WIGWAM REVERBERATION REVISITED

Brian Dushaw[a]

[a]Nansen Environmental and Remote Sensing Center, Thormøhlens gate 47, 5006 Bergen, NORWAY

Brian Dushaw, Nansen Environmental and Remote Sensing Center, Thormøhlens gate 47, 5006 Bergen, NORWAY fax: (+47) 55 20 58 01, e-mail: brian.dushaw@nersc.no

Abstract: *Operation WIGWAM was a test of a 30 kt nuclear depth charge conducted in deep water 500 miles southwest of San Diego on 14 May 1955. Its primary purpose was to determine the effectiveness of that device as an antisubmarine weapon. The acoustic pulse from the test, initially an intense shockwave, radiated throughout the North and South Pacific Oceans. Acoustic reflections from topographic features were recorded for several hours after the explosion by SOund Fixing And Ranging (SOFAR) hydrophones at Point Sur, California, and Kaneohe, Hawaii. Sheehy and Halley (1957) identified peaks of the recorded coda with reflections from specific topographic features at great distances (e.g., the Hawaiian Islands, French Polynesia, or Fiji). With modern data for seafloor topography and ocean sound speed, these coda were computed with surprising accuracy using simple geodesic rays reflected from islands and seamounts. The intensity variations of the coda are mostly determined by simple ray geometry, together with modest attenuation. Coda peaks are often obtained from rays arriving simultaneously from multiple, but disparate, topographic features.*

Keywords: *WIGWAM, atomic testing, long-range acoustic propagation, basin-scale acoustics*

1. INTRODUCTION

I first learned of the WIGWAM atomic test and its associated acoustic signals through Walter Munk soon after my arrival as a student at the Scripps Institution of Oceanography in 1987. Munk had been involved with the test. He was aware of the work that Sheehy and Halley [1] had done in 1957 on the hours-long acoustic coda of WIGWAM sound recorded at California and Hawaii [2]. Sheehy and Halley had identified the features in the coda as reflections from particular topographic features. In the late 1980s, Munk was working on a new analysis of the 1960 antipodal Perth-Bermuda acoustic test [3], and he was contemplating antipodal-scale acoustic propagation as a possible measure of the large-scale ocean climate. On seeing the Sheehy and Halley identifications, and those times since that I was reminded of that analysis, I had a sense of skepticism that such identifications were possible with any reliability. This paper summarizes a recent computation of the WIGWAM coda giving an updated identification of their peaks [4]. The reader is referred to the more complete analysis published in the *Bulletin of the Seismological Society of America* in 2015 [4] for further details; the short answer is Sheehy and Halley were mostly correct.

In retrospect, the motivations for this new analysis were threefold. First, a desire to resolve my long-standing skepticism regarding the Sheehy and Halley identifications. Second, after a decade or more of work on basin- and antipodal-scale acoustic thermometry [5, 6], I had at my disposal well-developed, global databases for ocean sea-floor topography, sound speed fields, together with handy code for manipulating these data and extracting sections of interest. In addition, the work on acoustic thermometry had highlighted the extraordinary stability of ocean sound speed: even at basin scales the oceanographic contributions to variations in travel time are less than 0.5 s over decades. Third, on being reminded yet again of the Sheehy and Halley result in late 2014, it occurred to me the problem was likely tractable by simple geodesics, that is, one likely did not have to implement actual computations of acoustic propagation. I could resolve my long-standing suspicions with only a couple of afternoon’s worth of work! (It took longer.)

2. THE GEODESIC HYPOTHESIS

As noted by Munk et al. [3], for very long range acoustic propagation, to first order one can just consider the sound propagating along the sound channel axis. The essential reason for this approximation is that the acoustic intensity is maintained for near-axis sound propagation. Deep-traveling sound disperses in time, making the final crescendo of an acoustic arrival pattern many decibels greater than the early part of the pattern. In other words, most of the acoustic energy is carried by the low order modes, which are confined near the sound channel axis. In addition, the horizontal refraction of such propagation is of no practical consequence in most regions of the Pacific [7]. (Horizontal refraction is essential for understanding the propagation of sound from Perth, Australia to Bermuda [3, 6], but that propagation entails interactions with the powerful Circumpolar Current, Agulhas Rings, and so forth.) The assumption that the acoustic propagation consists of sound following geodesic paths along the sound channel axis is straightforward.

The essential hypothesis on which this new analysis was based is that the recorded coda could be reproduced by (1) computing a dense fan of simple geodesics from the location of the WIGWAM shot, (2) determining where those geodesics intersect the sea floor at the depth of the sound channel axis (Fig.1), and (3) computing geodesics from those intersection points back to the location of the California or Hawaiian hydrophones (Fig.2). The WGS84 ellipsoid was used for the computations. The amplitudes of the coda could be determined by ray density, and the travel times could be determined from the range along the geodesic path and the average of sound speed at the depth of the sound channel axis. The required precision of the travel time computations was quite low, since only a digital scan of the coda reported by Sheehy and Halley [1] is available as data. A pixel size of the scan corresponded to 30 s of travel time; the entire coda recorded at California extended 4 hours.

