ATOC and Other Acoustic Thermometry Observations In New Zealand

PAPER

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ABSTRACT

A summary of participation of the New Zealand group in the ATOC (Acoustic Thermometry of Ocean Climate) program over a five year period is presented. Transmissions from Heard Island were observed in the Tasman Sea during the Heard Island Feasibility Test in 1991. The California-New Zealand underwater sound path was verified with explosive sources in 1992. Single hydrophone observations were made of transmissions to New Zealand from California from an electrically driven source first suspended beneath a floating platform in 1994 and later placed on the ocean bottom at Pioneer Seamount in 1995. Results from these experiments show that acoustic propagation to ranges of order 10 Mm appears to be characterised by large fluctuations occurring with a time scale of a few minutes.

INTRODUCTION

Underwater sound can be used to provide a measure of global ocean warming. Munk and Forbes (1989) showed that the estimated 0.005°C per year warming at the sound speed minimum would be measurable if long distance travel times of underwater sound were monitored for several years. They also noted that a sound source placed at Heard Island in the southern Indian Ocean would allow uninterrupted straight line paths for underwater sound to travel to great distances, including both coasts of North America. A feasibility experiment was conducted in 1991 and this led to the Acoustic Thermometry of Ocean Climate (ATOC) program which is currently in progress. ATOC is a large scale experiment with a network of sources and receivers mainly in the North Pacific Ocean. A description of experimental progress and results is available on the World Wide Web.

HEARD ISLAND FEASIBILITY TEST

New Zealand involvement in acoustic thermometry began with the Heard Island Feasibility Test (HIFT) which attempted to see whether underwater sound from a sound projecting source could be detected at long ranges. The sources used consisted of two 25 mm thick, 1.4 m diameter aluminum discs back to back clamped around the edge and driven at the center by a hydraulic piston. The signal transmitted was a bi-phase pseudo-random sequence centred at 57 Hz. The pseudo-random signal encoding was crucial to the experiment since coherent processing is able to give a large signal to noise enhancement (Birdsall and Metzger, 1986). Without coherent processing the signal level at long ranges would be lost in the ambient noise. The HIFT was very successful and sound from Heard Island in the southern Indian Ocean was detected as far away as California and the North Atlantic. (Baggeroer and Munk, 1992)

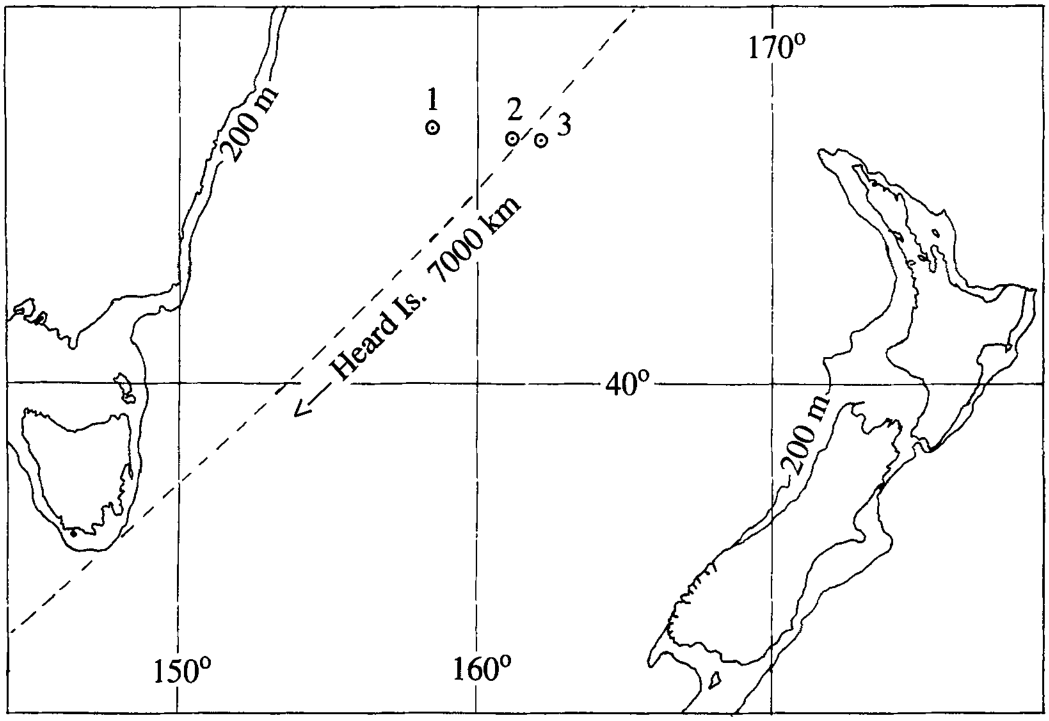
The New Zealand group listened for the Heard Island transmissions in the Tasman Sea using type 41B sonobuoys. The bearing of Heard Island from the middle of the Tasman Sea is about 225° as shown in Fig. 1. It was assumed that Tasmania would cast an acoustic shadow and it would be necessary to be well east of Australia to have a good chance of detecting the signals. The group was aboard HMNZS *Tui* and heading for the mid-Tasman when news was received that the Heard Island signal was being received at many locations. It was decided to stop and listen to the next scheduled transmission even though the ship was apparently well inside the acoustic shadow of Tasmania at site 1 as shown in the figure. Unexpectedly, a strong carrier signal was detected which began at the expected time for the source at a range of about 7 Mm.

