AD-A094 165 NAVAL OCEAN SYSTEMS CENTER SAN DIEGO CA F/G 20/1
UNDERWATER SOUND PROPAGATION PATHS BETWEEN PERTH, AUSTRALIA, AN--ETC(U)
AUG 80 J NORTHROP, C HARTDEGEN
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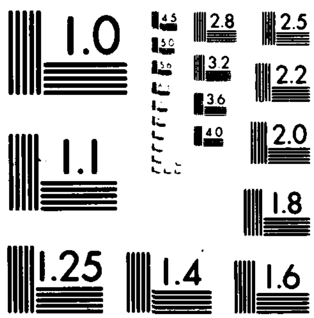

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UNDERWATER SOUND PROPAGATION PATHS BETWEEN PERTH, AUSTRALIA, AND BERMUDA: THEORY AND EXPERIMENT

J Northrop, NOSC
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AD A094165

August 1980

Interim Report: January — June 1980

Prepared for
USAF
Tactical Applications Center

Approved for public release; distribution unlimited

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ADMINISTRATIVE INFORMATION

This work pertains to the effective horizontal sound speed in long-range underwater sound propagation. The method includes ray-tracing techniques and compares results with previous field measurements along the 10694.8-mile path between Australia and Bermuda. Propagation loss predictions are also compared with measured values. The work was done under the NOSC contract with the Air Force Tactical Applications Center, Patrick Air Force Base, Florida, under the 1035 TCHOG Project authorization T/0158/0/NOSC. The work at the Bermuda SOFAR station, which is operated by the Palisades Geophysical Institute, is also supported by Office of Naval Research, Code 465K.

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ACKNOWLEDGEMENTS

This work was supported by the Air Force Tactical Applications center. Oceanographic data were obtained from NODC files by J.G. Colborn and data analyses were performed by P.G. Hansen of NOSC. The VEMA shots were fired by the Lamont-Doherty Geological Observatory of Columbia University, under the direction of Dr. John Nafe, and HMAS DIAMANTINA's by personnel of the Royal Australian Navy.

14 NOSC/TR-585

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NOSC Technical Report 585 (TR 585)

2. GOVT ACCESSION NO.: AD-A094165

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): UNDERWATER SOUND PROPAGATION PATHS BETWEEN PERTH, AUSTRALIA, AND BERMUDA: Theory and Experiment

5. TYPE OF REPORT & PERIOD COVERED: Interim Report, Jan[redacted]-Jun[redacted]980

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s):

J Northrop, Naval Ocean Systems Center
C Hartdegen, Palisades Geophysical Institute

8. CONTRACT OR GRANT NUMBER(s):

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Ocean Systems Center, San Diego, CA 92152

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: T/0158/0/NOSC

11. CONTROLLING OFFICE NAME AND ADDRESS: USAF Tactical Applications Center, Patrick AFB, FL

12. REPORT DATE: Aug[redacted]980

13. NUMBER OF PAGES: 11

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):

18. SUPPLEMENTARY NOTES:

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

Ray tracing
Sound-speed profile
Bathymetry
Explosive sound source

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

Oceanic great circle paths of nearly 180 deg of arc exist between the waters just west of Perth, Australia, and Bermuda. Archived sound-speed profiles at eight locations along this path were used, along with bathymetric data, as input to the RAYWAVE ray-tracing program to compute the effective horizontal sound speed and propagation loss over slightly different paths of 19,762.9 km and 19,806.8 km range. The sound speeds thus computed were 1480.9 ± 0.9 and 1479.8 ± 0.6 m/s, which compare favorably with the previously measured sound speeds (1484.7 ± 3.7 and 1481.48 ± 0.6 m/s, respectively). Propagation loss of 162 dB over this propagation path is effectively modeled by assuming spherical spreading out to a range of 10 nautical miles and semispherical spreading

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S/N 0102-LF-014-6601

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(15 log r) beyond, plus attenuation of 1.75 dB per 500 nautical miles. The RAYWAVE propagation loss prediction, after adjustment of the propagation path around Crozet Island, is 156 dB in the 10- to 50-Hz band.

