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SOUND RANGE-DEPENDENT PROPAGATION: AN EXPERIMENT ON DOWN-SLOPE PROPAGATION OVER THE ARGENTINIAN CONTINENTAL SLOPE.

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ABSTRACT

A range dependent acoustic down-slope propagation loss (TL) experiment was conducted in 1989 over the Argentinian Continental Slope, along a 50 km track, using two TRACKER aircrafts from the AntiSubmarine Warfare (ASW) squadron. One aircraft flew a prearranged track dropping 1.8 lb of TROTYL explosive charges, while the second aircraft remained in the area of a deployed calibrated passive sonobuoy, used as sonar receiver. Recorded broadband signals were analyzed with FFT techniques in selected 1/3 octave bands between 100 Hz and 400 Hz. A code based on the parabolic equation method (PE) was used to model the down-slope propagation losses. A reasonable agreement was obtained when theoretical predictions were compared with experimental evidence. This agreement improves at low frequencies. Moreover, at high frequencies the greater the range the better fit is observed.

RESUMEN

En 1989 se ha realizado una experiencia sobre el Talud Continental Argentino para medir pérdidas por propagación acústica (TL) en un medio cuyas propiedades físicas dependen de la distancia. en una extensión de 50 km. usando dos aviones TRACKER de la Escuadrilla Naval Antisubmarina. Uno de los aviones arrojaba cargas explosivas de 1.8 libras de TROTYL. siguiendo un rumbo prefijado, mientras el otro permanecía en el área de sembrado de la sonoboya. actuando como sistema receptor. Las señales en banda ancha fueron analizadas con técnicas de FFT, en bandas de 1/3 de octava entre 100 Hz y 400 Hz. Para modelar las pérdidas por propagación se ha utilizado un código basado en el método de la ecuación parabólica. Se obtuvo un ajuste satisfactorio al comparar las predicciones teóricas con la evidencia experimental. Este ajuste es mejor a bajas frecuencias. A altas frecuencias, se observa un acuerdo mayor para grandes distancias.

1. INTRODUCTION

The study of sound propagation numerical modeling at a shallow continental margin area, down the continental slope, and into the deep ocean, has been in continuous expansion over the past 15 years (Jensen and Ferla, 1989). When powerful digital computers became available in most research institutions, the development of more accurate solutions of the wave differential equation that governs the propagation of sound in complex range-dependent environments was stimulated. Many numerical codes based on different wave-theory solutions such as normal modes or parabolic equation techniques began to be widely used by the international acoustic community.

Therefore, we are confronted with the fundamental problem of how to ascertain that any numerical solution generated by a complex computer program is an accurate solution of our realistic physical phenomenon. Considering the theoretical aspect of the problem, it must be pointed out that closed-form analytic solutions are not available for checking the numerical results even for the most simple range-dependent environments. On the other hand, there are relatively few reports of down-slope sound propagation losses in the literature due to the experimental difficulties associated with sea measurements.

This paper discusses an off-shore Argentinian coast experiment performed during the fall of 1989 in a joint program with the AntiSubmarine Warfare squadron (ASW) of the Argentinian Navy. This experiment was designed as another step to provide a basis for propagation loss model evaluation. The present work, which is part of a long-term research program on sound propagation in shallow waters and nearby areas is believed to report the first quantitative information on the Argentinian Continental Slope underwater sound propagation.

2. EXPERIMENT AND DATA ANALYSIS

Measurements of down-slope propagation from shallow sources to a deep ocean buoy receiver were conducted using two TRACKER aircraft. Data were gathered along a 50 km track as shown in Fig. 1. One aircraft flew a prearranged track dropping 1.8 lb SUS (Signal Underwater Sound) MK 64 MOD 0 charges of TROTYL at range intervals of approximately 5 km. The average explosion depth was about 60 feet. The second aircraft remained in the area monitoring a hydrophone suspended from a deployed calibrated passive sonobuoy, at 60 feet below the sea surface. Fig. 2 schematically shows the source-receiver configuration.

The bathymetric and bathytermographic profiles, as well as the salinity values were measured from a ship, called Ocabalda. Fig. 3 shows the environmental data with the computed sound-speed profiles. Three distinct bathymetric regions characterize the experiment area: a 2.2 degrees slope (continental slope) between two essentially flat zones at a depth of approximately 120 m (continental shelf) and 1000 m (deep ocean). The geometric configuration gives rise to acoustic energy that is essentially bottom limited, since the explosives were detonated within the steep negative sound-speed gradient near the ocean surface. Geological sampling (Vozza, 1974) in the area has shown that the seabed is mainly fine sand.

