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NOT-IMPULSIVE TECHNIQUES FOR SONAR IMAGING

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Abstract: *Techniques based on impulsive sources are used since the beginning of the Underwater Acoustic science, to evaluate the distance of objects and to plot the profile of the sea bottom. In this paper the authors investigate the behavior of three not-impulsive techniques for the measurement of impulse responses: MLS (Maximum Length Sequence) signal, linear sine sweep and logarithmic sine sweep.*
This work will focus the attention on advantages and defects of these tree different methods, in comparison with the traditional pulse-based sonar techniques.
The mathematical theory for the generation of the MLS, sine sweep signals and for the deconvolution of the system's impulse response are first described. Then a software implementation of the measurement methods, based on the creation of plug-ins for a shareware waveform editor, running on a low cost PC is demonstrated.
Some experiments conducted under controlled conditions and in the sea show that the proposed techniques produce images of the bottom profile with higher signal-to-noise ratio and better spatial resolution than those obtainable with the impulsive technique. Moreover signal-to-noise ratio increases using sine sweep signal instead of MLS one.
The new techniques seem superior also for some practical aspects connected with their very nature, which make them almost inaudible and makes the sound source barely localizable: this is very important for military applications.

Keywords: *sonar imaging, not-impulsive techniques, wide-band measurements.*

1. INTRODUCTION

Most underwater Sonar techniques employed nowadays are based on impulsive signals. Although the use of impulses has many advantages, it causes also some problems: to obtain high signal-to-noise ratios very large impulse amplitudes are needed. These can be generated efficiently only through resonating transducers, which have of course only limited bandwidth. When wide-band pulses are required, usually a high power sparker is employed. Anyway also this kind of source has some well-known defects: it requires large equipment, it is expensive, and the pulses produced are not very repeatable.

In this work the authors investigate experimentally the behavior of three not-impulsive techniques for the measurement of impulse responses: MLS (Maximum Length Sequence) pseudo random signal [1,2,3], logarithmic sine sweep and linear sine sweep [4,5]. In order to perform the comparative experiments this work was separated in two parts: preliminary tests were conducted in air, and then the same tests were repeated in water. Obviously, the transducers employed were different in according with the medium: a loudspeaker and a microphone in air and a couple of wide-band piezoelectric transducers in water. In both cases, the emitter is driven by a test signal generated by dedicated software running on a small notebook PC. To map the bottom profile, the pair of transducers is moved on a straight line at constant speed.

The same personal computer employed for the generation of the test signal is also used to record and to process the signal coming from the receiver, and through a specially-developed software, performing a convolution, a series of impulse responses are obtained. A standard visualization tool is then used to map the sequence of impulse responses (with logarithmic amplitude) in pseudo-color plots, which enables the direct visualization of the sea bottom profile.

Through a proper synthetic aperture focalization algorithm, the transducer directivity can be greatly increased. Furthermore, the vertical resolution can be improved employing a pre-equalized version of the test signal (MLS and sine sweep), preconvolved with the inverse impulse response of the transducers, in such a way that the emitted signal deconvolves to an almost perfect Dirac’s Delta function, as suggested by Mommertz [6].

The paper focus on the experimental results, remainding to the previous papers already published by the authors for a theoretical analysis of the methods to be employed to obtain the impulse response deconvolution for the test signals employed (MLS, linear and logarithmic sine sweeps). The comparison between the results demonstrates that the performances of the Sonar system employing linear sine sweeps are significantly better than those achieved using impulsive signal or MLS signal: this makes it possible to work with low emitted power and without any averaging.

2. TEST SIGNALS

The not-impulsive signals used in this research are, as already said, MLS, logarithmic and linear sine sweep. The characteristics of the MLS (Maximum Length Sequence) pseudo random signal and its use in underwater measurements has been widely analyzed in other papers [1,2,3,7]; here it is important, instead, to recall the properties of the sine sweep method, which was described in detail by one of the authors in [4].