After correction for the Doppler effect resulting from a drifting source and a drifting receiver the signal strength results are shown in Table 1. The Transmission Code is the universal time of the transmission but it also identifies the type of signal transmitted. The Signal Level was determined by the ratio of carrier power to noise power in the pass-band of 45–69 Hz. The signal power projected in the horizontal was monitored at the source with each transmission, and this is incorporated in the final column, "Adjusted Level," to show what the carrier to noise ratio would have been if the signal power had been 216 dB(re 1μPa).

Table 1.

Date	Site	Latitude	Longitude	Transmission Code	Signal Level	Adjusted Level
30 Jan 91	1	33° 32′S	158° 27′E	0600Z	17 dB	14.5 dB
30 Jan 91	2	33° 41′S	161° 09′E	2100Z	19 dB	19 dB
31 Jan 91	3	33° 44′S	162° 09′E	0300Z	18 dB	28 dB
31 Jan 91	3	"	"	0600Z	15 dB	25 dB

Figure 1. The Tasman Sea showing the coastline and 200 m depth contour. The dashed line represents the boundary of the acoustic shadow of Tasmania for the source at Heard Island. Observation sites are labelled 1,2,3.



The first reception was recorded at site 1 in Fig. 1 which is about 220 km inside the acoustic shadow of Tasmania. The second reception was recorded at site 2 just inside the shadow boundary. For the other receptions at site 3 there is an unobstructed great circle path to Heard Island. The adjusted levels clearly show the effect of shadowing. However, the magnitude of the shadowing is much less than expected, as theoretically the acoustic field should fall off exponentially and be down about 23 dB at a distance of 10 km into the shadow.

The HIFT clearly established that coded underwater acoustic signals could be received at ranges up to 16 Mm and laid the foundation for the ATOC program. HIFT also showed that the weather at Heard Island made it most unsuitable as a location for a semi-permanent sound source.

PROPAGATION TEST

In September 1992 an experiment to test acoustic propagation conditions between California and New Zealand was performed. An aircraft dropped a series of 1.8 lb SUS charges off the California coast along the initial segments of great circle paths from Pt Sur to New Zealand and San Diego to New Zealand. Each was a group of 6 shots at 5 minute intervals. There were 5 sets of shots and all were into water depths greater than 2000 m.

A typical received signal for the propagation test is shown in Fig. 2. The graph shows relative signal level in dB as a function of time in a 60–80 Hz band. The signal rises about 35 dB above background and lasts for about 11 seconds. The slow rise and rapid fall of the signal shows the classic SOFAR crescendo.

The results for propagation loss are shown in Fig. 3. The propagation loss is plotted as a function of range but at this range the expected change in spreading loss with range is negligible. The plots show results for two runs analysed in one-third octave bands centred on 63 Hz and 80 Hz. The variation in signal level between shots looks large but the standard deviation is of order 2 dB and therefore quite small.

