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INFLUENCE OF BOTTOM REFRACTIONS ON THE PROPAGATION OF UNDERWATER SOUND.

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RESUME

Des expériences [J. S. Hanna, J. Acoust. Soc. Am. 53, 1686 (1973); R. E. Christensen et al., J. Acoust. Soc. Am. 57, 1421 (1975)] faites sur la perte d'énergie du son sous-marin, se propageant sur un fond sédimentaire non-consolidé, ont demontré la présence d'énergie sonore refringée par le fond et retournée dans l'eau. Les champs sonores refringés se marquent ou par le temps d'arrivée d'impulsions sonores (indiquant des parcours refringés à travers du fond), ou par leurs interférences avec des signaux stationnaires correspondant seulement à des réfléchissements par le fond. L'interprétation théorique de ces expériences était faite jusqu'ici en forme d'éstimations basées sur l'étendue des rayons. Dans une etude antérieure [A. Nagl et al., J. Acoust. Soc. Am. 63, 739 (1978)] nous avons developpé un formalisme de modes normaux de la propagation du son sous-marin contenant de couches d'eau avec des gradients linéaires de vitesse du son. Ce formalisme a été généralisé ici en introduisant un fond contenant des couches sédimentaires non-consolidés avec des densités et gradients de vitesse du son différents, et nous obtenons de cette façon des champs sonores refringés par le fond et interférant avec des champs réfléchis. Les effets d'interférence peuvent être utilisés pour determiner la vitesse du son et son gradient dans les couches du fond. [Recherche assistee par l'Office of Naval Research].

SUMMARY

Experimental measurements [J. S. Hanna, J. Acoust. Soc. Am. 53, 1686 (1973); R. E. Christensen et al., J. Acoust. Soc. Am. 57, 1421 (1975)] of the transmission loss of underwater sound propagating over an ocean bottom containing unconsolidated sediments have presented evidence on the presence of bottom-refracted energy being returned into the water column. The bottom refractions manifest themselves either via their pulse arrival times (indicating bottom-refracted paths), or via their interference with steady-state transmission loss data attributable to bottom reflections alone. The theoretical interpretation of these experiments has so far been carried out in the form of transmission-loss estimates based on ray theory and ray spreading. In a previous study [A. Nagl et al., J. Acoust. Soc. Am. 63, 739 (1978)], we have devised a normal-mode program of underwater sound propagation containing water layers of linear velocity gradients. This program has been extended to a bottom containing unconsolidated sediment layers of different densities and velocity gradients, and shown to reproduce bottom-refracted fields interfering with reflected sound. The interference minima can be used to determine the sound speeds and their gradients in the bottom layers. [Supported by the Office of Naval Research].

Sound traveling from a transducer source (T) to a receiver (R), both submerged in the ocean, can normally take several different paths: a direct path TR, a path including an extra surface reflection (TSR), and three paths involving a reflection from the ocean bottom B (including no, one, and two extra reflections from the sea surface S, i.e., TBR, TBSR or TSBR, and TSBSR). If, however, the bottom consists of unconsolidated sediments (silt-clay surficial sediments[1]) which show a positive velocity gradient (and additionally, a surface sound velocity less than that in the water), refraction of sound occurs which can direct bottom-penetrating sound energy back into the water, hence establishing a fourth bottom-interacting path which involves bottom refraction. More recent experimental evidence for such bottom-penetrating signals has been discussed by Hanna[2] (on the basis of its interference with bottom-reflected sound), and by Christensen et al[3] (on the basis of the travel times of short sound pulses); earlier evidence for such bottom refractions is quoted in the mentioned publications[2,3]. The bottom refractions are stronger at lower frequencies and at shorter penetration depths, since less bottom absorption takes place in these cases. Hamilton[1] states that conditions for non-reflective bottom returns should exist over most deep-sea ocean floors, and in some shallow-water areas.

The mentioned study by Hanna[2] analyzes experimental transmission-loss data on the basis of a (plane-wave) bottom-reflection coefficient r(θ) which includes the bottom-refraction effects, and which is used to obtain a theoretical estimate of the transmission loss as a function of range up to about seven water depths (18 NM) that contains the effect of interferences between bottom-reflected and bottom-refracted paths. He showed that the location in range of these interference features, by comparison with experimental data, could provide information on the velocity gradient in the sediment and on the sound velocity ratio at the water-sediment interface, but not on the density ratio at the interface.

