SONAR AND UXO

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Abstract: *Offshore wind, wave and tidal stream renewable energy developments generally occur in shallow water. If close to shipping lanes these areas may have been mined in past conflicts, but if away from shipping lanes they may have been used to dump obsolete and unwanted Unexploded Ordnance (UXO). In either case, a potential threat to shipping remains and appropriate mitigation is needed. The first step is to survey the area in question and identify likely hazards, and the only practical tool for such surveys is sonar. However, there are difficulties. Over the intervening period, these objects are likely to have become encrusted with marine growth, making them indistinguishable from naturally occurring features such as rocks, or they may have been buried by sediment, impenetrable to conventional minehunting and sidescan sonars. This paper will paper will review results from a number of projects aimed at solving this problem ranging from the joint Anglo-French Buried Mine Sonar programme dating back to the 1980s, through the pan-European SITAR project (Sea floor Imaging of Toxicity and Assessment of Risks caused by buried waste) to the commercial SEApara AUV mounted compact sub-bottom profiler. It will be explained that, even more important than the hardware, including the use of parametric arrays, appropriate acoustic waveforms must be chosen that give both seabed penetration and adequate resolution to classify the objects that may be detected as potential hazards or not. Finally, the paper will review the acoustics associated with such problems and discuss potential solutions, looking particularly at new approaches that may speed up surveys and enhance their reliability.*

Keywords: *Sonar, UXO, mine, minehunting, localisation, parametric array, Mills Cross, interferometry, monopulse, Ricker pulse*

1. INTRODUCTION

Unexploded ordnance (UXO), unexploded bombs (UXBs), or explosive remnants of war (ERW) are explosive weapons (bombs, shells, grenades, land mines, naval mines, cluster munitions, etc.) that did not explode when they were employed or which have been deliberately dumped and still pose a risk of detonation, sometimes many decades after they were used or discarded.

In addition to the obvious danger of explosion, buried UXO remnants can cause environmental contamination. With the passing of time, weapon casings corrode and decay and munitions-related chemicals such as explosives and perchlorates can enter soil and groundwater or, in the present case, the seabed.

1.1. The Problem

Where UXOs present a threat they need to be located and then neutralised by physical removal, controlled explosion or simply marking their position. At sea, mines have traditionally been detected using their magnetic signature – visual detection in the sea can often be limited to a few metres, as in Fig.1. However, many mines have non-magnetic casings, specifically to avoid detection, or the casings may have oxidised to the extent that there is little or no detectable magnetic material remaining. Alternatively, they may have become buried in sediment to the extent that there is little or nothing visible on the surface. Fig.2 shows a semi-buried box discovered during the SITAR project [1], and it is clear that such an object is not easy to distinguish visually.

The alternative is sonar, the approach employed by minehunting vessels, although this has its own limitations. Mines may be indistinguishable from natural features such as rock or, again, they may be buried. This presents a problem for sonar systems because low frequencies are required to penetrate the seabed, but high frequencies are needed to resolve enough detail to make a distinction between natural and man-made objects.

Fig.1: Close-up video image of a mine in 23m water depth.

Fig.2: Video image of semi-buried box in 71m water depth.

It should, of course, be pointed out here that dolphins have no trouble detecting buried fish, even with their very high frequency sonar [2,3].

1.2. Some History

It is of interest to note that this problem is far from new, and has worried the author to a greater or lesser extent throughout his career. Table 1 lists the most relevant projects worked on over the past three and a half decades.

Date	Organisation	Project
~1980	Sperry/AUWE/GESMA	Buried Mine Sonar
1983-1988	Bath University	PhD – Effect of fluctuations on beamforming SMH Mine Countermeasures Section
2002-2004	Bath University	SITAR
2005-2010	SEA & GESMA	SEAPara Redermor 2 biomimetic waveforms
2010-2016	Ultra Electronics	Forward Look Sonar

Table 1: Relevant projects worked on by the author.

2. A POTENTIAL SOLUTION

Parametric arrays represent a solution that deals with two problems – surveying the seabed for (potentially buried) targets and precise localisation of the target, once detected.

2.1. Parametric Arrays

Parametric arrays have been understood since the 1960s [4], but only occasionally implemented. The principle is that if two signals are transmitted at a high enough level, distortion products will be generated with frequencies that are the sum and the difference of the two original frequencies. This allows the possibility that two very high, slightly different, primary frequencies can generate a very low difference frequency component, with a narrow beamwidth, but hardware that has the much smaller dimensions (and weight) required for the same beamwidth at the higher frequencies.

The low frequency beam can be used to detect buried objects, but a limitation arises if the primary frequency beams interact with the seabed [5]. For this reason, the distance between the primary transmitter and the seabed must be maintained, albeit at the cost of high frequency absorption over the intervening distance.

