Results from the Elba HF-2003 experiment

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Abstract. In October of 2003, a high-frequency propagation and acoustic communications experiment was conducted off the Italian island of Elba. The experiment followed closely a previous experiment off Kauai (Hawaii Islands) [1]. In particular, a 5 km propagation path along the 100-m isobath was selected. Relative to the Kauai Experiment, the Elba test was significant both in terms of what was similar and what was different. The experiment geometry was identical and a similar mixed layer structure was expected. However, since NURC has worked extensively in this area in past tests we were able to confidently select two sites, one with a very soft bottom and one with a very hard bottom. The comparison between measurements at the two sites in Elba and in Kauai is very illuminating in terms of the propagation conditions and the performance of the acoustic communications scheme. A final significant change was the inclusion of multiple input/multiple output (i.e. using source/receive arrays) communications schemes. We summarize preliminary results from this experiment.

INTRODUCTION

The ELBA HF-2003 trial was a pre-cursor to a planned 3-year (2004–06) collaborative program on High Frequency Acoustics, involving the following institutions: NURC, APL-UW, NRL, SAIC, SPAWAR, UDEL, WHOI and Univ. of Algarve (PO). This joint research effort seeks to significantly improve our understanding of the propagation and scattering of high frequency (5–50 kHz) acoustic waves in the presence of oceanographic variability in shallow water. Yearly field tests are planned to characterize the propagation as a function of 1) source/receiver geometry, 2) arrival angle, 3) carrier (center) frequency, 4) ocean volume structure, 5) bottom type and roughness, and 6) boundary dynamics, including effects of surface waves, bubbles, and noise. Much of the characterization will depend on accurate propagation modeling. The modeling effort seeks to explain, and ultimately predict, the factors that significantly alter operational effectiveness of acoustic communications for applications such as AUV-based MCM detection and classification systems.

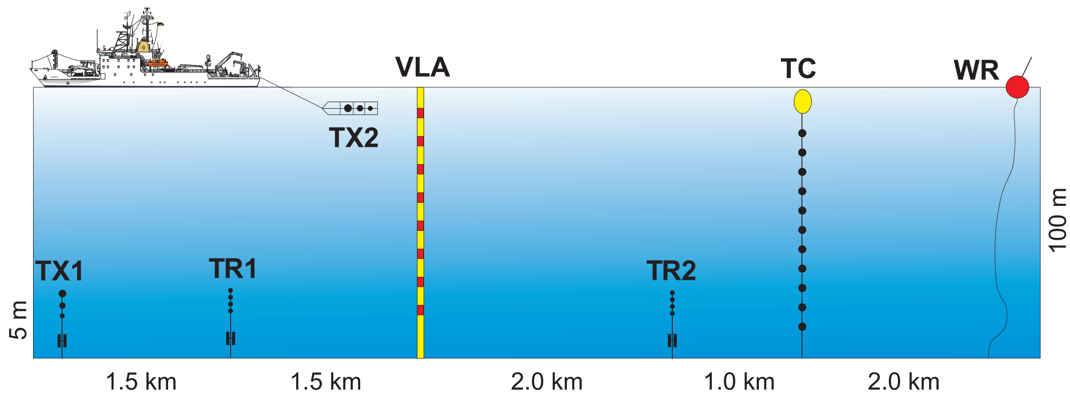

FIGURE 1. Schematic of the experimental setup.

EXPERIMENTAL SETUP

Two experimental sites in approximately 100 m water were selected: One north of Elba with a hard sand bottom and one south of Elba with a soft silt bottom. A schematic of the equipment deployed at each site in shown in Fig. 1. Two telesonar testbed sources and two receivers were supplied by SPAWAR. These are autonomous bottom-moored systems deployed as shown in the figure. One source (TX1) was moored, with the three transducers placed around 5 m off the bottom. The second source (TX2) was towed up and down the acoustic track by *R/V Alliance*. These sources cover a frequency range of 8–50 kHz. The sources were programmed to transmit a sequence of different signals, including LFM's and a variety of communication encodings, to be repeated every 5 min.

The two telesonar receivers (4 hydrophones each, 5 m off the bottom) were placed at ranges of 1.5 (TR1) and 5.0 km (TR2) from the moored source. In addition, the NURC vertical line array (VLA) with 8 hydrophones covering most of the water column was moored at a range of 3.0 km from TX1. The VLA data, with an upper frequency limit of 16 kHz, were received directly on board *Alliance* via a radio link.

