PULSED REVERBERATION OBSERVED IN THE MEDITERRANEAN SEA

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ABSTRACT

This paper presents the experimental set-up, geometry and environmental conditions for pulsed channel soundings in the Mediterranean Sea. A short five-cycle pulse at a transmit frequency of 50 kHz is utilised to probe the ocean channel at a high repetition rate. The fast fluctuations due to reflection and scattering are recorded on a transient analyser. The mean and coefficient of variation are used to analyse the pulsed response over a short period of time. Typical energy spreads induced by boundary reflection and scattering are in the region of 3 to 4 ms and could conceivably introduce inter-symbol interference in an underwater telemetry system where high bandwidth efficiency is required.

1. INTRODUCTION

There has been much interest in the possibility of developing underwater acoustic communication systems that are capable of operating at distances which are long in comparison with depth of immersion Coates et. al.[1], [2]. Such channels are characterised by much fluctuation, induced by the surface and direct path, Coates and Owen [3]. The channel response is described by the time varying channel function $h(\tau,t)$, where τ describes fast scattering fluctuations and t describes the slow surface or volume induced fluctuations, Spindel [4]. For communication purposes the averaged energy decay with respect to τ, for the propagation paths, will define the level of inter-symbol interference. The variation with respect to the slower fluctuations, the t domain, will define the rate at which synchronisation, equalisation and other signal processing techniques can track the time-variant channel. Amongst others, Wales [5] and Spindel [4] have investigated the properties of microwave and acoustic communication delay spreads in the τ domain. There are however few published practical results for typical shallow-water acoustic communication channels. Here we use the term 'shallow' to imply that range >> channel depth. Under some circumstances in water which is actually deep by comparison with range the channel itself may still be "shallow" if both transmitter and receiver depth << range.

As a series of two papers, Alkhalidi [6], the following describes the general experimental geometry and conditions with some example averaged pulsed responses. The variance is also used to describe the level of fluctuation in a short period of time. Section 1 outlines previous pulsed experiments where emphasis has been placed on the ability of the channel to support underwater communication. Section 2 outlines the practical geometry of the channel, the transmit transducer and receive transducer characteristics. Section 3 describes the environmental conditions for which the experiments were performed and the deep-water sound speed profiles. Emphasis is placed on the inherent inability of traditional single profile ray tracing to accurately model the inshore propagation characteristics. Section 4 shows an example of a time varying channel response $h(\tau,t)$ and the averaged response over a set period of time. This is used to identify various propagation paths in the ocean. Finally the variation of the response in the 't' domain is also presented and related to the geometry of the experiment.

2. EXPERIMENTAL BACKGROUND

Over the past few years there has been increasing emphasis on high-frequency forward propagation in shallow channels. Inherent in such a channel is the low grazing incidence at the surface interface and high Rayleigh parameter roughness associated with incident frequencies up to 600 kHz, Coates [7]. Wideband propagation measurements for short range millimetre wavelength radio channels are abundant, however acoustic propagation contains temporal surface and volume scattered contributions that are difficult to model for low grazing incidence. Typically multiple scattering and shadow correction have to be considered for angles less than 20°, Fortuin [8].

The existing experimental literature is largely confined to low-frequency continuous and measured wave propagation. Brown [9] considers the forward scatter of 500 cycle pulses ranging from 160 Hz to 1.36 kHz. Histograms of surface reflection coefficients are estimated for sea states 1 to 3 as a function of the Rayleigh parameter. He showed that there is a fundamental limit to the level of fluctuation at a Rayleigh parameter of 0.7. Later Spindel and Schultheiss [4] characterised the acoustic surface reflection channel through impulse response measurements. The channel time-varying transfer function, frequency dependant modulation function and channel bifrequency function are applied to the time-varying response from a model rough surface. Instantaneous and averaged impulse responses are used to explain the time spread nature of the channel where the Rayleigh parameter is very large. However, in line with theoretical predictions at the time, the experimentation was limited to angles greater than 20°. Goddard [10] describes a fisheries underwater telemeter for use in a multi-path channel. As one would expect the limiting factor associated with communication performance was the influence of the surface reflections. Goddard presents the mean and variance of acoustic pulses in the t and τ domain at low grazing incidence when the transmitter and receiver are moving through the water. Much closer to the work reported here Thomas, Moldon and Ross [11] examine short-pulse transmissions to measure the range of multi-path delay and the coherent frequency bandwidth. Thomas et. al. concentrate on the properties of a measured communication channel. The conclusions made are that there is much more variability and less stationarity exhibited in propagation and reverberation in shallow water.

