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A COMPARITIVE REVIEW OF HIGH RESOLUTION SYNTHETIC APERTURE SONAR AND RADAR RESEARCH

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1 INTRODUCTION

High resolution imaging sonars are widely used in all water depths to deploy or locate a large variety of underwater objects on the seafloor, such as pipelines, cables and lost objects or wrecks. Military applications include detailed characterization of given littoral waters with objectives such as detecting sea mines and mine-like objects, as well as hazards to navigation. These objects may be either proud on the seafloor or, naturally or purposely, buried in the first few meters of marine sediment.

For reliable object recognition, the resolution of an imaging sonar must be a small fraction (typically 1/10 to 1/20), of the size of the object under investigation. Depending on the application, the sonar resolution can vary from a few centimeters to a few meters, at ranges varying between a few tens of meters and a few hundreds of meters. More precisely, the resolution of a linear array is characterized by a set of two parameters: the range resolution, determined by the sonar bandwidth, and the angular resolution, determined by the ratio of the aperture length L to the acoustic wavelength λ. The cross-range resolution is the product of the angular resolution and the range, and therefore degrades with range. It is the single most important parameter that determines the performance of an imaging sonar.

For the range of operating frequencies used in imaging sonar, say from 10 kHz to 1 MHz, it is generally not difficult to achieve high range resolution, especially with the recent advances in wideband sonar technology. As an example, consider a sonar aperture of L=1.2 m operating at 500 kHz (λ=0.3 cm), with 20 kHz bandwidth, i.e., a 4% relative bandwidth, which is modest according to present standards. The corresponding range resolution is 3.75 cm, which seems sufficient for even the most demanding applications. However, the cross-range resolution at 150 m is 37.5 cm, i.e., ten times larger. Increasing L by an order of magnitude is usually not an option due to platform constraints (size, weight). The tenfold gain in cross-range resolution can then only be obtained by reducing the operating range and operating at a higher central frequency, e.g., at 25 m range with a central frequency close to 900 kHz. This, however, considerably reduces the area coverage and hence the effectiveness of the survey. Furthermore, in applications such as minehunting with manned surface vessels, this reduction in range is simply not acceptable, due to the increased risk to personnel and equipment.

Synthetic aperture sonar (SAS) offers the promise of a cross-range resolution which is independent of range and wavelength and thus appears a very attractive option for high resolution seafloor imaging. The basic idea [1] is to displace the aperture across range, in order to reproduce the characteristics of a large virtual antenna. More precisely, the data from multiple successive pings are collected and processed as though they were the elements of a virtual (or synthetic) array, whose length is determined by the displacement of the real (or physical) antenna during the data collection. Due to the linear increase of the transmission beam footprint with range, the number of integrated pings, and hence the length of the synthetic aperture, increases in proportion to range which allows the cross-range resolution to remain constant with range.

For example, assume the above 500 kHz sonar were displaced across range at v=6 knots. With a ping repetition period (PRP), of T=0.2 s, corresponding to a maximum range of 150 m, it is sufficient to integrate a maximum of N_{max}=10 pings to achieve a cross-range resolution of 3.75 cm over the whole swath. This corresponds to a maximum SAS integration time $T_{SAS} = N_{max} T = 2$ s. The same array length could be used to achieve even more ambitious SAS performance, such as a 1.25 cm x 2.5 cm resolution in range x cross-range up to 225 m. Typical operating parameters of this SAS could be f_0 = 300 kHz, B=60 kHz, v = 4 knots, T=0.3 s. Such a sonar system is being developed for the NATO Undersea Research Centre to support its research into remote minehunting in support of expeditionary operations (Fig.1).

In addition there are great benefits in SAS for imaging the superficial layer of marine sediments, as required for locating shallowly buried objects. A bottom penetrating sonar must operate at low frequencies (typically below 15 kHz), in order to reduce the absorption of sound in the sediment, which is usually much higher than in seawater, especially in hard consolidated sediments such as sand. The problem is then to maintain sufficient cross-range resolution to detect and classify buried objects. For a sonar aperture L= 1.2 m operated at 12 kHz (λ=12.5 cm), the cross-range resolution is close to 15 m at 150 m, which is much too large for the identification of small objects, e.g., sea mines. If this sonar were displaced across range at v =6 knots, with a ping repetition rate of T=0.2s, a 15 cm cross-range resolution up to the range[1] of 150 m could be achieved with N_{max} =100 pings (giving T_{SAS} = 20 s).

