EXAMPLE OF ENERGY PARTITIONING BETWEEN WATERBORNE AND SEDIMENT PATHS IN UNDERWATER ACOUSTIC PROPAGATION

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Abstract

Examples of acoustic energy partitioning at the seafloor are presented using results obtained in a recent experiment conducted off the Oregon Coast by the Naval Oceanographic and Atmospheric Research Laboratory. The energy partitioned into the ground and waterborne paths are compared for several source-receiver separations and water depths. The ground path is shown to increase in significance with decreasing frequency and, in some situations, to be as efficient a propagation path as the high-frequency waterborne path.

Introduction

The propagation of sound in the sea has been of interest for at least five decades. The first significant underwater acoustic measurements to be documented, were probably the shallow-water experiments conducted by Worzel and Ewing[1] in late 1943 and early 1944, the results of which were placed in a theoretical framework by Pekeris[2] in his pioneering work on acoustic waveguides. These early investigators were keenly aware of the partitioning of energy between the waterborne path and the seafloor ("ground") path, particularly at low frequencies. In spite of this, and the large number of experiments conducted since, both by acousticians and seismologists, partitioning remains poorly quantified. In part this resulted from limitations in earlier recording instrumentations, particularly in dynamic range. In large part, however, partitioning received little attention by either group because it belonged to that nebulous region lying between their interests. In particular, seismologists concentrated mainly on deep-earth structures, for which waterborne signals are of relatively little value. Underwater acousticians have until recently emphasized higher frequencies, for which bottom penetration is less significant, and narrow band data, from which it is difficult to isolate subseafloor paths. In recent years, the interest in low frequency (LF, < 100 Hz) and very low frequency (VLF, < 20 Hz) acoustic propagation, has focused attention on energy partitioning between waterborne and subseafloor paths. At low-frequencies (particularly VLF), the relatively small sediment attenuation allows significant penetration of acoustic energy into the seafloor, thereby necessitating inclusion of the effects of the seafloor on the propagation of the energy.

In this paper a first order measure of acoustic energy partitioning at the seafloor is proposed which attempts to compare the level of deeply penetrating energy with the level of energy propagating through the water column and shallow sediments. Such a measure is useful, as it allows one to evaluate the importance of the deep-earth structure in predictions of VLF propagation. This parameter is expected to vary with details of the environment and experimental geometry, but to be sufficiently robust to be characterized by general environmental parameters such as water depth, sediment thickness, and/or stratigraphic and tectonic setting. Based on this measure, the paper provides examples of energy partitioning observed in data obtained from recent propagation measurements conducted by the Naval Oceanographic and Atmospheric Research Laboratory (NOARL).

Measures of Energy Partitioning

To clearly establish the basis for the measure of partitioning used in this paper, a typical response to an underwater explosion ("shot") is discussed. Figure 1 presents the measured response of a water column hydrophone to a 10 km-distant shot. Characteristic features of the response are labelled. The low-frequency arrival preceding the waterborne wave—i.e., the ground wave—represents energy travelling at a speed greater than that of the waterborne wave; hence, this is energy propagating in the bottom for a large part of its travel path. The frequencies contained in the ground wave are generally very low (here predominantly less than 10 Hz). The higher frequency components of the signal have been attenuated during deep penetration into the bottom layers.

Analysis of the ground wave can provide information on the geoacoustic properties of the bottom and subbottom strata. In most of the shot records the ground wave appears to consist of several (two or three) packets of energy commonly referred to as distinct arrivals or seismic phases. This is often indicative of several bottom strata of different geoacoustic properties.[3] However, a simple correspondence of phases with subbottom layers is not necessarily

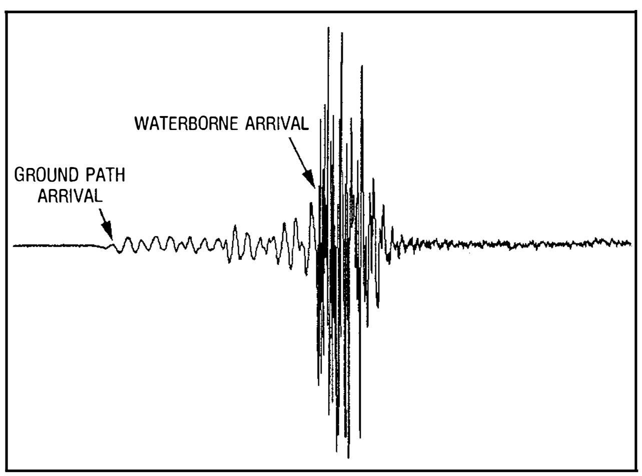

Figure 1. Hydrophone response to a 10-km distant explosion, showing ground wave and water path arrivals.

