International Hydrographic Review, Monaco, LXXII(1), March 1995

A REVIEW OF THE ACID SYNTHETIC APERTURE SONAR AND OTHER SIDESCAN SONAR SYSTEMS

by V.S. RIYAIT, M.A. LAWLOR, A.E. ADAMS, O.R. HINTON. B.S. SHARIF [1]

Abstract

The ACID project was part of the MAST Programme and was funded by the European Communities, to develop a synthetic aperture sonar for high resolution mapping of the seafloor. The collaboration of several European Institutions has enabled the ACID synthetic aperture sonar to be developed and tested during sea trials in May 1993. This paper discusses how the ACID synthetic aperture sonar system fits into the existing field of conventional sidescan sonar systems and the potential advantages to be gained using synthetic aperture processing techniques. The main advantage of the ACID sonar is that its azimuth resolution is independent of range and of the transmitted signal frequency. Sonar designers can, therefore, use lower operating frequencies and still obtain high azimuth resolutions. However, this paper also highlights the need for developing techniques which can increase the area mapping rate of synthetic aperture sonars which is essentially limited by the azimuth sampling constraint. Images from sea trials during May 1993 are presented which show areas of the seafloor before and after synthetic aperture sonar processing.

I. INTRODUCTION

Investigations into synthetic aperture sonar have to a great extent followed the theoretical and experimental work of the early research into synthetic aperture radar in the 1950s and 60s [1]. There are many airborne and spaceborne synthetic aperture radar (SAR) systems routinely in use today and we have become used to seeing high quality images of the Earth from space [2]. However, there are still no commercial synthetic aperture sonar systems in regular use. This lack of use of synthetic aperture techniques in sonar has in part been due to the difficulty of avoiding signal ambiguities. These ambiguities are a consequence of the relatively low speed of propagation of sound in water. Research into synthetic aperture sonar

[1] University of Newcastle upon Tyne, Department of Electrical & Electronic Engineering, Merz Court, Newcastle upon Tyne, NE1 7RU. UK.

has also been limited due to early studies which seemed to suggest difficulties, such as the instability and inhomogeneity of the medium. Later studies have shown that the stability of the ocean medium could lend itself to forming relatively long synthetic apertures over reasonable coherent integration times [3], [4]. Finally, the difficulties of knowing the position of the transducer within the ocean medium to an accuracy to within a fraction of the transmitted wavelength have also precluded development of synthetic aperture sonar.

II. SYNTHETIC APERTURE SONAR PROCESSING

Synthetic aperture processing is a technique for achieving high azimuth resolution by signal processing means. The coherent integration of signal returns from a small moving antenna can be used to synthesise a large synthetic aperture. It is therefore important that the amplitude and phase of the returned signals are retained for coherent processing. In order that the required processing gain can be achieved, the phase of the signal must be stable, between pulses, to within a fraction of the transmitted wavelength, a widely accepted criterion is $\lambda/4$. Almost without exception, synthetic aperture radar systems use narrowband processing techniques as their fractional bandwidths are usually less than or equal to 0.1. The ACID sonar uses broadband processing techniques as it transmits a wideband signal, it therefore cannot use narrowband signal analysis. The sonar uses synthetic aperture processing to produce a system capable of 1 metre azimuth resolution at up to 750 metres maximum slant range with a 2 metre long array. The azimuth resolution of the synthetic aperture sonar is shown in equation (1) and its derivation can be found in [5].

$$\delta_a = d \;/\; 2 \quad \text{----} \; (1)$$

As can be seen from equation (1) the azimuth resolution is independent of frequency and range compared with the resolution of a sidescan sonar whose azimuth resolution is given by equation (2).

$$\delta_a = R\lambda \;/\; d \quad \text{-----} \; (2)$$

Where,

δ_a = azimuth resolution (metres)
R = range (metres)
λ = wavelength of signal (metres)
d = real antenna length (metres)

III. A SURVEY OF SIDESCAN SYSTEMS

Achieving better azimuth resolution is an important consideration for many applications. Traditional sidescan systems can increase their azimuth resolution by :

- increasing the operating frequency
- increasing the transducer length

Increasing the frequency at which the sonar operates produces a narrower beamwidth but results in a reduced useable range due to higher attenuation with increasing frequency. However, increasing the transducer length means that a larger towfish has to be deployed from a survey vessel. A larger towfish means that a well equipped survey vessel is needed with a highly trained crew which adds to the survey cost and time. Therefore, there is potential benefit to be gained by giving the sonar designer a method of selecting the required operating frequency required for the maximum range and retain the azimuth resolution.