The main difference between MLS and sine sweep signals is about the not-linear effects: MLS measurements are easily disturbed by not-linear distortion, which cause severe artefacts, appearing both as artificial background noise and, even worst, as spurious peaks which can be easily confused with reflections coming from not-existent objects (false echoes). With sine sweeps, instead, these artefacts can be separated in time domain from the "clean" linear impulse response, provided that a linear deconvolution technique is employed (instead of the circular deconvolution, which causes the not-linear artefacts to "fold back" and contaminate the response).

In practice, this is obtained very simply by linear convolution of the recorded signal with a suitable inverse filter. As demonstrated in [4], and confirmed independently in [5], this inverse filter is simply the time-reversal of the sweep signal itself.

3. SOFTWARE IMPLEMENTATION

The generation of the test signals and the deconvolution of the impulse responses have been implemented as plug-ins working inside the Adobe Audition 1.5® host program. These plug-ins allow to generate signals like MLS, linear and logarithmic sine sweep; Audition makes it possible to playback the test signal in loop mode, so the first transducer emits continuously, while the software is recording the signal captured by the second transducer. The sound card used was an Edirol FA-101, equipped of 8 outputs, 9 inputs, with a maximum sampling rate of 192 kHz. Another plug-in is used to deconvolve the recorded signals (by convolution with the inverse filter), allowing to transform the sampled signal in a sequence of impulse responses.

The above plugins are part of the *Aurora* package [8], and can be freely downloaded from the Aurora web site [9].

After the measurement is done, a separate visualization program makes it easy to display the sequence of impulse responses as a traditional sonar graphical plot; a new version of the measurement software is under development, capable of real-time display of the sonar plot during the measurement.

4. EXPERIMENTS

In order to evaluate the feasibility of the system and the behavior of each test signal, different experiments were conducted. In the first step, the measurements were performed in air; then, after evaluating the preliminary results, new measurements were performed under water, initially inside a large pool, then in the sea. Next subsections describe the different tests performed from the authors and the results achieved.

