PARAMETRIC SYNTHETIC APERTURE SONAR FOR THE DETECTION OF BURIED MINES: A FEASIBILITY STUDY.

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1 INTRODUCTION

This paper presents the findings from an initial feasibility study investigating the issues crucial to the detection and classification of buried objects using a parametric source.
The first section of the paper demonstrates from an example the typical parametric source beamwidths and levels that can be expected given a secondary source frequency.
These findings are directly fed into a sonar equation model to predict the typical buried target signal to noise ratios that can be achieved in simple cases. These results will provide the discussions in the second section of the paper and indicate the target detection rates for varying seabed types, frequency and geometrical conditions (target burial depth and range).
Finally, the third section of this paper will consider the potential gain of stripmap/spotlight SAS for the detection of buried objects. This gain will depend again on seabed type, frequency and geometry as the azimuthal match filter to correctly focus the target becomes distorted with environmental effects.

2 PRIOR RESEARCH

The most relevant paper found on parametric SAS is a comparison between traditional beamforming and synthetic array processing of buried target by Pinto et al. (2002)[1]. Two field experiments using the TOPAS 2-16 kHz parametric source are described. In the first instance conventional beamforming using the 12m horizontal line array is applied. The Simrad Topas was used as a source. Mounted on a 10m tower in a pan and tilt assembly, the system operated at a primary frequency around 40kHz with a source level of 238dB. Secondary source levels varied from 190dB to 213dB in the 2 to 16kHz band. A 8kHz Ricker wavelet pulse with a 6kHz bandwidth was used and beamwidth of the source was 9° azimuth and 5° elevation. The HLA (the receiver) consisted of 128 elements at λ/2 apart at 8kHz. Beamwidth is 0.775° at 8kHz. Seabed was mainly medium sand with a sediment sound speed of 1720m/s at 200kHz. Sound speed in water was measured at 1520m/s. The critical grazing angle is then 28°. The target field consisted of 3 spheres 1.06m diameter and 3cm shell thickness. Burial depths from centre of the sphere were 0.9m, 0.5m and 0m. Also 2 cylinders 2m long 0.5 m diameter and 6mm shell thickness were insonified. All targets were placed at a range smaller than 10m. The paper assumes a simple signal model for the sub-bottom echo in the form:

$$|A(f)| = Ae^{-\alpha f}$$

Where A and α are constants and f is the transmitted frequency. The parameter α depends on the length of the two way travel path in the sediment and the propagation loss mechanism (below critical angle this is the sediment attenuation, above it is the penetration loss of the evanescent wave). The signal to noise ratio is then expressed as:

$$\rho = \frac{A}{SN_r} e^{-\alpha f}$$

Where S is the amplitude of the spectrum of the transmitted pulse and N is the amplitude of the spectral density of the backscatter. In the case of a proud target $\alpha = 0$. Processing of buried targets then involves a filter optimisation stage to de-convolve seabed penetration effects and this is achieved through a bank of filters where the parameter α is varied.
First some conventional beamformed results using the environmentally adapted filter are shown. There are slight mismatches in target positioning which are attributed to unknowns in geometry, but in general specular echoes from the buried targets are clearly visible. Classification is based on target echo structure and resonant features which can clearly be analysed.
Previous results are compared to a SAS spotlight mode setup. Experiments were undertaken at GESMA. The same source was employed but in a spotlight configuration. The transmit signal was a 5ms LFM from 2 to 10 kHz. A vertical line array 16 elements spaced λ/2 apart at 8kHz was used as receiver. There are two main advantages for a VLA:

- Allows synthesis of a 2-D receiver
- Elevation directivity allows for multipath to be resolved

