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Spatial and temporal variations in acoustic propagation in Dabob Bay during PLUSNet'07 Exercise

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Abstract We present the spatial and temporal variability of the acoustic field in Dabob Bay during the PLUSNet07 Exercise. The study uses a 4-D (3-D in space with 1-D in time) data-assimilative numerical ocean model to provide input to an acoustic propagation model. The ocean physics models (primitive-equations and tidal models) of the Multidisciplinary Simulation, Estimation, and Assimilation System (MSEAS), with CTD data assimilation, provided ocean predictions in the region. The output ocean forecasts had a 300m and 1 to 5m resolution in the horizontal and vertical directions, at 3-hour time intervals within a 15-day period. This environmental data, as the input to acoustic modeling, allowed for the prediction and study of the diurnal and semi-diurnal temporal variations of the acoustic field, as well as the varying spatial structures of the field. Using the CSNAP one-way coupled-normal-mode code, along- and across-sections in the Dabob Bay acoustic field structures at 100, 400, and 900 Hz were forecasted and described twice-daily, for various source depths. Interesting propagation effects, such as acoustic fluctuations with respect to the source depth and frequency as a result of the regional ocean variability, wind forcing, and tidal effects are discussed. The novelty of this work lies in the possibility of accurate acoustic TL prediction in the littoral region by physically coupling the real-time ocean prediction system to real-time acoustic modeling. This work also offers an opportunity to study 4-D acoustic modeling in the future.
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1 Introduction

Acoustic propagation in shallow water is a challenging scientific and engineering research topic and an area of major concern to the US Navy. Of particular interest is the influence of water column variability on acoustic propagation. In the recent Persistent Littoral Undersea Surveillance Network (PLUSNet) 07 exercise in Dabob Bay, acoustic models, combined with the 4-D (3-D in space, 1-D in time) MIT numerical ocean models with data assimilation (MSEAS, including the Harvard Ocean Prediction System - HOPS) and seabed geoacoustic models were used to generate acoustic transmission loss (TL) reports on a daily basis. The joint ocean and acoustic predictions allowed for the investigation of acoustic TL fluctuations due to the regional ocean variation, wind forcing, (internal) tide effects for different source depths and frequencies. The novelty of this research is the real-time combination of the ocean prediction system, acoustic modeling and data assimilation.

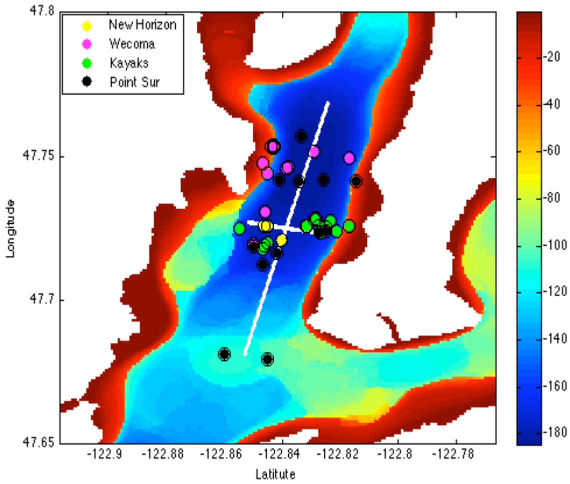

Figure 1: The bathymetry of Dabob Bay and CTD samplings' locations

2 The integration of ocean and acoustic modeling

2.1 Ocean modeling

Physical processes and variabilities occur in the ocean on millimeter to planetary space scales and on seconds to climate time scales; all of which may significantly affect acoustic propagation. It has been noted that spatial variability of the sound speed field will introduce difficulties in range-dependent acoustic propagation modeling. MSEAS with HOPS [1], ESSE [2, 5] and tidal modeling [6] provides the opportunities to research these problems. The ocean sound speed prediction was provided on a daily basis during the PN07 exercise at 3-hour time interval. To obtain accurate acoustic propagation modeling, the background sound speed profile is one of the most important factors. The acoustic modeling in this study is largely based on HOPS predictions to provide water column sound speed profiles. The geoacoustic model is provided by Naval Oceanographic Office (NAVOCEANO).

During the exercise, several research vessel and platforms conducted CTD measurements at various locations, depths, and times. An essential check of the validity of an ocean prediction system is to compare predictions to CTD measurements.