The short selection of literature reviewed above all have common aspects, in each case the incident angles are such that multiple scattering and shadowing do not occur. The following experimentation outlines a shallow grazing angle (7° minimum), high-frequency pulsed propagation test.

3. EXPERIMENTAL SET-UP

The site of the experimentation is in the coastal area of Cap-Ferrat in the south of France. The transmitter transducer array consists of 19 staves of 3 Toeplitz elements resonant at 50 kHz. The diameter of the elements is 25.4 mm, with 30 mm separations. The beam width is 3° in the vertical plane and 17° in the horizontal plane. The band width of the array is 10 kHz. This allows a short transmit pulse of 5 cycles. The pulses were generated by a HP 8116a function generator and fed into a power amplifier with 18 APEX PA09 power amplifiers. (Each power amplifier drives a group of three transducer elements).

The experimental geometry is shown in Figure 1. The transmit array is 35 m below the surface. The main beam of the array pointed directly ahead. The receive vertical line array is approximately 1750 m from the transmit side.

The depths of the first 4 elements are at 100 m , 150 m, 175 m and 200 m. The geometry is such that there are no bottom reflected paths hitting the receive elements. Refracted and surface reflected paths are present depending on which receive array element is utilised.

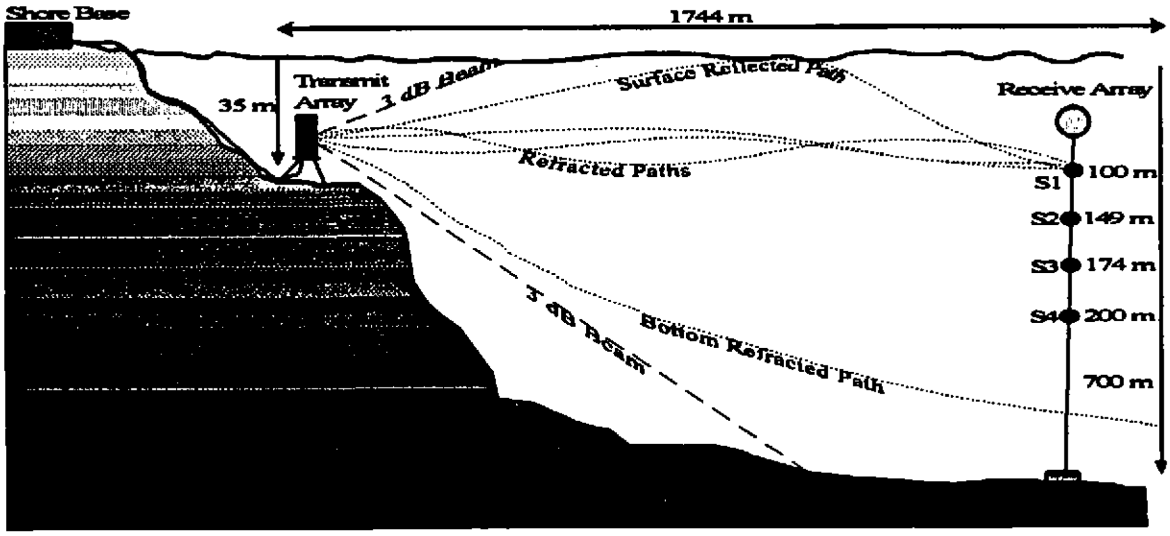

Figure 1 - Cap-Ferrat Geometry, South of France.

4. ENVIRONMENTAL CONDITIONS

The experimentation was carried out at the end of April and beginning of May. The sound speed profiles were obtained *in situ* with XBT's. Two sound speed profiles are shown in Figure 2. These were taken on the 26th April and the 3rd May.