Table I
A survey of sidescan systems and the ACID sonar

	ACID	GLORIA II	SEAMAR C II	TOBI	SYS 09	Simrad	Klein
Model						MS 992	Hydro Scan
Array length in metres	2	5.33	3.8	3	3.79	0.66	1
Frequency in KHz	8	6.6	11/12 CW	30	9/10	120/330	500
Pulse repetition interval in seconds	0.69	20-40	1-16	4	0.5-19	0.78-25	
Survey speed in knots	3 (typical)	12 (max)	9 (max)	1.5-2.5	8.5 (max)	2-5	16 (max)
Beamwidth in radians & degrees (-3dB)	0.094 (5.37)	0.043 (2.44)	0.036 (2.06)	0.019 (0.95)	0.044 (2.5)	0.013 / 0.005 (0.75 / 0.29)	0.003 (0.2)
Depth range in metres	100-500	200-11,000	100-11,000	10,000 (max)	60-10,000	1,000	12,000 (max)
Swath width in metres	500	60,000 (max) 30,000 (typically)	10,000	3,000	20,000	500 / 200	100
Area coverage rate (m^2/s)	750	360,000	80,000	6,000	170,000	1250 / 500	1,600
Resolution at far range in metres	1 (at all ranges)	1290	180	28.5	880	7 / 0.7	0.3

By comparing the ACID sonar with lower frequency/longer range sonars, one can see that the potential for improving the azimuth resolution in these sonars can be as high as 1000 times. Systems such as GLORIA and TOBI tend to be used for deep ocean mapping of large to medium scale geological structures.

With the use of synthetic aperture techniques it would be possible to develop long range sidescan sonars with a constant resolution at all ranges. Higher frequency/shorter range sonars, for example the Klein Hydroscan system operating at 500 KHz (see Table I), have a sub-metre azimuth resolution. The Klein sonar has an azimuth resolution of 0.3 m at 100 metres slant range. However, TOBI has an azimuth resolution of 25 m at 1500 metres slant range.

It has to be remembered that the required coherency of the processing is much more stringent at shorter wavelengths, so that the fish would have to be stable to within 1mm between pings at a frequency of 500 KHz. However, with synthetic aperture processing we would not be required to use such a high frequency to obtain the same azimuth resolution. The question would have to be whether the cost of adding a sophisticated real-time processing system to a high frequency sonar could be justified by organisations in order to obtain slightly better azimuth resolution. The benefits of synthetic aperture processing lie in the low to medium frequency sonars, that is within the range 6 - 150 KHz. This would encompass sonars such as TOBI and the Simrad MS 992 when operating using its 120 KHz channel.

IV. RESOLUTION AND IMAGE QUALITY

This section presents images from the ACID sea trials during May 1993, near Toulon, France. The images show sidescan sonar data before it has been processed and directly after synthetic aperture sonar processing. The azimuth resolution of the ACID sonar is shown by measuring the -3dB point of selected targets and also by measuring the contrast within the targets as a way of measuring the quality of an image more quantitatively. The images presented show features which appear as point targets within the sonar beam. Although, it is apparent that the images shown in Figures 1 & 2 and 5 & 6 show unfocused and focused images, this process is still subjective. We can compare the contrast of an image to determine image quality. Poor focusing results in a low contrast compared with focused images where the contrast is higher [7]. The contrast of an image can be defined as the square of the image variance divided by the square of the image mean as stated by equation (3).

$$\text{contrast} = (\sigma \;/\; I_{mean})^2 \text{ ---- (3)}$$

Where,

σ =variance

I_{mean} =intensity mean

The images presented highlight the gain in azimuth resolution obtained with synthetic aperture processing at all ranges. The Figures given in Table II present the azimuth resolution which has been calculated from the azimuth cross-sections of the unprocessed and processed targets. These Figures are calculated from a selected

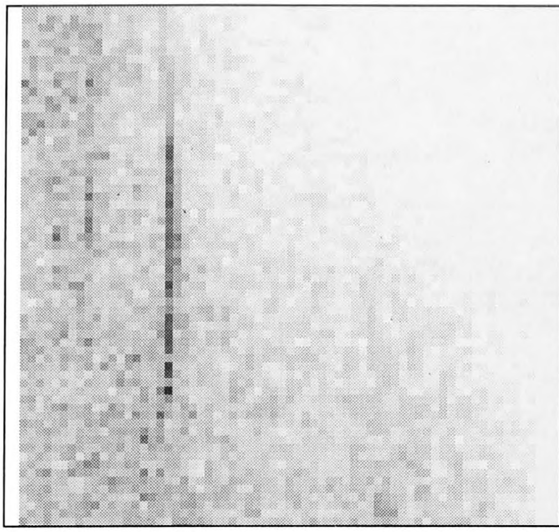

FIG. 1.- Unprocessed target with an along track sampling of 0.6 m and a range resolution of 0.4 m.