2.1.1 Sound speed profile variations

The PN07 experiment in Dabob Bay was an integrated experiment involving several different kinds of platforms, which included three surface research vessels (R/V Point Sur, R/V New Horizon, and R/V Wecoma), several Autonomous Underwater Vehicles (AUV) and Kayaks, and seven sea gliders. In Figure 1, we depict all CTD sampling locations during PN07 in Dabob Bay (except data from the Sea Gliders). The different color dots indicate the different platforms which conducted the CTD sampling. Four different platforms are listed: the three R/Vs and Kayaks.

The measured CTD profiles from each platform are shown in Figure 2. In each panel, there are two thick dark lines (red and black) in addition to other thin lines. The thin

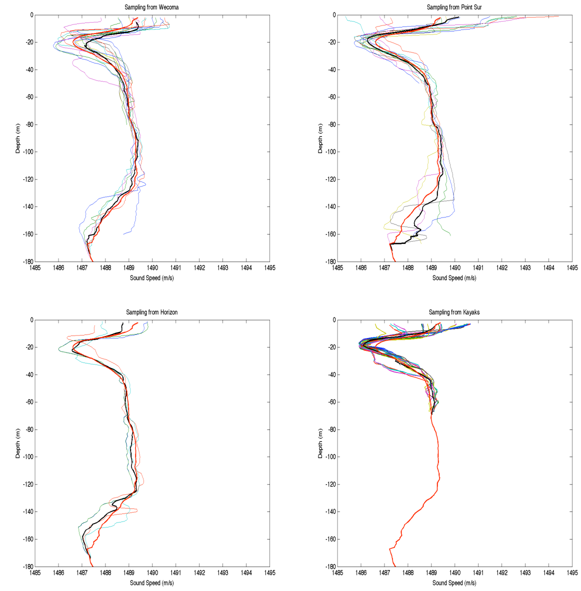

Figure 2: Sound speed profiles from different platforms

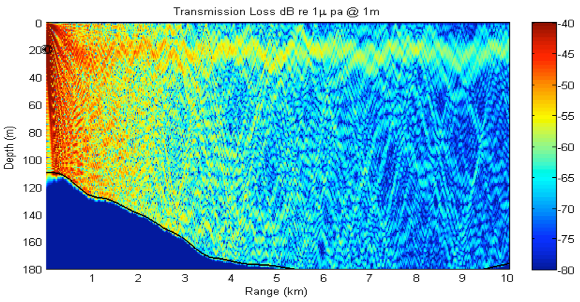

Figure 3: Acoustic TL modeling (900 Hz)

lines are the sampling from that platform. The black dark line is the average of the sound speed profiles from that single platform. The red dark line is the average of the all sound speed profiles.

The interesting finding from those sound speed profiles is the persistent sound channel at a depth of 20m during the PN07 experiment period. From the 50m to 120m depths there is an essentially constant sound speed background layer. In the center of Dabob Bay, the deep region from 120m to the bottom, there is another low sound speed region that attracts sound energy. However, since it is close to the bottom, most energy will be either reflected, absorbed or attenuated by the bottom layer. Therefore, the sound channel at the near-surface depth of 20m is the dominant sound channel for acoustic transmissions in the Dabob Bay. It can lead to significant sound attenuation, especially in "summer effect" conditions when the sea surface is heated and with characteristics of "quiet, near glass-like". The reported difficulty of underwater communication during the exercise on Oct. 10th was possibly a result of this effect. An illuminating example for the sound propagation is shown in Figure 3. As shown, the sound energy is mainly trapped in that sound channel at depth of 20m for the frequency of 900 Hz.

To evaluate the MSEAS-HOPS output, we first compared CTD data to predicted sound speed cross sections, averaged over a day. In Figure 4, we show two examples of these comparisons on Oct 4th and 7th during the experiment. The left panel shows the bathymetry map of Dabob Bay and the CTD samples locations with different colors indicating the different platforms. The right top two panels show the sound speed section along/across Dabob Bay from the output of HOPS. The right bottom panels show the average sound speed profiles from HOPS and the CTD samplings from different platforms, respectively. In general, the HOPS prediction captured the most prominent character of 20m depth sound channel and near bottom sound channel, but it lacks some details when compared to CTD samplings. This is in part due to the averaging and to the limited ocean data in the region.

