Rapid Determination of Seafloor Acoustic Reflectivity by Exploiting Frequency Variability within Striations Data

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Abstract— **For shallow oceans, multi-path interference generates a pattern of striations when broadband data received on a single hydrophone are viewed on a range-frequency display. The frequency variations within this data are known to be related to the ocean depth, and to the seafloor acoustic reflectivity. A simple process has been developed by which the frequency spacing of the striations data may be extracted, and the reflectivity determined by inversion, using data obtained from an incoherent source such as a ship-of-opportunity. The technique is demonstrated both by simulations, and using ship-generated data obtained in shallow water off Perth, Western Australia. The seafloor reflectivity values derived from application of the technique are used in predictions of transmission loss which are compared with measured transmission losses, and with transmission losses predicted using seafloor descriptions based on bottom grab samples.**

Keywords—seafloor inversion; shallow ocean; striations

I. INTRODUCTION

It is well known that sound transmission to short and medium ranges in shallow oceans is dependent upon the seafloor reflective properties. The multiple paths of acoustic transmission combine constructively and destructively such that sound transmitted over a broad frequency band forms a pattern of lines or swaths, known as "striations", when amplitude levels at each range are plotted against frequency. An example of such a plot is shown in Fig. 1 for a simulation of a seafloor half-space of coarse sand. Here, Transmission Loss (*TL*) is shown in 10 m steps of horizontal range to 4000 m, and in 1 Hz steps of frequency to 500 Hz. The wavenumber-integral model HANKEL [1] was used for these simulations. The ocean was simulated as isovelocity (1500 m/s), of depth 80 m with both source and receiver at 18 m, seafloor compressional speed and attenuation were 1800 m/s and 0.7 dB/λ, shear speed and attenuation were 600 m/s and 1.5 dB/λ, and density was twice that of seawater (geoacoustic parameters from Jensen and Kuperman's Table 1 [2]).

Fig. 1 simulates the *TL*, as for a coherent source moving away from the receiver, and is identical to the received signal from a source of Source Level 0.0 dB. For a broadband source of opportunity, e.g. a passing ship, the source signal has no temporal coherence, and resembles random noise. Fig. 2 simulates the data received from such a random source, for the same scenario as Fig. 1. The data on the range-frequency plot are obtained as a series of spectra received at subsequent times, and for a random source each spectrum contains a value in each frequency bin which is an uncorrelated Gaussian value about a mean determined by the multi-path combination. Each of these random samples may be averaged according to the bandwidth-time product implied by temporal and spectral sampling. It is apparent from examination of Fig. 2 and comparison with Fig. 1 that sufficient averaging of the data in the former would yield a good approximation of the latter.

This paper describes a process which has been found to be effective in averaging data received from a random source and shows how the variability within the striations data may be used to invert for an effective acoustic description of the seafloor.

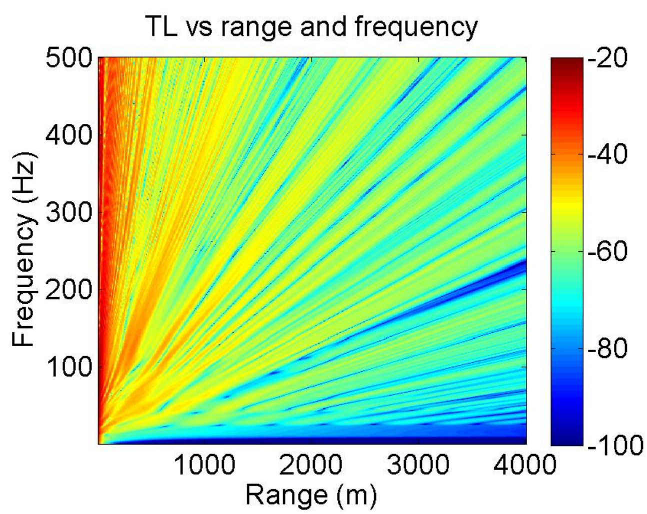

Fig. 1. Simulated range-frequency Transmission Loss showing striations, frequency to 500 Hz, for 80 m ocean, coarse sand seafloor, coherent source