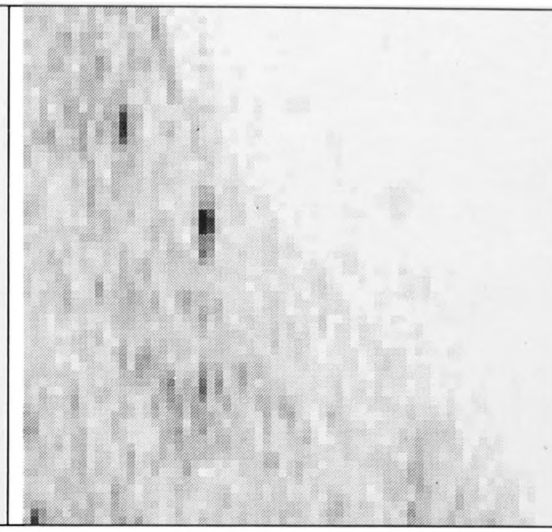

FIG. 2.- Target after synthetic aperture processing with an along track sampling of 0.6 m and a range resolution of 0.4 m.

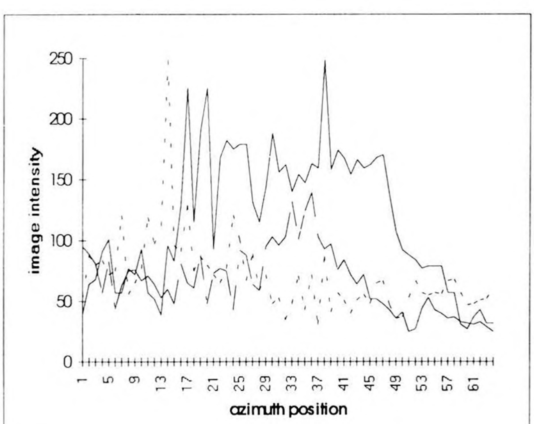

FIG. 3.- View in azimuth of the unprocessed target with the solid line showing the centre of the target (azimuth sampling is 0.6 m).

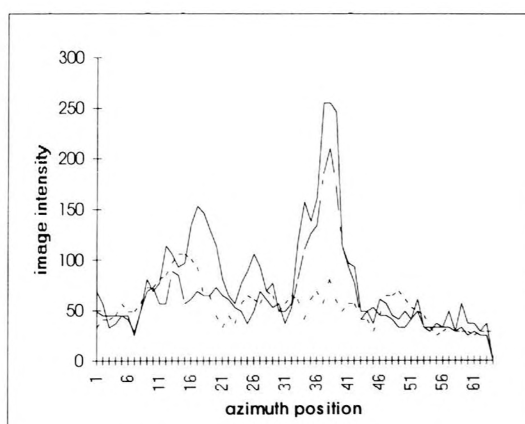

FIG. 4.- View in azimuth of the processed target with the solid line showing the centre of the target (azimuth sampling is 0.6 m).

azimuth line from the target returns and as such provide only an approximation of the azimuth resolution. The calculated contrast values presented in Table II give a quantitative measure of the quality of the unprocessed and processed images. The contrast is seen to be higher in the processed images.

Table II
Image measures of the ACID sonar

	un-processed image (Fig. 3)	*processed image (Fig. 4)*	*un-processed image (Fig. 7)*	*processed image (Fig. 8)*
resolution (-3dB)	19.5m	2.1m	9.9m	1.2m
contrast	625.05	651.06	1169.78	1371.30

V. AREA MAPPING RATE CONSIDERATIONS

Area coverage rate is an important parameter of a sonar system. The mapping rates are given in Table I for each of the sonar systems by using the expression given by equation (4)

$$A = VW \text{ ---- } (4)$$

Where,

A = area mapping rate (m^2/s)
V = sonar speed (m/s)
W = swath width (m)