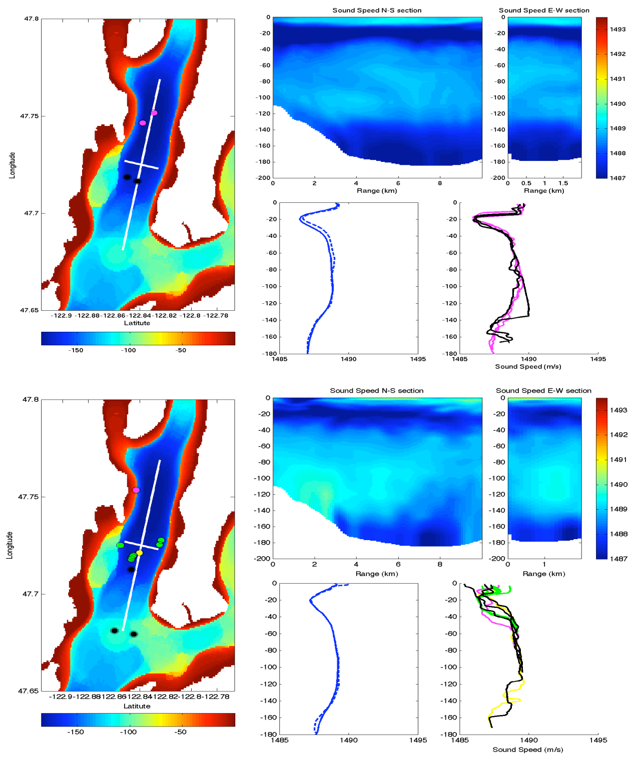

Figure 4: Comparison of sound speed profiles between the CTD data and HOPS output on Oct. 4&7th.

2.2 Acoustic modeling

The normal modes code used here is called the Coupled SACLANTCEN normal mode propagation loss model (C-SNAP)[3]. It was developed as a range-dependent propagation loss model by Ferla, *et al.* on the base of a widely used and efficient range-independent normal mode code, SNAP, and a numerical solution technique for one-wave mode coupling obtained from KRAKEN. Despite the great achievements obtained with fast field and parabolic equation models, normal mode programs still remain a very efficient, simple, and practical tool for describing ocean acoustics in range-independent environments. C-SNAP generalize the range-independent problem to a range-dependent one by dividing the propagation path in a sequence of range-independent segments and using normal modes to represent the acoustic field in each segment. It uses a finite-difference algorithm to solve for the range-independent problem and assumes that the acoustic field is dominated by the outgoing component. To preserve accuracy, an energy-conserving matching condition is implemented at the coupling interfaces.

3 The variation of acoustic transmission loss in Dabob bay

3.1 Acoustic transmission loss with different geoacoustic model

Accurate acoustic propagation modeling requires knowledge of the bathymetry as well as the sediment geoacoustic properties. In addition to bathymetric data, NAVOCEANO generously provided sediment data in the form of HFEVA sediment types for Dabob Bay. The sediment types were translated into grain size and gridded. Sediment thickness varies greatly throughout Dabob Bay due to its complicated geologic history. However, Helton's 1976 report on the Dabob Bay Range notes that the unconsolidated sediment varies to at least 4.5 feet (1.3716 m). Lacking seismic reflection or similar ground-truth data, this value was adopted as a uniform sediment thickness in one of our geoacoustic models.

For the bottom layer, a grain size of 0 phi was chosen based upon Helton's report about: "...whatever the state of the surface sediment veneer (loose, hard, or dense/compacted), a harder underlaying layer most generally begins 3 to 50 feet below the mudline (contact with water) and consists of glacial till." Till is associated with moraines which has a sound speed ratio of 1.3 [4] . Similarly, the HFEVA "Muddy Sandy Gravel "sediment classification has a sound speed ratio of 1.2778 and a grain size of 0.

	Silt-Clay Model	HFEVA Model	unit
Sediment Depth	2	1.3716	m
Sediment Density	1.376	1.7922	g/cm^3
Sediment Attenuation	0.6	0.128	dB/λ
Sediment Sound Speed	1522	1509	m/s
Bottom Density	2.5	2.08	g/cm^3
Bottom Attenuation	0.1	0.37	dB/λ
Bottom Sound Speed	2000	1764	m/s

Table 1: Seabed properties of two geoacoustic models

Two geoacoustic models were tested during PN07. One geoacoustic model was a rough estimation from historical data, which is isotropic 2-meter deep silt-clay sedimental layers on the hard bottom. The other was the HFEVA model, which is much closer to the real seabed bottom. These two geoacoustic models' main parameters are listed in Table 1.

