DOPPLER DOMAIN DECOMPOSITION OF THE UNDERWATER ACOUSTIC CHANNEL ARRIVING PATHS FOR THE CALCOM'10 EXPERIMENT

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ABSTRACT

Underwater communication offers great challenges for the researchers due to its time variable channel. In recent literature many methods are proposed for tracking these time variable channels, however robust algorithms are required since there are situations where the actual ones fails without any obvious reason. In deep water the underwater communication channel is characterized by a long multipath spread where each of the paths is affected by different environmental variation. The Doppler spread function enables us to understand these changes by analysing instantaneous time spectrum variability. To study the effects of environmental variations an isolated path is analysed by computing its Doppler spread spectrum. By inspecting the Doppler spread spectrum for different time windows an interesting behaviour is observed which is expected to be due to surface waves. Surface waves affect the Doppler by shortening and stretching the path between the transmitter and receiver. In this paper we have processed CALCOMM'10 sea trial data which took place from 22nd to 24th of June at the south coast of Portugal.

Keywords: Underwater Communication, Signal Processing, Doppler

I. INTRODUCTION

Underwater communication is one of the most challenging areas of research in the field of communication and signal processing. One of the most important factors that make underwater communications a challenging task is the time variability of the underwater channel that is due to: tides, currents, transmitter/receiver motion, surface motion and internal waves, among others. Due to this factors it is very difficult to estimate the underwater channel impulse response (IR) during data transmissions and adaptive receivers are required to track channel variations and deconvolve the transmitted sequences [1-2]. Those adaptive algorithms minimize the mean square error between the emitted signal and its estimation by updating the taps of the equalizer. However they do not take into account explicitly the variations due to channel's environmental properties and sometimes without a known reason fail to track the channel. With the objective of a future understanding of how the environmental variability affects the underwater communications adaptive algorithms, this paper presents a preliminary work where the channel environmental properties variability is analysed using the Doppler spread function.

The underwater channel can be modelled as double spread signal which means that the received signal is dispersed both in time and frequency. In time-domain the channel multipath causes a delay spread that can be estimated by pulse compressing the transmitted signal, resulting in a channel impulse response estimate in a given instant of time that spreads along a delay axis. In the frequency-domain the channel variability causes a Doppler spread that can be estimated considering several IR estimates along time and computing the Fourier transform of those channel-samples along the time axis. These dispersions/spreads mainly depend on the operating frequency, propagation conditions and channel geometry. In current literature the Doppler spread is used to estimate a number of underwater environment parameters. In [3] the Doppler was used to estimate the sea surface by calculating the amount of Doppler shift in the surface reflected signal. In [4] a Fourier-based Doppler estimator was used to estimate the Doppler shift in the frequency of a pilot tone on each path of the multipath channel and this information was further used to estimate the time-delay spread. In this paper the Doppler spread of a single arriving path is analysed and it was found that it can be composed of more than one Doppler shift due to combination of direct path and surface reflected path.

The underwater channel is characterized by a long multipath spread where each of the paths is affected by different environmental properties variations. For example: (i) the direct path Doppler spread is mainly due to the receiver/transmitter motion or to the internal tides; while (ii) the surface reflected path Doppler spread receives a strong contribution of the surface motion. Due to the channel geometry it can happen that the direct and the surface reflected paths arrive to the receiver simultaneously (i.e. with the same delay) contributing destructively to the acoustic field due to their phase differences. Such phenomenon strongly affects underwater communications since the data sequences transported by each path contribute destructively at the receiver side (and poses a significant challenge to equalizers since they track a receiving path that is in fact composed by two paths with different dynamics). The existence of those simultaneous paths can be easily identified in simulations with sound propagation models since they allow the direct computation of the delay and phase of each path. Nevertheless with real data IR estimates the simultaneous arriving of the two paths is not visible. However the Doppler spread of the two paths is different since they are affected by different channel dynamics resulting that in the Doppler domain the two paths can be tracked independently.

In this paper we have isolated each path and observed its Doppler spread. The attained Doppler is then compared with the environmental variability. For this analysis we have used the data from the CALCOMM'10 experiment which was conducted at Vilamoura, in the south of Portugal from 22nd to 24th of June 2010. The paper is organized as follows; in Section II we will present some theoretical and mathematical analysis of the problem. In Section III the environment in which the data was collected and specification of the transmitted signals are presented. Doppler spread results will be presented in Section IV and Section V will conclude the paper with some conclusions and future work.