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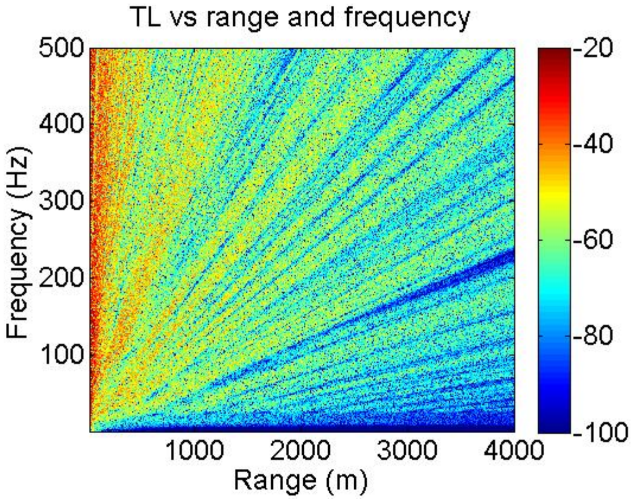

Fig. 2. Simulated range-frequency Transmission Loss showing striations, frequency to 500 Hz, for 80 m ocean, coarse sand seafloor, random source

II. Range-Frequency Striations In A Shallow Ocean

The occurrence of range-frequency striations in broadband data received in a shallow ocean may be understood by examining the phase coherent addition of multi-path arrivals [3]. It is simple to show that a phase change between the ray arrivals due to a change in frequency is equivalent to a phase change between the same arrivals due to a change in source to receiver range, with a constant of proportionality which varies linearly in frequency and inversely in range. An important consequence is that the phase relationship between two arrivals may be held at zero if the frequency is increased by δf and the range increased by $(r\ \delta f)/f$. A consequence is that $\delta f/\delta r = f/r$ along the region of unchanged phase separation, and so lines, or swaths, of varying thickness, known as striations appear on the range-frequency plot. If the axes are linear, the striations appear on the plot as straight lines originating from $f = 0$, $r = 0$, as is obvious in Fig. 1. The above includes the assumptions that (i) there are enough propagating modes to describe a continuous variation of grazing angles for the multi-path arrivals, and (ii) the rate of change of the phase difference with range $d\phi/dr$ is dominated by transmission path length effects and not the effects due to phase variation upon reflection at the seafloor. The relation $\delta f/\delta r = f/r$ is commonly expressed in terms of angular frequency $\omega = 2\pi f$ as

$$(r/\omega)[d\omega/dr] = \beta \tag{1}$$

where β is an invariant for a waveguide [4], but is not necessarily of value exactly 1.0 as implied here.

III. Frequency Variability-Based Inversion Along Striations

The technique for inversion of seafloor reflectivity used in this study is described by Jones et al. [3], [5], [6]. Although developed separately, this may be considered as a frequency-domain variant of the channel impulse response technique described by Smith [7] and used by Prior and Harrison [8]. That is, both techniques exploit the approximation of the channel impulse response function as an exponential for which the time constant may be expressed in terms of the shallow ocean depth D and the value F dB/radian, the presumed function of bottom loss vs. grazing angle for small grazing angles. In particular, for an isovelocity ocean, the impulse decay time constant may be shown to be $\tau \approx [10\log_{10}(e)]D/(c_w F)$ seconds, where c_w is the speed of sound in seawater.

As shown by Schroeder [9], for a transmission environment with an intensity impulse decay function which is exponential, the spectral autocorrelation function of the received sound pressure amplitude may be expressed as

$$\rho_{|p|}(\Delta f) = 1/\left[1 + (2\pi\tau\Delta f)^2\right] \tag{2}$$

where Δf, a key statistic in relation to this work, is the frequency displacement (Hz) for a specified de-correlation.

For convenience in analysis of practical data, it was decided to use the value Δf_h being the frequency displacement at which the autocorrelation function falls to 0.5. From (2), $\Delta f_h = 1/(2\pi\tau)$ Hz. Substituting for the time constant τ gives $\Delta f_h \approx \ln(10)c_w F/(20\pi D)$ Hz. This expression may now be inverted to obtain the bottom loss parameter F based on the spectral variability statistic Δf_h, viz.

$$F \approx 27.3 D\Delta f_h / c_w \text{ dB/radian} . \tag{3}$$

In processing data, the frequency spacing of features within the sound channel response spectrum are processed to determine values of Δf_h. (Approximately, average spacing between frequency maxima is about $3\Delta f_h$ Hz [3].) The value F dB/radian, is then inverted using (3). In practice, the received signal from any broadband source may be used.