It can be seen that the ACID sonar has an area coverage rate of 750 m^2/s compared with 6,000 m^2/s for TOBI for example. The lower mapping rate of the ACID sonar is due to the limitation imposed by the synthetic aperture processing technique, which restricts the antenna to moving no more than half the array length between pings. Therefore, the ACID sonar, with an array length of 2m, cannot move more than 1m between pings in order to ensure that the grating lobes of the synthetic array are adequately suppressed by the real antenna beam. If the mapping rate is to be increased then moving the sonar at higher speeds has a number of consequences. An increase in sonar speed necessitates an increase in the PRF to avoid range ambiguities. The maximum slant range is then reduced which is shown in equation (5) and is taken from [8], so that the mapping rate stays constant.

$$2v/L_r < \text{PRF} < c_0 / 2 (R_{max} - R_{min}) \text{ ---- } (5)$$

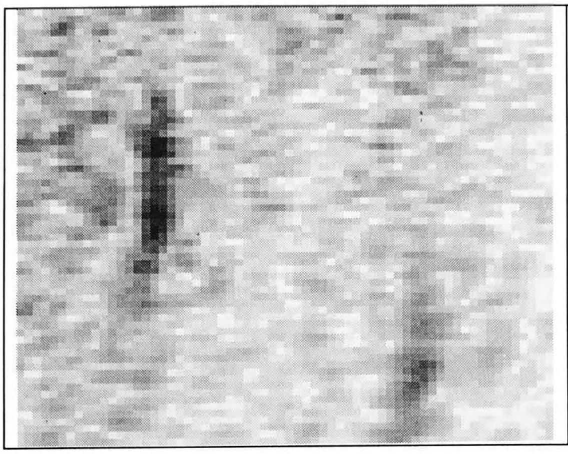

FIG. 5.- Unprocessed image of a target with an along track sampling of 0.6 m and a range resolution of 0.4 m.

FIG. 6.- Target after synthetic aperture processing with an along track sampling of 0.6 m and a range resolution of 0.4 m.

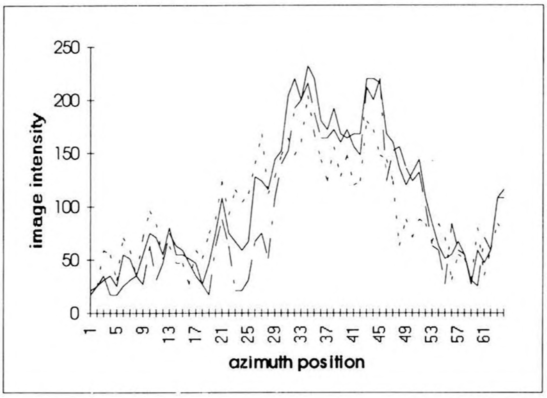

FIG. 7.- Azimuth view of the unprocessed target with the solid line as the centre of the target (azimuth sampling is 0.6 m).

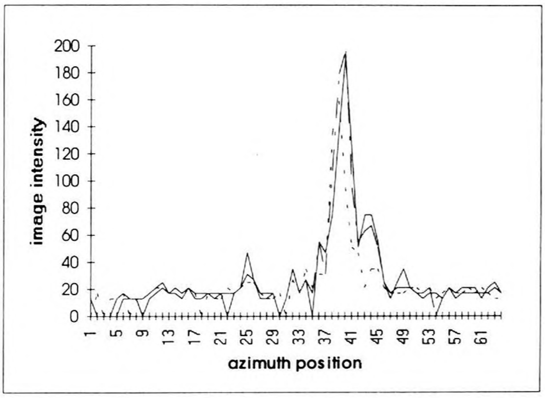

FIG. 8.- Azimuth view of the processed target with the solid line as the centre of the target (azimuth sampling is 0.6 m).

where,

v = sonar speed (m/s)
L_r = physical length of array (m)
c_o = speed of sound in water (m/s)
R_{max} = maximum slant range (m)
R_{min} = minimum slant range (m)

In order to increase the mapping rate without sacrificing azimuth resolution it is necessary to relax the restrictions imposed by either the azimuth or range ambiguities using methods such as wideband synthetic aperture processing allowing spatial undersampling [9] or increasing the array length, and then using vernier array processing to regain resolution [10].