A second acoustic experiment was done with the SAIC/WHOI equipment to test the MIMO (Multi-Input/Multi-Output) concept for acoustic communications. Here two drifting ships were employed, one with the source array suspended over board, and one with the receiver array. Transmissions were done at different ranges both north and south of Elba.

Environmental monitoring was done with an 11-element thermistor chain (TC) and a waverider buoy (WR). In addition, several CTD's and XBT's were taken throughout the trial period. Whereas sediment properties for the southern site are well-known from previous experiments, there is no historical information for the northern site. Hence sediment grab samples were collected and seismic profiling carried out for the full track. Finally, ambient noise measurements for geoacoustic inversions were done on a vertical array suspended from *R/V Alliance*.

PROPAGATION ENVIRONMENT

The thermistor chain result north of Elba over a period of 42 h is shown in Fig. 2. Note that the upper 60 m of the water column is quite stable and well mixed. Below there is a sharp thermocline where the temperature drops around 4°C within a few meters. Near the bottom there is colder water, which generates a sound channnel limited below by the bottom and above by the thermocline. We also see that the there is strong internal wave activity causing the thermocline to move up and down by around ± 5 m. Despite this strong internal wave activity, the Elba site presented much less variability in the lower part of the water column than Kauai. In Kauai, it was not unusual for the thermocline to complete disappear and reappear over the course of a day.

Figure 3 shows a single sound-speed profile measured in the northern site with the associated ray trace (results are from the BELLHOP Gaussian beam-tracing model). Note the so-called bouncing ball paths refracted in the lower duct.

The BELLHOP model can also predict the accordion pattern of arrivals that would be seen by a vertical array in the water column. In particular, we simulate the field due to an impulse transmitted from the telesonar testbed to the VLA which was placed at a range of about 3 km. This result is seen in the left in Fig. 4 where each fold of the accordion represents a successive surface or bottom reflection. The arrivals come in pairs with the first path directed up into the water column and the second being simply the downgoing path, which is almost immediately reflected from the bottom. Since the source is close to the bottom the upgoing and bottom-reflected paths follow almost the same trajectory from then on to the receiver. One can also see the energy of the 'bouncing ball' paths in the lower part of the water column. Since the sound speed is lower near the bottom, those paths are not the first arrivals.

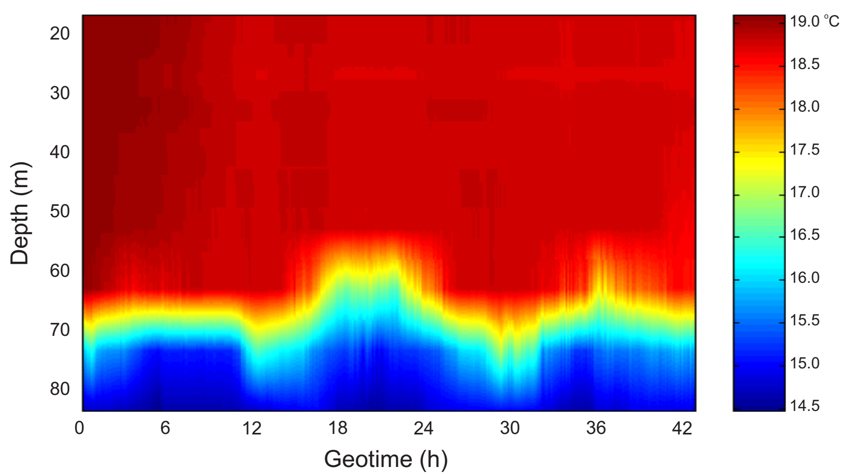

FIGURE 2. Moored thermistor chain data recorded over a 42-h period North of Elba.

PRELIMINARY RESULTS

Measured and modeled impulse responses

An important part of this experiment is to gain confidence in our ability to predict acoustic propagation at these high frequencies. Figure 4 shows a comparison between the modeled and measured impulse responses on the VLA. This result is obtained by using pulse compression techniques (matched-filter or replica correlation) to convert the LFM's or chirps into an equivalent impulse. Note the precise correspondence between the model and the data.

The experimental sites were carefully selected to present very different bottom types. Figure 5 shows a comparison between the impulse responses at the two sites. Note that as expected, the northern site with the very reflective bottom shows extensive multipath spread, i.e. lots of echoes, whereas the southern site shows almost no multipath. Multipath spread, as discussed later, is a critical parameter in prediction acoustic modem performance.