The narrow beam of the parametric source limits the length of the synthetic aperture. Hence the source was scanned peridodically from -15° to 15° by steps of 1°. PRF was 1Hz due to data acquisition limitations and displacement speed limited to 1cm/s.
Targets consisted of a flush buried metallic cylinder 2m long and 0.5m diameter and a partially buried sphere 1m diameter. Results are extremely encouraging but dependent on the adaptive filter. Good target location and improved resolution demonstrates a good estimation of the real target size. There is also presence of resonant echos for classification purposes which match up fairly well with a model. The main advantage of combining parametric sonar and sas resides in the narrow transmission beam without sidelobes allowing a high level of rejection of the azimuth grating lobes of the SAS. Thus a relaxation of SAS spatial sampling constraint could be permitted without the appearance of high grating lobes.
Work on parametric sonar was started by Westervelt[2] in 1963 and he initially developed a simplified model to predict the behaviour of parametric sources. Further studies demonstrated the limitations of this model and by 1977, a more complex but robust model was developed for circular and rectangular arrays by Moffet and Mellen[3]. It is this latter model that will be employed throughout this study. For in depth details on this particular model the reader is referred to the paper. Parametric gain is defined as a function of primary to secondary frequency ratio, the amount of small signal primary absorption in the nearfield and a scaled primary source level. The parametric gain can then be used to determine beam pattern characteristics.
The estimation of a buried target signal to noise ratio is based on the sonar equation[4] and a simplified geometry model for the penetration of the sound wave into the sediment. It is assumed that as the sound penetrates in and out of the sediment a transmission loss[4] is applied, attenuation[5] is directly proportional to the two-way distance in the sediment and the target strength is proportional to the insonified area of the target.

3 PARAMETRIC SONAR

This section presents a summary of the results of the modelling of a parametric sonar in an attempt to understand the fundamentals of the generation of a parametric source, its source level and its beamwidth. Input parameters are the array size and shape, the primary source frequency and the secondary frequency. In this study, the array is always taken to be rectangular. Input parameters are in turn varied to produce parameterised performance charts that will help design an array size and frequency and provide an initial answer to the feasibility of parametric synthetic aperture sonar. As a starting point, the primary frequency is equal to 110kHz; the array is 8cm wide and 4cm high. This section will illustrate the effects of varying source level and secondary frequency and varying source level and array length. Overall results are given from the entire study which analysed the effects of varying all input parameters.

3.1 Varying source level and varying secondary frequency

For a given array size, primary frequency and secondary frequency:

- The parametric source level increases linearly with primary source level before saturation point and very slowly decreases beyond this region.
- The 3dB beamwidth is constant before saturation point and increases rapidly beyond this point for high primary to secondary frequency ratios.

For a given array size, primary frequency and primary source level:

- The secondary source level increases with secondary frequency.
- The 3dB beamwidth increases with secondary frequency.

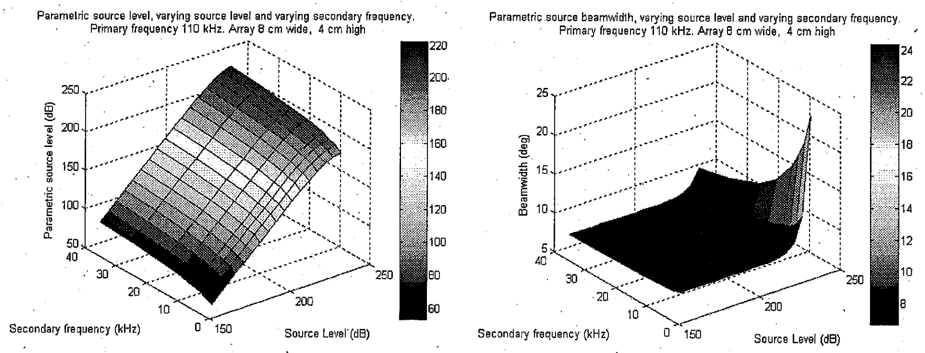

Figure 1: Parametric source level surface (on left) and parametric source beamwidth surface (on right) for varying source level and varying secondary frequency.

3.2 Varying source level and varying array length

For a given array size, secondary frequency and primary frequency:

- The parametric gain increases linearly with primary source level before saturation point and slowly decreases beyond this region; the parametric source level varies accordingly with a liner increase before saturation followed by a plateau.
- The 3dB beamwidth is constant before saturation point and increases rapidly beyond this point for high primary to secondary frequency ratios.

For a given array height, primary frequency, secondary frequency and primary source level:

- The secondary source level remains fairly stable over the chosen array lengths but shows a tendency to decreasing with array length.
- The 3dB beamwidth decreases with array length as expected.