When comparing the area mapping rates given in Table I, it should be noted that these figures represent a two-sided coverage rate except for the ACID sonar. The low frequency sonars such as GLORIA II, SEAMARC II and SYS 09 have a maximum range of tens of kilometres and survey speeds of around 10 knots which means that the area coverage is consequently high. However, along with this, it should be noted that the resolution at far range is poor, for example the resolution of GLORIA at far range is 1.29 km and 0.88 km for the SYS 09 system. The Klein Hydroscan system although it has a very short range of about 100 metres or less, has a high survey speed of 16 knots due to the short range and multiple beams. From Table I it is clear that the lower frequency sonars have a high area coverage rate and as the frequency of the sonar increases the area coverage rate falls rapidly. However, it must be noted that although the ACID sonar has a similar frequency to GLORIA, SEAMARC II and SYS 09, it is difficult to make direct comparisons between these systems. It is more accurate to compare the ACID sonar with the Simrad MS 992 sonar operating at 120/330 KHz. This shows that the area coverage rates are quite comparable, with the ACID and Simrad sonar (operating at 330 KHz) having area coverage rates respectively of 750 m/s^2 and 500 m/s^2. The azimuth resolutions are also comparable with the ACID sonar having a 1m resolution and the Simrad MS 992 having a 0.7m resolution. At its lower operating frequency of 120 KHz, even though the mapping rate is increased to 1250 m/s^2 the azimuth resolution at far range is reduced to 7m.

VI. CONCLUSION

It has been shown that synthetic aperture sonar has the potential for high azimuth resolution at all ranges. Results presented from sea trials highlight the dramatic improvement in azimuth resolution that has been achieved using synthetic aperture processing.

Area coverage rate is an important factor in most survey systems due to the financial constraints on surveys. However, there is also a need for providing researchers and surveyors with sidescan sonar systems with good resolution at long ranges. Techniques are being investigated which allow the synthetic aperture area coverage rate to be increased without sacrificing azimuth resolution. Vernier array processing will allow an increase in azimuth resolution for a given boat speed. The limiting factor on survey speed in synthetic aperture sonar systems is related to overcoming the azimuth ambiguities which occur when undersampling the synthetic aperture.

ACKNOWLEDGEMENTS

This work was funded as part of the ACID and SAMI projects under the European Communities' MAST programme under contract numbers MAST CT89-00002-CD and MAS2-CT93-0048. The partners in these projects are CPE-LYON (France), IFREMER (France), DMI (Denmark), RESON (Denmark).

References

[1] SHERWIN C.W., RUINA J.P., RAWCLIFFE R.D., "Some early developments in synthetic aperture radar systems", IRE Trans. Mil. Electron. 6, No. 2, pp 111-115, April 1962.

[2] CURRIE A., "Synthetic aperture radar", Electronics & Communication Engineering Journal, pp 159-170, August 1991.

[3] CHRISTOFF J.T., LOGGINS C.D., PIPKIN E.L., "Measurement of the temporal phase stability of the medium", J. Acoust. Soc. Am., Vol. 71, pp 1606-1607, 1982.

[4] GOUGH P.T., HAYES M.P., "Measurements of acoustic phase stability in Loch Linnhe, Scotland", J. Acoust. Soc. Am., Vol. 86, pp 837-839, 1989.

[5] CUTRONA L.J., "Comparison of sonar system performance achievable using synthetic-aperture techniques with the performance achievable by more conventional means", Journal of the Acoustical Society of America, Vol. 58, pp 336-348, August 1975.

[6] FLEWELLEN C., MILLARD N., ROUSE I., "TOBI, a vehicle for deep ocean survey", IEE Electronics & Communication Journal, pp 85-93, April 1993.

[7] BLACKNELL D., QUEGAN S., "Contrast as a measure of focus in synthetic aperture radar images", Proc. 2nd IMA Conf. Mathematics in Signal Processing, , pp 215-227, December 1988.

[8] CHATILLON J., BOUHIER M., ZAKHARIA M.E., "Synthetic aperture sonar for seabed imaging: relative merits of narrowband and wideband approaches", IEEE J. Oceanic Eng., Vol. 17, No. 1, pp. 95-105, January 1992.

[9] HAYES M.P., GOUGH P.T., "Broadband synthetic aperture sonar", IEEE J. of Oceanic Eng., Vol. 17, No. 1, pp 80-94, Januray 1992.

[10] LAWLOR M.A., ADAMS A.E., HINTON O.R., RIYAIT V.S., SHARIF B.S., "Methods for increasing the azimuth resolution and mapping rate of a synthetic aperture sonar", IEEE Oceans 94 Conf. Proc., Vol. III, pp III-565 - III-570, October 1994.