Hybrid (LF/HF) bottom characterization

An additional goal of the experiment was to test a proposed hybrid (HF/LF) scheme to derive bottom (geoacoustic) properties. The scenario envisioned is one where a system uses a compact array of HF sensors to measure the directionality of the ambient noise. As shown by Harrison and Simons [2] there is a simple relationship between the ambient noise that appears to come from the surface and that coming from the bottom. In essence, the surface is considered as a nearly perfect mirror and the bottom as a somewhat murky one. Noise in the HF band is predominantly due to breaking waves and therefore widely distributed. Noise seen on a vertical line array looking towards surface or bottom is then really a sum due to the 'barbershop mirrors' formed by surface and bottom. However, it can be shown that if the bottom is murkier, then the ratio of energy between looking up to the surface and down to the bottom is a direct measurement of the bottom reflection coefficient. This sort of measurement is easily made with small HF arrays and can then

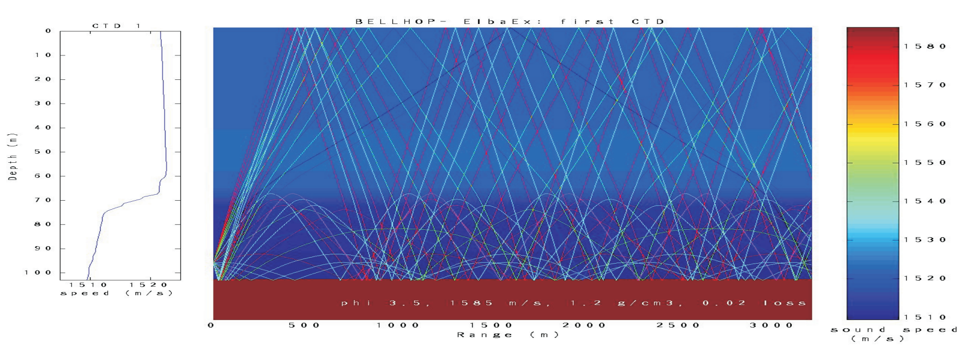

FIGURE 3. Representative sound-speed profile and ray trace for source near the bottom.

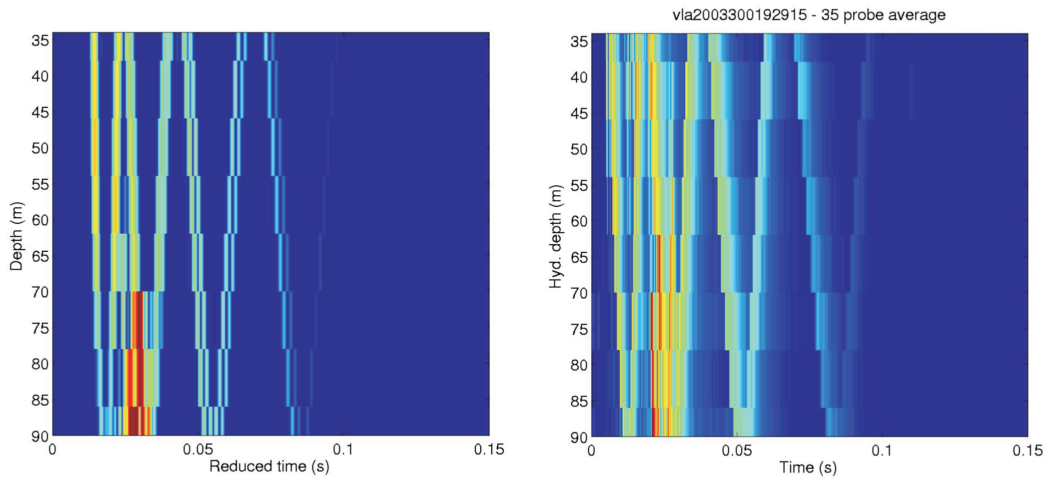

FIGURE 4. Comparison of modeled (left) and measured (right) impulse responses along track N. The data is derived from the VLA positioned about 3 km from the source.

