The Effects of Local Structure on Seafloor Ambient Noise at the Hawaii-2 Observatory

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Abstract - **Analysis of long time series, broadband (0.001-60Hz) seismometer and hydrophone data from the Hawaii-2 Observatory reveals many time-independent characteristics in power spectral density and coherence that persist regardless of the type or location of the noise sources. These characteristics can be attributed to the water depth, sediment thickness, igneous crustal structure, and other geological features local to the observatory. It is important to recognize these characteristics as due to local structure so that they do not confuse the interpretation of noise generated by storms and earthquakes in terms of other physical processes such as infra-gravity wave excitation and propagation, wave-wave interaction, breaking waves, Rayleigh/Stoneley/Scholte wave effects, and propagation and leakage from the ocean wave guide. Some examples of local, physical mechanisms include: 1) shear wave resonances (modes) in sediments [24], 2) water multiples (organ pipe modes) in the ocean [31], and 3) secondary scattering of Scholte waves from local seafloor heterogeneities [23].**

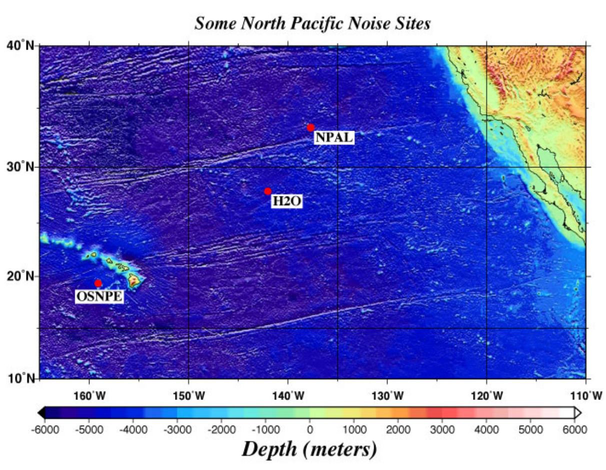

Fig. 1. Location diagram of the Hawaii-2 Observatory (H2O - shallow buried three-component seismometer with seafloor pressure), the Ocean Seismic Network Pilot Experiment (OSNPE - borehole, shallow buried, and seafloor three component seismometers with seafloor pressure) and the North Pacific Acoustic Laboratory (NPAL - seafloor vertical component geophone with seafloor pressure).

I. INTRODUCTION

We present three poorly understood observations in the coherence between the pressure and vertical particle velocity of the broadband ambient noise field in the North Pacific: a) distinct strong coherence bands in the microseism spectrum from 0.05 to 1Hz, b) distinct intermediate coherence bands in the upper holu spectrum (punctuated with sediment resonances) from 1.0 to 10Hz, and c) the time dependence of coherence of the primary (PM) and long period double frequency (LPDF) microseisms in the 0.04 to 0.15Hz band. The data sets of interest are the Hawaii-2 Observatory (H2O) data (a nearly continuous 3.5 year record from 5 October 1999 to 26 May 2003) [1-3] and the Ocean Seismic Network Pilot Experiment (OSNPE) data (Feb-June 1998) [4] (Fig. 1). At these sites we have boreholes into the basaltic basement to give definitive physical properties of the sub-seafloor.

Shear wave resonances (Scholte modes) are a common feature in ambient noise records, earthquake records and controlled source signal records (Fig. 2). By understanding the behavior of these features we can improve signal-to-noise ratio in earthquake and

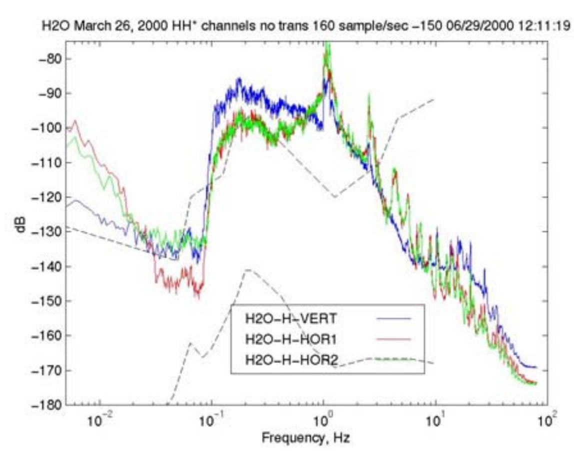

Fig 2. Power spectral densities (in counts) for the three inertial channels at the H2O site showing the strong resonances on the horizontal channels between 1 and 20Hz. Some but not all of the peaks are also seen on the vertical channel.

controlled source records, and we can use the ambient noise field to infer the structure of the sediments and upper crust.