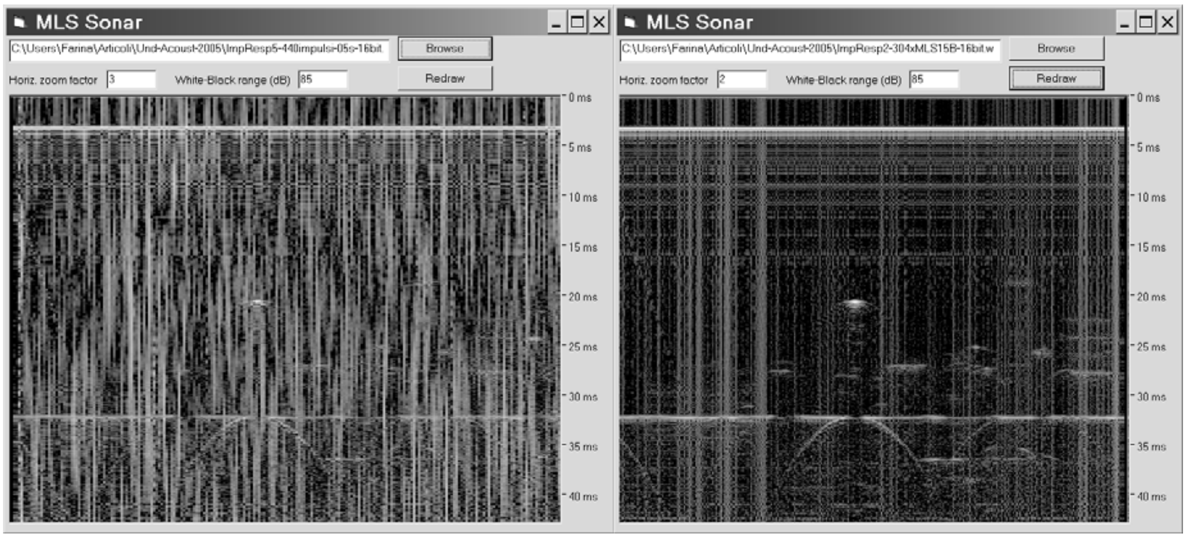
4.1. "Air" measurements

The goal of this experiment was to draw the profile of the furniture inside a large shed, located at Industrial Engineering Dept. of University of Parma, and containing mechanical equipments (turn, drill, etc.) and cupboards. The scanning equipment is formed from a self-powered loudspeaker and a microphone suspended at 5.5 m over the floor, moving at a speed of 0.13 m/s thanks to the loading bridge installed in the shed. Transmitter and receiver are connected directly with the Edirol Firewire sound card, which is driven by the notebook PC. The measurement was performed four times, employing different test signals with a sampling rate of 48 kHz. The first test signal used was the MLS (order 15) with a period L equal to 32767 samples (0.683 s long), which is repeated 240 times to allow the scanning of the whole length of the shed. The recorded signal is deconvolved and the first 4096 samples of each impulse response are stored.

The second and third signals employed were sine sweeps, “logarithmic” and “linear” respectively, with frequency increasing from 200 Hz to 20 kHz, duration 1.0 s and 0.5 s. Also these test signals were repeated a number of times sufficient to map all the shed; again, the recorded signals are deconvolved and stored.

The fourth measurement was performed generating a series of periodic pulses, with a repetition rate of 0.5 second. In this case, the recorded signal is already the required sequence of impulse responses.

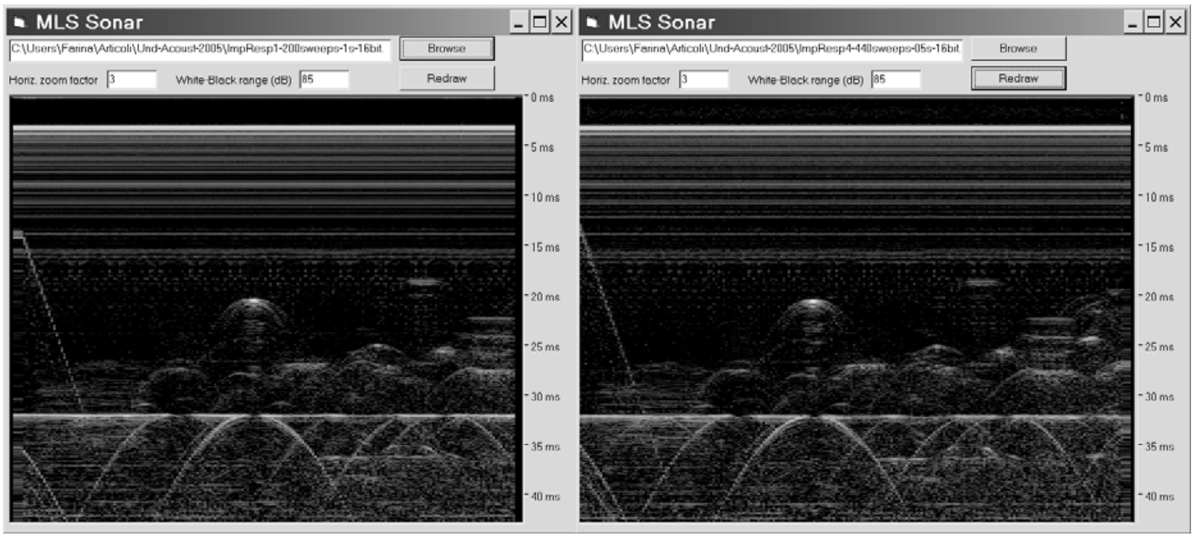
The same settings are employed for processing all the measurements and for transforming them in sonar images: each impulse response was first logarithmically transformed and then each sample was mapped to a 256-levels grayscale. The result is assembled in a matrix of pixels, in which each vertical line (from left to right) represents an impulse response, with the zero of time at the top of the image (Figs. 1 – 2).