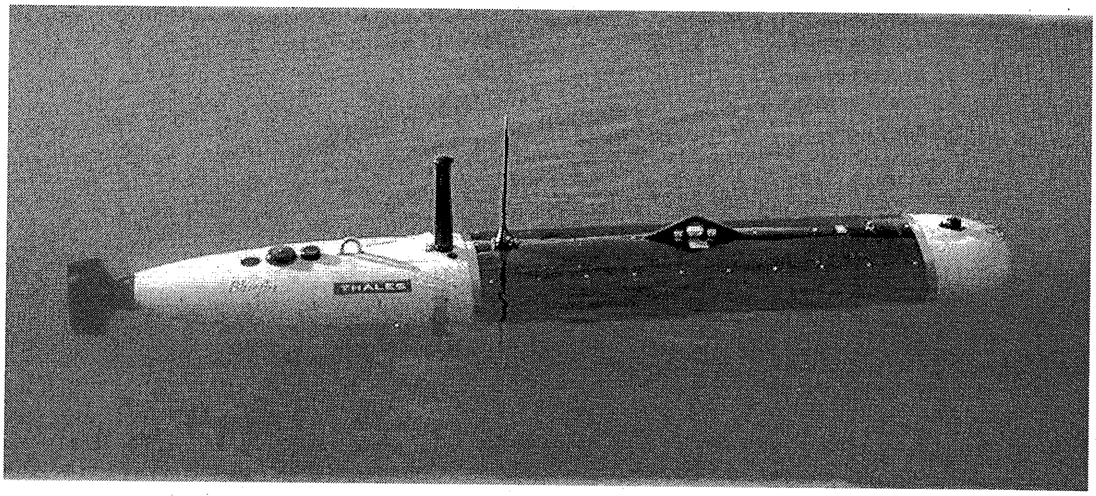

Figure 1: Bluefin Odyssey Autonomous Underwater Vehicle (AUV) under development for the NATO Undersea Research Centre by Thales Naval Systems. This AUV is equipped with an 270-330 kHz wideband interferometric SAS for sea mine detection. Clearly visible are the two antennas for radio and wireless Ethernet communications when the vehicle is at the surface as well as acoustic localization and communication transducer systems when the vehicle is submerged. The sonar is in the middle section (black) of the vehicle which contains all the electronics as well as data storage and on-board processing capabilities.

2 RADAR AND SONAR

The synthetic aperture concept was introduced in airborne radar back in the 50's and then successfully extended to spaceborne systems in the 80's, despite order of magnitude differences in the speed and range of the respective systems. There are numerous operational synthetic aperture radar (SAR), systems throughout the world. The situation in sonar is markedly different, with only a small number of experimental prototypes operated by universities or naval research laboratories. The important differences in the physics explain only in part this development lag relative to radar. It is clear that mankind has devoted much more effort to the observation of the Earth's surface than to the bottom of its oceans, certainly due to the much greater impact of the former on the world's economy and politics. Nevertheless, the interest in SAS has markedly increased during the past few years. This is closely related to the keen interest of several NATO navies in high-resolution surveys using autonomous underwater vehicles (AUVs), in which SAS is identified as an enabling technology to achieve large area

[1] In hard marine sediments, such as sand, and in shallow or very shallow water, critical angle effects will limit the achievable range to significantly less.

surveys. The comparatively low speed of operation makes the SAS well suited to deployment on AUVs which typically operate at 2-6 knots, to save energy and increase overall mission time.
Various laboratories, including the NURC, are fielding AUV-based SAS systems for demonstration. It is likely that, if the remaining technical issues find a satisfactory solution, these systems will lead to the first of their kind operated by NATO navies, hopefully followed by other scientific and commercial applications.

3 OPEN TECHNICAL ISSUES

The main open technical issues in SAS relate to spatial sampling and to the adaptive focusing required to compensate for unwanted platform motion and sound speed variations. In addition there is a requirement for image formation algorithms which are both accurate and computationally efficient. None of these issues are new. They also arise in SAR where satisfactory solutions have been found. The applicability of these solutions to SAS is not always obvious due to order of magnitude differences in the physical parameters involved, and the SAS community is actively investigating this. In addition, SAS, unlike SAR, will often have to operate in a shallow waveguide where multipath is the rule.