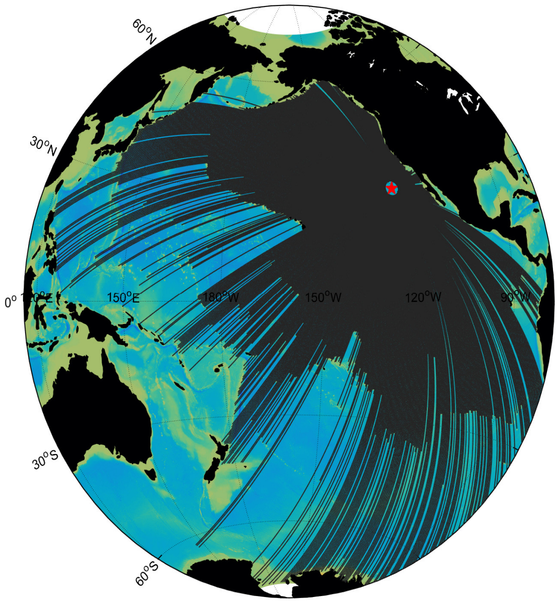

Fig. 1: Location of the WIGWAM shot and subsequent acoustic illuimination of the North and South Pacific Basins. The geodesic paths terminate at topographic features. From the termination points, geodesic paths are then computed to the hydrophone locations. Reprinted by permission from [4] © Seismological Society of America.

3. ADJUSTMENTS

The simple geodesic model worked well at reproducing the recorded arrival coda (Fig.2), but two corrections were required. First, no acoustic reflections were obtained around the half-hour mark. These reflections correspond to interactions with deep seamounts in the Eastern North Pacific, which lie well below the sound channel axis. To account for these interactions, a second set of geodesics were computed to topographic points at 1500 m depth. These deep interactions generated the arrivals around the half-hour mark of the coda. Second, the predicted amplitudes of the later arrivals were too large. The amplitudes in general were computed from ray density, with the number of rays arriving in a given time interval proportional to amplitude. This number was computed on a log scale, and then scaled in an ad hoc fashion to give amplitudes similar to the measurements. A single scaling factor was used to account for the entire coda. The amplitudes of the latter parts of the computed arrival were too large because sound attenuation had been omitted. By including a nominal attenuation for low-frequency acoustic propagation, the computed and measured coda agreed fairly well.

While it would be reasonable to implement a more realistic scheme such as computing the propagation paths of acoustic modes, accounting for horizontal refraction, etc., the decision was made early on to keep the analysis as simple as possible. The essential point of this analysis was that the recorded coda were mainly a product of simple geometry, rather than a product of the details of acoustic propagation. Indeed, the greatest unknown in this analysis is the precise mechanisms governing the acoustic interaction with the sea floor, leading to the reflected energy. Further, as reported by Sheehy and Halley [1], the recorded acoustic frequencies were broadband and centered on 40 Hz (see [6] for an explanation). At these frequencies mode coupling is important, so even the assumption that the acoustic propagation is dominated by the lowest few modes is not correct [6]. It made little sense to implement a complex analysis of acoustic propagation, given the unknown properties of the bottom interaction (what are the effects of the local slopes, focussing by geometry of the isobaths, specific geophysical properties of the sea floor, etc.?) and other complications.