A calibrated passive sonobuoy SSQ 57-A detected and amplified the shot arrivals to module a self-contained FM transmitter. The FM signals from the sonobuoy were transmitted to the associated sonobuoy receiver (R 1170/ARR 52 A) in the aircraft. The demodulated broadband signals from the receiver were recorded on a TEAC R 71 magnetic tape recorder.

At the laboratory, the acoustic signals were converted into digital data records through a general purpose analog to digital equipment (HP 1000 with 4 kHz-sampled data system) and processed with an "ad-hoc" written analysis software. Digital data plots were then generated, such as the ones shown in Fig. 4.

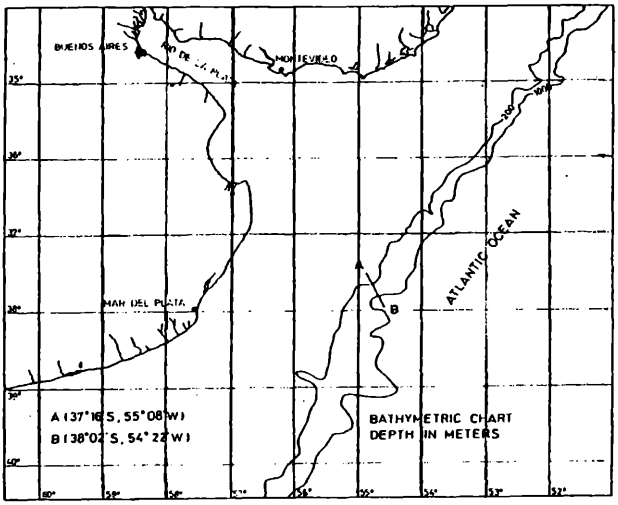

Figure 1. *Chart showing the track for the propagation experiment.*

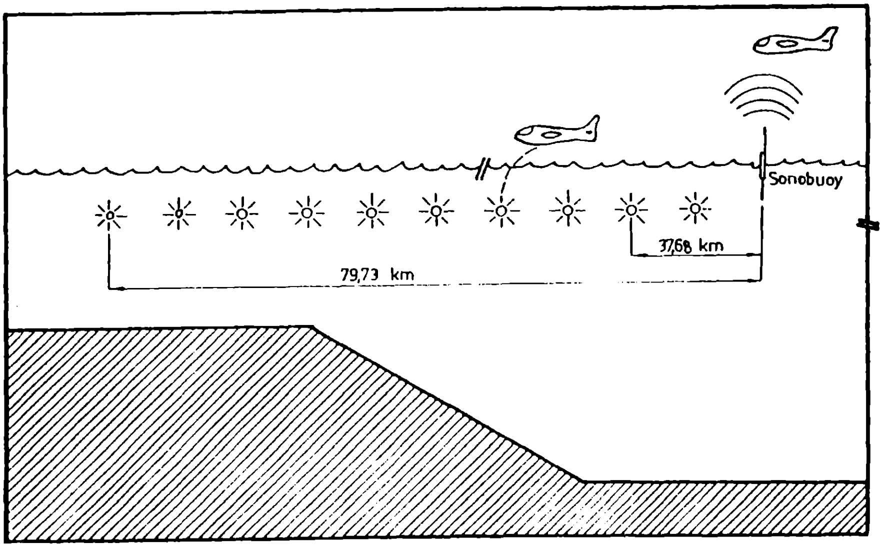

Figure 2. *Schematic source-receiver configuration.*

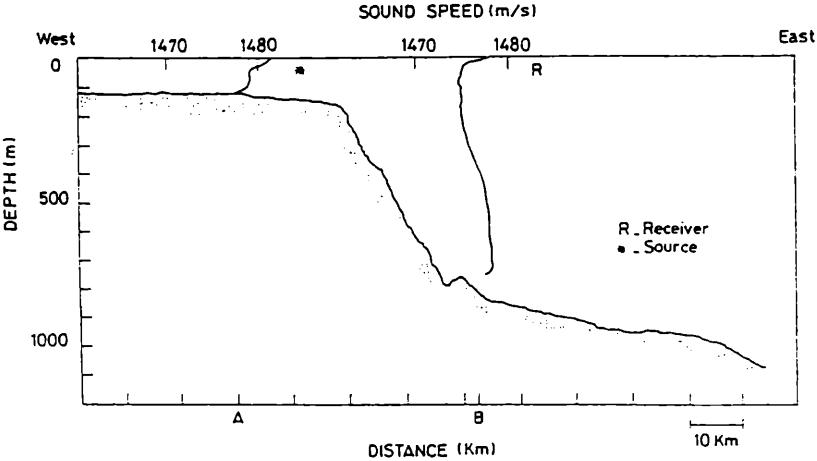

Figure 3. *Bathymetry and sound speed profiles.*

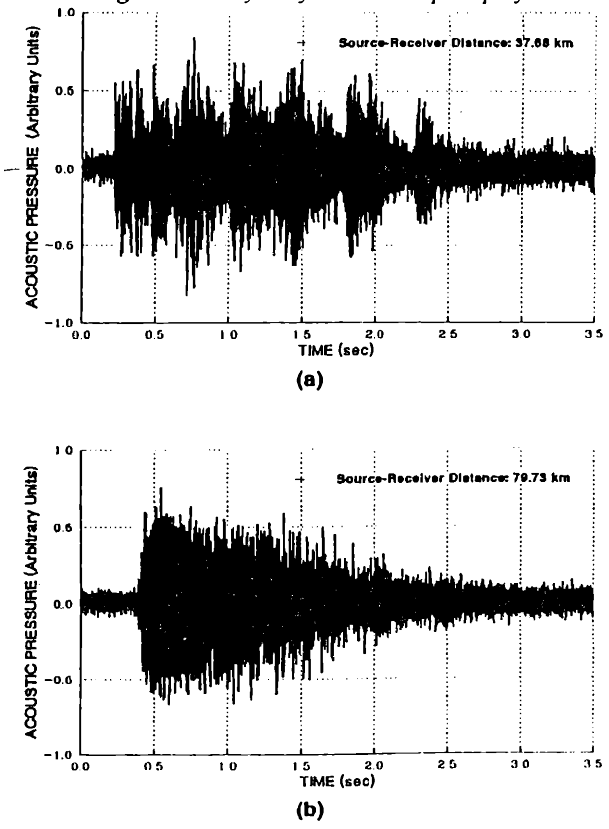

Figure 4. *Digitized broadband acoustic signals for the sonobuoy in deep waters and the explosive detonated: (a) in deep waters; (b) over the continental shelf.*

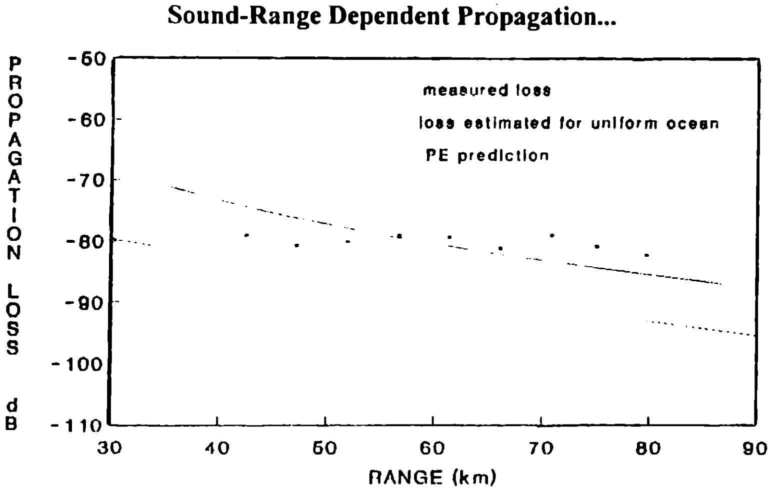

Figure 5. *Measured propagation loss (closed squares) and estimated loss for a range-independent oceanic environment, for 200 Hz. Comparison with PE method predictions.*

FFT transforms were computed, squared and averaged to provide estimates of the total acoustic energy in 1/3 octave bands from 100 Hz to 400 Hz. The Weston (Weston, 1960) data were used to determine source levels of SUS charges in the required 1/3 octave bands. The difference between the source level and the measured intensity level, for a given 1/3 octave band, was found for computing the propagation loss for each source (see Fig. 5).

No data is shown in Figs. 6, (a) and (b), neither for source-receiver distances less than 40 km nor for distances longer than 90 km, because it was previously checked that charges dropped inside approximately a 40 km range caused saturation of the hydrophone pre-amplifier receiver while charges dropped outside, approximately a 90 km range, were below the signal/noise threshold . This resulted in the discarding of data records outside the 40 km to 90 km range.

3. THEORETICAL BACKGROUND

The parabolic equation (PE) method has proved to be an efficient approach for solving underwater sound propagation problems in range-dependent environments because it replaces the reduced wave equation, which is a boundary value problem, with an initial value problem. Since the PE was first applied to underwater acoustics (Tappert, 1977), it has undergone extensive development including many improvements in accuracy (Lee, 1984).