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

Analysis of very-long-range propagation paths in high latitudes is pertinent to the detection and location of sounds originating in the Southern Ocean, where the surface waters are cold and, consequently, surface sound speeds are low and propagation is mostly in the RSR (Refracted/Surface Reflected) mode. At Bermuda, continuously refracted (RRR) rays are confined to the SOFAR (SOund Fixing And Ranging) channel. Although whales are said to utilize these high- to low-latitude propagation paths for communication, it has yet to be shown that reliable transmission paths exist. This paper shows that transmission half-way around the world can be modeled and reviews the results of earlier field tests. The purpose is to form a better understanding of the complicated process of sound transmission from high to low latitudes and to exercise the RAYWAVE program over very-long-range propagation paths.

PREVIOUS WORK

Underwater sound propagation in the Southern Ocean from South Africa to South Island, New Zealand, was well documented during one phase of Project Neptune by Kibblewhite et al. (Ref. 1). Further studies detailed propagation paths from South Africa and the southern Indian Ocean to Ascension Island and Fernando de Noronha in the South Atlantic (Ref. 2). Reception of various SOFAR shots east of Bermuda led M Ewing to believe that a 300-lb shot should be detectable out to a range of 10,000 miles* (Ref. 3). Shots fired by the R/V VEMA and HMAS DIAMANTINA off Perth, Australia, were received at Bermuda and Fernando de Noronha on SOFAR hydrophones (Ref. 4). These data are the basis for comparison with the RAYWAVE computations discussed in this report.

METHOD

Exact shot positions and travel times were supplied by the Bermuda SOFAR station and are shown in Table 1. Great circle paths between source and receiver were computed and plotted (Fig. 1) on a bathymetric chart (Ref. 5). Archival sound-speed data from National Ocean Data Center (NODC) files were searched for deep casts near the propagation paths at the season of the year (March) when the measurements were made. Table 2 shows the location of these casts and the dates they were made. These data were used as input to the ray-tracing computer program (Ref. 6) and results compared with the field data.

*All distances in nautical miles.

	Hydrophone Position		Shot Position				Effective Horizontal Sound Speed, m/s	
	Lat.	Long.	Lat.	Long.	Distance, km	Travel Time, hours, minutes, seconds	Observed	Computed
VEMA-Bermuda	32°11′ N	64°36′ W	33°36.3′ S	113°29.0′ E	19,762.98	3: 41: 18 3: 42: 24	1488.4 1481.0	1480.91 ± 0.9
DIAMANTINA-Bermuda	32°11′ N	64°36′ W	33°13′ S	113°43′ E	19,806.77	3: 43: 44 3: 45: 55	1482.09 1480.88	1479.8 ± 0.6
DIAMANTINA-Fernando de Noronha	3°56′ S	32°23′ W	33°13′ S	113°43′ E	14,549.28	2: 43: 43 ± 1 min 2: 43: 54 ± 1 min		

Table 1. Hydrophone and shot positions, travel times, distances, and measured and computed sound speeds for the Perth, Australia, to Bermuda and Fernando de Noronha propagation paths.