3.1 SPATIAL SAMPLING

Imaging sonars operate with a PRP equal to the two-way travel time to the maximum range. A basic constraint on synthetic aperture operations is that the distance traveled between two successive pings should not exceed half the length of the physical aperture, in order to ensure adequate spatial sampling of the SAS. That is,

$$vT = v\frac{2R_{\max}}{c} \leq \frac{d}{2}, \qquad (1)$$

where d is the length of the physical aperture, assumed to consist of a single transmit/receive element and c the sound velocity. The quantity $v\ R_{max}$ can be interpreted as the (one-sided) area coverage rate (ACR). The quantity *d/2* on the right hand side is the cross-range resolution of the synthetic aperture, which is constant with range and frequency. This equation therefore shows that the ACR is limited by the cross-range resolution. The consequences for synthetic aperture design are fairly disastrous in sonar. To achieve 3.75 cm cross-range resolution up to 150 m, as for the 500 kHz SAS system discussed in the introduction, the along-track speed *v* would have to be less than 0.5 knot!
The spatial sampling constraint is much more of an issue in SAS than in airborne SAR because of the much higher relative velocity v/c, in (1), of underwater platforms with respect to aircraft. For a slow-speed SAS cruising at 1.5 m/s, v/c is 10^{-3}, whereas for an airborne SAR cruising at a typical aircraft speed of 300 m/s, v/c is 10^{-6}. This arises from the fact that c is approximately 1500 m/s for sonar compared to 300,000 km/s for radar, i.e., 200,000 times smaller. For the above platform velocities, a 1 m physical aperture limits the range of the SAS to 250 m, whereas the airborne SAR can reach 250 km.
A major step towards reducing the spatial sampling shortfall was taken by Cutrona in 1973 [2], who, by so doing, possibly made the single most important contribution to the field of SAS. He extended the SAR design of a single element physical aperture to a multi-element physical array, consisting of a transmitter of length d a receiving array of N elements, of total length L. This is a very natural design for a physical sonar which are almost always designed in this manner. The use of separate transmitter and receiving arrays decouples the cross-range resolution from the ACR, allowing the first to remain d/2 while the ACR is increased by a factor of N. For a multi-element SAS, the spatial sampling spatial criterion reads

$$\alpha \equiv \frac{L}{2vT} \geq 1. \qquad (2)$$

As an example, a single transmitter of length 7.5 cm and a minimum of 16 receive elements, each of length 7.5 cm, would be needed for the above 3.75 cm resolution SAS. The grating lobe structure of the physical array, hence also that of the synthetic array, could be improved by increasing the number of elements (say 24 elements of length 5 cm).

This example shows that SAS requires a sizeable, and fairly complex, physical array to maintain ACR compared to existing survey systems and that its main benefit is the much improved (by a factor 10 to 100) cross-range resolution. Further increases in ACR requires in principle a corresponding increase in length and complexity of the physical sonar. For example, operation at 10 knots speed, up to 750 m range, would require a 10 m long aperture and upto 200 elements spaced at 5 cm if 3.75 cm cross-range resolution is to be achieved. As this is clearly an issue, many rather clever designs have been proposed, using multiple transmitters, multiple frequencies or coded waveforms, in an attempt to increase the ACR beyond the limit (2). However in all the cases reviewed by this author [3], there is a price to pay in terms of image quality, most often in terms of image contrast, compared to the correctly sampled SAS which complies with (2).

4 ADAPTIVE FOCUSING

The most important problem in implementing SAS is associated with the effects arising from track-keeping errors, i.e., the deviations of the platform from an ideal linear track. These are due to external forces acting on the sonar platform, due to surface waves and underwater currents, which are only partly compensated for by the active controls of the vehicle. The projection of these errors in the line of sight introduces phase errors in the SAS beamforming, given by

$$\phi(t) = 4\pi \frac{\gamma(t)}{\lambda}, \qquad (3)$$

where $\gamma(t)$ is the projected error and λ the acoustic wavelength. If $\gamma(t)$ contains only low frequencies, compared to the characteristic frequency $1/T_{SAS}$, the maximum acceptable phase errors are of the order of 100 deg rms. For high frequency errors, the tolerance is much smaller, of the order of 10 deg rms. It is clear therefore that, for most applications, the track-keeping errors cannot be ignored. This poses the fundamental problem of sensing the platform motion as the accuracy requirements can be very challenging. Indeed at 300 kHz, a 10 deg phase shift correspond to a motion of less than 0.1 mm! The term micronavigation has been introduced to describe the very specific, short term, relative positioning required by SAS.