C:\Users\Farina\Articoli\Und-Acoust-2005\ImpResp5-440impulsi-05s-16bit.
Horiz. zoom factor 3
White-Black range (dB) 85

C:\Users\Farina\Articoli\Und-Acoust-2005\ImpResp2-304xMLS15B-16bit.w
Horiz. zoom factor 2
White-Black range (dB) 85

Fig. 1: Images obtained in air with the impulsive technique (left) and with MLS (right).



C:\Users\Farina\Articoli\Und-Acoust-2005\ImpResp1-200sweeps-1s-16bit.
Horiz. zoom factor 3
White-Black range (dB) 85

C:\Users\Farina\Articoli\Und-Acoust-2005\ImpResp4-440sweeps-05s-16bit.
Horiz. zoom factor 3
White-Black range (dB) 85

Fig. 2: Images obtained in air with the sine sweep technique: log (left) and linear (right).

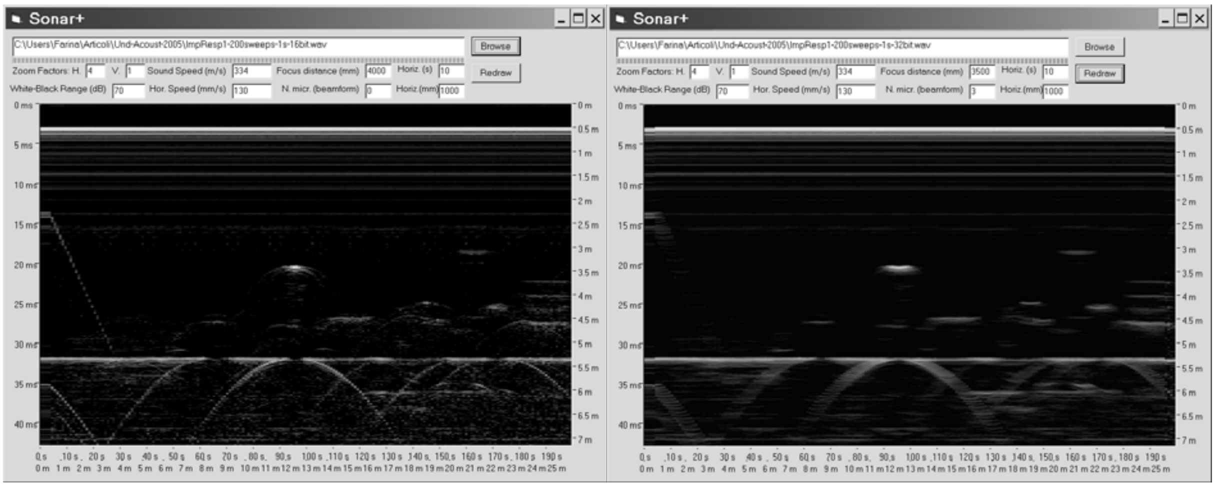
Observing these pictures, it is easy to note two horizontal white lines at 0.3 ms and at 32 ms: the first represents the acoustic cross-talk between the emitter and the receiver and the

second is the reflection over the floor of the shed. Shapes of the furniture and of the mechanical equipment contained in the room, instead, are indicated from other profiles between two lines depicted above. An important aspect of these measurements is the signal-to-noise ratio (S/N): the pictures show that it increases going from the impulsive technique to MLS, and it increases even more when using sine sweeps. Fig. 1, in fact, shows how the image obtained employing the MLS signal appears clearer than the one obtained directly playing wide-band pulses; the two images of Fig. 2 are even better, without any vertical "white stripes" caused by poor S/N ratio. This improvement of S/N is easily explained with the fact that the sine sweep signal radiates an amount of energy which is very large compared with the energy radiated from the MLS signal or from a single pulse.
No significant advantage was observed employing log sweep instead of linear sweep, so it was decided to prefer the latter, which is easier to manage and has more energy at high frequency, where the piezoelectric underwater transducers perform better..