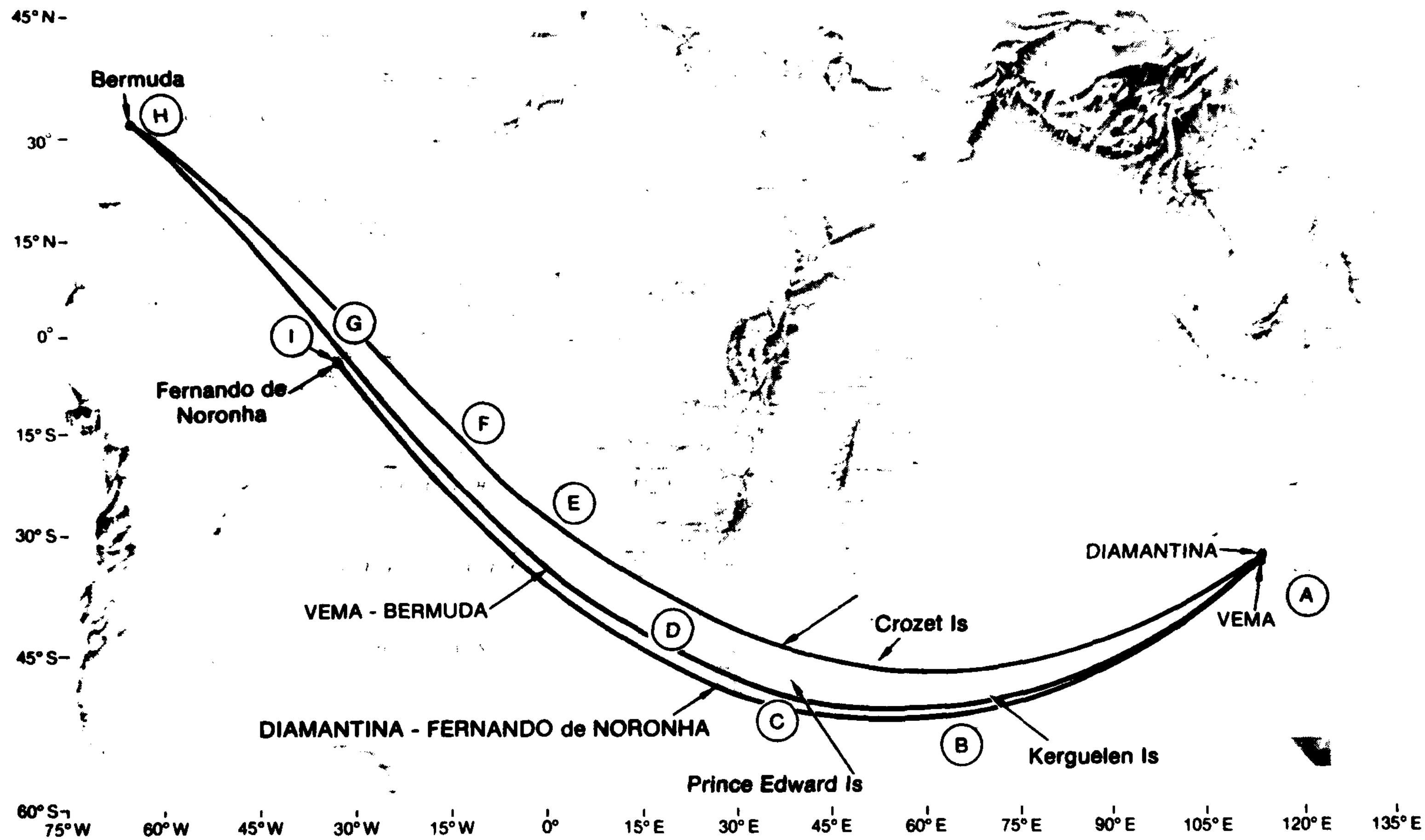

Figure 1. Bathymetric chart showing the great circle propagation paths from Australia to Bermuda and Fernando de Noronha. Letter symbols along the path are locations of sound-speed profiles used in the ray-trace computations.

PROFILE	LATITUDE	LONGITUDE	MONTH	DAY	YEAR
A	40°05′ S	120°07′ E	MAR	3	1960
B	54°0′ S	63°13′ E	FEB	4	1969
C	51°55′ S	35°42′ E	MAR	4	1963
D	43°18′ S	16°02′ E	NOV	9	1957
E	26°03′ S	8°01′ E	APR	4	1961
F	11°30′ S	11°56′ W	SEP	21	1963
G	5°59′ N	30°06′ W	MAR	6	1963
H	32°19′ N	64°12′ W	FEB	13	1959

Table 2. Positions and dates of the sound-speed profiles used in the RAYWAVE program.