A similar problem occurs in airborne SAR [4], where the aircraft can be buffeted randomly by turbulent flow. It was solved there by using very low noise aided inertial navigation systems (INS) followed by data driven techniques, known as autofocusing techniques, to correct the residual navigation errors. Typically the INS could cope with the high frequency errors (compared to $1/T_{SAS}$), leaving the autofocusing to cope with the low frequency errors, in particular the inertial errors induced by residual sensor biases. The performance tradeoffs between a variety of autofocusing algorithms, such as fitting the target return, phase gradient autofocus (PGA), contrast maximization and multi-look registration have recently been reviewed in the SAR domain [5]. Amongst the SAR autofocusing algorithms, PGA seems to have been the least unsuccessful in SAS [6,7]. However by far the most widely used algorithms are based on the Displaced Phase Centre Antenna technique described below.

5 DISPLACED PHASE CENTRE ANTENNA

The renewal of interest in SAS has much to do with the use of the Displaced Phase Center Antenna (DPCA) technique, which holds the promise of providing a robust solution to the micronavigation problem. F.R. Dickey and coworkers [8], from General Electric are generally credited with inventing the DPCA back in the 1950's, to improve the performance of Moving Target Indicator (MTI) radars mounted on moving platforms[2]. Dickey had also noted that the DPCA could be used to measure the ground velocity of a radar (or sonar) and introduced the terminology of correlation navigator to describe this variant of the principle. The DPCA is used to measure the across-track displacements of the sonar between successive sonar pings, which are then integrated along the length of the SAS. The principle of the measurement is as follows:
Assume first that the sonar antenna is aligned along track and that it does not move in the along-track direction between two successive pings 1 and 2, being subject only to a small cross-track displacement γ. This will lead to a phase shift between the two echoes from a given scatterer on the seafloor, which is given by

$$\phi = \frac{4\pi}{\lambda}\gamma\cos\theta \approx \frac{4\pi}{\lambda}\gamma, \tag{5}$$

where θ is the angle between the direction of the scatterer and boresight to the sonar antenna. Provided the cross-track displacement and the angular spread in θ around broadside due to the sonar beampattern remain small, this phase shift can be assumed constant for all the scatterers in a given range bin, or even a small set of range bins. It can then be estimated by a short-term phase+amplitude cross-correlation of the signals from the two pings. The correlation is expected to be high, regardless of the presence or absence of strong scatterers, provided the medium and the scattering geometry do not change significantly between pings and the noise is low. In addition, temporal changes in the medium which do not decorrelate successive pings but only introduce an additional phase shift can be treated as effective motion errors and corrected for as well. On the other hand time-varying multipath, due to sea surface interactions, will lower the correlation. This has indeed been found experimentally to be a major cause of decorrelation.
Next, when the platform is moving along-track, the DPCA principle is applied to arrive at an effective fixed along-track position. For a transmitter T and a receiver R, the effective radiation center, or phase center, is the point C=(T+R)/2, i.e., at the middle of segment TR. Consider next two sub-arrays R_l and R_t of the receiving array, respectively at the leading and trailing edge of the array, whose centers are separated by 2vT. The length of these sub-arrays is $L-2vT=L(1-1/\alpha)$, so that a basic requirement for DPCA micronavigation is an oversampled SAS, i.e., $\alpha > 1$. By arrangement, the leading phase centers at ping 1 have the same along-track position as the trailing phase centers at ping 2 (Fig. 2). Therefore

