Impact of Thermocline Variability on Underwater Acoustic Communications: Results from KauaiEx

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Abstract. In July 2003, the KauaiEx, high-frequency acoustic experiments were conducted off the coast of Kauai, Hawaii. Both acoustic communications signals and probe signals (to measure the channel impulse response) were transmitted in the 8-50 kHz band. These signals were transmitted over several days from fixed and moving platforms and were received at multiple ranges and depths using vertical arrays and single hydrophones. Extensive environmental measurements were made simultaneous to the acoustic transmissions (e.g. measurements of the water column temperature structure, wind speed and surface wave heights). The experimental site has a relatively reflective seabed made up of sand that was combined with highly variable oceanographic conditions which led to communications performance closely tied to source/receiver geometry. In this paper, the correlation between environmental factors and communications performance will be discussed. The focus is on communications signals in the 8–13 and 14–19 kHz frequency bands at source receiver range of 3 km. Results show the performance in the higher band was approximately the same as for the lower band. Results also show a strong dependence on receiver depth with the deeper hydrophones having fewer bit errors. The ocean sound speed structure at this site appears to have a large impact on the communications performance and the time variability.

INTRODUCTION

During June and July of 2003, the KauaiEx series of experiments were conducted off the island of Kauai, Hawaii. These experiments were designed to measure the environment and simultaneously transmit acoustic communications waveforms over a period of several days. These tests involved both towed and fixed sound sources. In this paper, two topics are addressed: 1) the performance of underwater communications in the 8–13 kHz band as compared with the 14–19 kHz band and 2) performance over time to determine if environmental factors have a significant influence. The first topic, comparing frequency bands, is important since the ability to use higher frequencies implies having a larger available bandwidth (for obtaining higher data rates) and a decrease in the physical dimensions of sources and receiver arrays. The higher data rates are obviously important for many applications, but the smaller dimensions can be also be important as these systems begin to be installed on smaller platforms (e.g. autonomous underwater vehicles). The second topic, determining the impact of the environment on performance, is important for predicting when and where underwater communications systems will fail. Many of the environmental factors that influence performance can be either measured *in situ* or obtained through archival data. Knowing that particular environmental factors will cause a failure of communications systems may influence how, when or where a system is deployed.

In this paper, Multi-Frequency-Shift-Keying (MFSK) signaling is considered. MFSK is both simple and robust and for that reason it is currently used in commercially available modems. MFSK is robust because it is a non-coherent method (uses intensity and not phase of the signal) and this makes it valuable in uncertain operating environments. The main attraction of the coherent methods is their potential to more efficiently use the available bandwidth (i.e. obtain higher data rates). However, this comes at the price of more complex processing to overcome channel variability. In addition to being valuable in its own right, the simple and robust nature of MFSK signaling makes its performance a useful yardstick against which to measure other methods.

The first section of this paper describes one deployment from the KauaiEx experiments and the data that is used for the analysis. Both the environmental and acoustic communications signals are described. The next section shows the relationship between the water column temperature structure, the wind speed and communications performance.

KAUAIEX

Details of all the experiments during KauaiEx are described in Ref. [1]. In this paper, only the second deployment, which took place from June 30 to July 3, 2003 will be considered. The geometry for the experiment is shown in Fig. 1. Data analyzed here is from the testbed transmissions (Tx Testbed near the middle of the track) with the source located about 5 m from the seabed. The receiver array (MPL-VLA2) is about 3-km away had 16 hydrophones spaced 5 m apart with the first channel about 8.5 m from the seabed.

Environmental measurements

As can be seen from Fig. 1, there were extensive environmental measurements including: five strings of thermistor sensors to measure water column properties along the acoustic track, a waverider buoy to measure wave-heights, and an Acoustic Doppler Current Profiler (ADCP). Other geophysical measurements such as grab samples, seismic profiling and multibeam mapping were also made to help characterize the seabed. The entire data set is too large to consider in this paper so only a small amount of data will be discussed here with the main focus on the water column variability in the vicinity of MPL-VLA2.