PROPAGATION

The shooting location off Perth, Australia, (Fig. 1) is north of the subtropical convergence. The travel paths from there to the Atlantic cross the Antarctic convergence near the Kerguelen Islands at lat. 50° S. At these and higher latitudes, the deep-ocean SOFAR channel ceases to exist south of the Antarctic convergence, and all propagation paths are RSR. West of the Kerguelens, the propagation path leaves the region of the Antarctic convergence, crosses the subtropical convergence again, and passes into the south Atlantic gyre, where the SOFAR channel is present with the axis depth near 1000 m (Ref. 7). The path passes northwest from there, and RRR propagation persists to Bermuda.

SOUND VELOCITIES

At the source location off Perth, there is a surface duct with a layer depth of 200 m and sound speed of 1507.0 m/s. There is a pronounced SOFAR channel with a minimum sound speed of 1483.5 m/s at 1200 m depth (curve A of Fig. 2). Where the Antarctic convergence is encountered along the path, at 52° S, the surface sound speed is reduced dramatically to 1463.0 m/s, and there is only a 30-m surface duct (curve B of Fig. 2). There is a shallow sound channel at 200 m depth with a sound speed of 1454.8 m/s. Below that the sound speed increases, and there is no deep sound channel.

Westward along the track in the Southern Ocean, the surface sound speeds are near 1457.0 m/s, and the secondary sound channel has sound speeds as low as 1452.5 m/s at 200 m depth (curve C of Fig. 2). The great circle track then curves northward, and a profile at 43° S, 16° E reverts back to the classic SOFAR channel type, with a pronounced minimum of 1477 m/s at 800 m depth (curve D of Fig. 2).

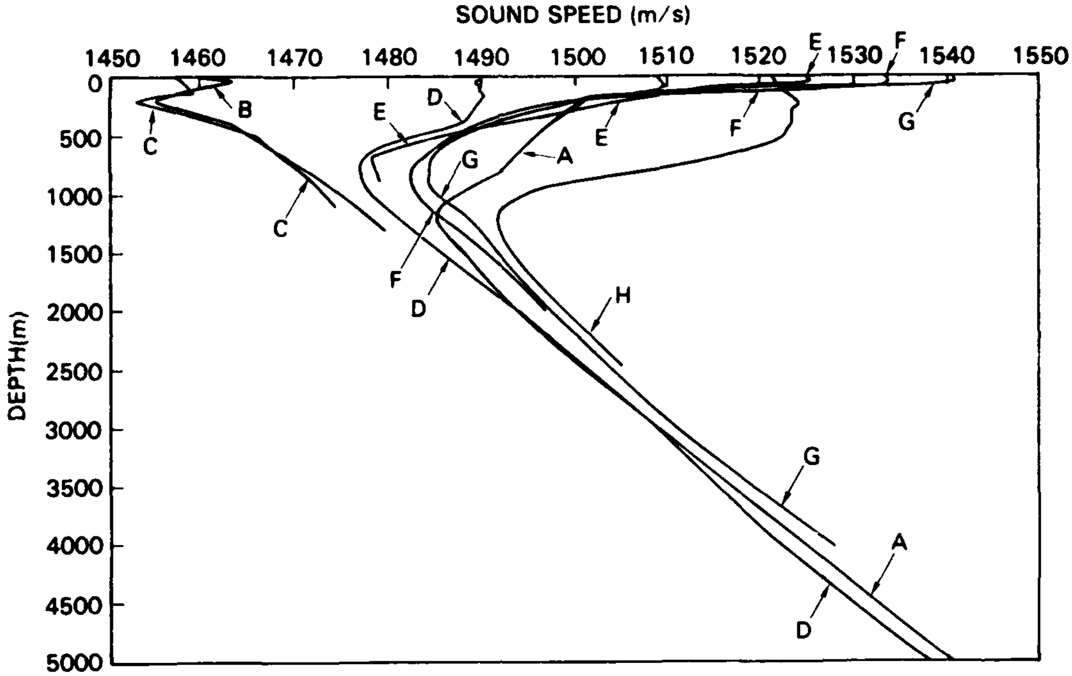

Figure 2. Sound-speed profiles used in the ray-trace computations. For position of profiles along the track, see Figure 1.