II. THEORETICAL BACKGROUND

Figure 1 shows a ray trace drawing of an acoustic underwater propagation. Starting from the left the source transmits an impulse $\delta_p(t)$ that will reach the hydrophone by a number of paths (with different delays) which includes watercolumn refracted, bottom and surface reflected paths. The watercolumn refracted paths are due to the sound speed profile C(z,r) which is a function of depth and range. Due to number of paths, it results a complex IR structure composed of paths with different delays and due to the channel environmental properties variation each path is affected by a different amount of Doppler.

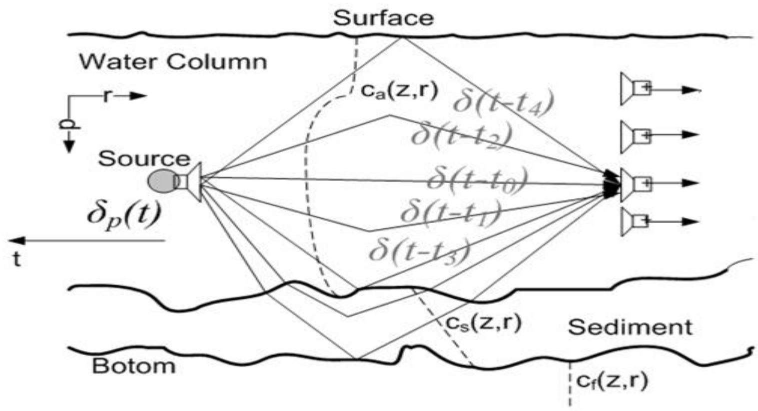

Figure 1. Underwater Environment with source transmitting impulses which reach the hydrophone array through different paths

Doppler distortion is usually analysed as a compression/expansion of the received signal. However it was shown that it can be analysed at the path level since [5]

$$h_{mp}(\mathrm{t},\mu) = \mathrm{g_{mp}}\left(\mu + (\mathrm{t}-\mu)\frac{\mathrm{v}}{\mathrm{c}}\right)\mathrm{e}^{\mathrm{j}\omega_\mathrm{c}\left(\mu+(\mathrm{t}-\mu)\frac{\mathrm{v}}{\mathrm{c}}\right)} \quad (1)$$

where $g_{mp}(t,\mu)$ is a single path, p, propagating between the source and the hydrophone, m, transmitted at an instant $t = 0$ and received at the hydrophone after a delay μ. Due to the channel properties variability the length, $l_p(t)$ of the path changes with a velocity $v = \partial l_p(t)/\partial t$. The ratio between such velocity and the sound speed, c, induces a delay variation in the g_{mp} argument and a frequency shift given in (1) by the complex exponential. Such frequency shift is responsible for the Doppler spread that also depends on the central frequency, ω_c, of the narrowband transmitted signal.

Equation (1) represents a time variable IR for a single path which can be easily generalized to p paths by

$$h_m(t,\mu) = \sum_p h_{mp}\delta(\mu - \mu_{mp}) \quad (2)$$

where $h_m(t,\mu)$ incorporates all the Doppler experienced by the m^{th}hydrophone of the array due to all arriving paths.

Figure 2 shows an example where a surface suspended array receives a signal transmitted by a fixed source. For clarity only the direct path and a surface reflected path between the source and the hydrophone are shown. Considering that the only environmental variability is due to the surface motion it results that there will be a Doppler induced in both paths. In fact, the direct path p_1, will be affected by the up-down and range movement of the surface suspended array that will result in a velocity, v_1, of the path , p_1. The surface reflected path p_2, is affected by the array motion and by the surface motion at the location where the surface reflection occurs resulting in a velocity , v_2, for path , p_2. As it was mentioned before such velocities are a function of the paths length variability and their sign is positive when the path enlarges and negative if the path become shorter. When a signal is transmitted in such channel the largeness / shortness of the path makes a corresponding expansion / compression of the received signal that is given by [6]

$$\Delta f_D = \omega_c \beta \tag{3}$$

where β is the expansion/compression factor given by

$$\beta = \frac{1}{1 - {}^{v}/_{c}} . \tag{4}$$

Putting the value of β from (4) in (3) it results

$$v = \frac{c \Delta f_D}{f_c + \Delta f_D} \tag{5}$$

that relates the velocity with the corresponding Doppler spread Δf_D.