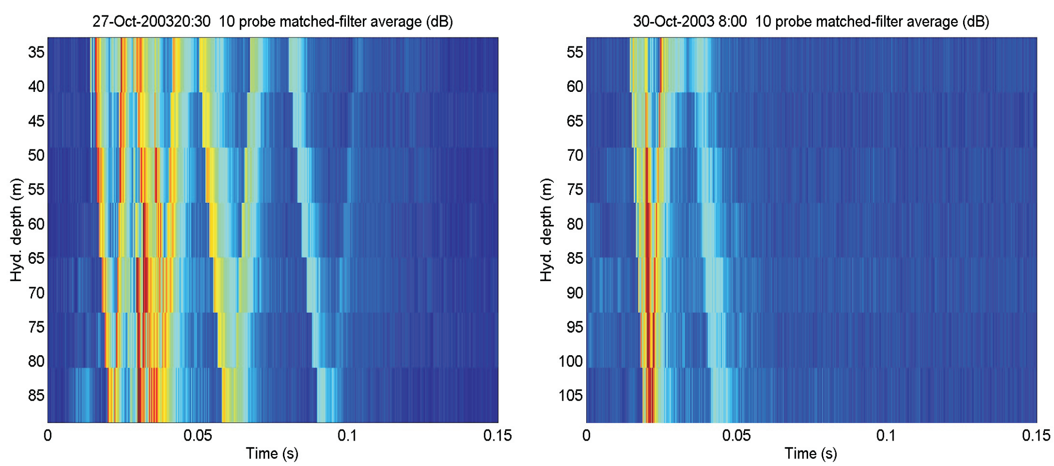

FIGURE 5. Comparison of measured impulse responses along tracks N and S.

be extrapolated down to lower frequencies of interest for other applications.

An example of the technique is shown in Fig. 6. The left panel shows the directionality of ambient noise as a function of frequency as measured north of Elba. Note that the most noise comes from shallow angles. Ambient noise at steeper angles is absorbed in the bottom. Taking the ratio of the up- and down-going energy yields the reflection coefficient as a function of angle of incidence and frequency as shown in the right panel of Fig. 6.

This technique is potentially of great importance in providing immediate knowledge of the bottom properties. Future work in this program will examine the ability to extract both surface and bottom losses.

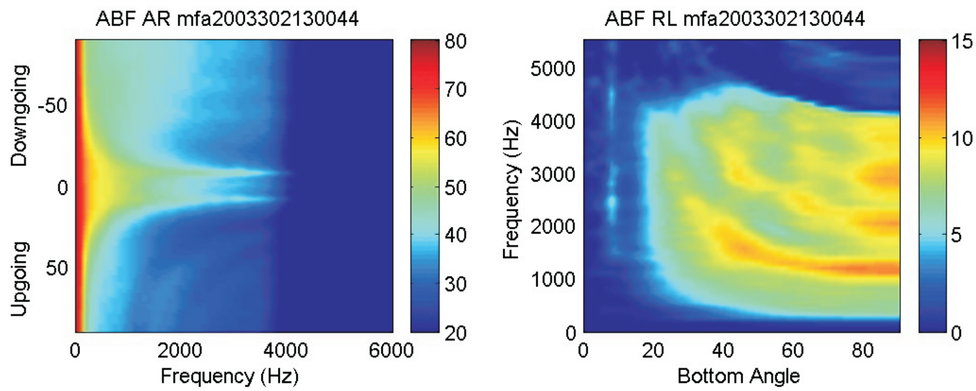

FIGURE 6. Directionality of ambient noise (left) for the northern site. Bottom reflectivity derived by processing the ambient noise (right).

Effects on acoustic communications

The variation in bottom conditions and multipath spread is of critical importance for acoustic communications. For instance, one very common approach to communications involves frequency-shift keying (FSK). This may be compared to playing a piano where each chord is used to encode information. The decoder is nothing more than a spectrum analyzer, which, like the human ear, detects which tones have been played. In some ways, the ocean may be compared to a badly designed concert hall with excess reverberation. To decode the pattern of notes, time must be allowed between each chord so that the reverberation can die down. Thus the multipath spread can limit the transmission rate. Therefore one consideration for optimal data rates is to seek a channel with low multipath spread, i.e. low reverberation.

Interestingly, conditions of low multipath spread are essentially the opposite of what we normally consider to be ‘good’ propagation conditions. The direct path (neglecting refractive focusing) is a spherical wave expanding from the source and losing energy in a spherical manner. In essence, it is the multipath that gives us the much-improved cylindrical spreading law because the surface and bottom continually reflect the energy that otherwise would be lost. However, that multipath is often simply clutter for the simple FSK communication approach.

These effects of multipath are illustrated in Fig. 7. Note first of all that the northern site with its reflective bottom shows significantly higher SNR. However, the bit error rates are actually much higher. These results are derived from our MFSK algorithm at 2400 bps as recorded on the VLA. It should be noted that in a practical implementation we also include channel coding to dramatically reduce the errors. We generally prefer to study environmental effects on the uncoded waveforms to minimize the number of transmissions required.

Numerous other modulation schemes, including Direct Sequence Spread Spectrum and various coherent Phase-Shift Keying methods were also tested in the experiment and are currently being processed.