4.1.1. "Virtual" beamforming - focalization

Due to the poor directivity of the loudspeaker and microphone, the shapes of the objects, mapped by the sonar, are not well defined. The receiver (microphone), in fact, records the sound emitted from lateral lobes of the speaker and reflected from same objects. It means the system recognizes an object before the sonar is over it. Of consequence, the profiles of the objects appear wider than that real ones. This artifact, appreciable in Fig. 2, can be reduced through a proper algorithm of synthetic aperture focalization; in this way the transducer directivity can be greatly increased. The processing software has been modified, allowing a "virtual" beamforming making use of a number of adjacent impulse responses – optimal results were obtained employing a virtual array of 7 microphones.

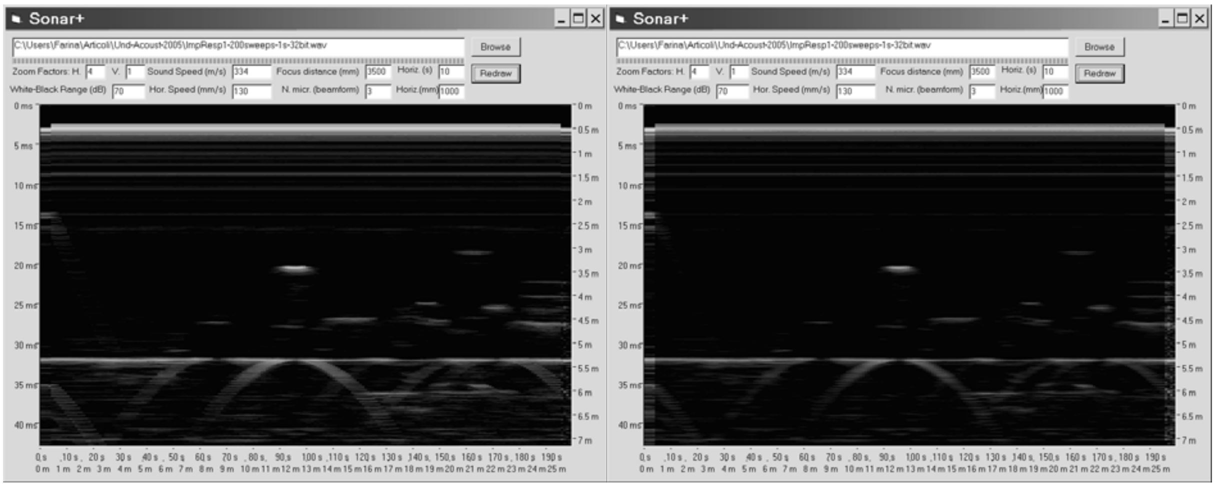
The following figures show a measurement without any beamforming (Fig. 3 - left), a measurement with fixed focalization at 3.5 m (Fig. 3 - right), one with dynamic focalization (Fig. 4 - left) and one with dynamic focalization and Hanning weighting (Fig. 4 – right).



C:\Users\Farina\Articoli\Und-Acoust-2005\ImpResp1-200sweeps-1s-16bit.wav
Zoom Factors: H. 4 V. 1 Sound Speed (m/s) 334 Focus distance (mm) 4000 Horiz. (s) 10
White-Black Range (dB) 70 Hor. Speed (mm/s) 130 N. micr. (beamform) 0 Horiz.(mm) 1000

C:\Users\Farina\Articoli\Und-Acoust-2005\ImpResp1-200sweeps-1s-32bit.wav
Zoom Factors: H. 4 V. 1 Sound Speed (m/s) 334 Focus distance (mm) 3500 Horiz. (s) 10
White-Black Range (dB) 70 Hor. Speed (mm/s) 130 N. micr. (beamform) 3 Horiz.(mm) 1000

Fig. 3: Measure without beamforming (left) and with fixed focalization at 3.5 m (right).