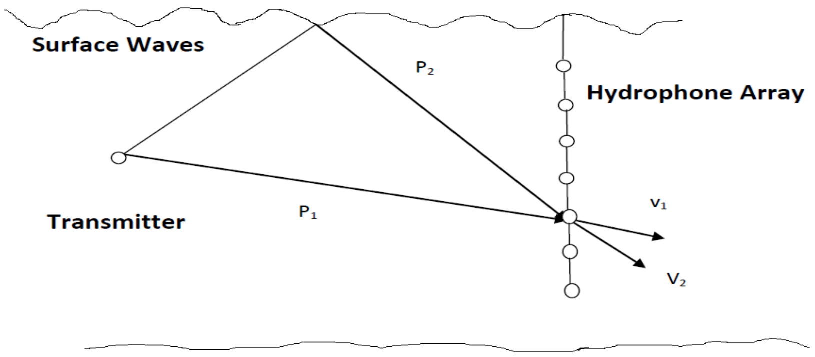

Figure 2.Two arrivals from transmitter to the receiver and their velocity projections

III. EXPERIMENT DESCRIPTION

The data for analysis was collected during the CALCOMM'10 experiment, which took place off the south coast of Portugal, about 12 nautical miles south east of Vilamoura, from 22nd to 24th of June 2010. The main objectives of the experiment are to collect field calibration data for tomography purposes and transmit communication signals in different frequency bands to analyse the performance of underwater communication systems.

The acquisition system used for gathering the data comprises two acoustic oceanographic buoys (AOBs), one with 8 hydrophones and the other with 16 hydrophones. There are two sources of transmission for low and high frequency named AERU and PASU respectively [7].

The data presented in this paper was taken on Day 2 of the experiment from the 16 hydrophone array in which all the hydrophones are equally spaced at 4 m. We will be focussing mainly on the communication signals transmitted during the experiment. Some details about the different transmitted signals during the experiment are shown in table 1.

Code	Type	Duration (sec)	Baud Rate (bps)	Start-stop freq. (kHz)	Silence at the end (sec)	Sampling Freque-ncy
LF_AERU1	LFM	0.1	-	2.64-3.75	0.2	50000
MF_AERU1	LFM	0.1	-	5.0-7.0	0.2	50000
MF_PASU1	LFM	0.1	-	5.0-7.0	0.2	44100
HF_PASU1	LFM	0.1	-	10-15	0.2	44100
LF_AERU2	QPSK	30.2	500	2.9-3.5	0.2	50000
MF_AERU2	QPSK	30.2	1000	5.5-7.0	0.2	50000
MF_PASU2	QPSK	30.2	1000	5.5-7.0	0.2	44100
HF_PASU2	QPSK	30.2	2000	11.0-14.0	0.2	44100

Table 1. Signal Specification for the CALCOMM'10 Experiment

Figure 3a) shows a down refracting sound speed profile measured during the experiment. Figure 3b) shows the source and receiver locations during data transmissions plotted over the bathymetric map of the area where the experiment took place. During the data transmission analysed in this paper the source array distance was around 850 m with a downslope bathymetry, the source was located at about 12 m depth and the first hydrophone of the array was located 6.3 m from the surface.

(a) (b)