The concept of the bottom loss versus grazing angle slope, F dB/radian, relevant to small grazing angles less than the critical angle, is illustrated using Fig. 3. Here the solid curve is the bottom loss versus grazing angle function for the coarse sand seafloor assumed for Fig. 1 and Fig. 2, for all grazing angles between 0° and 90° incidence. With the bottom reflection loss shown on a dB scale, it is easy to see that the bottom loss versus grazing angle function, for small grazing angles, has a form which is close to linear, as is well known. For this seafloor, the critical angle $\beta_c = \arccos(c_w/c_b) \approx 33.6°$, and is clearly greater than the span of angles in which the near-linear function of bottom loss applies.

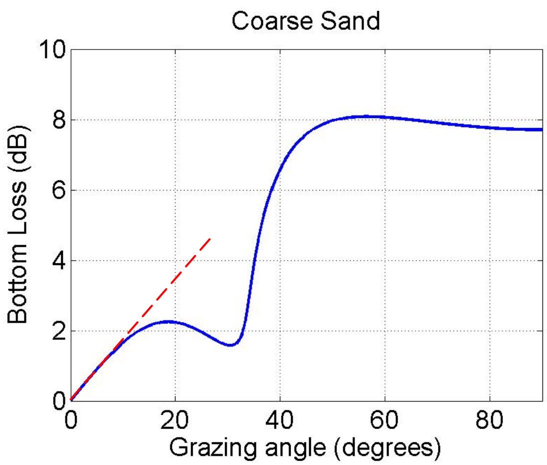

Fig. 3. Bottom Loss versus grazing angle for coarse sand seafloor (blue line), bottom loss versus grazing angle *F* dB/radian valid for small angles less than critical angle (red dashed line)

Sound transmission to medium or long ranges in a shallow ocean may be shown to be dominated, in the main, by components which are incident at the seafloor at small angles, with the result that a reasonable description of the relevant seafloor interactions may be obtained by approximating the bottom loss versus grazing angle function as a line of fixed slope that matches the small angle component of the complete function. That is, the red dashed curve in Fig. 3 may be used in place of the accurate blue curve, with little loss of accuracy for medium to long range transmission. An accompanying approximation for reflection phase may be made (e.g. [10]), and so reasonable estimates of phase coherent sound transmission may be obtained through use of a suitable transmission model, solely based on a knowledge of the reflectivity parameter *F* dB/radian. The assumption that the reflection loss, in dB, for small angles is a linear function of grazing angle is not new, for example the reflectivity parameter *F* is identical to the term α_{dB} of Prior and Harrison [8].

The determination of Δf_h from data received from an uncorrelated source within a noise background benefits from averaging the mean-squared spectral pressure data received at different range points prior to the frequency autocorrelation. A method was devised to perform this averaging along the slope of the striations [3], which for a channel invariant of 1.0, are assumed to follow straight lines radiating from $f = 0$, $r = 0$. It was necessary to limit the range span over which this might be carried out, as the bandwidth between the lines assumed for the striation pattern increases with range, whilst the frequency spacing of features scales with Δf_h, and is unchanged with range as implied by (3).

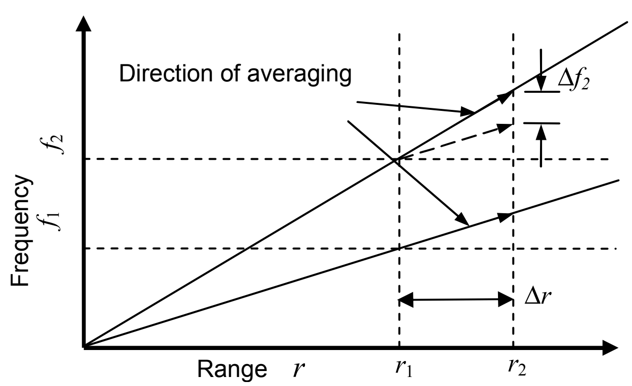

Fig. 4. Striations on range-frequency plot and implications for averaging spectrum

