolution temporal measurements of the sea surface wave height. However this system is not able to provide information of the directionality of the waves. Future activities will include a more accurate modelling of the sea surface. A more refined system to measure the sea surface wave height at high resolution, which is based on stereo photogrammetry [6] and provides also the estimation of wave directionality, is under development and is foreseen to provide realistic inputs to available scattering and propagation modelling tools.

5. ACKNOWLEDGEMENTS

The authors wish to thank all the NURC personnel who contributed to the success of the MARES'08 sea trial, in particular P.A. Sletner, D. Galletti, G. Parisi, M. Paoli, F. Cernich, R. Chiarabini, O. Chiappini and the CRV Leonardo crew. Special thanks go to P. Guerrini and A. Bellettini for the fruitful discussions.

REFERENCES

[1] **Tesei, A., *et al.***, High-frequency scattering from rough interfaces: Measurements from MARES’08, In *ISURC’08*, NURC, La Spezia, Italy, P.L. Nielsen, C.H. Harrison, and J.-C. Le Gac Eds., pp. 181-188, 2008.
[2] **Canepa, G., *et al.***, High-frequency forward scattering from rough interfaces: Model-data comparison, In *ISURC’08*, NURC, La Spezia, Italy, P.L. Nielsen, C.H. Harrison, and J.-C. Le Gac Eds., pp. 189-196, 2008.
[3] **Pouliquen, E., *et al.***, Time-evolution modelling of seafloor scatter. I. Concept, *J. Acoust. Soc. Am.*, 105 (6), pp. 3136-3141, 1999.
[4] **Bergem, O., et al.**, Time-evolution modelling of seafloor scatter. II. Numerical and experimental evaluation., *J. Acoust. Soc. Am.*, 105 (6), pp. 3142-3150, 1999.
[5] **Canepa, G., *et al.***, *Manual of BORIS-SSA: Bottom response from inhomogeneities and surface using small slope approximation*, NURC Memorandum M-0152, La Spezia, Italy, 2005.
[6] **Canepa, G., *et al.***, Underwater stereo-photographic measurement of small scale roughness: limits to spatial correlation accuracy, *J. Acoust. Soc. Am.*, 123 (5-2), p. 3085, 2009.

Document Data Sheet

Security Classification

Project No.

Document Serial No.
NURC-PR-2009-009

Date of Issue
December 2009

Total Pages
8 pp.

Author(s)

Tesei, A., Canepa, G., Zampolli, M.

Title

Measurements and modelling of high-frequency acoustic scattering by a rough seafloor and sea surface.

Abstract

Keywords

Issuing Organization

NURC
Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
NURC
(New York) APO AE 09613-5000]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@nurc.nato.int