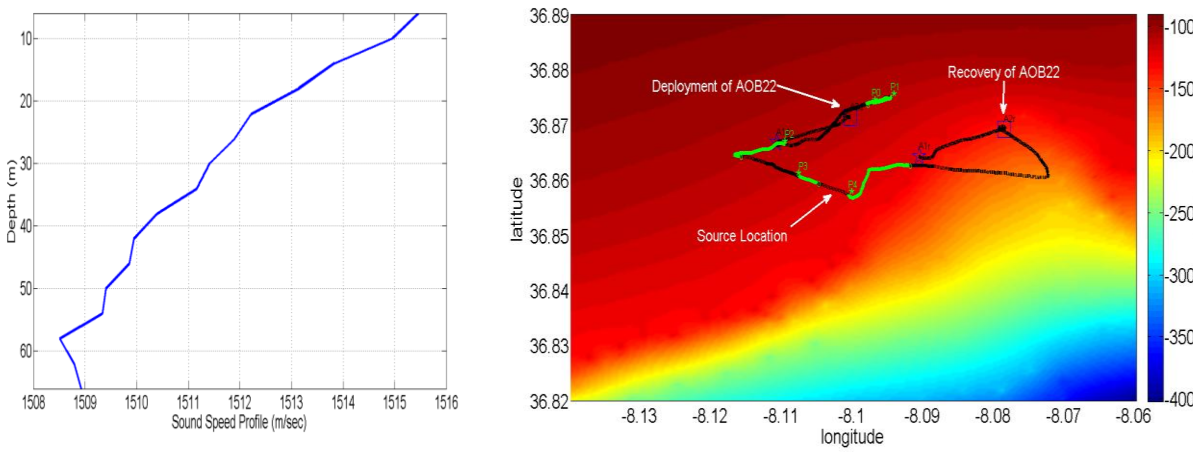

Figure 3: (a) Down reflecting sound speed profile during Day 2; (b) Day 2 bathymetry map of the work area with GPS estimated locations of AOB21 (A1d) and AOB22 (A2d) deployments and their recovery (A1r,A2r), ship/source track (dotted line) and ship track during field calibration events (green lines).

IV. DATA PROCESSING AND RESULTS

This paper address the low frequency chirps (LF-AERU1 code, see table 1) with the central frequency band of 2.64 to 3.75 kHz, a duration of 0.1 sec and a repetition rate of 0.3 sec. during 15 sec. The received chirps were first passed through a band pass filter to remove the out of band noise, then the filtered signal was converted to baseband and finally the baseband signal was pulse compressed with the transmitted chirps to get the channel IR estimate. Figure 4 (a) shows the estimated arriving pattern that comprises all the IR estimates along the array of hydrophones and (b) along the 15 seconds of transmissions for channel 3.

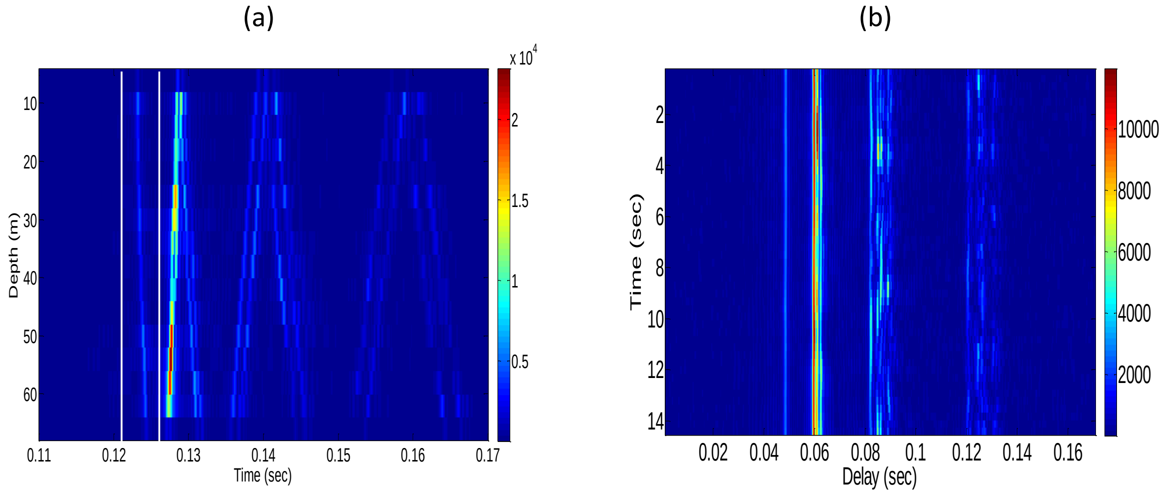

Figure 4: Impulse response estimates: (a) for 16 Hydrophone array and white lines showing the selected arrival; (b) for channel 3 along the 15 seconds

The arriving pattern (see figure 4a) presents a first arrival followed by a second arrival with much higher power. Observing the second wavefront, (with a stronger power) it is clear that the signal arrives first to the bottom hydrophone and at last to the top hydrophone, since the source is placed close to the surface (at 12 m depth) this reveals that this wave front should be due the bottom reflecting paths. The first wavefront, with a smaller power than the second, arrives first to the top hydrophone and at least to the bottom hydrophones suggesting that it should travel in the top down direction which is only possible for the direct path and/or for the surface reflecting path. Simulations with the Bellhop acoustic propagation model [8] reveals that in such environment the first wavefront is due to a destructive interference of the direct and surface reflecting wavefronts, that arrives to the array simultaneously, with the same delay but with opposite phases [9]. The main objective of this paper is to identify the presence of those two paths (direct and surface reflected) in the first wavefront without using an acoustic propagation model but rather using a Doppler based method.