We here present a mode-theoretical study of the transmission loss through an ocean of intermediate depth with variable sound velocity, overlaying a sediment layer with a velocity gradient that lies on top of an isovelocity basement (Fig. 1a). The sound velocity variation in the water is chosen comparable to that of Hanna[2], as well as the 2% sound speed ratio at the surface of the sediment, and the sound speed gradient of $g = 2\ sec^{-1}$ ($1.5\ sec^{-1}$ for Hanna). Our water depth is chosen as 850m, and the frequency as f = 15 Hz (in order to keep the modes down to a manageable number of ten), the sediment depth as 125m (density $1.5\ gm/cm^3$), and the sound velocity in the basement as 1800 m/sec (density $1.8\ gm/cm^3$). The transmission loss calculated from this model is then compared with that corresponding to an isovelocity (c = 1500 m/sec) sediment which does not give rise to any backward-refracted energy (Fig. 1b). We find indeed a clear set of additional interference features in the transmission loss corresponding to a sediment with velocity gradient (Fig. 1a), which show a similar character to those in the transmission loss data that were analyzed by Hanna[2], and that can be interpreted as being caused by the interference between bottom-reflected and bottom-refracted sound.

Our normal-mode model is that developed by us earlier[4], but applied to a stratified geometry, and extended so as to include (fluid) bottom layers of densities constant within each layer, but differing from that of other layers. The depth-function modal solutions are given by Airy functions in each layer of variable sound speed.

Figure 2a shows the normalized modal depth functions Nos. 1-4 for the $g \neq 0$ case of Fig. 1a, and Fig. 2b the depth functions for the g = 0 case of Fig. 1b. The diminution of sound energy in the lower part of the sediment, due to back-refraction into the water by the gradient, is evident in Fig. 2a. In the following figures, we present our mode-theoretical calculation of transmission loss

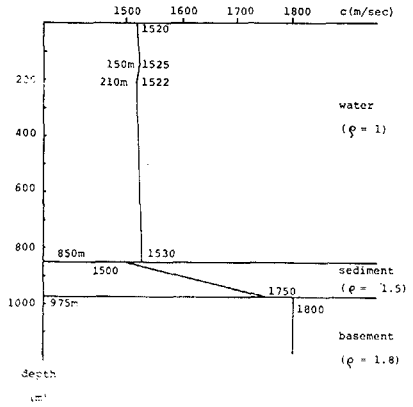

Fig. 1a

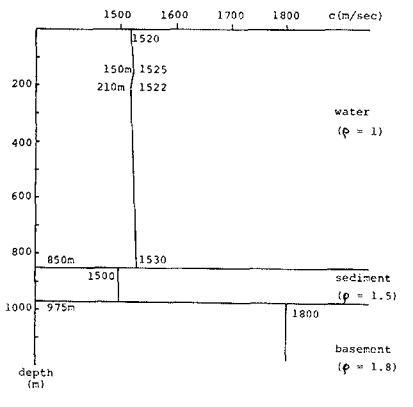

Fig. 1b

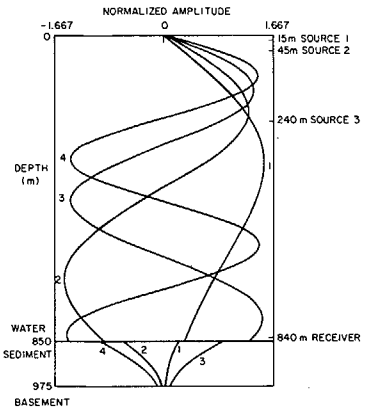

Fig. 2a

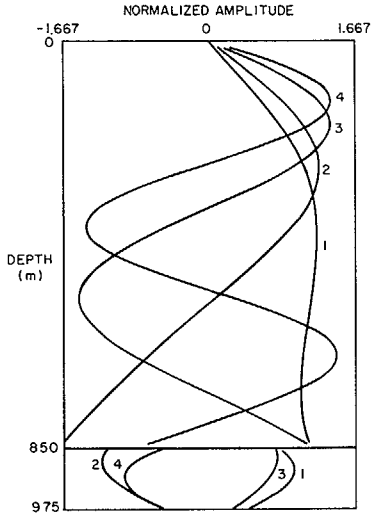

Fig. 2b

up to a range of 10.5 km: Fig. 3 corresponds to a source depth of 15m, and Fig. 4 to a source depth of 45m. In both cases, the receiver is placed on the bottom, as in Hanna's example[2]. Figures 3a and 4a correspond to the $g = 2\ sec^{-1}$ sound speed gradient in the sediment, and Figs. 3b and 4b correspond to $g = 0$.

Considering first Fig. 3b which only contains bottom reflections, we see a set of simple interference features which in the calculation stem from the modal interferences, but which may be physically interpreted by the interferences of rays along the different water-borne paths mentioned at the beginning (including the "Lloyd's Mirror" interference between the TR and TSR paths). Comparing to this the results of Fig. 3b for the case $g \neq 0$, we see that the bottom refraction which is present in this case has introduced an additional set of interference features which did not exist before, viz. those at ranges of 2.3 km, 5.9 km, and probably also at 10.1 km, and others. Comparing similarly the two corresponding figures, Fig. 4a and Fig. 4b for the 45-m source depth, similar features are visible including extra bottom-refraction interference minima at the same ranges. Another calculation carried out at a source depth of 240m showed less clear-cut results.