A higher order PE code based on a Padé series was used for modeling the propagation loss measurements in this experiment. Variations with range in bottom density and attenuation, as well as in water and bottom sound speeds, were included following the procedure described by Collins, 1989. A brief review is made of the derivation of the PE, which has been numerically solved through standard techniques of finite differences to obtain computed propagation losses (directly connected with the acoustic pressure, Urick, Chap. II, 1983) for the experimental oceanic environment.

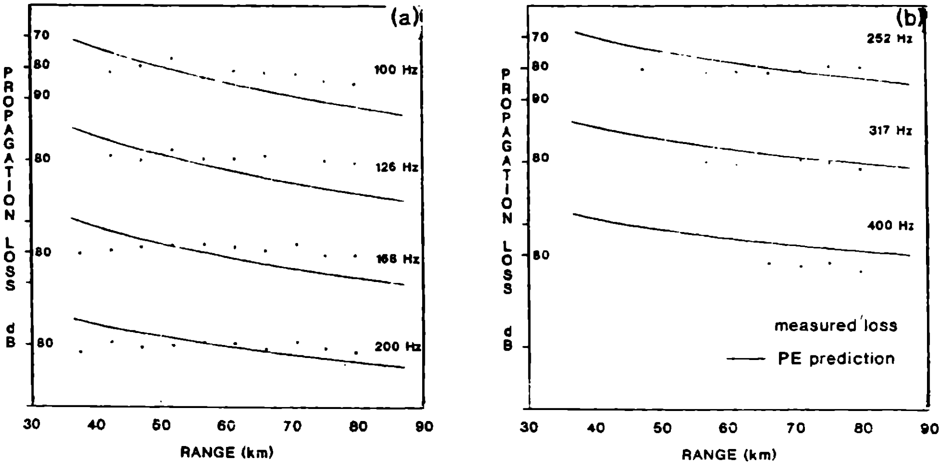

Figure 6. *Comparison of PE model results with measured propagation loss values for 1/3-octave-band between: (a) 100 Hz - 200 Hz, (b) 200 Hz - 400 Hz.*

When a time harmonic dependence is assumed for the acoustic pressure, it may be factored as

$$P(\vec{r},t) = P(\vec{r})\cdot e^{(-i\omega t)} \qquad (1)$$

where t is time, $\vec{r}$ is the Cartesian position vector, and ω is the circular frequency. The reduced wave equation that governs the propagation of sound in range-dependent oceanic environments is

$$\rho \quad \vec{\nabla}\cdot((1/\rho)\vec{\nabla}(P)) + k^2 \ P = -4\pi \quad \delta(\vec{r}-\vec{r}_0) \qquad (2)$$

where P is the acoustic pressure, point $\vec{r}_0$ is the source location; ρ is the water density; and k is the complex wave number. The acoustic complex pressure P is assumed to satisfy the pressure-release boundary condition $P=0$ at the sea surface and the outgoing radiation condition at infinity.

Under the assumption that azimuthal variations are negligible, Eq. (2) may be expressed in cylindrical coordinates as

$$\frac{\partial^2 \rho}{\partial z^2} - \frac{1}{\rho}\frac{\partial \rho}{\partial z}\frac{\partial P}{\partial z} + \frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} + k^2 \ P = -\frac{2}{r}\delta(r)\delta(z-z_0) \qquad (3)$$

with z being the depth below the sea surface and r being the horizontal distance from a source at depth . In Eq. (3), small variations of density with range have been assumed so that is ignored.

The parabolic approximation (PA) begins assuming the possibility of expressing the solutions of Eq.(3) as the product of two functions, that is

$$P(r,z) = r^{-1/2} \cdot Q(r,z) \tag{4}$$

where $Q(r,z)$ is weakly dependent on r. After some algebra, substitution of Eq.(4) into Eq.(3), applying the farfield approximation $k_0 >> 0$ and dropping terms $O(r^{-2})$, leads to

$$\frac{\partial Q}{\partial r} = i\, k_0\, (1+X)^{1/2}\, Q \tag{5}$$

$$X = \frac{1}{k_0^{\,2}}\left(k^2 - k_0^{\,2} + \frac{\partial^2}{\partial z^2} - \frac{1}{\rho}\frac{\partial \rho}{\partial z}\frac{\partial}{\partial z}\right) \tag{6}$$

with $k_0 = \omega/C_0$ where C_0 is a reference sound speed.
It must be pointed out that for range-independent domains the equation (1) factors exactly to equation (5). However, for range-dependent environments the differential parabolic equation (5) is an accurate approximation for the cases in which the range-dependence is smooth.