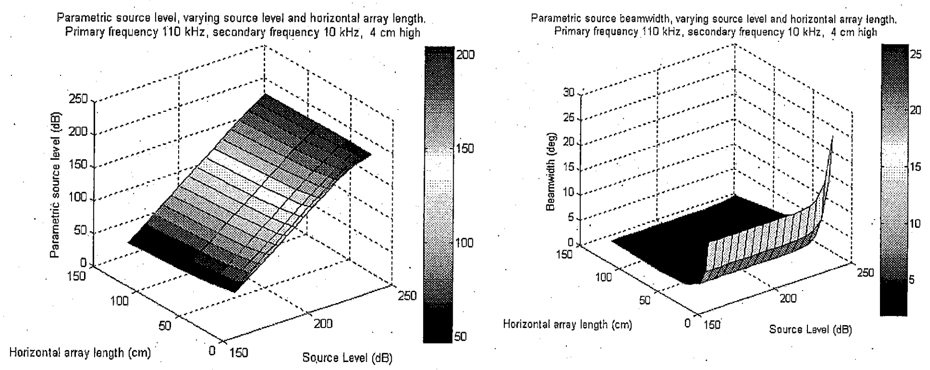

Figure 2: Parametric source level surface (on left) and parametric source beamwidth surface (on right) for varying source level and varying secondary frequency.

3.3 Conclusions

Simulations were centred around a system consisting of a small line array 4cm high by 8cm long at a primary frequency of 110kHz and a secondary frequency of 10kHz.

The main benefit of a parametric source is its high directivity which is incompatible with stripmap mode synthetic aperture sonar processing. To increase beamwidth several options are available:

- Increase the primary source level to saturation point.
- Increase the secondary frequency.
- Decrease the primary frequency.
- Reduce the array size (horizontal or vertical) with a stronger effect in the horizontal dimension.

The disadvantage lies in the high primary source levels required to produce a sufficient secondary frequency for long range applications. An increase in secondary source level can be achieved by:

- Increasing the primary source level.
- Increasing the secondary frequency.
- Decreasing the primary frequency.
- Reducing the array size.

Nevertheless, in spotlight mode, parametric sas could offer a solution to the detection and classification of short range buried mines. At high frequencies, the penetration of the wave into the sediment is rapidly attenuated and most targets would not be detected, whereas at lower frequencies they would. The comparison then between high frequencies and low frequencies side scan images would provide the detection of buried objects that may be of interest. Subsequently, the spotlight sas processing of these objects could improve resolution to facilitate object classification.

4 ENERGY MODELLING FOR BURIED TARGETS

This section details the estimated signal to noise ratios in two conditions: for varying frequency and varying sediment types and varying frequency and varying target depth. The results of the whole study demonstrate the limits of buried target detection as a function of frequency, sediment type, target burial depth and grazing angle. The signal to noise ratio is defined as the ratio of peak target echo amplitude to the background amplitude. Sediment type is related to the mean grain size in mm or in Φ where:

$$\text{size in } \Phi = -\log_2(\text{mean grain size in mm})$$

Sediment classification is defined according to Sleath's granulometric table [6].

Table 1: Granulometric classification according to Sleath [6]

Seabed type	Mean grain size	Size in Φ
Boulders	4096-256 mm	(-12) – (-8)
Cobbles	256 – 64 mm	(-8) – (-6)
Gravel	64 – 2 mm	(-6) – (-1)
Sand	2000 – 62 µm	(-1) - 4
Silt	62 – 4 µm	4 - 8
Clay	4 - 0.24 µm	8 - 12

4.1 Signal to noise ratios for varying frequency and varying sediment types

Figure 3 shows the estimated signal to noise ratio as a function of frequency and sediment type where range resolution is 75cm and a 10log(BT) gain has been applied on. The source level is set at 145dB, target range is 80m with a burial depth of 0.5m for a 1m diameter sphere, i.e. the top of the sphere is just level with the surface. In all signal to noise ratio estimations it is assumed that the system is not noise limited, as an indication an ambient noise level of 35dB does not significantly change the results.

For a mean grain size (Φ) smaller than 6, frequencies above 20kHz do not detect the buried target as sediment absorption becomes too high with frequency. For frequencies below 10kHz, signal to noise ratios for all sediment types are above 5dB and at the very low frequencies (4kHz and below) the minimum SNR is 10dB. These results are slightly pessimistic compared with observed ratios in [1], however exact sonar and environmental parameters are unknown and estimates here may not take into account all gains. For very low frequencies, it is interesting to note that it is harder to detect buried targets in fine sand than in coarse sand. This directly reflects the variations of the sediment attenuation coefficient as presented by Hamilton[5].