One of the primary frequency transmissions can, however, by used to precisely determine the seabed depth.

3. LOCALISATION

Having detected a potential object of interest, it is then necessary to determine its precise location before any action such as neutralising a mine can be carried out. There are a number of potential options that can be combined with a parametric array for obtaining the required high degree of angular resolution, including interferometry, monopulse and the Mills Cross:

3.1. Interferometry

Interferometry obtains the object position from the phase difference between the received signals from two spatially separated receivers.

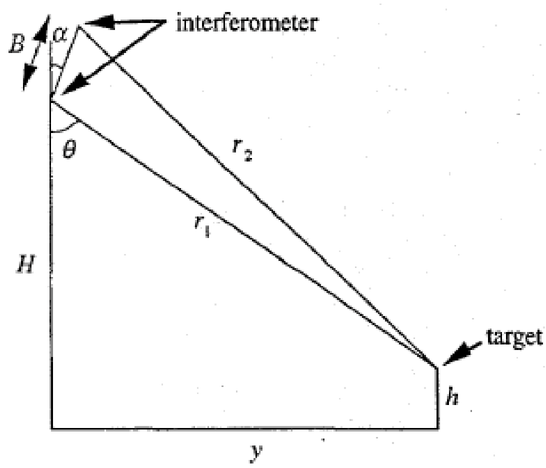

Fig.3: Geometry of interferometric localisation.

From Fig.3 it is may be determined that the phase difference ϕ between the two signals at either end of the baseline B is a function of B and its orientation α, the wavelength λ and the target height h:

$$
\begin{aligned}
\phi &= \frac{2\pi}{\lambda}(r_2 - r_1) \\
&= \frac{2\pi}{\lambda}\left[\left(r_1^2 + B^2 + 2r_1 B\cos(\theta+\alpha)\right)^{1/2} - r_1\right]
\end{aligned}
\qquad (1)
$$

If the quantities B, α, r_1 and λ are known (or can be estimated), then the target height h can be obtained from the measurement of the interferometric phase difference, ϕ. Its location in the horizontal plane is derived from the usual sonar metrics.

3.2. Monopulse

Monopulse is a concept referring to precision direction finding with a pulsed source of radiation [6]. The direction of the pulsed source, whether it is a scattering target or an active beacon, is determined by simultaneously comparing the signals detected via two or more receiver beams. The main reason for its development was that signals that are fluctuating, for whatever reason, might lead to significant errors in receiving systems that require many pulses to be processed to extract directional information. If the angular measurement is based on one pulse rather than many, however, pulse-to-pulse amplitude fluctuations of the signal have little or no effect on angular accuracy Although strictly a receiving concept, monopulse has been applied primarily in the field of active radar, and to a lesser extent, active sonar. A basic explanation of the operating principles, along with typical system descriptions, will be found in any competent radar textbook (e.g. [7]).

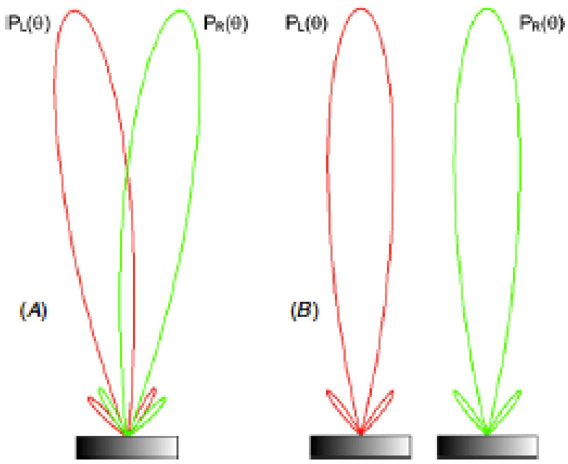

Fig.4: Two main monopulse configurations: co-located squinted beams in (A) for amplitude comparison and displaced receivers in (B) for phase comparison.

Monopulse systems as described by Rhodes [6] may operate by an amplitude comparison of squinted beams, as shown schematically in Fig.4(A), or by a phase comparison between two displaced receiving elements, as in 4(B) (squint is a radar term referring to two beampatterns which diverge by a small angle—the squint angle). This comparison may be either additive or multiplicative. In the so-called sum-and-difference implementation, the difference between the left and right beam outputs, *PL* and *PR* (the 'difference beam'), is also found to be proportional to θ over a limited range. To make the output independent of variations in signal strength, the result is normalized by dividing by the sum of *PL* and *PR* (the 'sum beam') or some other representation of the received level.

The normal phase comparison implementation is essentially an interferometer and, again, the output is approximately proportional to θ over a limited range.