In our preliminary analysis we have noticed a distinct and systematic banding pattern in the coherence between pressure and vertical velocity. Oddly this banding does not correspond to peaks in either the pressure or velocity spectra, which have been associated with sediment resonances. At H2O, coherence banding extends from 0.05 to 4.5Hz and above, and peaks in coherence are separated by 0.15 to 0.2Hz. There seem to be two fundamental regimes for this coherence banding: 1) the 0.05 to 1Hz range (Fig. 3) where squared coherence peaks (K^2) are about 0.8 to 1.0 and 2) the 1 to 4.5Hz range where coherence peaks are about 0.4-0.6 (Fig. 4). We do not have an explanation for the coherence banding, but we suspect that it is a resonance phenomenon in the sediment and upper crustal structure within a kilometer or so of the station. The amplitude of the sediment resonances appears to change with time (Fig. 4a). It is unclear whether the coherence also has a temporal dependence that correlates with changes in the sediment resonance levels.

The coherence between pressure and vertical velocity is also a useful tool for identifying primary (PM) and double frequency (DF) microseism energy that has been generated at distant coastlines by direct loading in shallow water and wave-wave interaction respectively (Fig. 5). High coherence levels (Fig. 5c) are observed between the pressure and vertical velocity for apparently distant and more locally generated DF microseism signals [2] and earthquake surface wave arrivals at the OSNPE site. These coherences appear independent of the spectral levels

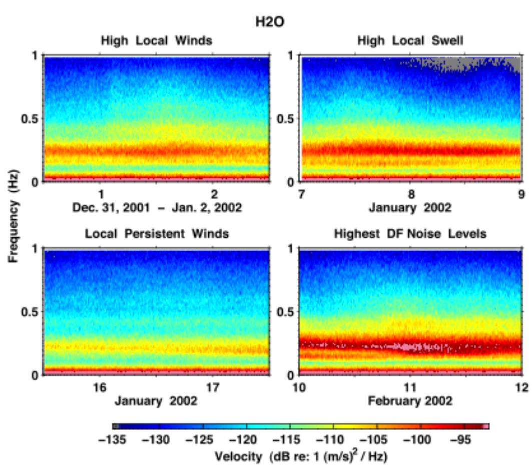

Fig. 3a: Vertical velocity spectrograms for the 0-1Hz band at H2O are shown for four different environmental conditions: high local winds, high local swell, local persistent winds, and high double frequency microseism levels. All except the February panel have the JOIDES Resolution present, which seems to make no difference for the 0-1 Hz band but could be important for 1-10Hz where the sediment resonances are observed.

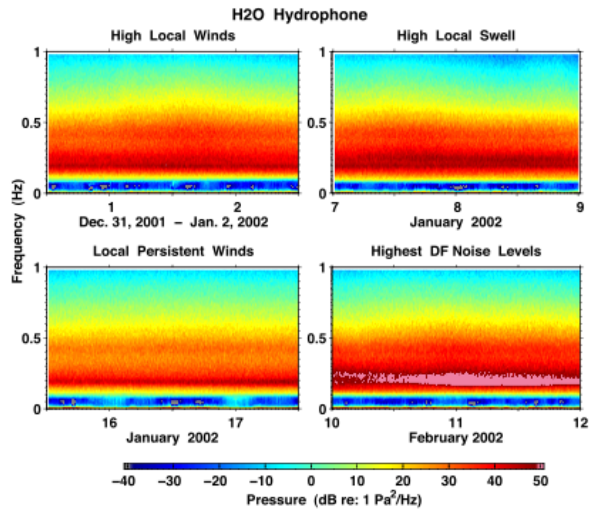

Fig. 3b. Pressure spectrograms corresponding to the vertical velocity grams in 3a. All spectra and coherence grams in this paper were computed using Welch averaging [37] with similar resolution and statistical properties as the Peterson low and high noise models [38].