The proposed method assumes that each of the paths is affected by different dynamics of the environment: the direct path is affected by the source and hydrophone motion while the surface reflected path is also directly affected by the surface waves motion (see figure 2) at the location where the surface reflection occurs. In order to identify the presence of those two paths in the first arrival we start by isolating the first visible arrival applying a window as it can be seen in figure 4a. After selecting the third hydrophone we have analysed the behaviour of the first arrival in time and Doppler for the IR estimates obtained by pulse compressing 50 chirps transmitted during 15 sec (see Figure 4b). Figure 5a shows the variability of the selected path with time. Figure 5b shows the corresponding Doppler spread where it can be observed that there are: (i) a main spot of Doppler at approximately 0.01Hz, and (ii) two side spots at 0.16Hz and -0.1Hz. Those observations reveal that in the channel there are more than one path. The main spot at 0.01Hz should correspond to a main path while the side spots can correspond to two different paths or to a single path that is affected by two different Doppler values as can be the case of a surface reflected path that when the wave goes down the length of the path reduces and when the wave is going in the upper direction the length of the path increases.

(a) (b)

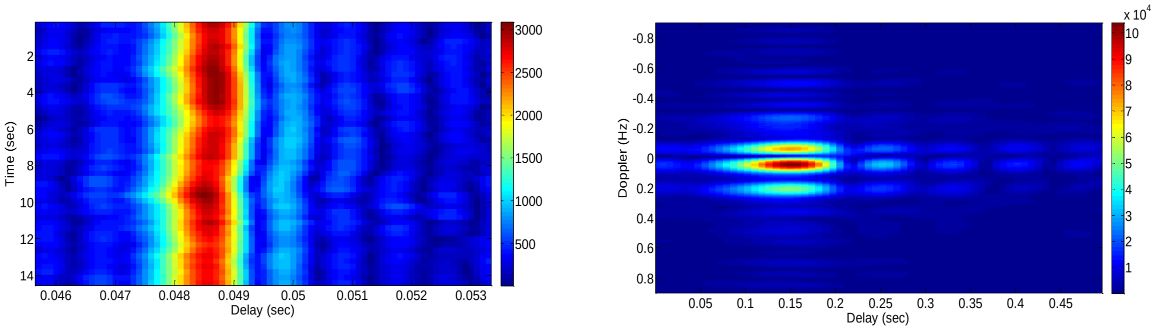

Figure 5. Doppler Spectrum for the selected arrival for 15 seconds

However if the side spots are due to a single surface reflecting path the two side spots should not be visible simultaneously in a short time slot since the up and down movement of the surface wave occurs at different times. Applying a time window of 4 sec to figure 5a the corresponding Doppler spread was computed.

(a) (b)

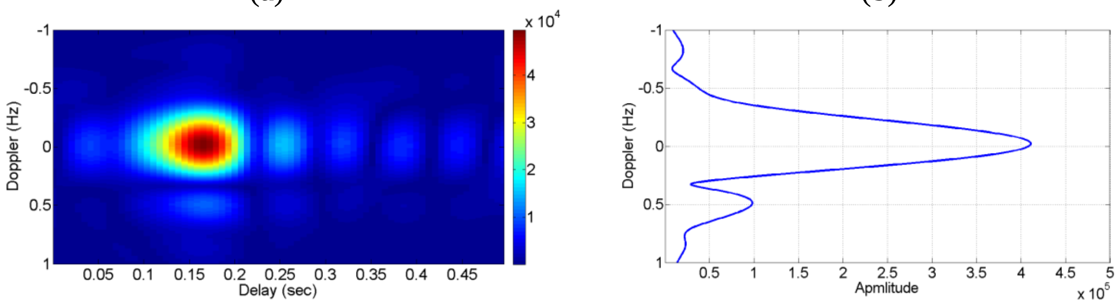

Figure 6. (a) Doppler computed only for 4 sec time window where we can see two Dopplers i) due to one main arrival at -0.01Hz and ii) due to a surface reflected arrival at approximately 0.5 Hz (b) Doppler summation over the delay axis

(a) (b)