In the South Atlantic (curve E of Fig. 2) the surface sound speeds rapidly increase to 1524.6 m/s at 28°31′ S. (See Table 1 for actual positions of the casts.) The SOFAR channel also becomes deeper (about 900 m) and has an axial sound speed of 1479.2 m/s (curve E of Fig. 2). Further on along the track, near the latitude of Fernando de Noronha (curve F of Fig. 2), the surface sound speed increases to 1533 m/s, making the SOFAR channel symmetrical.

In the equatorial zone, a typical sound-speed profile for March shows a surface sound speed of 1540.5 m/s and an axial sound speed of 1484.3 m/s at 900 m (curve G of Fig. 2).

Near Bermuda (curve H of Fig. 2), at the most distant hydrophone site, the SOFAR channel becomes even more symmetrical, the axial sound speed increases to 1491.5 m/s, and the axis depth increases to 1200 m. Minimum sound speeds along the track thus vary from a low of 1452.2 m/s off Antarctica to a high of 1491.5 m/s.

BATHYMETRY

The deep basin west of Perth, where the shots were detonated, is about 3000 fm (5486.4 m) deep (Fig. 1). West of that, the Southeast Indian Ridge is encountered with depths less than 2000 fm (3657.6 m). Southwesterly along the propagation path from there, deep water is again encountered before the shoals near Kerguelen Island and Crozet Island are crossed near the 100-fm (182.88-m) curve.

West of the Crozet swell, shoals around the Prince Edward Islands are crossed before the deep Agulhas basin is reached. The path then passes through the choke point between the Cape of Good Hope and the Schmitt-Ott Ridge, where depths of 500 fm (914.4 m) are charted.

The propagation path enters the South Atlantic via the deep Cape Basin and crosses the shallow 400-fm (731.52-m) Walvis Ridge before reaching the Angola Basin. The Mid-Atlantic Ridge is then crossed twice before the hydrophones at Bermuda are reached. These shallow areas block the steeper rays and reduce the duration of the received signal (Ref. 2).

RESULTS

FIELD DATA

Six 200-lb shots were dropped from the R/V VEMA on 1 March 1960 at the position shown in Fig. 1 and Table 1. These shots were received only on the hydrophones near Bermuda. Travel times varied from 3 hours, 41 minutes, 18 seconds to 3 hours, 42 minutes, 24 seconds*, giving effective horizontal sound speeds of 1488.4 and 1481.0 m/s, respectively.

On 21 March 1960, the HMAS DIAMANTINA fired three 300-lb Amatol shots at the position shown in Fig. 1 and Table 1. These were clearly received both at Fernando de Noronha and at Bermuda. All these shots used inaccurate pressure detonators, which fired between 400 and 1000 fm (731.52 m and 1828.804 m). The travel times to Bermuda varied from 3 hours, 42 minutes, 44 seconds to 3 hours, 42 minutes, 55 seconds, giving effective horizontal velocities of 1482.09 and 1480.88 m/s. In November, 1962, 14 depth

*In the original report of this work (Ref. 4) the travel time was incorrectly given as 144 minutes.

charges were detonated off Perth, Australia, by the Scripps Institution of Oceanography Research Vessel ARGO. These data are not presently available.

At Fernando de Noronha, the DIAMANTINA shots were well received, but the timing was suspected of being 1 minute off. Therefore, those travel times will not be discussed further in this paper.