Variations of the method are found in normal mammalian hearing [8], and in biological contexts phase or time comparison is usually referred to as inter-aural time difference (ITD) and amplitude comparison as inter-aural intensity difference (IID), respectively.

3.3. Mills Cross

The original Mills Cross Telescope, shown in Fig.5, was a two-dimensional radio telescope built by Bernard Mills in 1954 at the Fleurs field station of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) near Sydney, Australia [9]. Each arm of the cross was 1500 feet (450m) long and when the voltages of the two arms were multiplied a pencil beam was formed, but with rather high sidelobes.

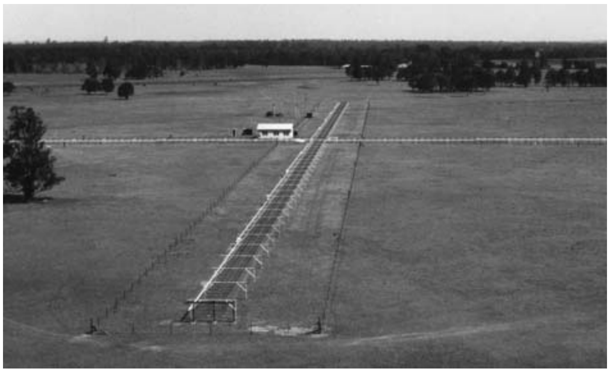

Fig.5: The original Mills Cross radio telescope

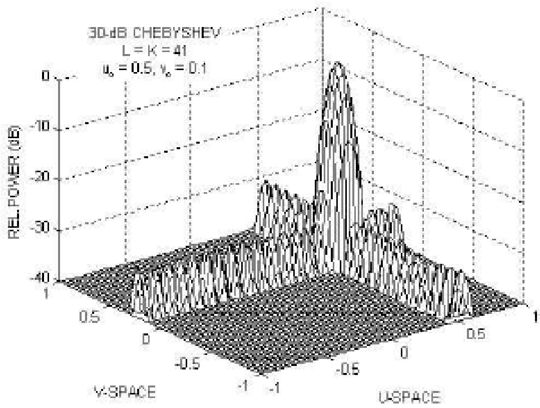

Fig.6: Example shaded Mills Cross beam pattern, steered off centre.

The term is now used for any array comprising two arms at right angles, but it is the multiplicative processing [10] that is needed to achieve maximum directivity. An example Mills Cross beampattern is shown in Fig.6. In minehunting applications, the result is often obtained with orthogonal linear transmit and receive arrays, and such an approach would be appropriate in the present context.

4. WAVEFORMS

The high level and frequency dependence of absorption in the seabed mean that any transmitted waveform is likely to be highly distorted by the time an echo is received. Conventional chirps are often used in seabed penetrating systems, but a detector based on a matched filter does not perform well because of this distortion.

There are more robust waveforms and one of the most popular is the Ricker pulse, sometimes called a Mexican hat and shown in Fig.7

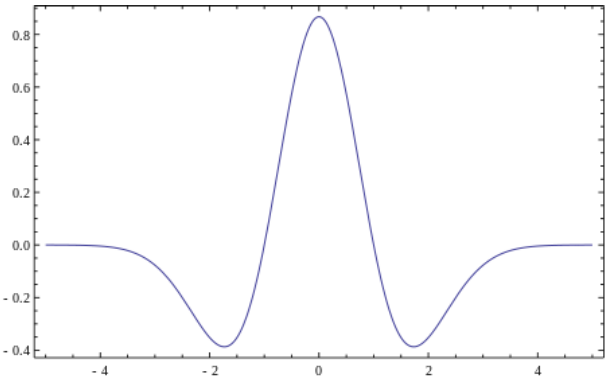

Fig.7: Ricker pulse, or Mexican hat waveform.

A Ricker pulse is a zero phase wavelet with a central peak and two sidelobes. It is the normalised second derivative of a Gaussian function and, interestingly it is its own autocorrelation function, so the output of a matched filter for a Ricker pulse remains the same as the input. These features mean that such a pulse suffers little or no distortion on passing through the seabed.

5. DISCUSSION AND CONCLUSIONS

In this paper, various approaches to detecting and localising buried UXO in the seabed using sonar have been considered. It is clear that the main requirements of seabed penetration and object classification are superficially incompatible – the first requires low frequencies and the second high frequencies. This can be overcome to a large extent by appropriate choice of waveforms and the Ricker pulse is a popular candidate and has been described here, along with some of its features. Also considered were approaches to localising buried targets aimed at achieving maximum resolution with a minimum of array/transducer hardware. Of the three methods examined, it is believed that only one, interferometry, has been used in the applications of interest.

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