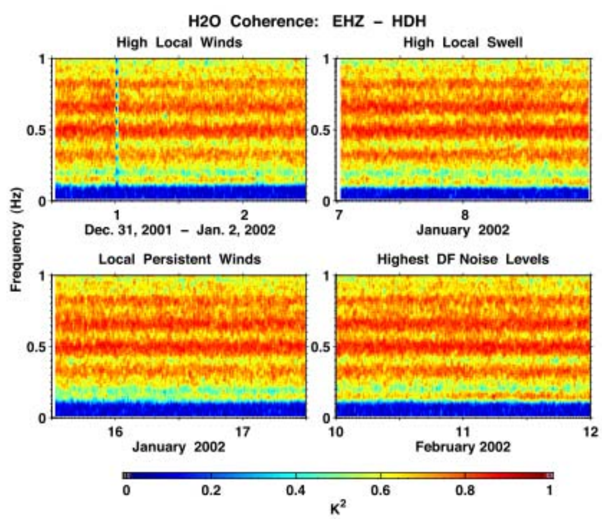

Fig. 3c: Coherence grams for the vertical velocity and pressure data in 3a&b show consistent high coherence bands. It is remarkable that the coherence bands are so steady in frequency and coherence level between 0 and 1Hz while the underlying magnitudes of the pressure and velocity spectra are varying dramatically. The near constant separation of the coherence bands (0.15-0.2Hz) between 0.3 and 0.8Hz is striking. If these are "organ pipe modes" in the water [29], why do they not appear as amplitude peaks in the spectra? Are these dependent on sediment and upper crustal structure?

and the signal source, and are higher than the sediment resonance band coherence at this site. Primary microseisms can only be generated in shallow coastal waters. In addition, because there is generally very little opposing wave energy at longer periods in the open ocean, DF microseisms (LPDF) levels at frequencies less than 0.125Hz are dominated by coastal generation where wave reflection and scattering from shorelines provides opposing wave energy.

Note that this study should not be confused with "compliance" studies which also involve the coherence of pressure and vertical displacement (velocity or acceleration) at the seafloor [5, 6]. Compliance is applied at frequencies from about 2-32mHz where the surface gravity waves (long-waves) directly load the seafloor. Here we are studying seafloor noise in the band from about 50mHz to 10Hz, where the surface gravity waves are too short to excite seafloor deformations by direct loading in the deep ocean. In the compliance band, the seafloor deformations are "forced"; in our band, the seafloor deformations are dominated by propagating seismo-acoustic waves (for example, Rayleigh waves and higher order surface waves or modes).

This study should also not be confused with work on tidally induced pore pressure variations and seafloor displacements [7-10]. At the low frequencies of the applied loads in both the tidal and compliance studies it is sufficient to assume static loading, there are no propagating acoustic or seismic waves. At the frequencies of this study (above 0.045Hz), there are clearly propagating Rayleigh waves (at the primary and double frequency microseisms for example) as well as propagating acoustic energy in the ocean (at frequencies above the microseism peak where we observe the sediment resonances and organ pipe modes). Models for seismo-acoustic propagation in porous media exist which include the effects of porosity, fluid viscosity, pore geometry and tortuosity [11, 12]. Although considering porous media effects may be necessary at some point in the future, for now we consider it an unnecessary complication.

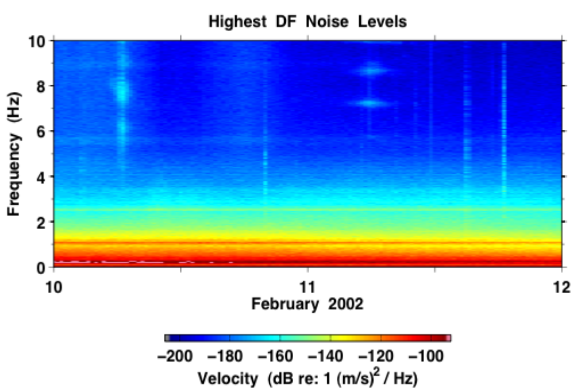

Fig. 4a. The vertical velocity spectrogram for the 0-10Hz band at H2O is shown for the February interval in Fig. 3 (the JOIDES Resolution is no longer at the site). The resonance peaks at 1 and 2.5Hz (see Fig. 2) are shown to persist throughout the two-day period. However, the amplitude of the 1Hz peak appears to be decreasing with time.