All the hydrophones involved had a peak frequency response at 150 Hz and a fall-off of 6 dB/octave on either side. The Bermuda hydrophones were suspended in the SOFAR axis (1320 m). The Noronha phones were on the bottom at 824 m depth.

RAY-TRACE COMPUTATIONS

In the RAYWAVE computations, 8 sound-speed profiles and 45 bottom-depth points were used. The program traces rays ranging from -59 to +59 deg in increments of 0.25 deg for 0-10 deg, 0.5 deg for 10-25 deg, 1 deg for 25-35 deg, and 1.5 deg for 35-59 deg for a total of 364 rays. Rays are traced from the receiver, so that only the eigenrays are actually traced. Up to five bottom reflection loss arrays are allowed in the program, but only one was used because propagation loss values are of only secondary importance in this report and, additionally, there is not much bottom loss data available for the southern part of the propagation path. The bottom loss values for 40 Hz were 5 to 30 dB linearly interpolated between grazing angles of 0 to 90 deg.

Using these computations for the great circle distance of 10671.16 miles (19,762.98 km) and 10694.80 miles (19806.77 km), respectively, for the VEMA and DIAMANTINA shots received at Bermuda, effective horizontal sound speeds of 1480.91 ± 0.9 and 1479.8 ± 0.6 m/s, respectively, were calculated. Ray arrival analysis showed that most of the received energy was in the ray bundles -5.5 deg and 5.75 deg (Fig. 3).

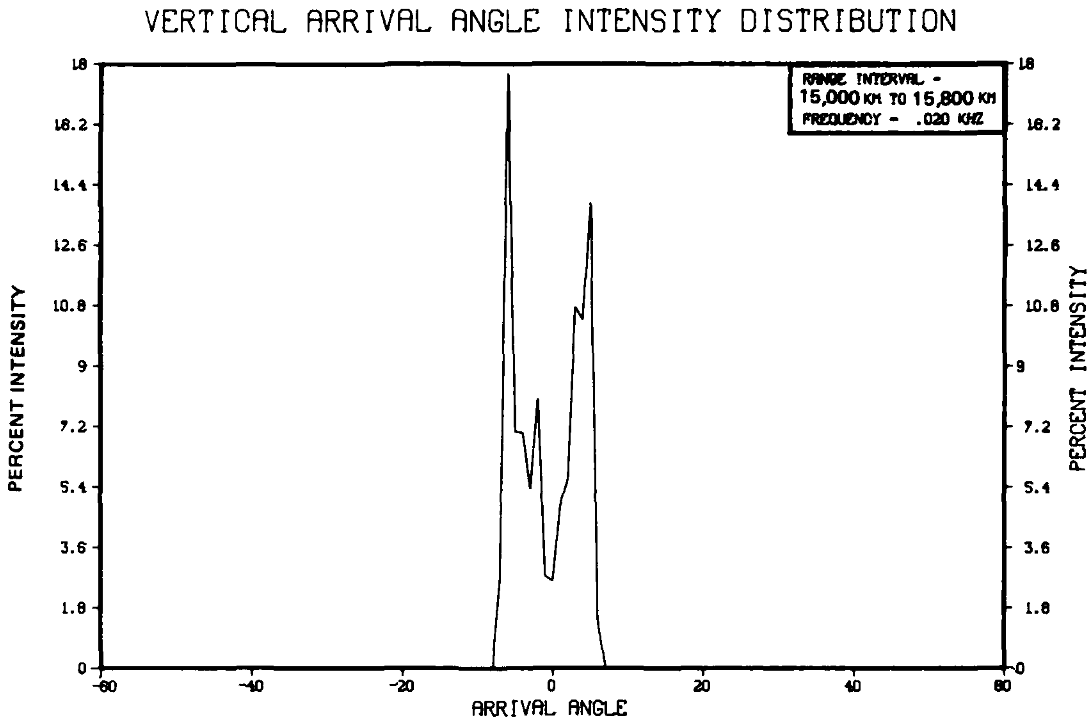

Figure 3. Ray arrival plot for the VEMA-Bermuda path.