The water column sound speed generally showed a region near the surface with a high degree of mixing due to the often windy conditions. The depth where the mixed layer ended and the thermocline began varied with location and time. In the left panel of Fig. 2 are 5 measured sound speed profiles taken during the 2nd deployment (on July 1, 2003). The mixed layer depth is 40–50 m for 4 of the profiles and decreases to about 20 m for one. In many locations around the world's oceans, the sound speed near the surface is highly variable responding to surface heating; however, in Kauai the mixing

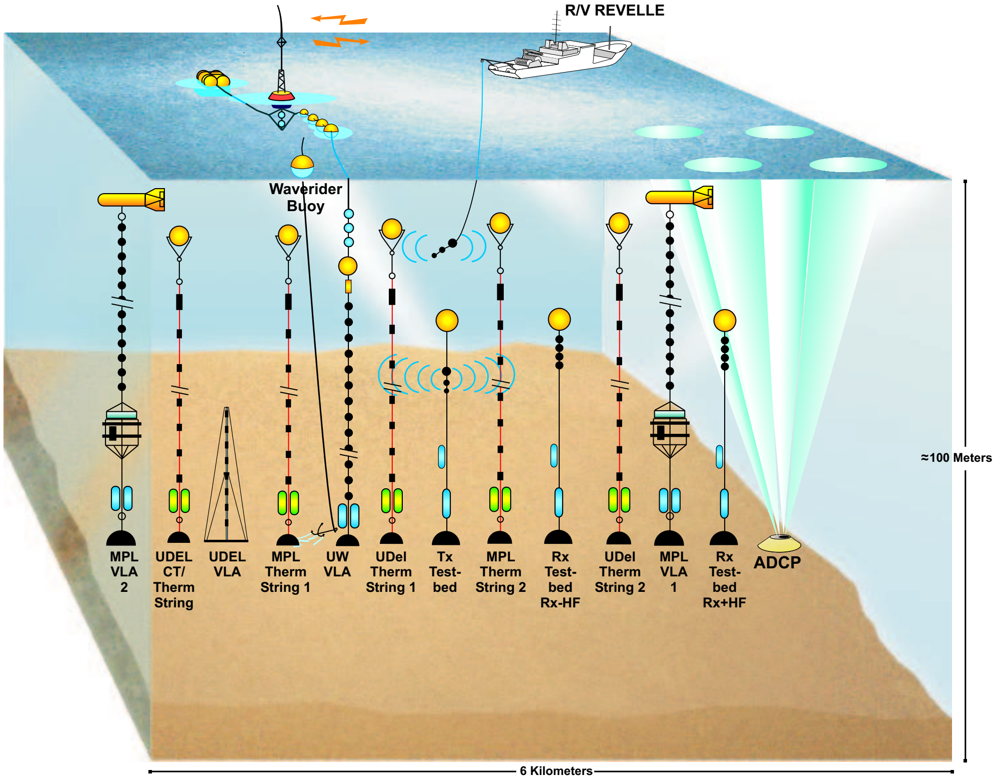

FIGURE 1. Experimental setup for the 2nd KauaiEx deployment (June 30–July 3, 2003). Data from the MPL-VLA2 (about 3 km from the moored source) is analyzed here along with measurements from the UDEL-CT/Thermistor string located about 500 m away. The VLA has 16 equally spaced hydrophones and spanned depths of 17–92 m.

causes the water near the surface to be more uniform with a high degree of variability occurring at greater depths. These sound speed profiles give a sense of the structure and variability, but the thermistor strings give a time history. In the right panel in Fig. 2, the data from the thermistor string nearest MPL-VLA2 is shown (labeled UDel CT/Therm. String in Fig. 1). There were 13 thermistors located at depths between 4 and 82 m. There is a clear, regular pattern evident in the thermistor data showing the thermocline depth moving up and down in the water column over time. The impact of these variations on the acoustic communications signals will be discussed in the next section.

MFSK transmissions

The MFSK signals considered here use two bands each with 128 frequency components spaced 40 Hz apart from 8 to 13.2 kHz and 14 to 19.2 kHz. We will refer to these as the low and mid bands. (An additional high band covering 25-50 kHz was also included in the experiment but is not discussed here.) The upper and lower 4 tones in each