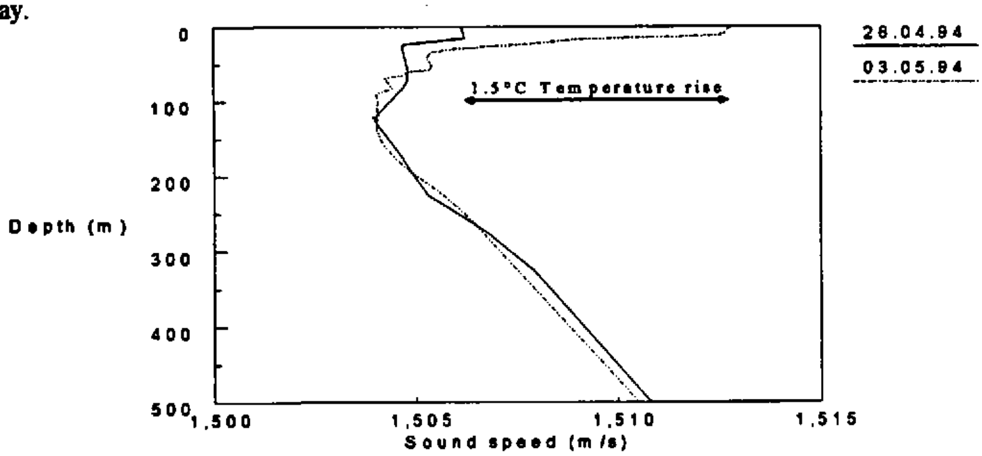

Figure 2 - Sound Speed Profiles

It can be seen that the sound speed profile changed significantly over a period of just a few days. The first sound speed profile, 26.04.94 was obtained shortly after a storm which had produced extensive mixing of the surface layer. By the time the second sound speed profile had been taken the significant warming of the calm sea - surface had taken place. Ray tracing shows that there are only two Eigen rays at the first three elements with the sound speed profile of the 26th of April. They are the direct and surface reflected paths. As will be seen the Ray tracing profiles do not agree with measured channel response. Possible explanations are that the temperature profile changed considerably from the receive array depth at 700 m to the transmit array depth at 35 m whereas the profiles were taken approximately 1000 m from shore side. The variability of sound speed profile with time, in our case the space of just one week, shows that XBT's are needed at frequent time and space intervals. A further explanation for ray-trace and channel response disagreement can be provided by the relatively shallow transmit transducer position. It may possible for internal wave and microstructure near the surface to affect the received Eigen rays considerably.

Typically the sea surface could be described as 2 to 3 on the Beaufort scale. This roughly corresponds to wave heights in the region of 10 cm to 30 cm or equivalent Rayleigh parameters of 1.6, 2.2, 2.5, and 2.8 at elements S1, S2, S3 and S4.

5. PULSED RESPONSE OF THE CHANNEL

To asses the pulse-to-pulse variation of the channel the function generator was set to pulse at 10 cycles every 45 ms. The repetition rate is high enough to capture all the pulse to pulse variation and long enough to separate any one pulse reflection interfering with the next received pulse. Figure 3 below shows an example response over 4.5 seconds taken on the 2nd of May. The highest element S1, is used as the receiver. The pulses are low-pass filtered at 10 kHz, 3dB cut-off, giving the envelope of the reflected paths.