PROPAGATION LOSS

Measurement

Measured propagation loss is difficult to assess because the signal levels received were not measured relative to an absolute reference, S/N ratios being deemed sufficient. If it is assumed that the noise level was 91 dB re 1 μPa and the S/N ratio was 3 dB, we can make a rough estimate of 94 dB re 1 μPa for the received level. Once the source level is known, propagation loss can be computed by subtracting the received level from the source level.

Although no source level measurements were made aboard ship, we assume that there were no partial detonations and the effective charge was 200 lb TNT. Since most of the energy received was below 50 Hz, we calculate the source level of a 200-lb shot in that frequency band by the following equation (Ref. 8):

$$I_o(F_L \text{ to } F_U) = I_o + 10\log\left[\frac{2}{\pi}\left(\arctan\frac{F_U}{f'} - \arctan\frac{F_L}{f'}\right)\right] \qquad (1)$$

where I_o is the source strength (or source intensity) in dB re 1 μPa at zero frequency, F_L and F_U are the lower and upper limits, respectively, of the frequency band of interest, and f' is the half-power frequency at the range where P = 100 psi, i.e.,

$$f' = \frac{1}{2\pi\theta'} = 1.13 \times 10^3\, W^{-1/3}\ \text{Hz} \tag{2}$$

where θ' is the time constant of the shock wave at this range and W the charge weight (lb):

$$\theta' = 1.41 \times 10^{-4}\, W^{1/3} \tag{3}$$

By means of these relationships, together with the curve for I_o (Fig. 4), a source level of 256 dB re 1 μPa at 1 yard is calculated for a 200-lb charge in the frequency band 10 to 50 Hz.

The observed propagation loss is then the difference between this value and the received level, or 162 dB.

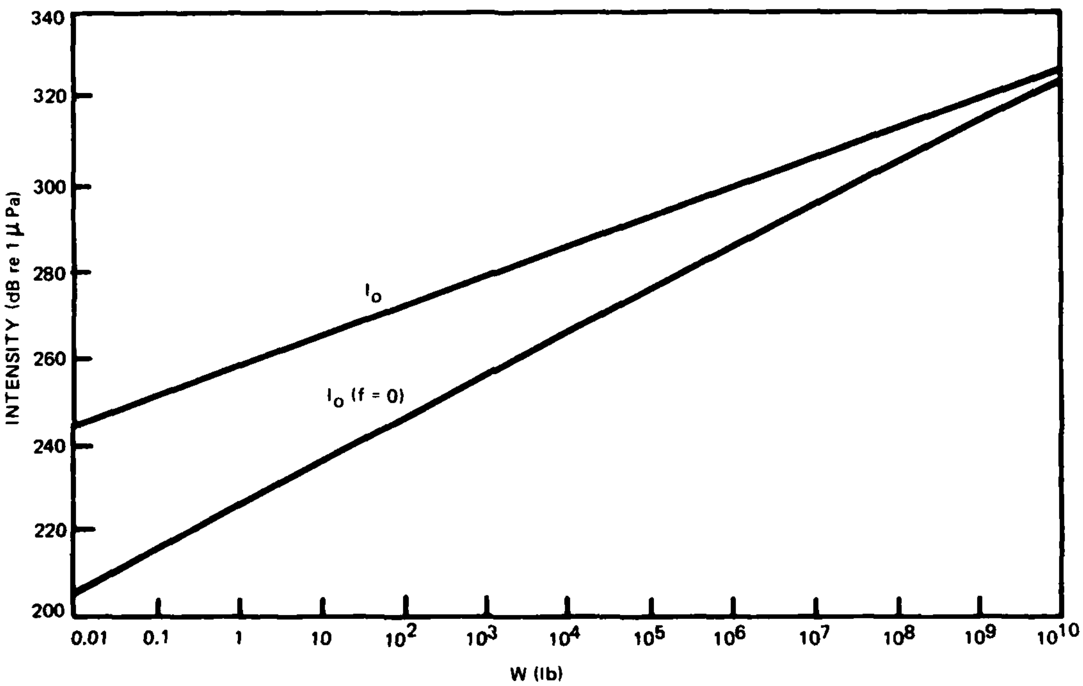

Figure 4. Plot of zero-frequency intensity vs charge weight for various size charges (from Ref. 8).