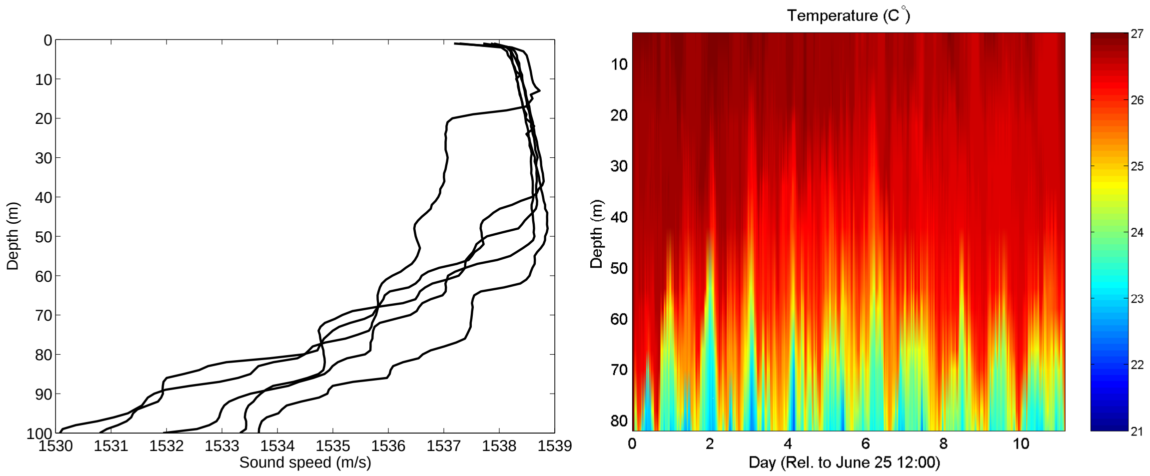

FIGURE 2. Left panel shows measured sound speed profiles taken on July 1, 2003 near the experimental site. Note the change in depth of the mixed layer. The right panel shows a time history of the ocean temperature during the experiment. This was from the UDel CT/Therm. string located near MPL-VLA2.

band are reserved for pilot tones to compensate for Doppler. The information is passed using a subset of the 128 frequencies that can be modified every 25 ms. One detail of the modulation scheme is the use of 1 of 4 coding. This means 4 tones are used to encode 2 bits of data. The advantage of this is that in decoding, only a decision about which of the 4 tones is loudest is needed to determine if the transmission is a 0-0, 0-1, 1-0 or 1-1. This method is less sensitive to intensity variations than having the decoder decide if a tone is a 1 (on) or 0 (off). Based on the frequency band used here, the maximum data rate in each band is 60 bits in 0.25 ms, or 2400 bits per second (bps) over each band (4800 bps total). To transmit at lower data rates, the time duration of the tones is increased (e.g. 1200 bps is achieved by holding the tones on for 50 ms).

Preceding the MFSK transmissions is an m-sequence that is used to determine the signal start. To decode the data, the receptions are matched filtered (with the replica m-sequence) to acquire the start of the signal and frame the MFSK transmission. A spectrogram is then taken of the MFSK portion of the time series using a non-overlapping boxcar window of 25-ms duration. The highest tone in each of blocks of 4 tones is then determined. Although errors can be reduced by coding the transmissions prior to transmissions (at the expense of data rate) this has not been done here and all errors reported are the raw bit errors. Channel coding improves the communications performance but then requires many more transmissions to collect the statistics required to interpret the environmental effects.

The overall performance of the different data rates in the two frequency bands is shown in Fig. 3. The left six panels shows the bit errors versus signal to noise ratio (SNR) for the low band and the right six panels for mid band. Within each band there are different data rates in each of the six panels. In general, both bands and all data rates follow the trend that better SNR leads to lower bit errors. On the other hand, there is also considerable scatter in the plots. As expected, the lower data rates show fewer errors for the same SNR.

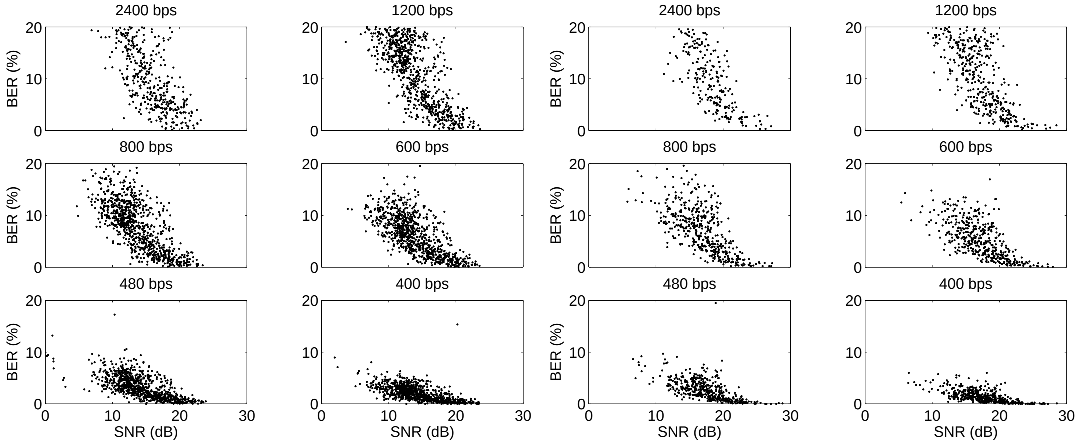

FIGURE 3. Bit errors as a function of SNR for different data rates in two frequency bands. The left six panels show the low (8–13.2 kHz) band at data rates of 2400, 1200, 800, 600, 480 and 400 bits/sec. The right six panels are the same for the mid (14–19.2 kHz) band.