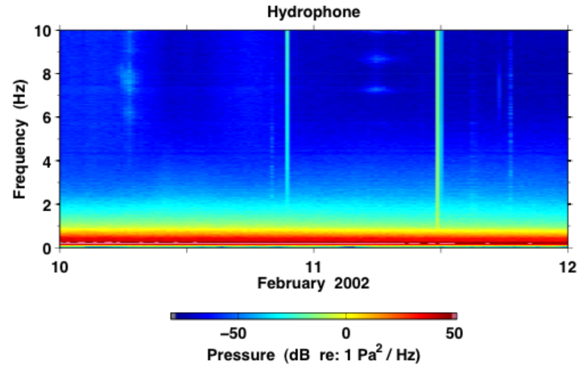

Fig. 4b. The pressure spectrogram corresponding to 4a. The strong 1Hz peak in vertical velocity is not apparent in pressure during this time period. This is strange since normally pressure is correlated with particle velocity (for example, for Rayleigh waves on the seafloor or for acoustic waves in the water column).

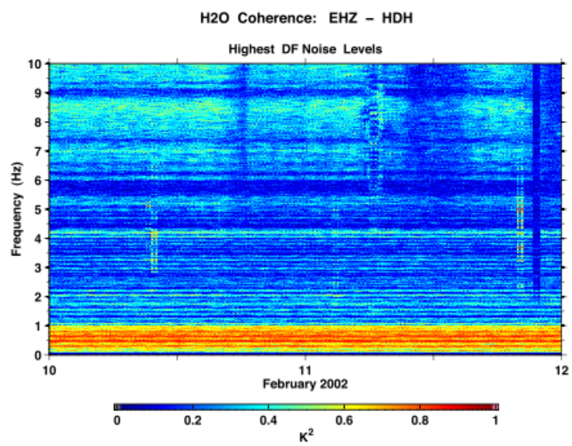

Fig. 4c. Coherence grams for the vertical velocity and pressure data in 4a&b show consistent bands from 1 to at least 4.5Hz. The coherence behavior seems to be independent of the resonance peaks in the spectra. Some sediment peaks are coherent and others are not. The time-domain finite-difference (TDFD) method (Fig. 6) is a useful tool to study the effects of basement roughness and subseafloor heterogeneity that may be responsible for this effect.

II. SEDIMENT RESONANCES

Shear wave resonances (or Scholte modes) occur primarily in the "Holu" spectrum between about 0.2 and 20Hz [13]. Analysis of shear resonances in impulsive source marine data has been carried out by Whitmarsh and Lilwall [14], Schreiner et al [15, 16], Caiti et al [17], Ewing et al [18], Bromirski et al [19] and Nolet and Dorman [20]. Analysis of shear resonances in horizontal component ambient noise was first carried out by Butler [21] using data from the OSS IV borehole seismic experiment in DSDP Hole 581C [22]. Butler assumed a homogeneous sediment layer and showed good agreement between shear velocities (210m/s) from seismic refraction results and from the cepstral analysis of the resonances. Dorman et al [23] also demonstrated, by forward modeling of modes, the importance of depth dependent shear structure in the sediments on ambient noise above the microseism peak.

An inversion method for estimating shear wave properties in depth dependent sediment models using ambient horizontal component noise data has only recently been proposed by Godin and Chapman [24, 25]. This theory is based effectively on the analysis of scalar waves in a laterally uniform waveguide. Thus, the role of Scholte (or interface waves) is not included. Since the wavelength of 0.5Hz shear waves in soft sediments (say Vs=200m/s) is 400m or more, it could easily exceed the thickness of the sediment layers, which are typically 300m or less in most deep ocean basins. One would expect a full wave theory that includes interface wave effects to be more appropriate in this environment.

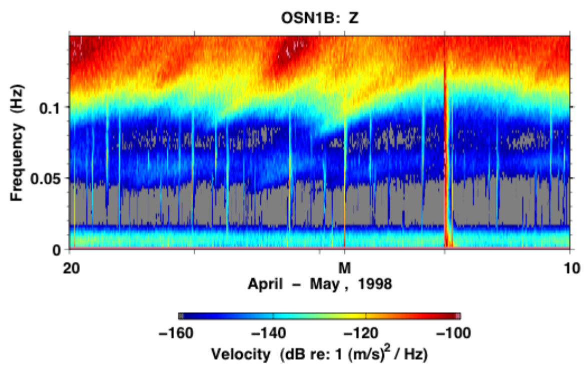

Fig. 5a. The vertical velocity spectrogram for the buried receiver at the OSNPE site.