[2] A ground-based MTI radar exploits the Doppler effect to detect moving targets in large ground clutter. The problem is that when the MTI radar is mounted on a platform moving at ground velocity v, ground clutter returns also have a Doppler shift, given by $2v/\lambda \cos\theta$, where θ is the angle between the direction of the clutter return and the aircraft velocity vector. The Doppler spread due to the antenna beampattern can then mask that of low velocity targets. By shifting the effective radiation center of the antenna backward between instants t_1 and t_2, using several transmit or receive elements on board the aircraft, the DPCA compensates for the forward motion of the radar with the result that the radar is effectively stationary between t_1 and t_2. For example, subtracting the two signals at t_1 and t_2 cancels out the return from fixed ground targets, leaving only the returns from moving targets (up to noise). The introduction of phase arrays and digital signal processing has led to a considerable expansion of the initial DPCA technique, which is now best viewed as a particular case of Space Time Adaptive Processing (STAP), a topical subject in radar. In the recent years there has also been interest in applications of STAP in low frequency active sonar.

the correlation should be performed between the seafloor echoes received by the leading sub-array at ping 1 and the trailing sub-array at ping 2.
In this derivation it is assumed that the along-track displacement vT is known. When this is not the case, the whole procedure can be repeated while varying the sub-array length, to retain only the length for which the correlation peak is greatest. This length relates directly to the required displacement vT.

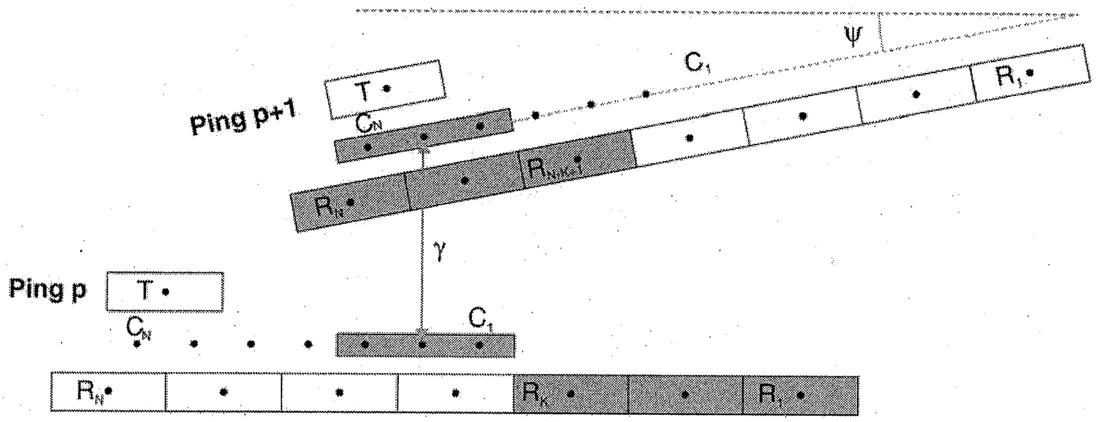

Figure 2: Displaced Phase Center Antenna (DPCA) technique. Shown are the sonar transmitter T, the receiving array of N elements $R_1,\ldots, R_N$, and the corresponding phase centers $C_1=(T+ R_1)/2,\ldots, C_N = (T+ R_N)/2$ at two successive pings p and p+1. Shown in color are the DPCA elements, whose phase centers have the same along-track position for both pings, effectively canceling the along-track displacement of the sonar to increase the cross-correlation of the seafloor backscatter at p and p+1. The cross-track displacement γ is estimated as the corresponding correlation lag. Also shown is a change in heading ψ of the array between pings.

A theoretical study regarding the accuracy of DPCA micronavigation [9] has revealed that the main sources of error are those induced by errors in estimating the heading of the physical array during the SAS integration time. Initial applications of DPCA [10] assumed that the sonar kept a constant heading during the SAS integration time. This requires, however, a high degree of vehicle stability which is often unrealistic. A more robust alternative is to estimate the heading of the physical array. Raven [11] invented an extension of DPCA capable of estimating the changes in heading of the sonar antenna from ping to ping. The attractive feature of this algorithm, for relatively low budget SAS experiments, is that all the components of the motion required to focus the SAS can be extracted from the data, without the need for any additional instrumentation. It has been implemented and validated experimentally by several authors [12,13].
The problem with extracting all of the motion components using DPCA is that it puts very stringent accuracy requirements on the algorithm which, as shown in [9], severely limit the achievable SAS performance, in terms of both image quality and ACR. The most promising way ahead is by use of inertial gyroscopes to measure the heading, since most often only a medium accuracy gyro (e.g., 0.1 deg/√hr), is needed. The first experimental results to date using such a "gyro-stabilized" DPCA were presented in [14], using a wideband sonar synchronized with an inertial navigation system and mounted on a multi-axis motion actuator, itself displaced on an underwater rail, allowing arbitrary non-linear trajectories to be generated. Excellent SAS performance was obtained even in the presence of large motion errors including changes in heading. Thus, in SAS as in SAR, the most promising solution combines adaptive focusing methods with inertial navigation. The main difference is that in SAS the emphasis has been on methods which exploit the spatial coherence properties of the backscatter from featureless seabeds (e.g. a bottom of flat mud or sand with or without targets present) whereas SAR seems to have favored methods which rely on targets. This may also have to do with the greater