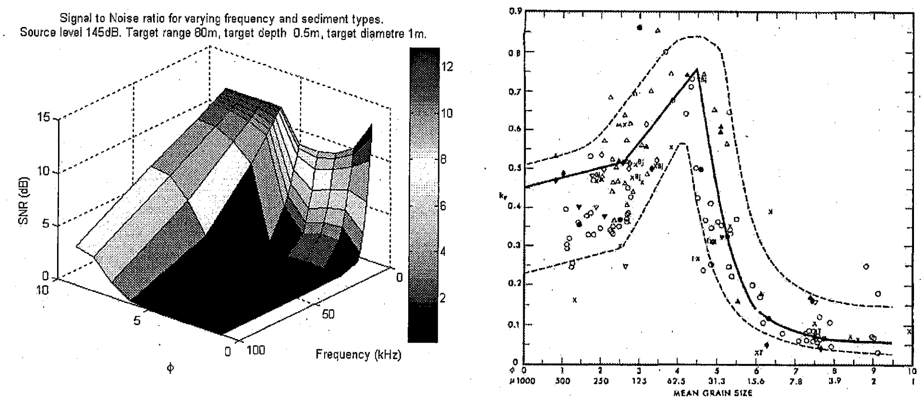

Figure 3: Signal to noise ratio for varying frequency and sediment types. Range resolution is 75cm with a wideband system (left) and compressional wave attenuation in wavelengths vs mean grain size (right) [5].

4.2 Signal to noise ratios for varying frequency and varying target depths

Signal to noise ratios when frequency and target depths are varied are plotted in Figure 4 for four types of sediment. In the upper left corner, target burial depth is varied from 1 to 10m in a coarse to medium sand bottom. For all depths, it is only the very low frequencies (below 1kHz) that can penetrate the sediment and detect with enough signal the target. Results are very similar for a seabed of fine sand (upper right corner) and the SNR is in fact lower as the sediment attenuation coefficient is higher. For a seabed of silt, (lower left corner), frequencies of up to 4kHz can detect the target down to 10m burial depth with a minimum signal to noise ratio of 8dB. A target buried at less than 2m can be detected with frequencies up to 20kHz with a SNR greater than 8dB. Finally, for a clay sediment (bottom right corner), frequencies up to 50kHz can detect a target buried at 2m deep with a SNR of 9dB. At lower frequencies typically below 6kHz, SNR predictions reach easily 10dB for targets buried up to 10m. Paradoxically, estimations predict a 1dB higher SNR for targets buried at 10m than at 1m for very low frequencies. This is due to the estimation of the transmission coefficient lower at smaller grazing angles which is the case as the target is buried deeper vs the attenuation in the sediment which becomes negligible in comparison.

4.3 Conclusions

Results from the study are simulated in a pessimistic fashion and represent for most instances a worst case scenario. Signal to noise ratios given in [1] in medium sand attain consistently 15dB using a higher source level and wider bandwidth at 8kHz .

From the simulations it is anticipated that a minimum source level of 145dB is required for medium range (up to 150m) buried target detection in an environment and operational setup where multipath does not interfere. The frequency should be lower than 6kHz for consistent and robust detections of 1m diameter targets buried up to 3m deep although experimental results have shown buried target detection at 8kHz in ideal experimental conditions.

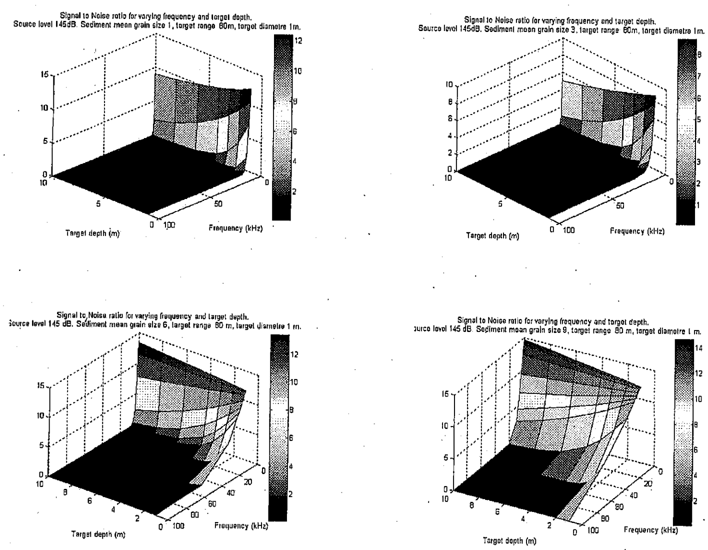

Figure 4: Signal to noise ratio for varying frequency and varying target depths. From left to right and top to bottom graphs respectively correspond to sediment type (coarse sand) phi=1, (fine sand) phi=3, (silt) phi=6 and (clay) phi=9.