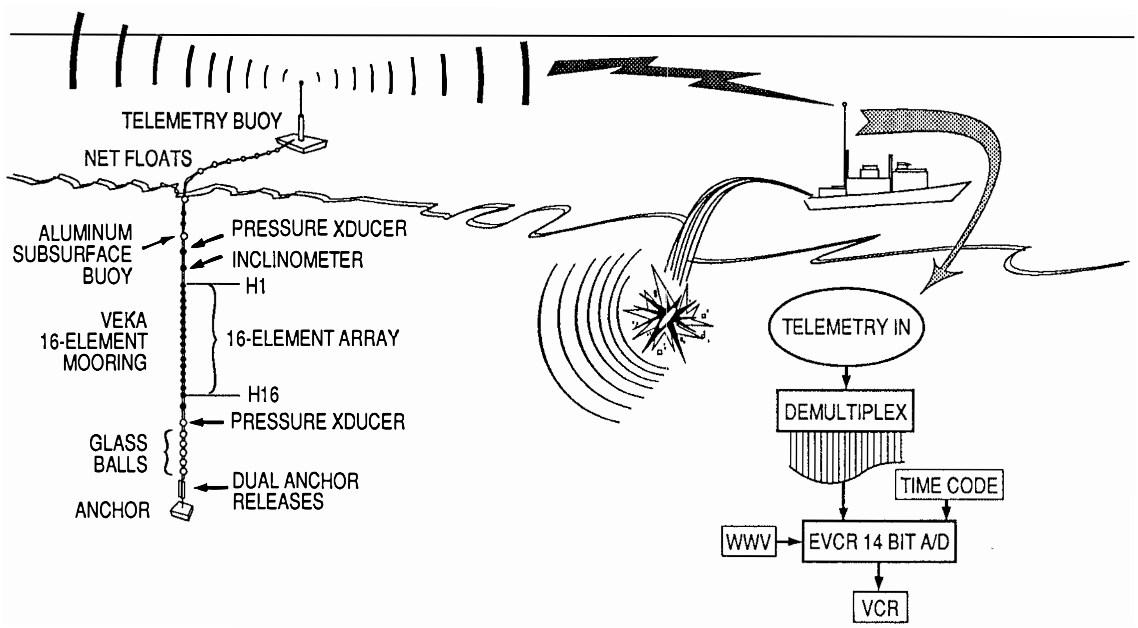

Figure 2. A test arrangement and data acquisition system of the VLF 87 experiment.

correct since multipath propagation will typically generate more phases than layers. Based on other data, not presented here, we believe the early part of the ground wave arrival in Figure 1 to be energy returning from below acoustic basement. Acoustic basement in this area consists of a lithified sediment 1500 m below the seafloor. The later higher amplitude ground wave arrivals probably represent energy returning from depths shallower than this. By including all of these multiple phases under the category of ground path energy, we claim to produce a parameterization which is more stable and less dependent on the details of the propagation path.

The arrival of the high-frequency waterborne acoustic wave is followed by a region in which waterborne and late-arriving ground waves interfere and eventually die away. These late-arriving ground waves can be attributed to multipath propagation in the slow-speed shallow sediments.

Based on the preceding, a reasonable first-order measure of deeply penetrating energy is provided by the total spectral energy in the time series including the high-speed, low-frequency ground waves preceding the waterborne arrivals. The spectral energy in the time series including subsequent arrivals, beginning with the acoustic water wave, represents energy propagating predominantly in the water column and upper sediment layers of the sea bottom. The further partitioning of the energy into compressional, shear, and converted shear waves will not be considered in this paper.