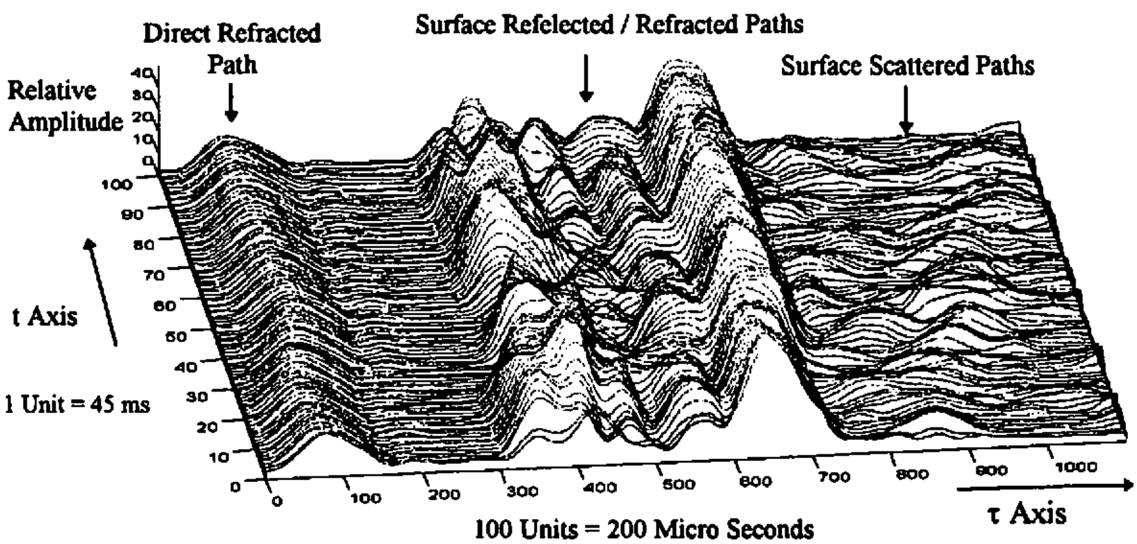

Figure 3 - Pulsed Response every 45 ms on the 2nd May 1994

The direct refracted Eigen ray is clearly visible with very little fluctuation in amplitude or phase. Conversely the surface reflected and / or refracted Eigen rays show considerable fluctuation in amplitude and phase. It is unclear whether refracted Eigen rays arrive at approximately the same time as the reflected surface rays. However it is certainly clear that surface scattered paths are evident beyond the refracted and / or reflected paths.Further insight into the channel reflection and scattering process can be derived by taking an average of the response over a period of time. The well understood temporal effects of volume inhomogenity are on a time scale of the order of seconds to minutes. To asses the effect of refraction, reflection and scattering only a short six second integration time is utilised. This ensures a local form of stationarity in the data. Figure 4 shows the averaged pulsed response of the channel.

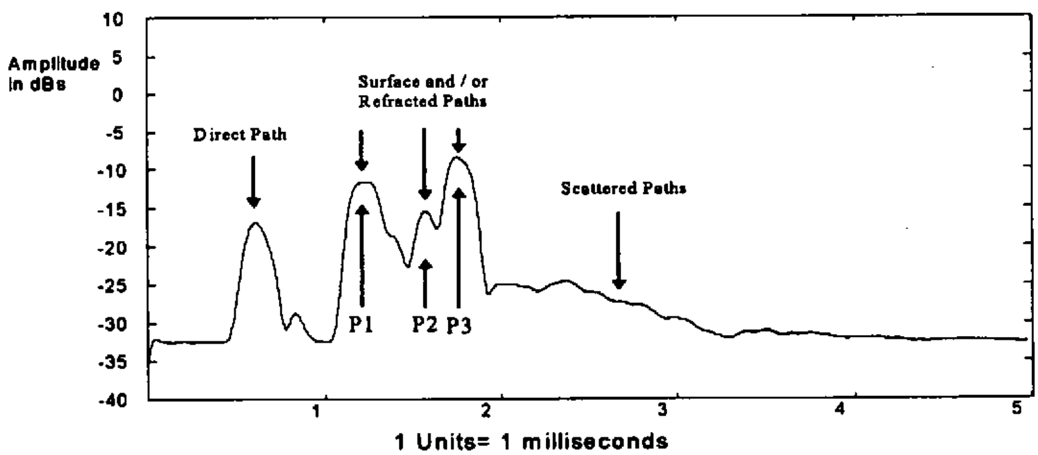

Figure 4 - The Averaged Channel Response for Element S1

The averaged response shows some distinct characteristics which are important in an oceanographic and acoustic telemetry sense:

- The averaged direct path is 8 - 10 dB less than the surface reflected and refracted paths. This will degrade the overall performance of a high-bit-rate communication system where the signal-to-reverberation ratio is low.
- The total time-spread is in the region of 3 ms. The time-spread will determine the communication symbol rate, equalisation and modulation format.
- The scattered paths are clearly less than the refracted path of surface bounces paths but none the less contribute to the time spreading characteristics of the channel.
- The secondary peak at just under 1 ms is the ringing of the transducer.

Figure 4 does not show which arrival corresponds to a scattered or reflected path. Typically refracted path fluctuation is much less than the rough moving, surface induced fluctuation. With this aspect in mind Figure 5 shows the coefficient of variation of the reflected pulses in the t axis for each scattered bin in the τ axis. The coefficient of variation is defined as the standard deviation of $h(t,\tau)$ where the data ensemble is in the t axis, τ kept constant divided by the mean of the ensemble in the t axis. The direct path shows little percentage coefficient of variation over the 6 second integration time. The Eigen rays P1 to P3 can be associated with a refracted of reflected path by comparison of their relative percentage variation. P2 and P3 probably correspond to refracted paths while P1 is the surface reflected path. This is evident in the coefficient of variation magnitudes. Scattered arrivals show a much higher variation and uneven variation decay along the τ axis. This is most likely a consequence of taking such a short data ensembles. The spikes apparent in Figure 5, between the relatively low variance refracted arrivals are caused by time arrival fluctuations of the paths. The envelope ringing up and decay of a pulse will cause more variation with respect to the flat portion of the received pulse.