Sonar+

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Zoom Factors: H. 4 V. 1 Sound Speed (m/s) 334 Focus distance (mm) 3500 Horiz. (s) 10

White-Black Range (dB) 70 Hor. Speed (mm/s) 130 N. micr. (beamform) 3 Horiz.(mm) 1000

Sonar+

C:\Users\Farina\Articoli\Und-Acoust-2005\ImpResp1-200sweeps-1s-32bit.wav

Zoom Factors: H. 4 V. 1 Sound Speed (m/s) 334 Focus distance (mm) 3500 Horiz. (s) 10

White-Black Range (dB) 70 Hor. Speed (mm/s) 130 N. micr. (beamform) 3 Horiz.(mm) 1000

Fig. 4: Measure with dynamic focalization without (left) and with Hanning weighting (right).

4.2. "Water" measurements

To analyze the sonar behavior in a real environment, another session of tests has been lead in the water. First the system has been tested in a large test pool kindly made available by W.A.S.S. (Whitehead Alenia Sistemi Subacquei) in order to correctly characterize devices to use in the measurement chain. Two hydrophones ITC 5264, equipped with parabolic reflectors, were employed as transmitter and receiver. The test pool measurements made it clear that it was advisable to employ linear sine sweep with these transducers, and that a proper pre-equalization was necessary in order to obtain a substantially flat power emission in the frequency range between 2400 Hz and 45 kHz.

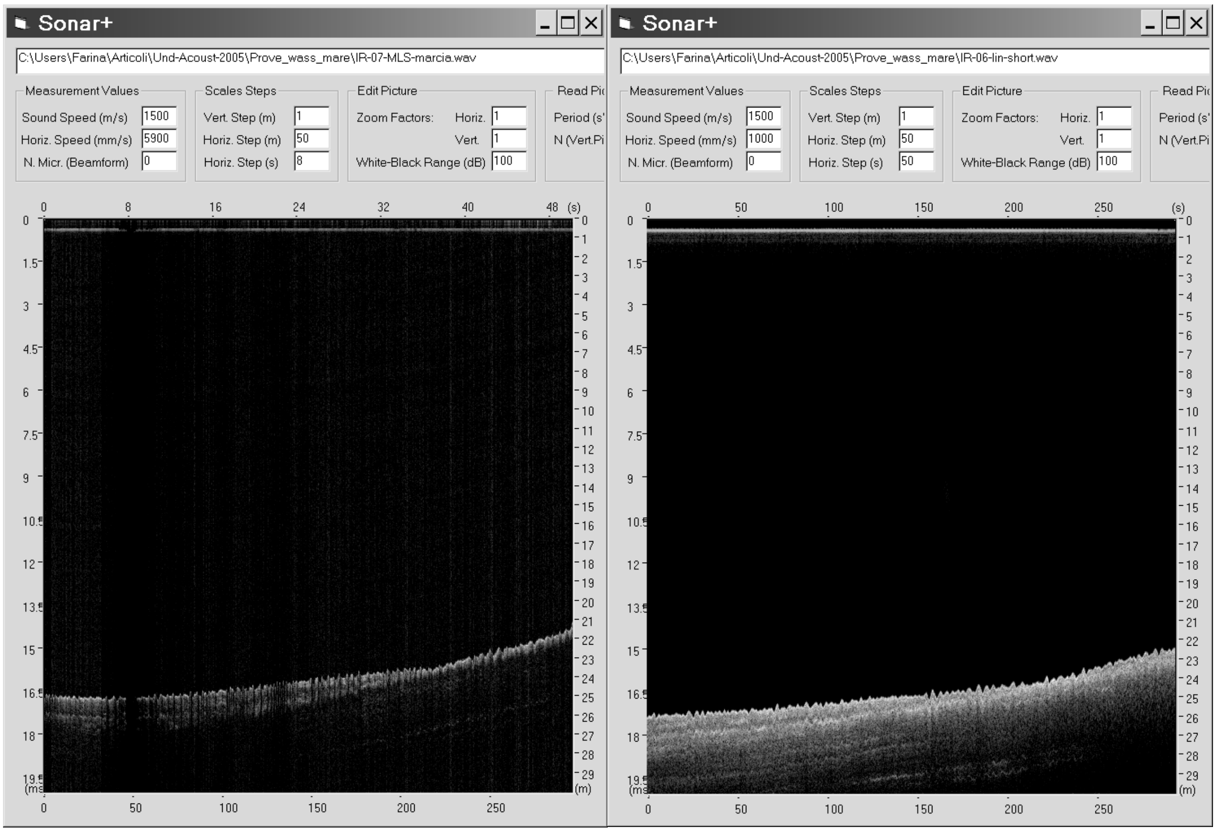
Subsequently, the same actuators were arranged on the rear of a special marine vessel, the "Whitehead III", also kindly supplied from W.A.S.S.. During those tests, conducted in the gulf of La Spezia (Italy), the vessel marched at about 2 knots and the sonar system was fed with a 0.5 seconds long linear sine sweep, and with multisweep (this is a signal obtained superposing 5 sine sweeps, with starting time delayed 0.2s each after the other), with frequency increasing from 2.4 kHz to 48.0 kHz (F_{samp} = 96.0 kHz).