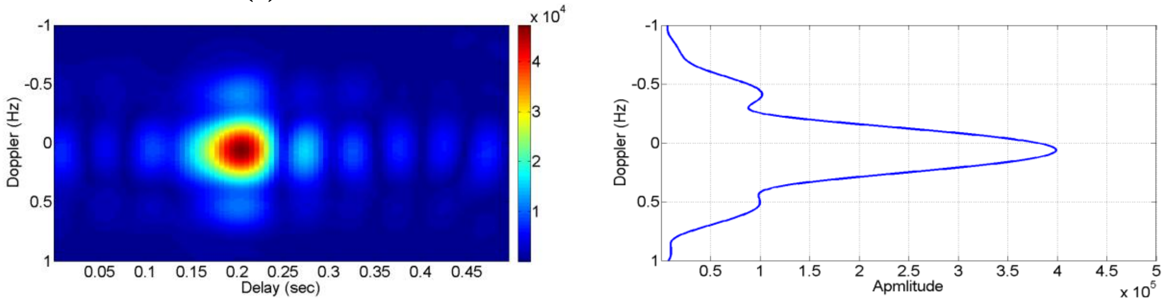

Figure 7. (a) Doppler computed only for 4 sec time window where we can see three Dopplers i) due to one main arrival at 0.1 Hz and ii) due to a top reflected arrival at ~ -0.4 Hz and at ~0.5 Hz, (b) Doppler summation over the delay axis

(a) (b)

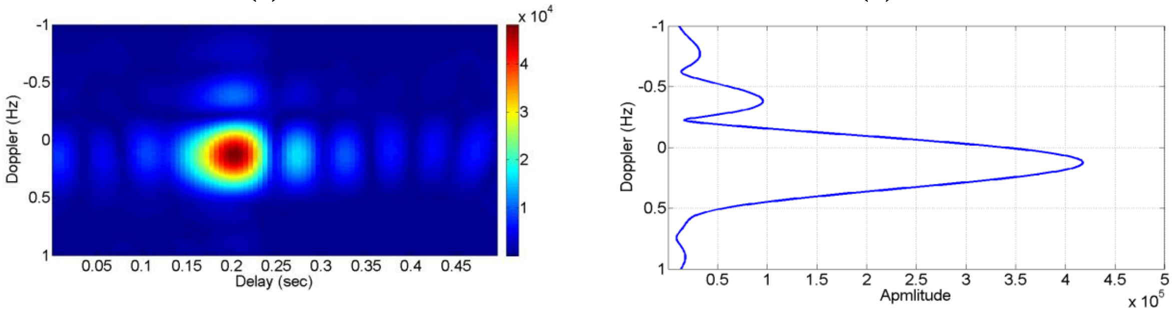

Figure 8. (a) Doppler computed only for 4 sec time window where we can see two Dopplers i) due to one main arrival at 0.1 Hz and ii) due to a top reflected arrival at ~ -0.4 Hz, (b) Doppler summation over the delay axis

Figure 6, 7, 8 (a) show the Doppler spread computed with a window of 4 where the window slides 0.5 sec from 6 to 7 and then 8. Figure 6, 7, 8 (b) show the corresponding Doppler spread summation along the delay axis. These figures allow for the following observations: (i) figure 6 (a) shows a main spot at -0.01 Hz and a relevant side spot at ~0.5Hz; (ii) figure 7 (a) shows a main spot at 0.1Hz and two side spots at approximately -0.4Hz and 0.5Hz; and (iii) figure 8 (a) shows a main spot at 0.1Hz and a side spot at 0.4Hz. In all cases the main spot is due to the direct path (p_1 in figure 2) that due to the array motion presents different Doppler values for the 3 different windows nevertheless with values around zero. The side spots are due to surface motion that makes the surface reflected path (p_2 in figure 2) larger and shorter, in the following manner: in case (i) the Doppler value is positive revealing that for that window the surface wave is moving up and the path is becoming larger; in case (iii) the Doppler value is negative revealing that for that window the wave is moving down and the path is becoming shorter; and for case (ii) there are two side spots one negative and the other positive revealing that for that time window the surface wave is crossing a crest, where before the crest the path is becomes larger and after the crest the path becomes shorter.

V. CONCLUSION AND FUTURE WORK

In this paper a Doppler domain analysis of underwater acoustic channel time variability was done. The Doppler analysis was applied to channel impulse response estimates obtained during the CALCOMM’10 experiment. Isolating a single path from an IR estimate and computing its Doppler spread it was possible to identify that it comprises two paths (a direct and a surface reflected) that at the receiver side add destructively. Moreover it was possible to identify the environmental phenomenon that generates the time variability of the channel.

Future work will address the use of the Doppler spread function estimates in the development of robust equalizers for underwater communications.

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