The extent of range Δr over which averaging may be carried out along the lines of the striations can be seen to be related to the size of increase in the bandwidth Δf_2 in Fig. 4. It is reasonable to set the desired minimum value of Δf_2 at Δf_h since the latter is known to be a measure of the frequency extent of spectrum features It may be shown that

$$\Delta f_2 = (r_2 - r_1)(f_2 - f_1)/r_1 \, . \qquad (4)$$

If the slopes of the striations are now assumed to be not greatly different, and if the range and frequency extents $r_2 - r_1$ and $f_2 - f_1$ are not large relative to absolute values, it is possible to make some substitutions by use of the expression $\delta f / \delta r = f / r$. In particular, it may be assumed that $(r_2 - r_1)/(f_2 - f_1) \approx r_2 / f_2 \approx r_1 / f_1 \approx r / f$, and $f\,(r_2 - r_1)/r$ may be substituted for $f_2 - f_1$ in (4) to give $\Delta f_2 \approx f\,(r_2 - r_1)^2 / r^2$. Making the substitution $\Delta f_2 < \Delta f_h$, and obtaining Δf_h from (3), the range extent of averaging Δr may then be found as

$$r_2 - r_1 = \Delta r < r\sqrt{0.037\, c_w\, F/(D\, f)}. \qquad (5)$$

Fig. 4 demonstrates that this averaging is carried out along the lines of the striations between frequency values f_1 and f_2 and range values r_1 and r_2. The assignment of Δf_h as the desired limit to the increase in bandwidth is somewhat arbitrary, but is reasonable as, on average, the amplitudes of spectral values in the channel response have a correlation of 0.5 at this frequency separation. This "matched-slope" averaging along the slopes of the striations can be expected to have the bonus effect of suppressing the contribution from tonals in data received from a ship of opportunity, as these are at fixed frequency, whereas the matched-slope averaging occurs over a frequency band. This suppression of tonals will have limitations in the case of very strong tonals, but is not considered further here.

IV. Demonstration Of Technique - Simulation

The technique of averaging along the slope of the striations, termed "matched-slope" averaging, was applied to the range-frequency data shown in Fig. 2, thus simulating an application to data from a random source (see Jones et al. [3] for more details). Prior to this determination, the value of *F* dB/radian, the small-angle slope of the bottom loss vs. grazing angle function was determined from a layered-media reflection model as 10 dB/radian, using data from 0° to 10° grazing

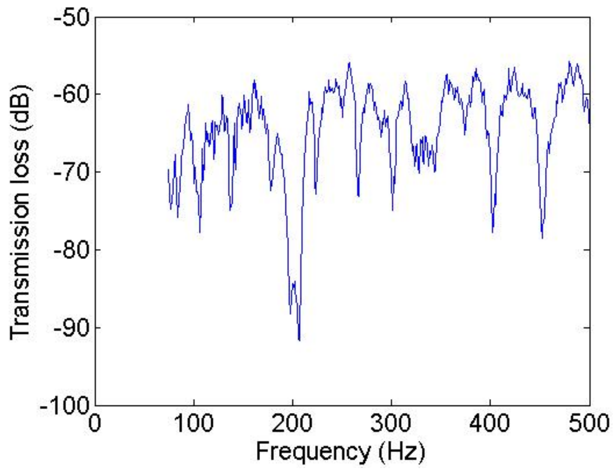

Fig. 5. Transmission Loss vs. frequency after matched-slope averaging data in Fig. 2 over range 3.5 - 4.0 km

angle. (A line of this slope is shown in Fig. 3.) The matched-slope averaging was carried out on data between 75 Hz and 500 Hz, starting at range 3,500 m and concluding at range 4,000 m. This large frequency span was permissible as the reflectivity of a uniform half-space may be anticipated to be frequency independent. With range steps at 10 m, this implies that 50 sets of frequency variable data were averaged prior to the autocorrelation used to determine Δf_h. The lower frequency limit of 75 Hz was based on an estimate that multi-modal transmission (about 5 modes) existed [3] above this frequency. Based on (5), and with prior knowledge of the bottom loss vs. grazing angle function F, for this scenario the allowable range extent Δr becomes about 1100 m for 75 Hz and 420 m for 500 Hz, and so the 500 m range span was judged to be marginally adequate.

Fig. 5 shows the spectrum derived using the matched-slope averaging. From this, the value of Δf_h was obtained by an autocorrelation of the amplitude data [3], [5] as 7 Hz. Then from (3), the bottom loss vs. grazing angle slope F was determined as 10.2 dB/radian, which is very close to the known value of 10 dB/radian.

Using at-sea data, the value of F is initially unknown, of course, and so the range extent Δr will be selected to ensure an adequate signal to noise in the determination of the matched-slope averaged spectrum. The inverted value of F is then used in (5) to determine whether the initial value of Δr is excessive, in which case a smaller value must be chosen, and the value of F re-determined. This process needs to be repeated until the inverted value of F, used as an input to (5), shows that the range extent of averaging which was used in its determination is not excessive.