A first series of measurement was performed on the side of Palmaria island facing inside the gulf.

The following Fig. 5 shows the profile of the sea bottom in front of the Palmaria island obtained in real time using the sonar system with the software elaborated by the authors. The comparison is between the MLS signal and the linear sine sweep, and it can be seen how the first produces an image with lower resolution and larger noise contamination than with the linear sine sweep.

Although these measurements were performed inside the gulf, where the sea was significantly calm, attempts to use wide-band pulses did not produce any visible image of the sea bottom.

Then a second series of measurements were performed in the open sea, outside the Palmaria island, in front of the Tinetto cliff. Fig. 6 shows the profile of the bottom near Tinetto cliff: the micro ripple appearing on the bottom profile is due to the boat pitching during the advancement over the waves.



C:\Users\Farina\Articoli\Und-Acoust-2005\Prove_wass_mare\IR-07-MLS-marcia.wav

Measurement Values
Sound Speed (m/s) 1500
Horiz. Speed (mm/s) 5900
N. Micr. (Beamform) 0

Scales Steps
Vert. Step (m) 1
Horiz. Step (m) 50
Horiz. Step (s) 8

Edit Picture
Zoom Factors: Horiz. 1
Vert. 1
White-Black Range (dB) 100

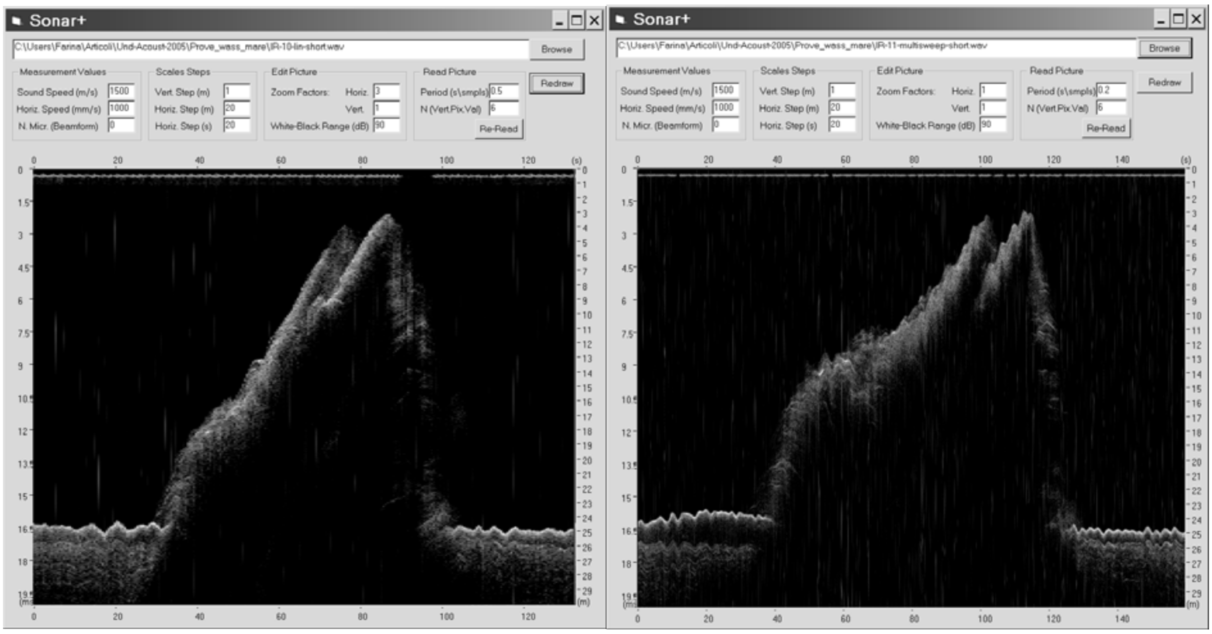
C:\Users\Farina\Articoli\Und-Acoust-2005\Prove_wass_mare\IR-06-lin-short.wav

Measurement Values
Sound Speed (m/s) 1500
Horiz. Speed (mm/s) 1000
N. Micr. (Beamform) 0

Scales Steps
Vert. Step (m) 1
Horiz. Step (m) 50
Horiz. Step (s) 50

Edit Picture
Zoom Factors: Horiz. 1
Vert. 1
White-Black Range (dB) 100