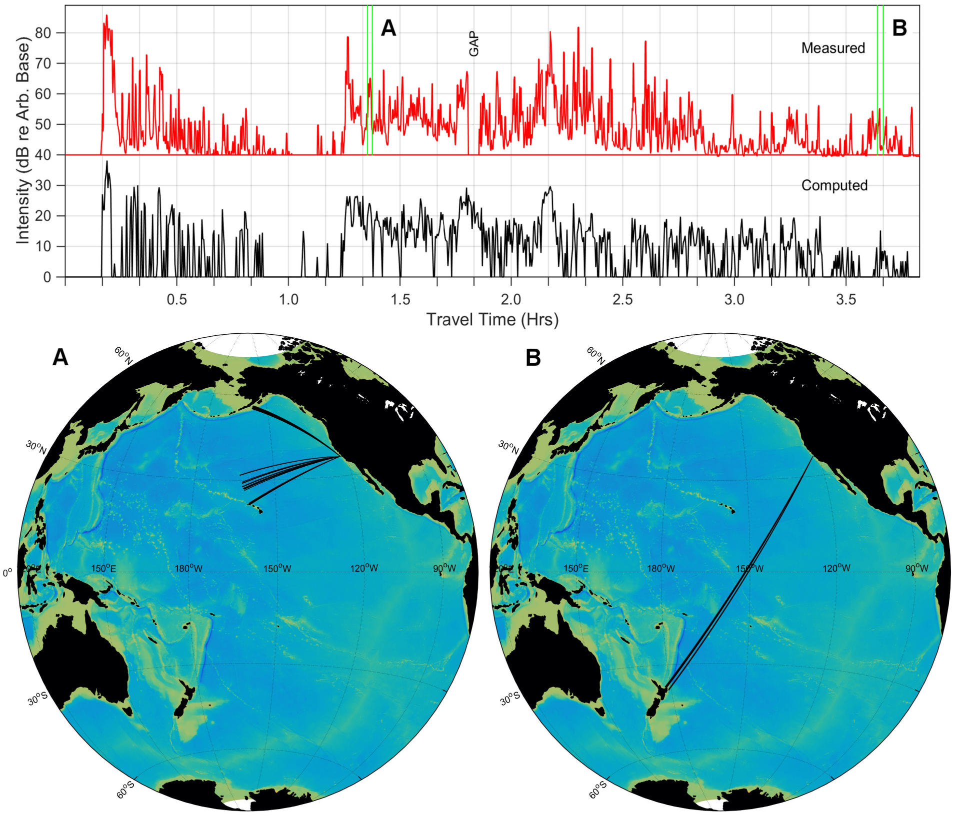

Fig. 2: The coda computed from the simple model (black line, top panel) agrees remarkably well with the measured coda (red line, top panel). Features or peaks of the coda, such as A, often corresponded to coincident arrivals at California from disparate reflection points. Near the end of the coda, peak B corresponded to a reflection from the north coast of New Zealand, though Sheehy and Halley originally identified this peak as a reflection from Okinawa. Reprinted by permission from [4] © Seismological Society of America.

4. DISCUSSION

The analysis was motivated by a long-standing skepticism concerning the original Sheehy and Halley analysis. It is likely their identifications of acoustic peaks with topographic features relied on great circle computations of a few selected peaks. The subsequent decades-long experience with basin-scale acoustics and ready access to high-quality databases for the sea floor and ocean sound speed justified this new, simple computation.

The identifications of Sheehy and Halley proved to be mostly correct. The new analysis showed that some of the recorded peaks arose from coincident arrivals from disparate reflections. Sheehy and Halley identified a late arrival peak as coming from a reflection from Okinawa, but that peak was from the north coast of New Zealand. Indeed, reflections from Okinawa were not possible, being blocked by other topographic features.

Given the success of this simple model at reproducing the observations, it is likely a somewhat better, perhaps more rigorous, model would be able to reproduce even the details of the observations. Having access to the original data would be useful, but initial attempts to located the data for the coda at the Marine Physical Laboratory in San Diego proved unsuccessful.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] **Sheehy, M. J., and R. Halley,** Measurement of the attenuation of low-frequency underwater sound, *J. Acoust. Soc. Am.,* **29**, pp. 464–469, 1957.

[2] **Munk, W. H., and F. Zachariasen,** Refraction of sound by islands and seamounts, *J. Atmos. Ocean. Tech.*, **8**, pp. 554–574, 1991. doi: 10.1175/1520-0426(1991)008<0554:ROSBIA>2.0.CO;2

[3] **Munk, W. H., W. C. O'Reilly, and J. L. Reid**, Australia–Bermuda sound transmission experiment (1960) revisited, *J. Phys. Oceanogr.*, **18**, 1876–1898, 1988.

[4] **Dushaw, B. D.**, WIGWAM Reverberation Revisited, *Bulletin of the Seismological Society of America*, 105(4), pp. 2242–2249, 2015. doi: 10.1785/0120150024 http://www.bssaonline.org/content/105/4/2242.abstract with Electronic Supplements.

[5] **Dushaw, B. D., P. F. Worcester, W. H. Munk, R. C. Spindel, J. A. Mercer, B. M. Howe, K. Metzger Jr., T. G. Birdsall, R. K. Andrew, M. A. Dzieciuch, et al.**, A decade of acoustic thermometry in the North Pacific Ocean, *J. Geophys. Res.,* **114**, C07021, 2009. doi: 10.1029/2008JC005124.

[6] **Dushaw, B. D., and D. Menemenlis**, Antipodal acoustic thermometry: 1960, 2004, *Deep-Sea Res. I*, **86**, pp. 1–20, 2014. doi: 10.1016/j.dsr.2013.12.008.

[7] **Dushaw, B. D.**, Assessing the horizontal refraction of ocean acoustic tomography signals using high-resolution ocean state estimates, *J. Acoust. Soc. Am.,* **136**, 1–8, 2014. doi: 10.1121/1.4881928.