density of man-made targets on the surface of the Earth than at the bottom of the ocean, with the possible exception of some highly cluttered waters in the vicinity of ports.

6 PROPAGATION

A further difficulty of SAS, compared to SAR, is that it will most often have to operate in a shallow water waveguide with multipath propagation, due to reflection and scattering by the air-ocean and ocean-bottom boundaries. As a result of the multipath propagation, the sonar images quickly lose contrast and become difficult to interpret beyond a critical range, which depends on the sonar parameters, but can be as short as 3-4 times the water depth. The performance of interferometriy is also severely degraded by multipath.

In addition to surface reflections arriving from positive angles, which can possibly be rejected by designing a baffle, there are also arrivals from negative angles due to multiple interactions between the seabed and the sea surface. Such multiple bounces are of particular concern in an operational situation where a wide transmission beam would be one option to cover the full swath. Indeed the bounced seabed return from short range would then arrive at the same time as the direct seabed return from long range and therefore degrade the quality of the long-range image. This effect of this higher order multipath is shown in Fig.3. The sonar of the system in Fig.1 was specially designed to study how this could possibly be mitigated by the use of multiple narrow beams both on transmit and receive, coupled with frequency diversity. The basic idea is to combine two sonars in a single design. The first operates in the 300-330 kHz band and is suited for short range imaging (as in Fig 3 left), whereas the second operates in the 270-300 kHz band and is suited for long range imaging (as in Fig 3 right). The vertical beamwidths of the sonars are designed so that the multiple-bounced seabed echoes from the short range sonar arrive during the reception of echoes from the long range sonar and can therefore be rejected by frequency filtering.

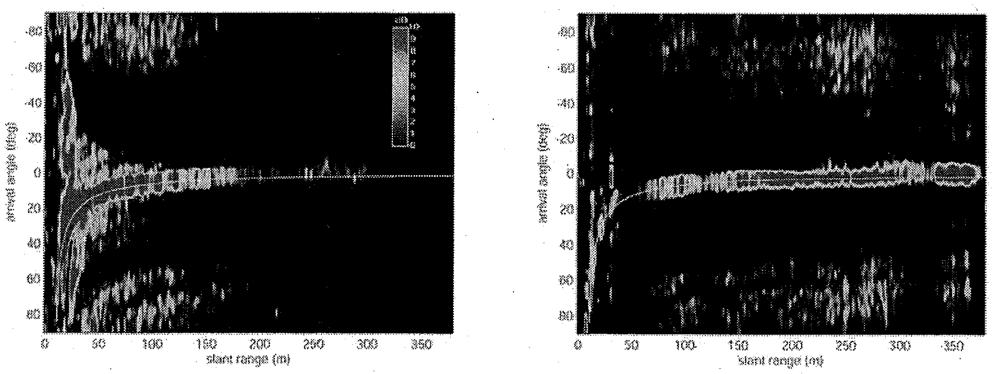

Fig.3 Effect of vertical beam pattern on long range ping-to-ping correlation (left wide beam, right narrow beam). In this experiment, a 100kHz sonar was deployed vertically from a fixed tower at 10m depth in about 20m of water. The receiver array is 1m92 and consists of 256 channels. The central 64 are also transmitters which can be addressed separately allowing the beampattern to be shaped at will. In the left of the figure, a wide transmission beam, with very low sidelobes to avoid all surface returns, was used and the SNR=μ/1-μ where μ is the ping-to-ping correlation is plotted as a function of range and arrival angle. The drop in SNR at long ranges is due to the contribution of higher order multipath which decorrelates due to surface action. The figure on the right shows how a narrow vertical beam steered at long range can be used to obtain high SNR at long ranges.