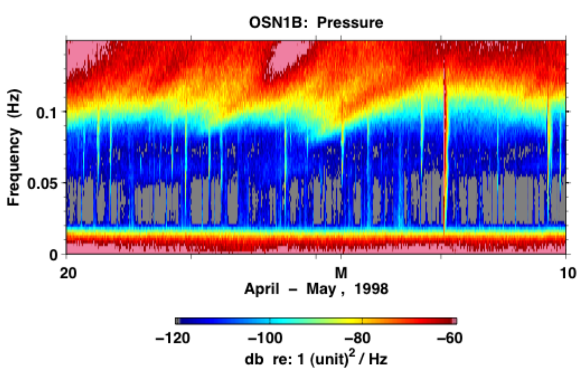

Fig. 5b. The pressure spectrogram for the OSNPE site.

Shear wave structure can also be inferred from ambient pressure and vertical component noise using the compliance method first proposed to estimate the shear modulus versus depth in the seafloor by Yamamoto and others [26, 27]. The compliance method was also modeled by frequency domain finite differences by Crawford et al [28] and they applied the method to analysis of data at frequencies below the microseism peak (less than 0.05Hz).

III. MICROSEISMS AND ORGAN PIPE MODES

Seafloor noise levels result from local to regional ocean gravity wave interactions in the open ocean above about 0.20Hz (the short period double-frequency microseisms) and also from similar wave-wave interactions at distant shorelines in the

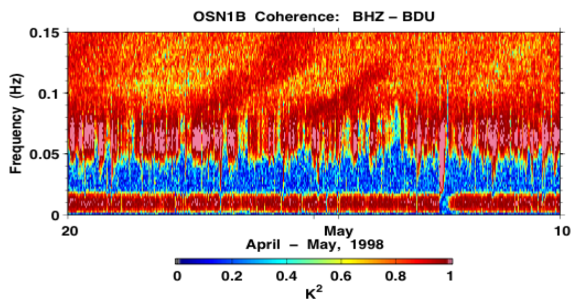

Fig. 5c. The coherence gram for the buried receiver at the OSNPE site. Note the high coherence, usually associated with surface waves, in the 0.05-0.08Hz band, even though the spectral amplitude is low. The short duration, somewhat broadband coherence peaks that extend below 0.05Hz result from earthquake surface wave arrivals, clearly observed for the event on about May 5. The high coherences in this band occasionally persist for many consecutive hours (e.g. on about April 25), suggesting that some events are not associated with earthquake signals. These are "primary microseisms", generated by direct loading in shallow water at the Hawaiian Islands or other more distant coastlines and are propagating to the site [2]. The two big coherence bands sloping upward to the right in the middle of 5c result from "double frequency microseisms". These are also Rayleigh surface waves, but they are excited by wave-wave interaction near shorelines. They are dispersed because the incident gravity wave field at the coast where they are generated is dispersed. (Note that the change in frequency is occurring over days.) The first arriving waves at the coast generally have higher amplitudes, which could explain the higher coherence early in the wave train. Are the primary and double frequency microseisms being generated at the same time and place, or are there specific locations which favor generation of each type?

0.085-0.20Hz band (the long period double frequency microseisms) [2], with primary microseisms also generated coincidentally at these coastal locations in shallow water (about 0.040-0.085Hz). Wave-wave interactions at higher frequencies up to about 6Hz (the Holu spectrum) and acoustic noise from breaking waves overhead [13] also contribute to the seafloor noise spectrum. Sediment resonances and associated coherence bands observed between pressure and vertical velocity appear to result only from locally generated noise.

Bradner and Dodds [29] observed peaks in spectral levels on seafloor vertical seismometers that they associated with leaky organ pipe modes in the water. They observed many more peaks in the band 0.1 to 10Hz than we have seen in more modern spectra and it is not clear how many of these peaks were instrument-related resonances. They associated the peaks with "organ pipe modes" in the water, but the frequency separation of these modes was about half a Hertz, much broader than 0.2Hz banding that we are seeing in the coherence (in comparable water depths).

Bradner's peaks were later modeled by Abramovici [30] using laterally homogeneous structures and thick uniform layers to represent the ocean, sediments and crustal structure (no SOFAR channel, for example). Abramovici did include shear wave resonances (modes) in his analysis.