Propagation loss PL in dB can be written

$$PL = 60 + 10 \operatorname{Log}(r) + \alpha r \qquad (1)$$

where r is the range in kilometers. Equation (1) assumes spherical spreading to a range of 1 km and cylindrical spreading thereafter. The attenuation coefficient α is usually assumed to be of the form $a + bf^2$ where a and b are constants and f is the frequency. The results in Fig. 3 are fitted by

$$\alpha = [0.32 + 0.69\,(f/100)^2] \times 10^{-3} \qquad (2)$$

Thus the attenuation at 100 Hz is 0.001 dB/km in agreement with the values compiled by Mellen et al. (1987). The overall propagation loss was about 107 dB and the ATOC source levels were expected to be 195 dB. This gives a predicted signal level of 88 dB at the New Zealand receiver which was expected to be satisfactory for the vertical array planned at that time.

ATOC Acoustic Engineering Test (AET)

The ATOC AET took place in November 1994 and was designed to test transmissions from an acoustic source off the California coast deployed at a depth of 650 m from the research vessel *Flip*.

As part of the test, a type 58A sonobuoy system with its hydrophone at the SOFAR axis depth of 1400 m was deployed from the tug *Arataki* about 90 km ESE of East Cape of the North Island of New Zealand. This was at a range of 9.66 Mm from the source. The sonobuoy was drifting at about 0.1 knots during the AET and it was necesary to correct the received signals for the Doppler effect. The source was also drifting very slightly with *Flip*. Of the eighteen receptions recorded only six were considered good in that the doppler correction and signal enhancement gave good results showing a clear arrival structure. A further five showed the presence of signal but enhancement gave little indication of structure. Surprisingly, the remaining seven receptions showed no indication at all of the presence of signal.

The best results from the New Zealand receptions from the AET are shown in Fig. 4. The top graph shows the expected theoretical signal amplitude envelope calculated by assuming adiabatic propagation through the gradually changing sound speed profile from source to receiver. The source pulse was assumed to be 2 cycles of a sine wave at 75 Hz. Sound speed profiles along the path were obtained from the Levitus, (1982) ocean climate database. The horizontal axis is time delay in seconds from the transmission of the pulse. The upper graph shows early isolated ray arrivals followed by the typical SOFAR crescendo and sharp cutoff due to multiple slow rays travelling in the sound speed minimum.

The six lower graphs show the results after processing of the six best individual receptions. Each transmission was 20 minutes of repeated frames of a phase-encoded pseudo random sequence (Birdsall and Metzger, 1988). One frame of the sequence is about 28 seconds long. Pulse compression and coherent averaging form the equivalent signal that would have been received if a single much stronger pulse had been transmitted. Enhancement of the signal-to-noise ratio is typically 30–40 dB. The travel time can be determined accurately modulo 28 seconds.

Figure 2. Time series of relative signal intensity in a 60–80 Hz band for shot 3.

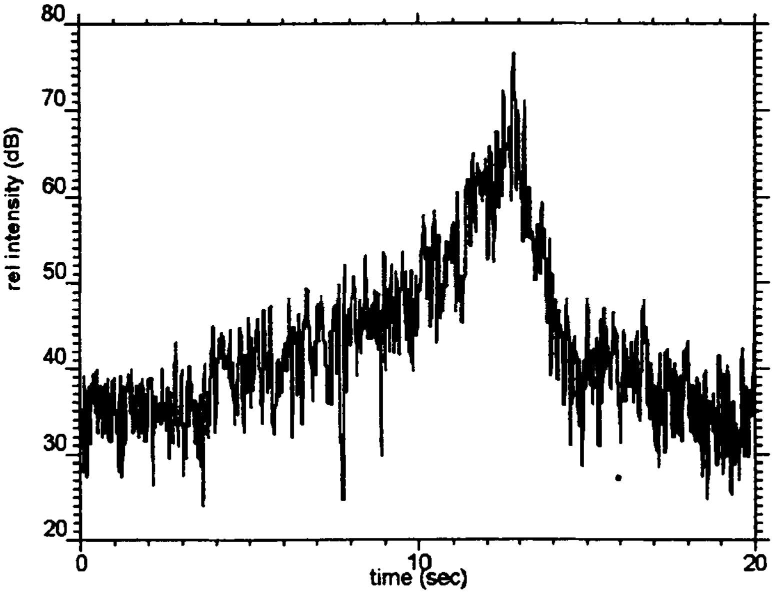


Figure 3. Propagation loss Pt. Sur to Mahia.