5 SYNTHETIC APERTURE SONAR PROCESSING FOR BURIED TARGETS

This section illustrates through a few examples how the synthetic aperture processing of a buried target may require additional information on seabed type and burial depth compared to the conventional SAS processing of a target on the seabed. As an example, Figure 5 illustrates the variations in the range migration parabola and the buried target amplitude history over the synthetic aperture length. These simulations suppose a 1m diameter buried target buried at 1m deep in the seabed at a range of 80m. Frequency is set at 4kHz, sonar height is 50m above the seafloor and a 10dB gain is applied assuming wide band processing. No beampattern effects have been taken into account. From left to right, sediment type is coarse sand, fine sand and silt. Amplitude of the target echo varies over the parabola and is dependent on sediment type. The shape of the parabola also varies with sediment as the speed of sound also varies with sediment. The minimum range at which the target is seen also varies with sediment: in coarse sand the target range is estimated at 80.114m, in fine sand at 80.294m and at 80.389 in silt. As SAS processing may be viewed as a match filter operation, it is the estimation of the filter coefficients which is essential to the correct focusing of a target. The following sections indicate how frequency, sediment type, burial depth and grazing angle may affect the target history and hence the azimuthal match filter.

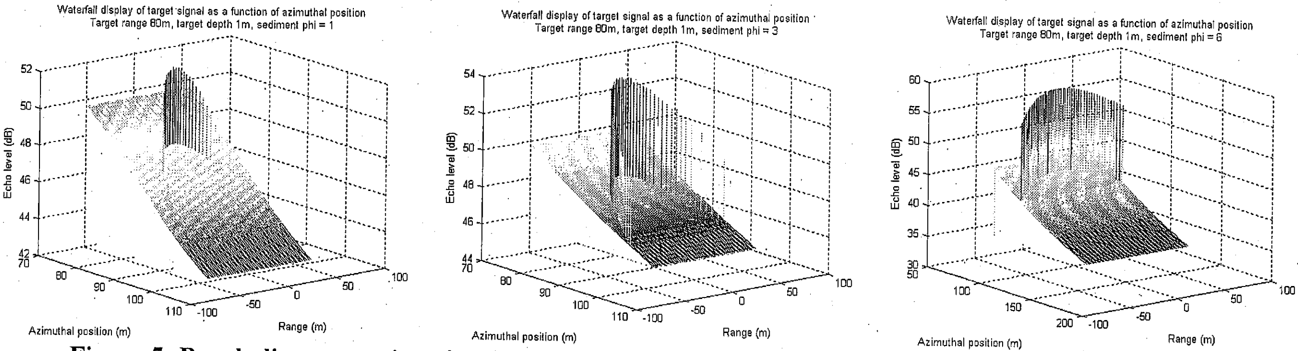

Figure 5: Parabolic range migration for a buried target for three types of sediment, type (coarse sand) phi=1, (fine sand) phi=3 and (silt) phi=6

In Figure 6, four graphs are shown giving the range difference between a conventional parabola of the estimated target position and a buried target parabola. Frequency is 4kHz, the target is buried 1m deep in four sediment types: coarse sand (phi=1), fine sand (phi=3), silt (phi=6) and clay (phi=9). The differences are given in metres (left axis) and in wavelengths (right axis). The difference is maximum for a coarse sediment at 1 wavelength for a 12.5cm resolution case. The difference then decreases, reaches a minimum for the silt seabed and then increases again. This reflects the variation in speed of sound in the sediment and differences in parabola would be nil for a sediment that has a sound speed value equal to that of the sea water. In this case, the incident angle on the interface and the angle of propagation in the sediment would be equal giving the impression of a direct path. If the speed of sound in the sediment is greater than that of water then the ray which reaches the target penetrates the sediment before the direct path. On the other hand, if the sediment sound speed is less than the seawater sound speed, the ray hitting the target penetrates the sediment after the direct ray.
When considering target positioning, time must be taken into account rather than absolute distance. This explains why the estimated target ranges do not vary in the same manner. The speed of sound in the coarse sand is much greater than that of silt and the refraction angle into the sediment required to hit the target is such that the ray to the interface is much shorter than the one required for silt. Hence the accuracy in target positioning for a target buried 1m deep is greater for coarse sediments than for silt and clay.