Later, Bradner et al [31], using vertical velocity

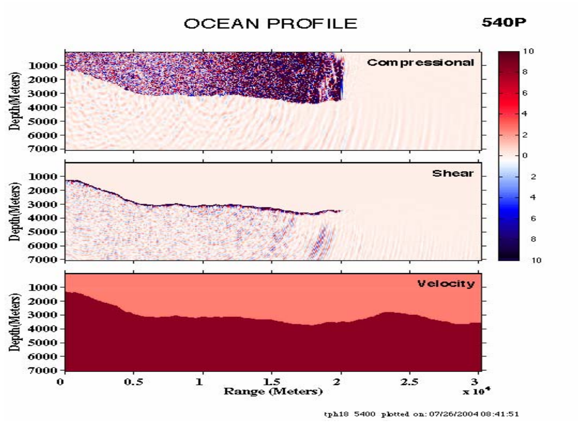

Fig. 6. This figure summarizes a two dimensional time domain finite difference calculation that can be used to study the physical mechanisms of scattering, resonance and propagation in a rough and sedimented seafloor environment [33, 39, 40]. The top two frames show the compressional and shear amplitude density computed for a point source in the water column with a dominant frequency of 10Hz out to ranges of 30km. The top of the model is a free surface; the water consists of a laterally homogeneous sound speed profile (SOFAR channel). The bathymetry is taken from an actual profile near the Kane Fracture zone and a 100m thick sediment layer with a shear velocity of 250m/s has been laid on top of the basaltic basement. The complexity of the resultant wave field even for a simple source is quite impressive.

from a free floating Swallow float as a proxy for seafloor pressure, showed a coherence plot (their Figure 10) that is remarkably similar to the coherence plots in Fig. 3 and 4. Of course they did not have the long time series with which to demonstrate the robustness of these features. They tried to compare the observed frequencies with Abramovici's model, but even Bradner admits "the agreement with organ pipe modes may be illusory."

We are now in a position to improve on Bradner's and Abramovici's work. We have buried and borehole sensors in addition to seafloor sensors with which to check for instrument resonances. We also feel that introducing gradients in the ocean sound speed profile (the SOFAR) channel and in the sediments and upper crust will modify the behavior of the coherence bands. And we have the ability to predict the effects of scattering and lateral heterogeneity with methods like TDFD (Fig. 6).

The early observations of shear wave resonances and coherence banding were based primarily on observations in relatively short duration experiments. However, with the development of permanent, broadband seafloor seismic observatories, long time histories of the resonances over a range of weather and sea state conditions have been obtained. The OSN Pilot Experiment, for example, is a rich data set with over four months of data on closely spaced seafloor, shallow buried, and borehole broadband sensors [4]. The shallow buried broadband sensor at H2O [1-3] has yielded a nearly continuous 3.5 year record from 5 October 1999 to 26 May 2003. These are ideal data sets for techniques that use the ambient noise field to infer properties of the surrounding sediments and crust. A review of the ambient noise field across the whole band from 1mHz to 10Hz has been presented by Webb [32].

IV. TIME DOMAIN FINITE DIFFERENCES

Since the sediment-basement contact is notoriously rough and laterally heterogeneous over a broad range of length scales, models that assume laterally homogeneous structure could easily be ignoring important physical scattering mechanisms which couple energy between high and low horizontal wave numbers (angles of incidence). The time domain finite difference method is becoming a popular technique for obtaining full wave solutions to complex wave equations (elastic, anelastic, poro-elastic) in range-dependent media (Fig.6).

Stephen and Swift [33] outline a Numerical Scattering Chamber approach that can be applied to full-wave interaction in a two-dimensional vertical plane through the seafloor. In order to closely approximate plane waves, the horizontal wave number content of the incident field can be restricted by using Gaussian pulse-beams [34]. The method has been extended to include the effects of anelasticity [35] and poro-elasticity [36].

IV. CONCLUSIONS

We have presented three poorly understood observations in the coherence between the pressure and vertical particle velocity of the broadband ambient noise field in the North Pacific: a) distinct strong coherence bands in the microseism spectrum from 0.05 to 1Hz, b) distinct intermediate coherence bands in the upper holu spectrum (punctuated with sediment resonances) from 1.0 to 10Hz, and c) the time dependence of coherence of the primary (PM) and long period double frequency (LPDF) microseisms in the 0.04 to 0.15Hz band. We hypothesize that the first two observations are dependent on the local structure of the sediments and crust surrounding the receivers and we propose that two-dimensional time-domain finite-difference methods are a suitable technique fro studying these processes in detail. The third observation could be useful in associating the observed ambient seismic noise field with the wave climate in the North Pacific.

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