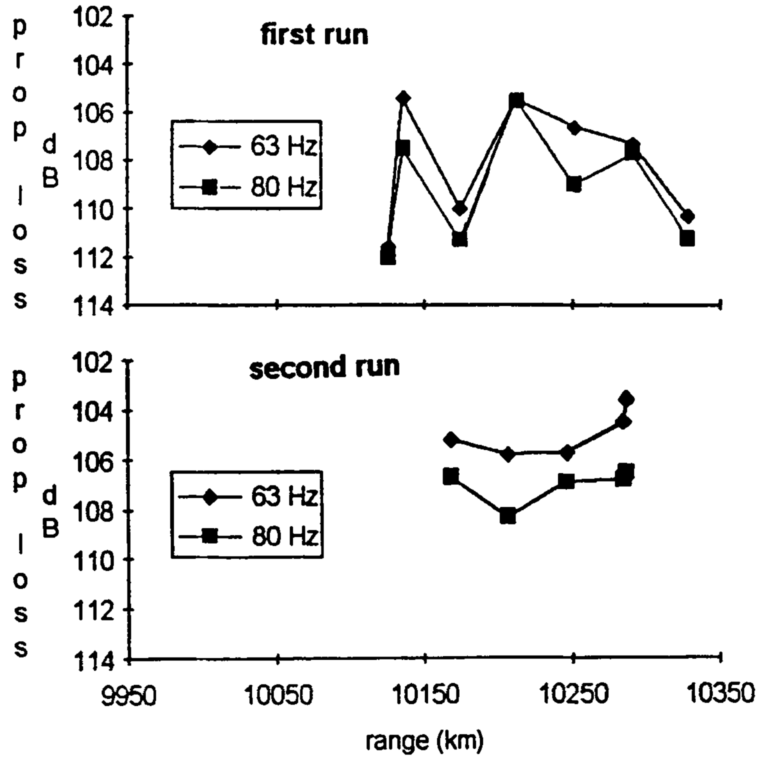


Figure 4 shows that the individual receptions vary considerably. There are no clear common features. This variability was not entirely unexpected as sound speed profiles are known to be affected by internal waves (Flatte et al., 1979). Our observations suggest that the propagation conditions change completely in the two hours between transmissions. Internal

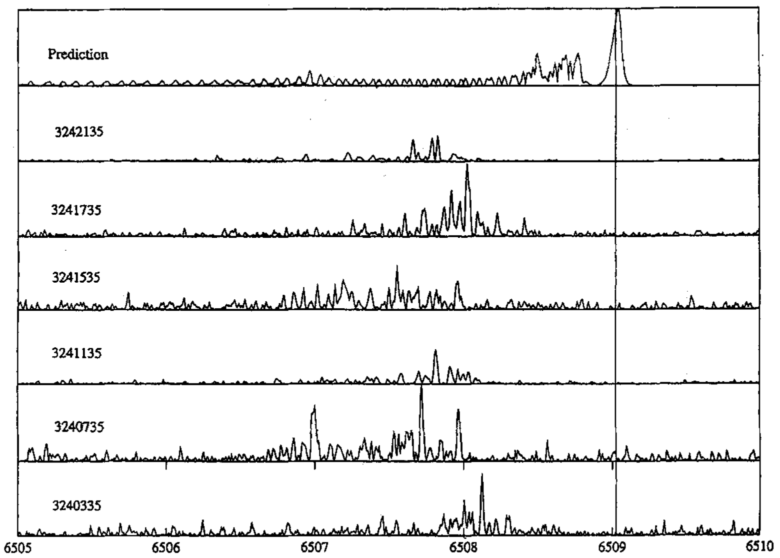


Figure 4. Time series of intensity for AET receptions. The top time series is a prediction assuming adiabatic mode propagation and the Levitus, 1982 database. The identification numbers are the julian day and hour at the start of the data file.

waves have periods substantially shorter than two hours, so it is not necessarily surprising that the receptions are not stable over two hour periods.