A family of Padé series is used. That is,

$$(1-X)^{1/2} - 1 = \sum_{j=1}^{n} \frac{a_{j,n}\, X}{1 + b_{j,n} X} + O(X^{2n+1}) \tag{7}$$

where n is the number of terms in the Padé expansion and the corresponding coefficients are given by

$$a_{j,n} = \frac{2}{2n+1} \sin^2\left(\frac{j\pi}{2n+1}\right) \tag{8}$$

$$b_{j,n} = \cos^2\left(\frac{j\pi}{2n+1}\right) \tag{9}$$

4. RESULTS AND DISCUSSION

Fig. 4 (a) shows 3.75 s of a recorded signal that has been digitized at a 4000 Hz sampling frequency , for an explosive source detonated in the deep ocean basin at a range of 37.68 km (Fig. 2). The ninth bottom reflected arrival, corresponding to deep water propagation, is distinctly identified in this broadband signal. As it is reasonable, it can be seen that the signals arriving after a large number of reflections reach the sonobuoy later, while time-intervals between two successive arrivals increase with the number of bottom interactions. The digitized signal shown in Fig. 4 (b) corresponds to an explosive source detonated at a range of 79.73 km (Fig. 2), in the continental shelf region, propagating over the continental slope till it is received at the sonobuoy. However, this broadband pressure signal seems to be a dispersed signal typical of shallow water propagation. That is in agreement with the 30 km of strong bottom interaction that takes place in shallow waters before the acoustic energy enters the deep ocean zone.

Fig.5 illustrates the advantage of modeling measured propagation loss in the experiment area, with a range-dependent propagation model, as the PE method, comparing with any traditional range-independent method. Following Dosso and Chapman (1987), the dashed curve shows the estimated losses due to geometrical spreading, attenuation in the water column and bottom interaction for a range-independent ocean over an assumed flat seabed of 880 m depth.

The sum of these three effects (Urick,1983) leads to propagation loss (or transmission loss, TL) given by

$$TL(r) = 10\log(r\,r_0) + 0.777 + \alpha\, r\; 10^{-3} + \alpha_b\, r\, 10^{-3} \qquad (10)$$

where the range r is expressed in meters; r_0 was taken to be 880 m; the logarithmic absorption coefficient α, was calculated to be 0.008 dB/km for a frequency of 200 Hz, according to the modified Thorp formula published in Urick, 1983. The bottom absorption coefficient, α_b, was estimated to be 0.173 dB/km by comparing the theoretical propagation loss due to the first two terms of Eq. (10) with the loss measured over the deep ocean basin out to about 37.68 km. This source-receiver distance was precisely selected as being the only range, among the detonation positions, corresponding to a whole propagation path in deep waters, and consequently, reasonably well predicted by (10). The excess loss for this range was assumed to be due to bottom interaction and the calculated value for α_b was used to compute the fourth term in (10).

From Fig. 5 it follows that the effects of bathymetry and spatial variability of sound speed profiles, included in the PE method used, should not be neglected when considering propagation through the experiment area. The estimated loss for an uniform ocean of 880 m depth exceeds significantly the measured values reaching a difference of approximately 10 dB for distances greater than 70 km. As it was expected, the curves predicted by the PE model show a better fit with the experimental data.

The data obtained for the whole experiment are shown in Fig. 6. The solid smoothed curves shown in Fig. 6 for 1/3 octave bands between 100 Hz and 400 Hz were computed by using a range-dependent PE calculation. The oceanic environment was represented by a twolayer model consisting of the water column over a sedimentary seabed, described as a viscoelastic solid (Blanc and Novarini, 1990). The measured bathymetric profile, shown in Fig. 3, was taken into account for the propagation loss computations. From the two measured speed profiles shown in Fig. 3, interpolated profiles were obtained to simulate a gradual range-dependence of the sound speed along the experimental track. For fine sand sediment, a compressional sound speed of 1798 m/s, a density of 2.008 g/cm^3 and a compressional wave attenuation of 0.89 db/λ in the bottom, were estimated from tabulated values (Baqués and Blanc, 1993).

The results presented in this paper provide an experimental evidence of the capability of the PE method to model sound propagation over the Argentinian Continental Slope, in the 100 Hz to 400 Hz frequency interval. As it can be seen in Fig. 6, the agreement between measured propagation loss values and PE predictions improves at low frequencies since for increasing frequencies, theoretical predictions underestimate experimental data. This feature is due to the limitations of the PE approximation. Moreover, for high frequencies a light better fit is observed at great ranges.

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