Fig. 5: Images of the sea bottom near Palmaria island, obtained with the MLS method (left) and with the linear sine sweep technique (right).



C:\Users\Farina\Articoli\Und-Acoust-2005\Prove_wass_mare\IR-10-lin-short.wav

Measurement Values
Sound Speed (m/s) 1500
Horiz. Speed (mm/s) 1000
N. Micr. (Beamform) 0

Scales Steps
Vert. Step (m) 1
Horiz. Step (m) 20
Horiz. Step (s) 20

Edit Picture
Zoom Factors: Horiz. 3
Vert. 1
White-Black Range (dB) 90

Read Picture
Period (s\smpls) 0.5
N (Vert.Pix.Val) 6

C:\Users\Farina\Articoli\Und-Acoust-2005\Prove_wass_mare\IR-11-multisweep-short.wav

Measurement Values
Sound Speed (m/s) 1500
Horiz. Speed (mm/s) 1000
N. Micr. (Beamform) 0

Scales Steps
Vert. Step (m) 1
Horiz. Step (m) 20
Horiz. Step (s) 20

Edit Picture
Zoom Factors: Horiz. 1
Vert. 1
White-Black Range (dB) 90

Read Picture
Period (s\smpls) 0.2
N (Vert.Pix.Val) 6

Fig. 6: Image of the sea bottom near Tinetto cliff, obtained with the linear sine sweep technique (left) and the linear sine multisweep (right).

5. CONCLUSIONS

The results of this research demonstrate that the not-impulsive techniques are very appealing for Sonar imaging. Among the various types of test signals evaluated, the linear sine sweep is the one yielding the highest Signal-to-Noise ratio. Its high immunity to external noise, coupled with the very fast and easy processing required for the deconvolution of the impulse responses, make it very appealing for underwater measurements. The software implementation on a notebook PC resulted in a powerful, low-cost system.

6. ACKNOWLEDGEMENTS

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