In Figure 5, we show an example for the frequency of 900 Hz, at source depth of 40m. The lower panel shows the comparison of acoustic TL at the receiver depth of 8.4m. These comparisons show the critical sensitivity of acoustical TL to the seabed bottom properties.

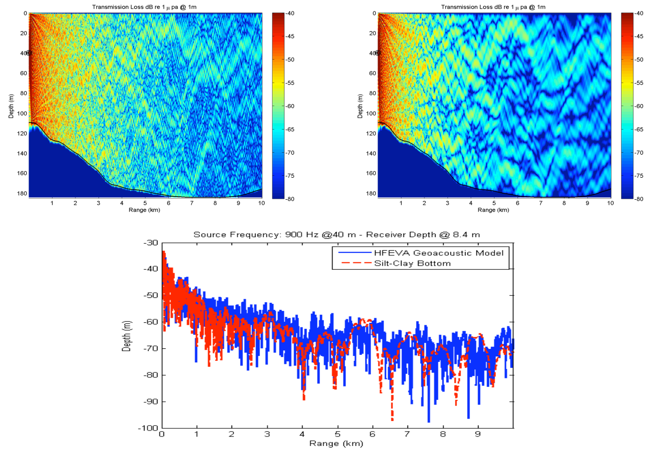

Figure 5: Acoustic TL prediction for 900 Hz source at depth of 40 m, for two different seabed.

The acoustic transmission loss calculations based on these two geoacoustic models are preformed by CSNAP. The TL prediction is based on the narrow band model with frequency range from 100 Hz to 900 Hz, at varied depth of 20m, 30m, and 40m.

3.2 Acoustic transmission loss variation during the 7-day experiment

The ocean sound speed section is obtained from HOPS ouput of temperature, salinity, and pressure. The sections along Dabob Bay with sound speed are shown in Figure 6. These are displays for 6 continuous days, from October 5th to October 10th, with a sample for each day. The prominent characteristic is the warm surface layer. In the fourth day (right central panel), this warm surface layer started to disappear due to the wind forcing. In the acoustic point of view, it leads to more refraction than surface reflection. The corresponding acoustic TL was calculated for different frequencies and source locations. Examples for the frequency of 100 Hz and 900 Hz at source depth of 20m, 40m and receiver depth of 27m are shown in Figure 7.

3.3 Acoustic transmission loss variation due to the wind forcing

We found that the lower frequency sound source (100 Hz) is much more sensitive to the wind forcing than higher frequency sound source (900 Hz). This wind forcing can be observed in Figure 6. There was a strong wind forcing process during the fourth and fifth days, which made the warm surface layer disappear in the following days. For the higher frequency sound source, the variation of acoustic TL is already perturbed by the random medium and not very sensitive to the upper boundary layer. We chose one particular receiver depth for the comparison of TL. The comparisons are shown in Figure 7.

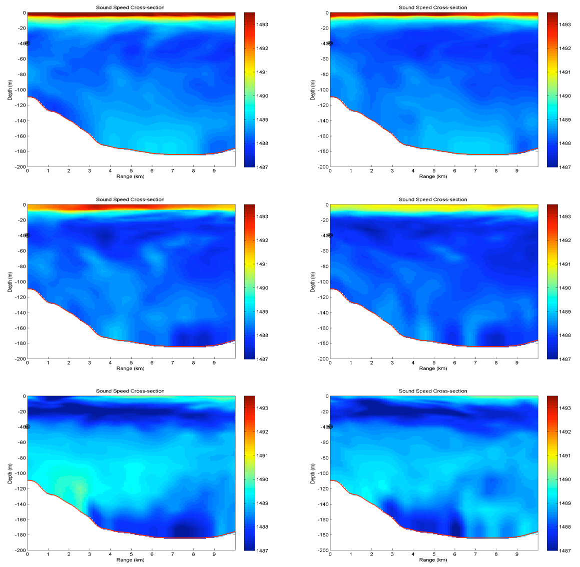

Figure 6: Sound fluctuation in continuous 6 days.