V. Demonstration Of Technique – Ship Of Opportunity

A sea trial was conducted [11] in which striations data were obtained for the purpose of applying the frequency variability-based inversion of reflectivity. At-sea measurements included the collection of received impulses from a 20 cubic inch airgun, from which best-fit values of seafloor bottom loss vs. grazing angle F were determined. Grab samples of surficial sediment were obtained for use in comparison with direct acoustic determinations of seafloor properties. The trial vessel was used to represent a ship of opportunity, and its acoustic signature was recorded on a single omni-directional hydrophone, during vessel run-bys, so that range-frequency patterns of striations might be obtained for analysis.

TABLE I. Seafloor loss vs grazing angle slope F obtained for trial site

Frequ (Hz)	**Seafloor Reflectivity *F* (dB/radian)**					
	Inverted from striations data					***Best fit to airgun transmission data***
	mean F	min F	max F	σ	Δr (m)	
63	1.6	0.8	2.5	0.5	280	1.5
125	2.6	1.7	3.9	0.7	250	3.4
250	3.1	2.4	4.3	0.5	200	5.3
500	6.3	4.0	10.2	1.5	200	4.6
1000	11.3	7.4	15.4	2.8	190	13.3
2000	20.3	4.7	37.2	8.1	180	40.1

The trial was conducted on 1st and 2nd March 2003 in shallow water over a seafloor which was approximately flat, of depth about 35 m, just north of Rottnest Island, Western Australia. Measurements were conducted over two days. A single hydrophone 8 m above the seafloor was used to record the acoustic transmissions from the airgun and the radiated sound from the trial vessel. Striation patterns were obtained from straight transits of the trial vessel, each at a constant high speed, along tracks West to East and vice versa, and also South-West to North-East and vice versa, over the hydrophone location. A total of 14 such runs was made. To obtain the ocean sound speed profile at the trial site several CTD casts were made each day: six on the 1st day; four on the 2nd.

The data in each of the striation patterns were processed using the technique outlined in section III, and a value of the bottom loss vs. grazing angle slope F was determined from the data in each octave band. Here, data within ranges to the hydrophone of 30 to 50 times the water depth were averaged using the matched-slope technique to determine the values of Δf_h and then F. Each value of F was presumed to apply at the respective octave band centre frequency. Table 1 shows the maximum and minimum values of F obtained from all 14 striation patterns, plus the average and standard deviation of F, for each octave band frequency. The inversion process has a low frequency limitation imposed by the need for multi-modal transmission as already mentioned, but also has a limitation from a maximum range within which the striation pattern is known to be dominated by seafloor losses. These limits are not considered here, but have been described by the authors [3].

It may be noted that the processing of the striations data did not include any manipulation to suppress the tonals from the trial vessel. These were suppressed by the nature of the matched-slope technique itself.

Based on (5), and the mean value of F from the inversion, the permissible extent of range averaging Δr was determined for each frequency, based on the centre range (1400 m) of the

1050 to 1750 m span, and is included in Table 1. It may be noted that the 700 m range span used for averaging exceeds the desired limits. However, the averaging was carried out on the spectrum values in mean-squared pressure form, for which the variation in amplitude with range had not been altered from the raw data. With the range extent for averaging being over a factor of 1.7 times the commencement range (30 to 50 times ocean depth), it is clear that the values closest to the source dominate over those from the most distant range, and so the effective range extent was much less than the actual 700 m.

Values of *F* were also obtained from a best-fit to the airgun data from one of the airgun runs, and are shown in Table 1. These were obtained using the KRAKENC model [12], for which candidate seafloor reflection loss vs. grazing angle values were varied to obtain a match. In general, the mean striations-based values of *F* are quite close to the best-fit values, with the exception at 2000 Hz for which the striations-inverted 20.3 dB/radian is about half the best-fit value. In each case, however, the *TL* obtained using the striations-inverted values as input to KRAKENC gave quite close agreement with measurement to the maximum range for which data are available. Fig. 6 shows an example, for which the 1/3rd octave measured data are compared to a simulation of 1/3rd octave transmission obtained by running KRAKENC at 21 single frequencies and incoherently averaging. Lastly, a uniform half-space description of the seafloor was based on the samples obtained from sediment grabs, which showed moderately well sorted, rounded, medium grained sand of average grain size 9.3 ϕ [10]. *TL* values obtained for this seafloor description, again using KRAKENC simulating 1/3rd octave transmission, are shown in Fig. 7. These show a greater divergence from measured data than for the case of the striations-inverted description, at all frequency ranges from 63 Hz to 2000 Hz. Fig. 7 shows the sediment grab-based *TL* as modelled by KRAKENC for the 125 Hz 1/3rd octave band – which is clearly not as close to the measured data as the mean striations-based