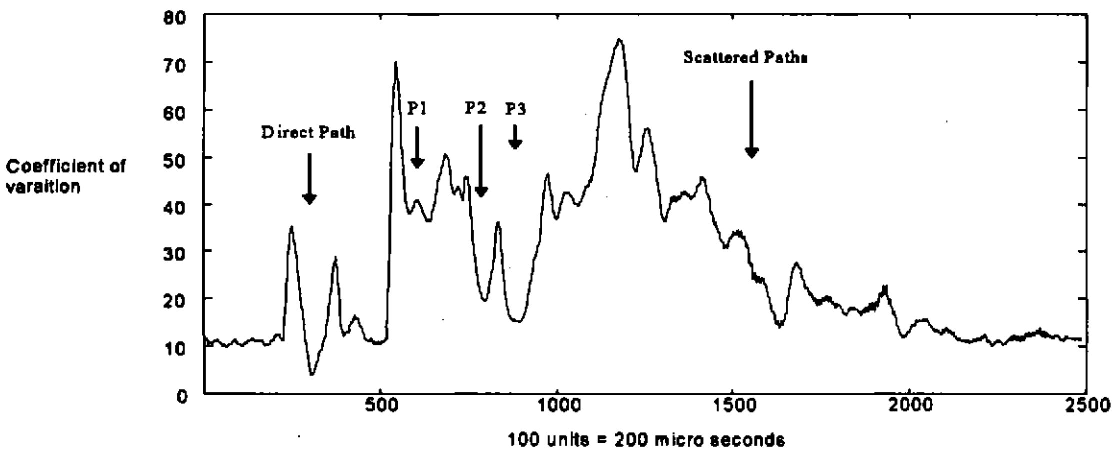

Figure 5 - Percent Variance for the Pulsed Response at Element S1

When elements S2, S3 and S4 are analysed, only a refracted and surface reflected pulse become apparent. Figure 6 shows an example of the waterfall graph, similar to Figure 3, for the second element in the line array, S2.