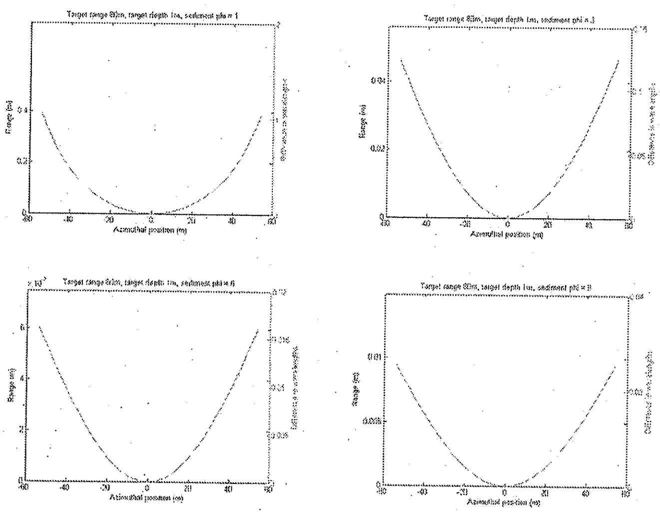

Figure 6: Difference in parabolas between a proud target and a buried target in different sediment types

5.1 Conclusions

This section has focused mainly on the distortion of the buried target parabola due to geometrical factors as well as sediment type. This is an essential observation as correct SAS processing requires accurate positioning of the target over time. The whole study revealed that the azimuthal match filter of a buried target depends on:

- The sediment type. Target position accuracy is greater and distortions in azimuthal match filter become small as the sediment sound speed is closer to that of water.
- The frequency. Target positioning is immune to frequency change as the speed of sound in the model does not vary with frequency.. However, synthetic aperture length varies with frequency, the lower the frequency the longer the synthetic aperture.
- The range. The target position estimates vary in mm with range as the grazing angle remains constant and the parabola variations are very small.
- The grazing angle. This parameter is significant as it determines the sediment refraction angle and the length of the path in the sediment. At smaller grazing angles, the target accuracy increases as the distance in the sediment decreases.

However, another important factor which has not yet been mentioned in this study, is the practical effective resolution gain that can be achieved with SAS processing for buried targets. The target will not always be visible over the whole synthetic aperture and this will in turn affect the practical achievable resolution when pings are coherently integrated. Two possibilities may arise. The target is not visible over the whole aperture but knowing the buried target parabolic history: some small signals, not detectable in a conventional sense still contribute to the coherent addition and participate in the resolution gain or some signals are too weak to increase resolution.
There will be a threshold that determines the point at which small signals will contribute and it is anticipated that this threshold may depend on sediment type, ambient noise, frequency, range and grazing angle.

6 CONCLUSIONS AND RECOMMENDATIONS

This study has focused on the modelling of parametric sonar generation, the estimation of signal-to noise ratio for buried targets and the sas processing of buried targets.
The pencil beam of a parametric source is incompatible with stripmap synthetic aperture sonar as there would be no resolution gain from such as setup. This leaves the only option of spotlight mode sas from a parametric source. However, the energy modelling and buried sas analysis have raised some issues. The target may not be visible over the whole synthetic aperture and this largely depends on the frequency, sediment type, source level compared to ambient noise, range and grazing angle. Further work is required to fully analyse the potential and practical achievable resolution gains. It is still anticipated that parametric sas could provide some benefits in well defined scenarios such as short range target classification. From purely a detection and classification of buried targets aspect, the real gain may be in a conventional low frequency sas system where higher source levels are more readily achievable enabling longer range dececption.
So, the study has initiated the debate on whether parametric sas is readily feasible and if it would effectively provide a substantial gain. It also reveals some interesting points that could be taken forward:

- A parametric source pencil beam could be highly beneficial for close up classification techniques; a high power highly directly beam could give the sufficient buried target SNR and signal structure to allow for better classification.
- A parametric source in low speed long range scan mode could potentially in one step detect buried targets of interest by comparing the high frequency returns (mainly seabed surface backscatter) and the low frequency returns (seabed interface and seabed volume returns).
- A conventional low frequency wide beam array would provide in the first instance the easiest SAS option for buried target detection.
- Parametric SAS would have to be achieved in a spotlight mode.
- The typical SAS parabola traditionally observed for proud targets becomes distorted and attenuated with penetration into the seabed and buried target sas therefore requires an additional step to estimate the azimuthal match filter.

7 REFERENCES

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