3.4 Acoustic transmission loss variation due to the tidal effect

To examine tidal effects on acoustic transmission loss, we utilized the MSEAS ocean outputs at 3-hour intervals over a 12 hour period, as shown in the four panels of Fig. 8 which are along-Dabob sections.

The acoustic transmission loss for these four different sections over one tidal period is calculated for different frequencies and source depths. Here, we plot the 100 Hz and 900 Hz cases, with two difference sound source depths at 20 and 40 m (see Figure 9).

Unlike the wind forcing effect, tidal effects do not seem to significantly spatially influence the acoustic TL prediction for the lower frequency source (100 Hz). However, for the high frequency sound source (900 Hz), the tidal effect seems to perturb the sound energy field without range dependence. While the wind forcing effect on the acoustic transmission loss apparently has some range dependence trend, such as the discrepancy increases as the distance increases in Figure 7.

The study of acoustic propagation in shallow water has to cope with the spatially and temporally varying environmental field. A useful output of the acoustic calculation is a statistical representation of the field variability, such as the TL spectra density as a function of time for given geographical regions and seasons.

Based on the output (temperature, salinity, and pressure) of 4-D ocean water column field of the Dabob Bay with 3-hour time intervals and 15-day duration, the frequency spectra of sound speed fluctuation is estimated for certain ranges and depths. The average is taken among all the spectra estimations, which is shown in Figure 10. The spectral peaks are associated with diurnal and semidiurnal tide and the higher order tidal harmonics. The frequency spectra of acoustic variables (intensity and phase) are shown in Figure 11 for different source frequencies (corresponding different rows: 100, 400, and 900 Hz from top to bottom) and depths (corresponding to different columns: 20m and 40m from

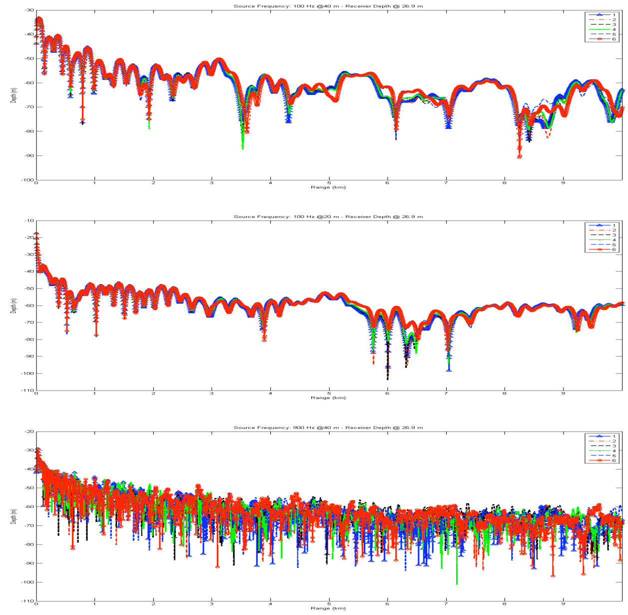

Figure 7: Acoustic TL prediction along the Dabob Bay for frequency of 100 Hz source depth of 40m (upper), 100 Hz source depth of 20m (center), and 900 Hz at source depth of 40m (lower); receiver depth of 27 m.

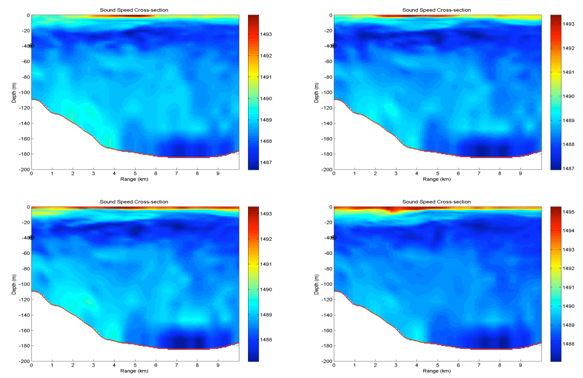

Figure 8: Sound speed fluctuation due to the tide effect in 12 hours period.

left to right). Apparently, tidal effects have much larger signatures in lower frequency and deeper source depth than higher frequency and shallower source depth.