Experimental Arrangement/Data Acquisition

The results discussed below were obtained in a VLF experiment conducted in 1987 in an area off the coast of Oregon. The test arrangement is shown schematically in Figure 2. A 16-element vertical hydrophone string was deployed in water depths of 183 m and 373 m. In addition, several ocean bottom seismometers (OBS) were deployed at various locations on the seafloor. Using explosives, airguns, and a cw sound source (fundamental frequency, 15 Hz), several upslope and cross-slope lines were completed. The 16 hydrophone outputs were multiplexed and telemetered via a UHF link to a nearby receiving ship. The received signal was then passed to an expanded video cassette recorder (EVCR) and converted to a VHS format video signal. The video signal was written on video tape with a standard VCR. Timing information in the form of IRIG-B time code was also recorded on the videotape. A common time base was provided by the WWV radio broadcast. The WWV signal was fed into the EVCR and digitized, multiplexed and recorded on video tape along with the acoustic data and IRIG-B signal. Subsequently (in the laboratory) the digitized data stored on the VCR tapes were played back through the EVCR to obtain the original 16 analog channels. Following low-pass filtering (100 Hz), the analog signals were digitized on a MASSCOMP computer at a sampling rate of 400 Hz. The digitized data were then written as multiplexed integers onto a 6250 bpi 9-track tape.

In this paper the response is presented of the top hydrophone (H1), located 293 m below the surface, to shots dropped along a 120-km long line beginning in shallow water (190 m), passing the hydrophone string, and terminating in deeper water (2740 m). Figure 3 shows the bathymetry along the shot-line and the locations of the hydrophones (marked by "x") and several of the shots (marked by circles). The shots consisted of 55-pound TNT charges and were detonated at depths ranging from approximately 60 to 90 m.

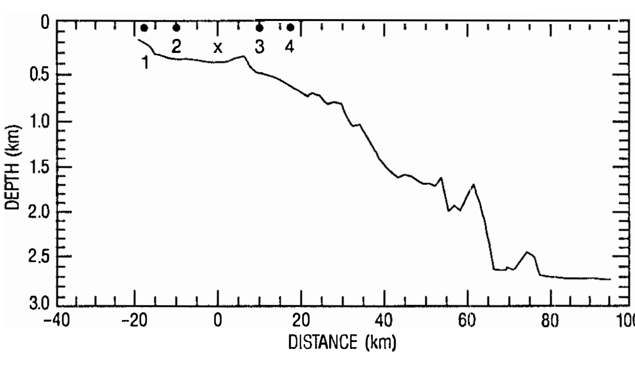

Figure 3. Bathymetry along the shot line 1. Location of hydrophone is marked by x; shot locations are marked by numbered circles (•).

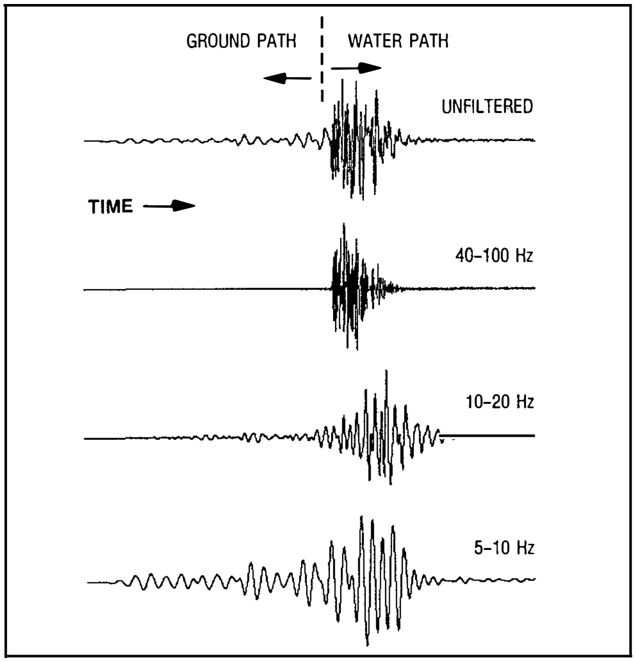

Figure 4. Frequency selectivity of the propagation paths.

Frequency Sensitivity of Energy Partitioning

Considered first is a display designed to illustrate the role of frequency selectivity in determining the relative importance of the ground and water paths. Figure 4 shows the response of hydrophone 1 to a 10 km-distant shot. The unfiltered data are shown along with the signal bandpass filtered into three different frequency bands. The sediment refraction (ground path) and water path are readily distinguishable on the basis of frequency content. In particular, the increase in relative importance of the ground wave with lower frequencies is quite evident. High-frequency propagation in the ground path is significantly attenuated, but is clearly dominant in the water path. Above 40 Hz, for example, the ground wave is not even discernible in this particular signal.