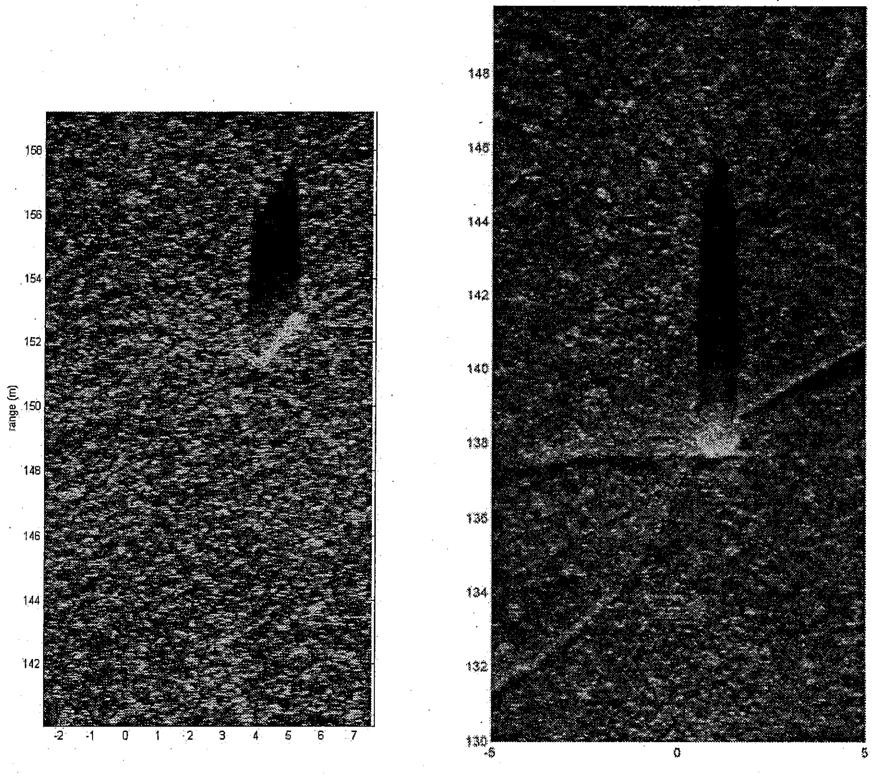

Fig.4. 270-330 kHz SAS images of simple canonical shapes (2m x 0.5m metallic cylinder & 1m metallic sphere) formed with the AUV in Fig. 1. Water depth 20m, Altitude =15m, Vehicle speed 3 knots. Also visible on the image on the right are the ropes used to retrieve the targets. Bottom type: hard mud.

7 ADVANCED OPERATING MODES

The squint mode and the spotlight mode are advanced SAR operating modes. In the squint mode the radar beam is steered away from the track by a given angle, known as the squint angle, whereas in the spotlight mode the beam is continuously trained on a given area of limited extent. The synthetic aperture length is then unlimited, allowing very high resolution to be obtained. Both these modes are applicable to SAS[7,16]. Multi-aspect SAS [13] is a more advanced mode which features a very broad transmission beam, well in excess of that required to achieve the specified resolution. It allows multiple squinted SAS beams to be formed simultaneously in the signal processor, without having to steer the transmission beam or maneuver the sonar platform, allowing the highlight and shadow structure to be tracked as a function of the squint angle. However a drawback of the multi-aspect SAS design is cost since the sampling of the physical receiving array must be increased to support the broad transmission beam. Interferometric SAS is another advanced mode which, as in SAR, provides information of target and seabed topography.

8 CONCLUSION

SAS has the potential for providing image quality that is unmatched by current sonars and is a key technology whenever high resolution is required. It is presently believed that the technology can contribute to a step change in the performance in detecting naval sea mines and correctly discriminating them from natural or man-made clutter. However SAS imposes substantial demands on navigational accuracy, which have, up to recent years, prevented its implementation in the ocean. This situation has changed, due to the emergence of powerful algorithms and low cost inertial instrumentation. Achieving extended area coverage in shallow water presents additional challenges due to the presence of multipath propagation which can possibly be mitigated by additional features in the sonar design, such as increased vertical directivity. Demonstration programs are underway in several NATO navies, as well as at the NATO Undersea Research Centre, to assess the robustness and operational effectiveness of these techniques.

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