Figure 4 also shows that the strongest part of the signal arrives about 1.2 seconds earlier than the theoretical signal. This could be indicative of ocean warming that has occurred since the Levitus database was obtained. However, the database is an aggregate of several seasons and may not give a reliable estimate of propagation conditions in any particular year.

ATOC PIONEER SEAMOUNT TRANSMISSIONS

In late 1995 the ATOC program placed an acoustic source on Pioneer Seamount 70 km off the California Coast. The source transmission schedule was arranged to study not only long distance acoustic propagation but also whether the acoustic source had any effect on marine mammal behaviour. The transmissions are 75 Hz phase encoded sequences as for the AET and are transmitted for 20 minutes every 4 hours. However, the source schedule is also controlled by the marine mammal research program. Transmissions only occur when marine mammal research is being conducted.

The New Zealand ATOC group arranged to receive some of the Pioneer Seamount transmissions using a moored autonomous recording system. The system was built by the Defence Scientific Establishment, Auckland and it was deployed and recovered by HMNZS *Tui*. The single hydrophone was at a depth of 1000 m and the system was moored in water 3500 m deep off the east coast of the North Island of New Zealand at 38°59.0′ S, 178° 47.8′ W. The direct path from Pioneer Seamount to the source is unobstructed to at least 4000 m depth.

The receiving system was active from 23 March to 25 April 1996 and there were 199 recordings. Unfortunately the source was transmitting for only 53 of these occasions, in three groups of three days beginning on 9, 15 and 22 April. For the 53 occcasions when the source was transmitting there was great variability in the signal-to-noise ratio at the receiver. This variability was not due to changes in background noise and so must be assumed due to changes in the propagation conditions. Surprisingly for 23 of the 53 occasions on which the source was transmitting there was no detectable signal at all at the receiver. This occasional lack of detectable signal was also noted above for the AET.

Processed results from the seven strongest receptions are shown in Fig. 5. The plots show the amplitude envelope of the signal after pulse compression. Unfortunately clock drift meant that precise timing was not available. The signals in Fig. 5 have been aligned on the highest peaks in an effort to see whether there is any common structure. It is clear that the signal structure varies considerably between receptions and there are essentially no common features. Each signal shows a series of arrivals of similar strength spread over a time of about 2 seconds. There is little evidence of the familiar SOFAR crescendo.

This variation in signal structure not only occurs between receptions but also occurs within a single reception as is illustrated in Fig. 6. The figure shows the arrival structure from three different sections of the same reception. Each signal results from pulse compression of 12 frames of the signal i.e. each is a summary of about 6 minutes of reception. There is a common peak at about 24.4 seconds from the frame start but apart from that there is wide variation in amplitude and arrival time for all other features of the signal.

DISCUSSION AND CONCLUSIONS

It is instructive to compare the signals in Figs. 4–6 from the acoustic projector with that in Fig. 2 from an explosive source. The signal in Fig. 2 is about 12 seconds long and the peak rises to about 75 dB above a background of about 35 dB. The signals in Figs. 4–6 are about 1.5 seconds in length and are 10–15 dB above the background noise.

If we look now at Fig. 2 and draw a horizontal line at 60 dB we find that it cuts off a portion of the signal about 1.5 seconds in length. In this time interval the signal rises a further 15 dB and subsides again. Therefore it appears that the received signals in Figs. 4–6 correspond to the small section of the signal in Fig. 2 which is above 60 dB. This suggests that the signals in Figs. 4–6 are only a small fraction of the total signal and correspond to the very highest peaks of Fig. 2. Thus the final crescendo is the only part of the arrival pattern with sufficient signal-to-noise ratio to be observable at long ranges with a single hydrophone and non-explosive sources. The SLICE89 experiment showed that the final crescendo at 250 Hz and 1000 km range does not contain stable arrivals but is highly scattered by internal waves (Worcester et al., 1994). Only the early, steep ray, arrivals were found to be stable in the SLICE89 experiment. Our single hydrophone measurements did not have sufficient signal-to-noise ratio to observe the early arrivals which may have been more stable.