Energy Partitioning at Several Source-Receiver Separations

Considered next is the partitioning for several source-receiver distances. It is expected, *a priori*, that the relative energy between the water and ground paths will be influenced by changing distance from the sound source in any realistic ocean environment. In addition to obvious geometrical spreading of the acoustic waves, changes in water depth result in modifications of the modal structure of the water column acoustic energy and therefore in the overall amplitude of water path phases. Varying sediment properties and bottom roughness influence the amplitude of the bottom interacting portion of the water path arrival. The amplitude of the ground path as a function of range is governed predominantly by the subbottom compressional (and to a lesser extent shear) velocity structure. The depths and magnitudes of major discontinuities between sedimentary layers and the velocity gradients within those layers exert strong controls on the focusing of energy emerging from the seafloor at different ranges. Scattering of energy by subbottom seismic velocity heterogeneities will result in redistribution of the emerging energy to different ranges and energy losses associated with scattering of energy out of the sagittal plane.

A cursory examination of the range-dependence of the data reveals that the ground wave becomes undiscernible above background noise at ranges exceeding approximately 20 km on either side of the receiver—that is, independent of whether the source was in shallow water or deep water. The waterborne arrival, on the other hand, was clearly visible even at the maximum source distance (approximately 100 km). On a nearby vertical seismometer sensor, which is more sensitive to ground wave energy because of its vertical directivity, ground waves can be observed to at least 60 km. It is believed that scattering of ground wave energy from subbottom heterogeneities plays a major role in the ground wave energy losses in this environment. Based on sparker profiles performed by NOARL during the experiment, and on published, interpreted seismic profiles[4,5], it is clear that the Oregon continental margin is characterized by a complicated bottom and subbottom structure involving faulted and folded sedimentary strata. A similar NOARL experiment was conducted in 1985 in the more "benign" environment (passive margin) off Cape Fear, North Carolina. In that experiment, the ground wave arrivals from similar shots were very clear at distances of at least 60 km and were significantly larger than observed in this experiment.[6] The character of the ground waves was also different in that the signals were more impulsive in the East Coast data while they were more distributed in time with longer wave trains in the Oregon experiment. This observation is consistent with an increased scattering contribution in the Oregon data set that would tend to degrade long range propagation of the ground wave.

Figures 5, 6, and 7 show comparisons of the spectra of energy observed in ground wave and "waterborne" paths for several source locations. In particular, referring to Figure 3, the source was located at: point 4 (range, 18 km; water depth, 692 m) for Figure 5; point 2 (range, 10 km; water depth, 390 m) for Figure 6; and point 1 (range,

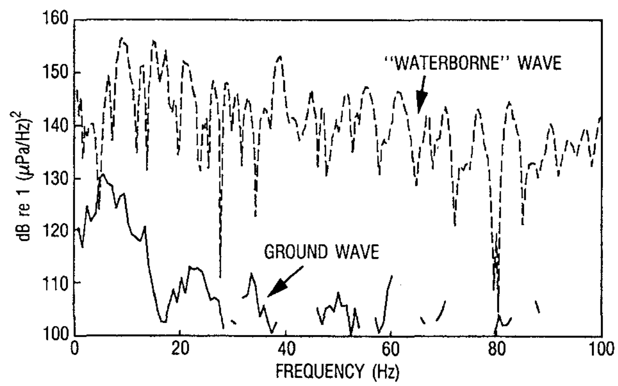

Figure 5. Energy partitioning: Source-receiver separation, 18 km, water depth at source, 692 m.

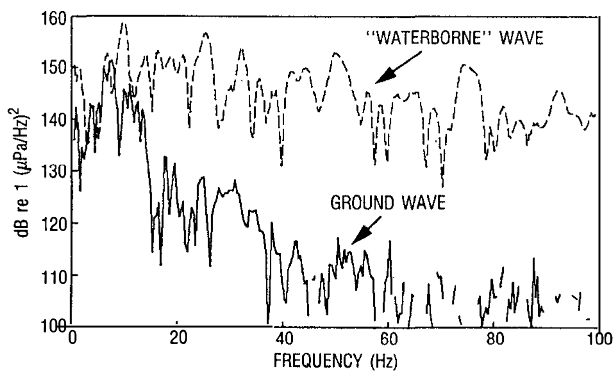

Figure 6. Energy partitioning: Source-receiver separation, 10 km, water depth at source, 390 m.