One might expect that the higher frequency band would have poorer performance since volume attenuation tends to increase the transmission loss at higher frequencies. However, an analysis of the statistics shows that we actually obtained better performance in the higher band. There are many other factors at work that explain this. First, the source level was 1–2 dB stronger in the higher band. Second, the ambient noise is lower. Third, scattering losses are higher. That latter effect decreases the signal level but simultaneously decreases the intersymbol interference associated with multipath. Ultimately, a reliable channel simulator is key to predicting the performance. However, it is noteworthy that the higher band has both better performance and provides a more compact system (smaller projector).

Another interesting lesson from these tests was the performance improvement with hydrophone depth. This can be seen in the left panel of Fig. 4 where the bit errors as a function of depth are averaged over about 1 day (at the data rate of 2400 bits/s for both the low and middle bands). The improvement in performance with depth is mainly due to higher SNR at deeper depths although there was no indication the ambient noise level was strongly depth dependent. The deepest hydrophone at about 91.5 m shows about 5% bit errors while the most shallow hydrophone at about 16.5 m shows about 30%. This trend is seen both on the short and the long time scale. Shown in the right panel of Fig. 4 is the ambient noise at the center frequency of the two bands averaged over the 1 day of transmissions. There is only a weak depth dependence of ambient noise although the much reduced ambient noise level for the higher band is evident.

IMPACT OF OCEAN THERMOCLINE ON COMMUNICATIONS PERFORMANCE

We can gain insight into the temporal variability of performance by looking at the time history of the bit errors taken over 1 day (again for 2400 bps). The 24-hour period

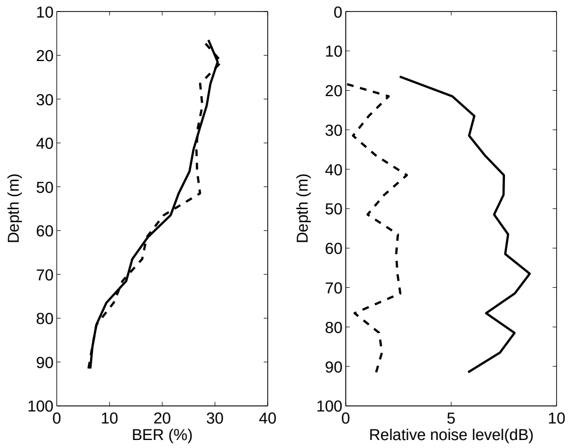

FIGURE 4. The left panel shows the depth dependent percent bit errors averaged over about 1 day of transmissions for the low band (solid) and the middle band (dashed). The right panel shows the corresponding ambient noise as a function of depth averaged over the same time period.

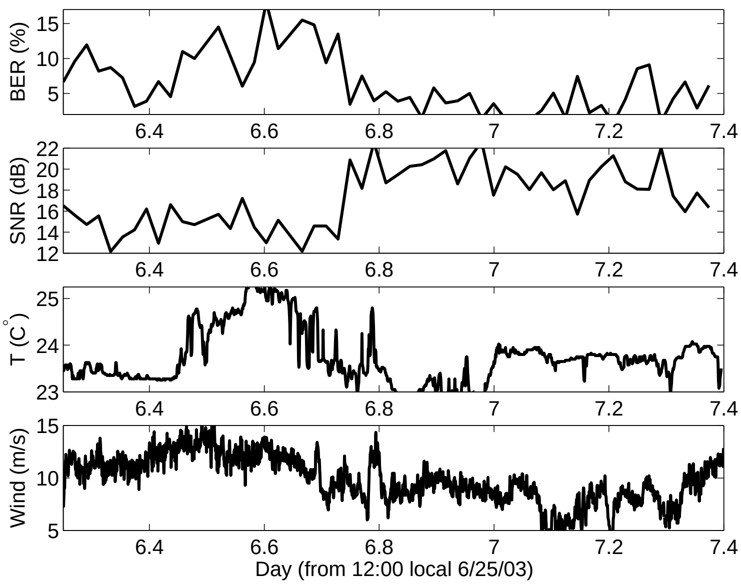

FIGURE 5. Top panel shows the percent bit errors for 2400 bps transmissions in the low band over about 1 day on the deepest hydrophone channel (91.5 m). Below is the corresponding SNR. The temperature at a thermistor located at 82 m depth about 500 m away is shown in the third panel. The lowest panel shows the wind speed during the same period. Days are relative to 12:00 on June 25, 2003 (local time).