The results shown in Figs. 4–6 show that the propagation conditions along the acoustic path from California to New Zealand fluctuate significantly on a time scale of a few minutes. The lack of detectable signal on a number of other occasions suggests that the fluctuations of the overall signal strength are of order 15 dB. This large variability is probably due to internal waves and indicates that improvement in the signal to noise ratio will only be achieved with a larger source or more hydrophones. Coherent averaging over more than a few minutes of signal seems to be unsatisfactory at very long ranges.

The other interesting result from the New Zealand participation in the ATOC program is that a strong signal from Heard Island was observed in the supposed acoustic shadow of Tasmania. This result remains puzzling.

Figure 5. Time series of intensity for best receptions from Pioneer Seamount.

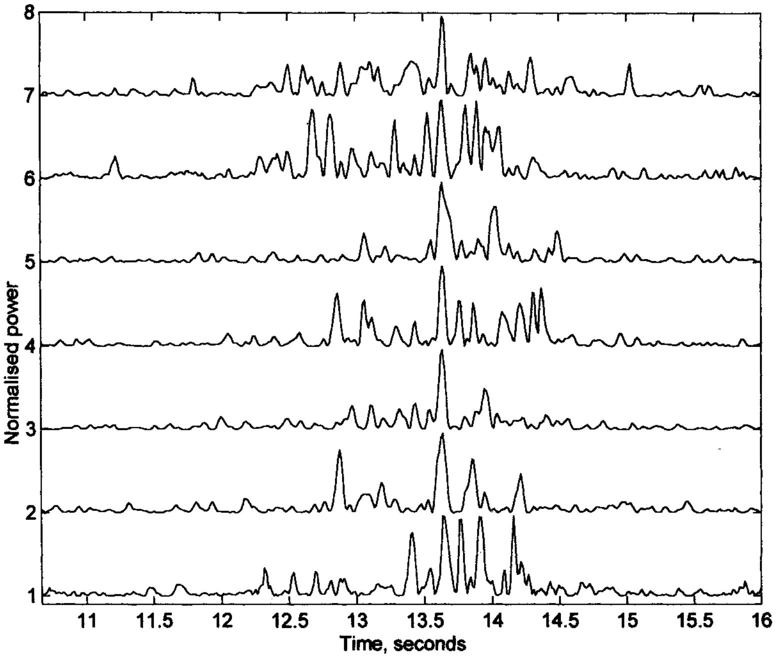
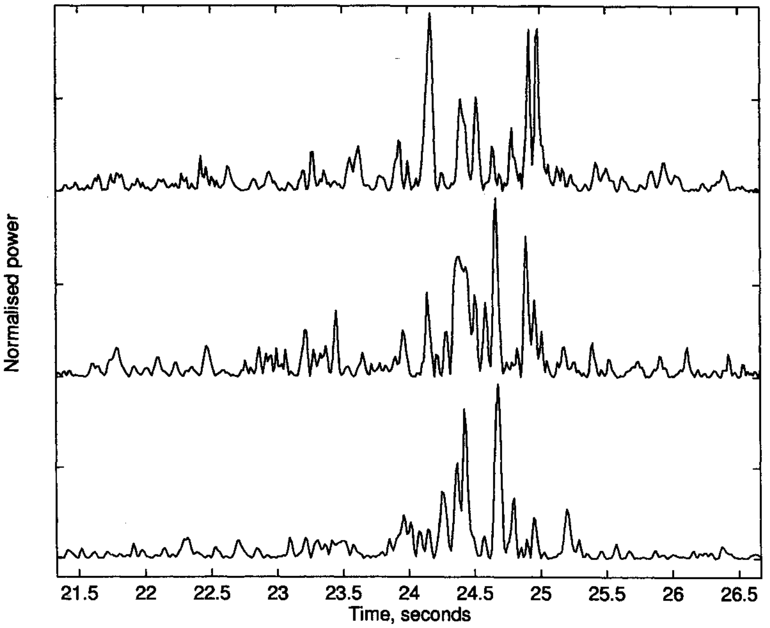


Figure 6. Time series of intensity for successive 12 frame samples of the same reception from Pioneer Seamount.



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