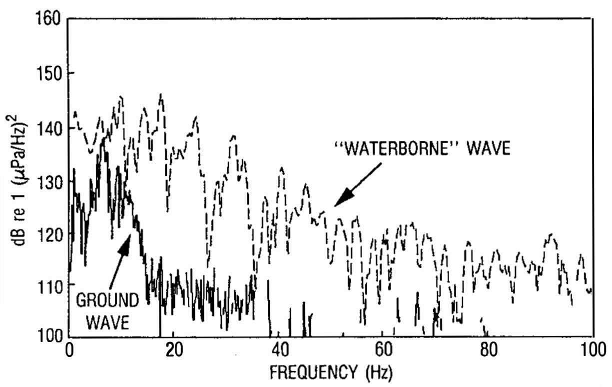

Figure 7. Energy partitioning: Source-receiver separation, 18 km, water depth at source, 250 m.

18 km; water depth, 250 m) for Figure 7. Therefore, by comparing the results in these three figures, one sees the effect of water depth (and range) on the energy partitioning. With the source in deep water, one would expect relatively good waterborne propagation over a broad frequency range. With the source in shallow water, however, increased bottom interaction will remove energy from the water path. Figures 5-7 confirm this expectation. There is a significant decrease in the energy in the waterborne path between 692 m (Figure 5) and 250 m (Figure 7). At the lower frequencies, much of the waterborne loss in the shallow-water region may be due to conversion into ground wave energy. For example, at approximately 5 Hz the ground wave energy in shallow water (250 m, Figure 7) is almost 10 dB higher than the ground wave energy in deeper water (692 m, Figure 5), whereas the corresponding waterborne energy is approximately 10 dB lower in shallow water. However, without a detailed analysis of the path of the ground wave one cannot say, unequivocally, that the gain in ground path energy in this particular instance is due to the loss in the waterborne path. While the loss in waterborne energy at the higher frequencies is also likely to be caused by conversion into ground waves, scattering and anelastic attenuation within the seafloor prevent this energy from reemerging as an observed ground wave.

A general observation from all the figures, independent of range, is the relatively high levels of ground wave energy at the lower frequencies. The ground wave component at location 2 (Figure 6) is especially dominant. The results at location 3 (not shown here) show a similar high level for the ground wave. The decreased spreading losses at the shorter ranges of shots 2 and 3 (both approximately 10 km) are inadequate to account for the increased response.

Conclusions

Based on a first order measure, examples of acoustic energy partitioning at the seafloor have been presented using water column hydrophone data obtained in a recent NOARL experiment conducted off the Oregon Coast. Analysis of the results suggest the following conclusions for this data set:

1. The ground wave arrival was detectable at ranges up to 20 km from the source; the waterborne arrival was detectable to ranges in excess of 100 km.
2. The ground path is significant at VLF frequencies (< 20 Hz) and, in some instances, is as efficient as the high-frequency waterborne propagation.
3. Partitioning of energy into the ground path is enhanced if the sound source is located in shallow water and degraded for a deep-water source. The converse is true for partitioning into the waterborne path.
4. The character of the ground wave arrivals suggests the presence of several subbottom layers of differing geoacoustic properties in the Oregon continental margin and a dominance of scattering losses from complicated subbottom structures. This is consistent with geologic surveys of the area.

References

1. Worzel, J. L. and M. Ewing (1948). Explosion Sounds in Shallow Water. In: *Propagation of Sound in the Ocean.* The Geological Society of America, Memoir 27, Boulder, Colorado.
2. Pekeris, C. L. (1948). Theory of Propagation of Explosive Sound. in Shallow Water. In: *Propagation of Sound in the Ocean.* M. Ewing, J. L. Worzel, and C. L. Pekeris. The Geological Society of America, Memoir 27, Boulder, Colorado.
3. Herring, C. Transmission of Explosive Sounds in the Sea. In: *Physics of Sound in the Sea. Part 1: Transmission.* Research Analysis Group, Committee on Undersea Warfare, National Research Council.
4. Snavely, P. D. Jr., H. C. Wagner, and D. L. Lander (1980). Geologic cross section of the central Oregon continental margin. *Geologic Society of America Map and Chart Series,* MC-28J.
5. Kulm, L. D. and G. A. Fowler (1974). Oregon Continental Margin Structure and Stratigraphy: A Test of the Imbricate Thrust Model. In: *The Geology of Continental Margins,* C. A. Burke and C. L. Drake editors, Springer-Verlag, New York.
6. Ali, H. B., L. D. Bibee, M. J. Authement, R. A. Stephen, and J. L. Becklehimer (1987). *Low-Frequency Seismo-Acoustic Propagation in a Sloping Ocean Environment: Measured Results and Numerical Predictions.* Naval Oceanographic and Atmospheric Research Laboratory, (formerly NORDA), Stennis Space Center, MS, NORDA Tech. Rep. 220.