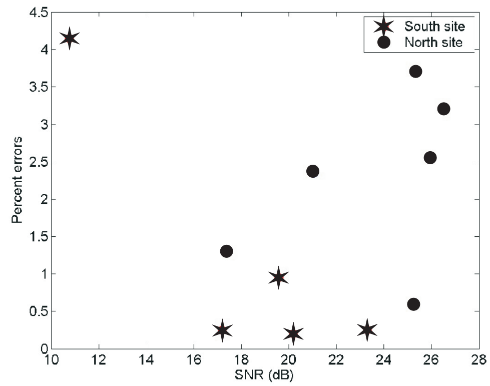

FIGURE 7. Comparison of measured bit error rates along tracks N and S.

High-data rate acomms (MIMO)

An additional focus in this experiment was to test Multiple Input, Multiple Output communications (MIMO). MIMO is a general term applied to systems that use multiple sources and receivers to increase the data rates and is currently an area of very active research in wireless communications (cell phones). In the ocean and with single sources and receivers we can today obtain bandwidth efficiencies of typically 3 bits/Hz, yielding perhaps 16 kbits/sec at distances of 5 km in shallow water. Obviously quality video images from AUV's or raw time-series data from off board horizontal line arrays require much higher data rates, motivating the development of MIMO systems. (Other terms used for MIMO are 'Spatial Modulation', and BLAST, which refers to a particular approach developed at Bell Labs.) Bandwidth efficiencies of 28 bits/Hz have been demonstrated in electromagnetic applications.

Roughly speaking, MIMO systems work by transmitting independent data streams along independent propagation paths. For instance one can imagine a source array that sends energy along different eigenrays and a receive array that separates the data streams by beamforming in the direction of those same independent eigenrays connecting source and receiver. However, such MIMO systems are limited by their ability to separate the arrivals. The various data streams are interfering with each other and the receive array has the difficult task of suppressing the interference to extract each data stream. For this reason, the promise of high-data rates with MIMO systems is generally accompanied by a requirement of high SNR.

Two groups fielded MIMO systems in the Elba experiment. The SPAWAR Systems Center, together with co-investigators from Northeastern University and Arizona State fielded a variety of STAP (space-time adaptive processing) schemes based on current work in wireless electromagnetic communications. The SAIC/WHOI team fielded a scheme previously developed by Kilfoyle [3] and referred to as 'spatial modulation'.

Tables 1 and 2 compare the performance of the latter in the northern and southern Elba sites. These are really extrapolations or estimates of performance derived from the measured data rates. Interestingly, the two sites again showed radically different performance. In both cases the bandwidth efficiency tends to peak at about 3 'channels', i.e. processing 3 independent data streams. With additional data streams the mutual inter-

TABLE 1. MIMO results along tracks N.

	1 MIMO channel	2 MIMO channels	3 MIMO channels	4 MIMO channels
Average SNR_{output}(dB)	19.0	15.0	13.8	11.3
	–	13.2	11.6	9.3
	–	–	9.6	4.9
	–	–	–	3.2
Capacity (bits/use)	6.3	9.5	**11.9**	10.7

TABLE 2. MIMO results along tracks S.

	1 MIMO channel	2 MIMO channels	3 MIMO channels	4 MIMO channels	5 MIMO channels	6 MIMO channels
Average SNR_{output}(dB)	17.8	15.9	15.1	13.4	9.4	7.9
	–	15.0	14.0	12.2	7.9	6.3
	–	–	12.7	11.3	7.2	5.7
	–	–	–	10.4	5.7	5.3
	–	–	–	–	4.7	4.2
	–	–	–	–	–	3.1
Capacity (bits/use)	5.4	10.1	13.9	**15.9**	12.8	12.2

ference starts to degrade the performance. In the northern site a bandwidth efficiency of 11.9 bits/Hz is attained which is a significant improvement over standard single channel systems. In the southern site with much less multipath, an even better bandwidth efficiency of 15.9 bits/Hz is attained.

These results clearly point to the importance of the environment in determining modem performance. Unfortunately our ability today to accurately predict multipath spread as well as the dynamics (fluctuations) of the multipath is very limited in the 8-50 kHz band which is currently the focus of underwater acoustic modems. Indeed, unexplained modem failures and associated network outages are a fairly common experience. The current research initiative in high-frequency acoustics promises to greatly improve our capabilities in this area.

ACKNOWLEDGMENTS

Appreciation is expressed to the Captain and Crew of the *R/V Alliance*, to Scientific and Technical personnel from NURC, in particular to Mark Stevenson for performing the duty of Chief Scientist on the second part of the trial. Portions of this work were supported by ONR under contract N00014-00-D-0115.

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