4 Conclusion

The integrated study, based on our MIT-MSEAS ocean prediction and data assimilation and on CSNAP acoustics propagation, shows the possibility of providing real-time acoustic transmission loss in shallow water environments, which is critical to the US Navy sub-sea exercises. In this study, we found the that seabed geoacoustic model has a strong influence on the the acoustic propagation prediction. The coupling allows implementing range-dependent acoustic propagation modeling based on the spatial variations of the speed of sound provided by MIT-MSEAS. During the exercise, we provided such predictions in two sections (cross/along) of Dabob Bay. Here, we only discussed the along section of Dabob Bay.

We studied acoustic fluctuations due to wind forcing and to tidal effects. The wind forcing disturbed the surface layer and affected the acoustic transmission, which different responses for different frequencies. For the low frequency (100 Hz), the wind forcing induced TL fluctuations (10 to 20 dB) in the section. In fact, during the experiment, there were periods during which no acoustic signal could be received. An explanation is that the warm surface layer generated a perfect refraction mirror on the surface, concentrating the sound energy in specific paths. Once strong wind forcing started, the refraction layer was disturbed, making the sound energy scattered more when it encountered the rough surface.

Tidal effects did not affect acoustics transmission in the spatial dimensions as much as the wind forcing. An interesting finding is that tidal effects do not have a range-dependence as strong as the wind forcing, which means the wind forcing has a stronger local impact on the acoustic transmission. The frequency spectra analysis of sound speed fluctuations and acoustic variables fluctuations in the 15-day period showed the strong tidal signature in the lower frequency transmission.

More study needs to be carried out to get more quantitative measures of the acoustic prediction fluctuations due to the ocean water column fluctuations in the region. We hope to be able to obtain acoustic data to evaluate the acoustic predictions. We expect some discrepancies between measurements and predictions, in part due to the scattering by the rough ocean surface and bottom which were not accounted for.

Acknowledgments

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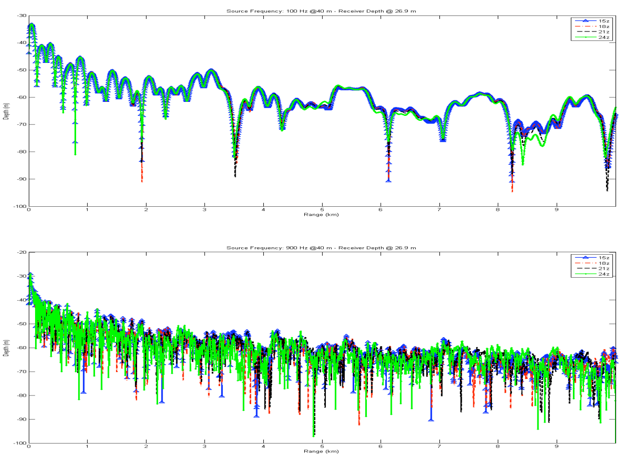

Figure 9: Acoustic TL prediction along the Dabob Bay for 100 and 900 Hz source at depth of 40m, and receiver depth of 27m.

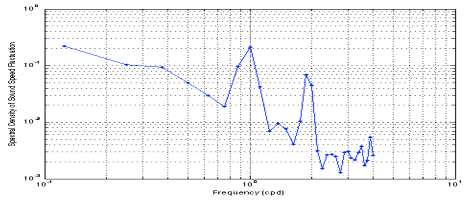

Figure 10: The frequency spectra of sound speed in Dabob Bay.

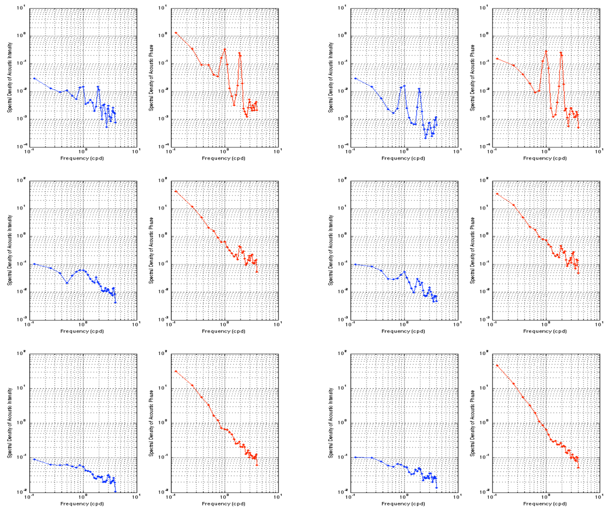

Figure 11: The frequency spectra of acoustic variables(intensity and phase) in Dabob Bay.

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