Predictions

Although simple geometric formulas are inadequate for modeling propagation loss over the very long ranges considered here, it is instructive to compare existing models. For example, RAYWAVE, when run for the DIAMANTINA-Bermuda path, predicted excessive propagation loss and almost complete blocking of the path at the 100-fm curve off Crozet Island (Fig. 1). Because the exact position of this island group is somewhat in doubt (Ref. 9), and the great circle track plotted in Fig. 1 may be less than perfect (because the ellipticity of the earth is not accounted for in calculating the great circle route), the path was adjusted *slightly* so that it crossed the 500-fm curve instead of the 100-fm curve south of Crozet Island. This computation gave a propagation loss of 140 dB at 40 Hz. In converting to the 10- to 50-Hz band, a loss of 156 dB is predicted.

A simpler computation for propagation loss (from Ref. 3), is

$$PL = 20 \text{ Log } R + \alpha R \tag{4}$$

where R is in yards and α is the attenuation coefficient. Using 1.6 dB per megayard* for α (Ref. 10), a loss of 178 dB is predicted.

Another method of predicting propagation loss assumes an inverse cube decay of intensity with range and ignores frequency attenuation (Ref. 2). This calculation gives 221 dB predicted loss over the Perth-to-Bermuda path.

A more appropriate loss prediction assumes spherical spreading out to 10 miles and semispherical spreading (15 log r) beyond, plus attenuation (Ref. 8). This formula gives a predicted loss of 165 dB, with r in nautical miles, and an attenuation of 1.75 dB per 500 nautical miles.

SUMMARY AND CONCLUSIONS

Both measured and computed travel times for underwater sound propagation over a distance of 19806 km (10694.38 miles) were determined for the Perth, Australia, to Bermuda transit. This travel path, involving propagation through the tropical and subtropical convergence as well as the Antarctic convergence, encompasses a distance of about halfway around the world (178.2 deg of arc) and is one of the few all-water tracks over which such very long ranges are possible. The calculated effective horizontal sound speeds were slightly lower than the observed sound speeds. Propagation loss was consistent with semispherical spreading beyond 10 miles and attenuation of 1.75 dB per megayard.

Shot positions for signal reception at antipodal stations are extremely critical. For example, the DIAMANTINA was only 27 miles from the VEMA position, yet reception at Fernando de Noronha was achieved for the former but not the latter. As shown in Fig. 1, the travel path for the DIAMANTINA shots to Bermuda passed north of the Kerguelen Islands and between Crozet and Prince Edward Islands, whereas the VEMA-to-Bermuda and DIAMANTINA-to-Fernando paths were south of all three of these islands.

RECOMMENDATIONS FOR FUTURE WORK

Travel paths to the antipodal point on a sphere should, theoretically, begin to converge after the first 90 deg of arc. The possibility of this horizontal convergence contributing to the strength of the observed signal may account, in part, for its reception after passing over such shallow areas as the Kerguelen Ridge, the shoals between Crozet Island and Prince Edward Islands in the Southern Ocean, and the Walvis Ridge and the Mid-Atlantic Ridge in the Atlantic. A two-dimensional ray-tracing program that allows for vertical and horizontal refraction in addition to geometric convergence should be developed to test the 180-deg convergence phenomenon. The program should also account for horizontal refraction around islands, such as Crozet Island, in the DIAMANTINA-to-Bermuda path shown here and correct for the ellipticity of the earth.

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*1 megayard = 500 nautical miles.

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