is important since there are diurnal events both with the oceanography and with the winds. The top panel of Fig. 5 shows a time history of the bit errors on the deepest hydrophone channel (91.5 m). The panel below shows the corresponding SNR. The period between about day 6.4 and 6.8 shows a marked increase in bit errors. There is a rough correspondence with SNR especially near day 6.8 when the SNR increases and the performance improves. The lower two panels in Fig. 5 show the temperature and wind

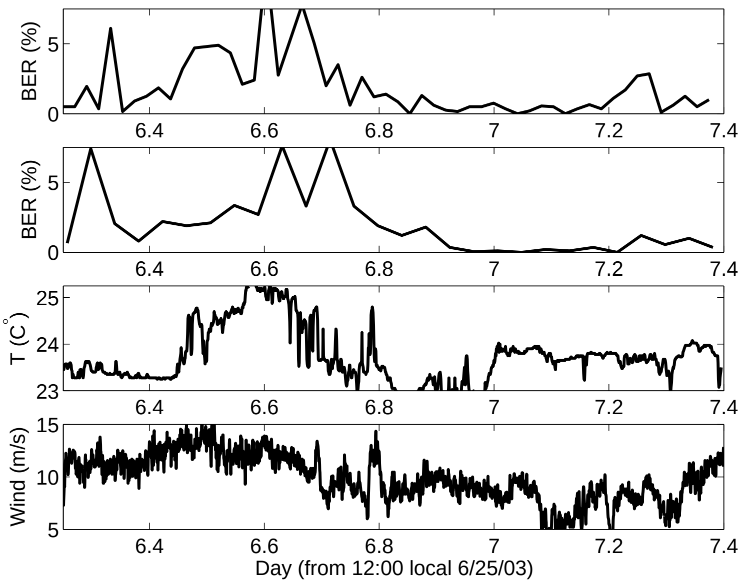

FIGURE 6. Top panel shows the percent bit errors for 2400 bps transmissions in the low band over about 1 day using a coherent average of the two deepest hydrophone channel (86.5 and 91.5 m). Below is the same for the mid band. The temperature at a thermistor located at 82 m depth about 500 m away is shown in the third panel. The lowest panel shows the wind speed during the same period. Days are relative to 12:00 on June 25, 2003 (local time).

speed during the same time period. During the period with increased bit errors there is a sharp increase in the water temperature and there is also some indication that the wind is changing during the same period. Wind increases generally cause the noise level to increase and this could be responsible for the decrease in SNR. However, if wind was responsible it is reasonable to assume the errors would show the same characteristics regardless of depth and this is not the case. For hydrophone channels in the mid to upper part of the water column where the water is well mixed there is no indication of bit errors increasing in this time period. Another example of the increases in bit errors during the period of day 6.4 to 6.8 is shown in Fig. 6. In this figure, channels 1 and 2 are combined coherently before decoding and the bit errors are therefore reduced. The top panel shows the results for the low band and below the mid band. The lower panels are again the temperature and wind speed. Although not conclusive, there appears to again be a correspondence between the increase of bit errors and the change in temperature. Also, note the end of the plot near day 7.4 where the wind speed begins to increase but there is no indication of increasing bit errors.

CONCLUSIONS

We have shown the performance of MFSK transmissions over 3 km in the 8–13.2 and 14–19.2 kHz bands. The two bands had about the same bit error rates for the same SNR, however, the higher band often had overall lower numbers of bit errors. This was due to a slightly higher source level of about 1–2 dB, but also due to a much lower ambient noise level.

There was also a marked difference in the performance in both bands as a function of receiver depth. The receivers near the sea-surface had the worst performance and, again, this was closely tied to differences in SNR as a function of depth. The ambient noise level did not seem to increase with depth and the loss of SNR is attributed to lower signal received at the shallower depths. In addition to correlation with SNR, there are indications that during certain periods when the water column becomes mixed throughout the water column the performance decreases on the deepest hydrophones. Future work will include acoustic modeling to determine if the observed time changes in the ocean sound speed structure can account for the observed changes in signal level over depth and time.

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