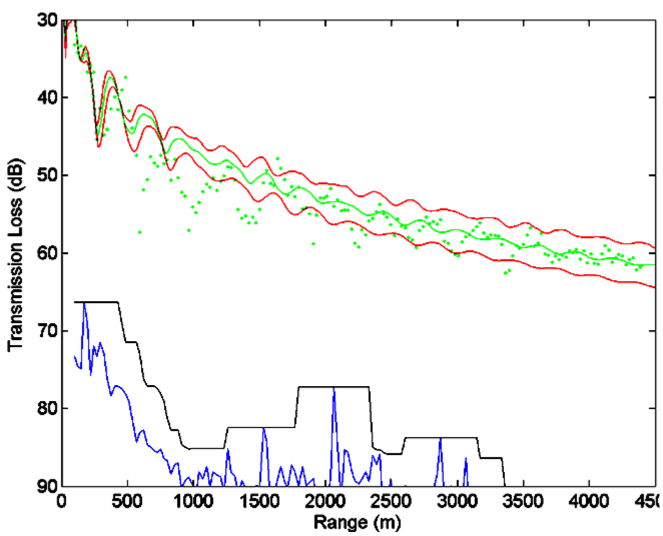

Fig. 6. 1/3rd octave Transmission Loss calculated using mean, max., min. *F* from striations (green & red lines), 1/3rd octave Transmission Loss measured from airgun (green points), background noise (blue & black lines); 125 Hz

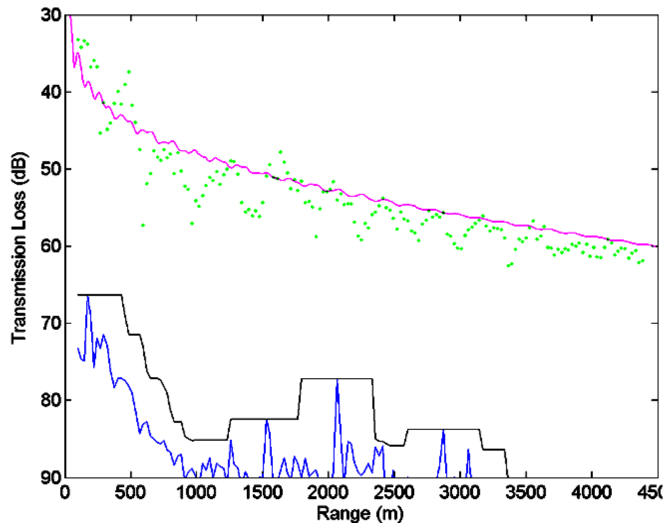

Fig. 7. 1/3rd octave Transmission Loss calculated using description from sediment grabs (magenta), 1/3rd octave Transmission Loss measured from airgun (green points), background noise (blue & black lines); 125 Hz

TL in Fig. 6. Note that, for all these KRAKENC modelling runs, the sound speed profile measured at the site was used as an input.

VI. Conclusions

A technique has been presented by which the seafloor reflectivity parameter *F* dB/radian may be inverted from range-frequency striation data obtained in a shallow ocean. The technique is based on the broadband method published previously by the authors, but has been extended to the case of signals received as a function of range. In particular, by averaging along the slope of the striations, data may be enhanced, and the inversion accomplished, when the sound source radiates a temporally uncorrelated random signal. This enhances the extraction of a frequency variability parameter Δf_h Hz from uncorrelated noisy data, and also suppresses tonals in data from a ship of opportunity, as the averaging is along the striations and not along lines of fixed frequency. Application of the technique has been demonstrated for both synthetic data, and data from a sea trial using actual vessel noise as the signal source.

The seafloor reflectivity values derived using the technique are shown to result in predictions of transmission loss which compare favourably to measured transmission losses. For the particular ocean site, these predicted values of transmission loss are closer to the measured data than transmission loss predicted using seafloor descriptions based on bottom grab samples.

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