Hanna[2] has interpreted the extra interferences introduced by the bottom refractions in terms of the zeros of the bottom reflection coefficient $r(\theta)$ where θ is the grazing angle of an incident plane wave. He has shown that interference nulls should be located at grazing angles θ determined by the vanishing of the argument of the Airy function, i.e.,

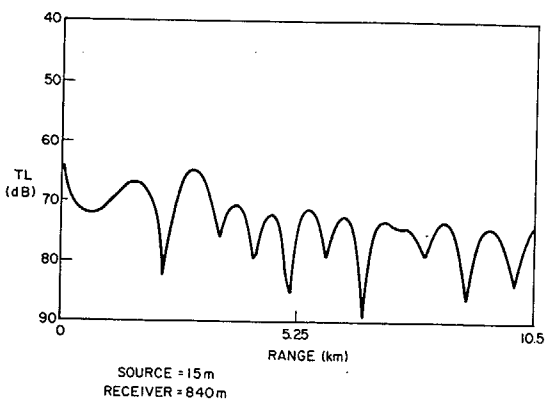

Fig. 3a

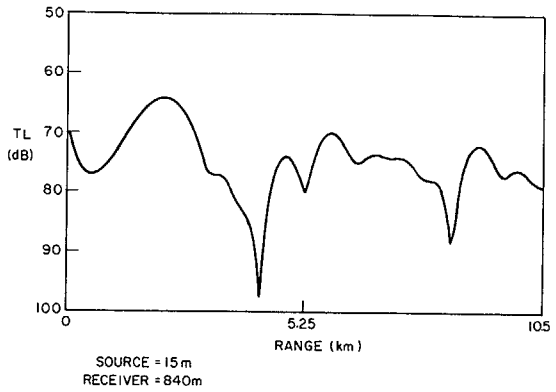

Fig. 3b

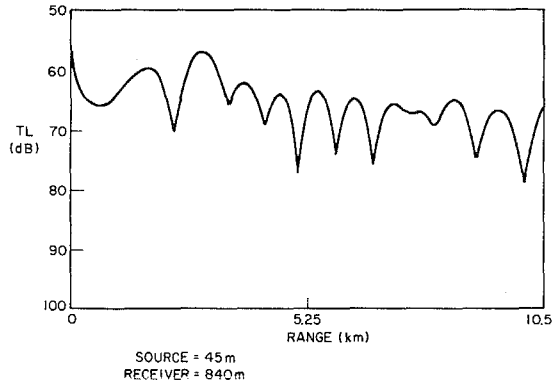

Fig. 4a

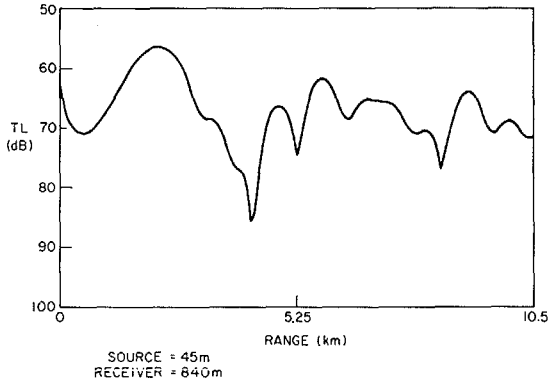

Fig. 4b

$$\cos\theta_i = \frac{c}{c_1}\left\{1 + a_i\left(\frac{g}{\pi f}\right)^{2/3}\right\}^{1/2}, \qquad (1)$$

where c and c_1 are the water and sediment sound velocities, respectively, at the water-sediment interface, and a_i the zeros of the Airy function. For our case, we find grazing angles θ_i = 30.55°, 43.70°, 54.17°...; a comparison with the bottom-refracted interference features of our calculation is being made.

References

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2. J. S. Hanna, "Short-range transmission loss and the evidence for bottom-refracted energy", J. Acoust. Soc. Amer. 53, 1686-1690 (1973).

3. R. E. Christensen, J. A. Frank, and W. H. Geddes, "Low-frequency propagation via shallow refracted paths through deep ocean unconsolidated sediments", J. Acoust. Soc. Amer. 57, 1421-1426 (1975).

4. A. Nagl, H. Überall, A. J. Haug, and G. L. Zarur, "Adiabatic mode theory of underwater sound propagation in a range-dependent environment", J. Acoust. Soc. Amer. 63, 739-749 (1978).