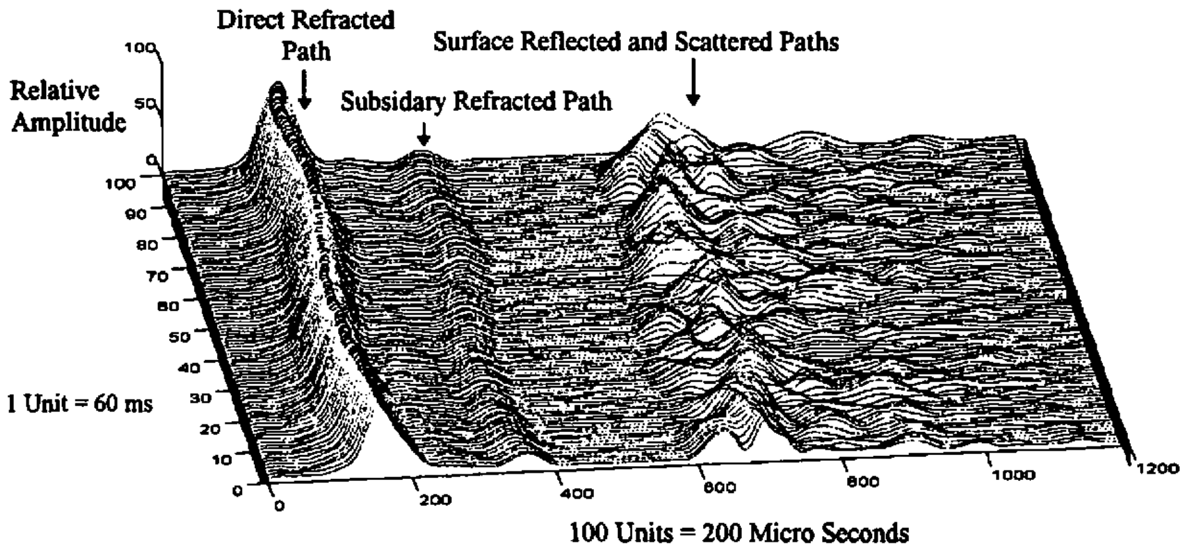

Figure 6 - Pulsed Response every 60 ms on the 2nd May 1994 - Element S2

There are now a distinct direct and subsidiary refracted paths with a clearly separated surface reflected and scattered path(s). Unlike Figure 3, the individual paths do not appear to interfere with each other. The repetition period has now been increased from 44 ms per wave to 60 ms per wave capture. The graph above shows a six second section of data. All elements below S1 followed the same pattern with a decreasing magnitude refracted path but a clear surface reflected and scattered component(s). Figure 7 shows the averaged response from elements S2, S3 and S4. Element S2 shows two steady direct paths and a time-spread third path corresponding to the surface reflection and scattering. Element S3 follows a similar pattern but with a larger separation between surface reflected and direct paths. At 200 m depth, the direct or refracted paths are not present and the received pulse consists only of reflected and scattered components. It is also noticeable that as the Rayleigh roughness increases, i.e. moving down the elements on the receiving array the surface reverberation return has less peak magnitude but more time spread.

Finally to asses the variation effects induced by the surface reflection and scattering the coefficient of variation or standard deviation / mean is applied along the slow variation or t domain for each scattering position of the τ axis. It is interesting to note that the percentage variance of the direct or surface reflected paths, in terms of peak envelope, increase from element S1 to element S3.

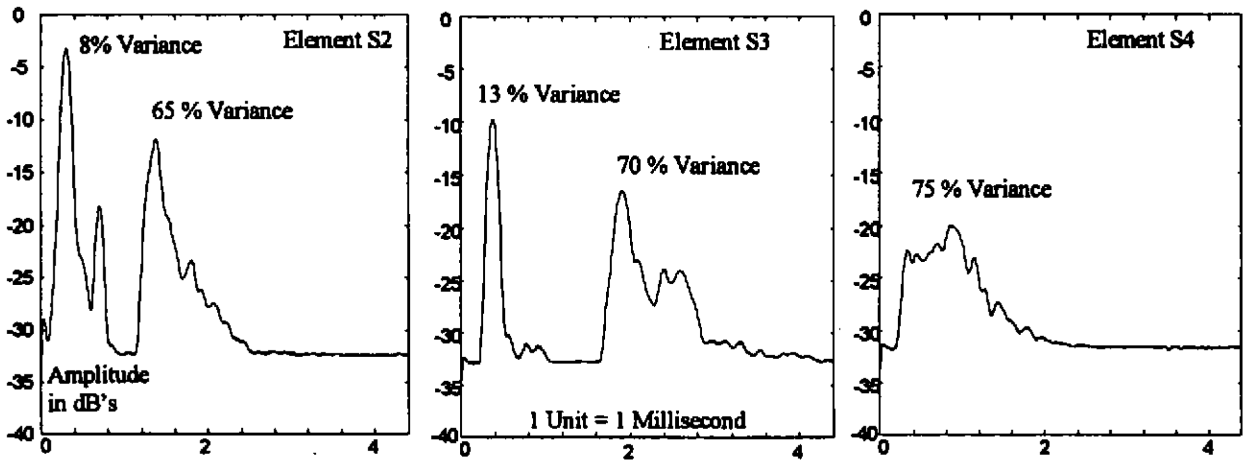

Figure 7 - The Averaged Amplitude with Scattering Domain Delay for S2, S3 and S4

It is possible to postulate a physical meaning to the increase in the direct / refracted path variance with transducer depth; Energy from the transmitter reaches the receiving hyrophones by rays refracted upwards towards the surface before refracting downwards to reach the receiver. Therefore the associated Eigen-rays travel closer to the surface as the receiver depth is increased and thus the influence of surface turbulence / bubble structure increases with receive hydrophone depth. This will be dealt with in more detail in a related paper [6].

CONCLUSIONS

The above results are interesting in that the short probing pulse method allows distinct analysis of refracted and reflected paths. The physical time separation between the direct and reflected paths is much greater than the pulse duration. Analysis of oceanographic parameters such as volume inhomogenities, internal waves and low grazing incidence surface reflection have become possible using the short-pulse method. By careful Ray tracing analysis the grazing angles, surface scattering area, volume scattering area and other oceanographic features can be directly related to the received pulses. However the use of Ray tracing becomes limited in inshore areas where temperature and volume structure may change rapidly. Limited conclusions can be draw from the above experimentation. Namely:

- Time spreads of up to 3 to 4 ms have been observed in the Mediterranean Sea
- It is possible to distinguish the refracted or direct paths from reflected and scattered paths by its constituent variation along the t axis for each τ axis bin.
- The surface scattered paths will contribute, by their variation and time-spread nature to the degradation of communication coherence.

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