a NATO Research Centre
un Centre de Recherche de l'OTAN

PARTNERING FOR MARITIME INNOVATION

Reprint Series NURC-PR-2007-015

Experimental results of a 300 kHz shallow water synthetic aperture sonar

Andrea Bellettini, Marc Pinto, Benjamin Evans

November 2007

Originally published in:

Proceedings of the 2nd International Conference and Exhibition on Underwater Acoustic Measurements: Technologies and Results, 25-29 June 2007, IACM – FORTH, Heraklion, Greece.

About NURC

Our vision

- To conduct maritime research and develop products in support of NATO's maritime operational and transformational requirements.
- To be the first port of call for NATO's maritime research needs through our own expertise, particularly in the undersea domain, and that of our many partners in research and technology.

One of three research and technology organisations in NATO, NURC conducts maritime research in support of NATO's operational and transformation requirements. Reporting to the Supreme Allied Commander, Transformation and under the guidance of the NATO Conference of National Armaments Directors and the NATO Military Committee, our focus is on the undersea domain and on solutions to maritime security problems.

The Scientific Committee of National Representatives, membership of which is open to all NATO nations, provides scientific guidance to NURC and the Supreme Allied Commander Transformation.

NURC is funded through NATO common funds and respond explicitly to NATO's common requirements. Our plans and operations are extensively and regularly reviewed by outside bodies including peer review of the science and technology, independent national expert oversight, review of proposed deliverables by military user authorities, and independent business process certification.

EXPERIMENTAL RESULTS OF A 300 KHZ SHALLOW WATER SYNTHETIC APERTURE SONAR

Andrea Bellettini[a], Marc Pinto[a], Benjamin Evans[a]

[a]NATO Undersea Research Centre, La Spezia, Italy

Marc Pinto, NATO Undersea Research Centre, V.le S.Bartolomeo 400, 19138 La Spezia, Italy, fax –39-0187-527331, e-mail: bellettini@nurc.nato.int

Abstract: *The design of a shallow water synthetic aperture sonar (SAS) requires an understanding of key system and environmental issues. The main factors which limit SAS performance are micronavigation accuracy, where micronavigation is defined as the problem of estimating the acoustic path lengths to allow the focusing of the aperture, multipath effects and view angle differential effects which degrade shadow classification performance. Micronavigation accuracy is successfully addressed by the gyrostabilized displaced phase centre antenna technique, which combines data-driven motion estimates with external attitude sensors. Multipath effects in shallow water are effectively countered by narrow vertical beams. View angle differential effects are mitigated by increasing the frequency and by designing the system with a minimum grazing angle of about 6 deg. The combination of these factors led to the choice of a 300 kHz centre frequency and of a multipath mitigation scheme which uses multiple vertical beams. Experimental results obtained with a sonar incorporating these features have produced SAS images with 1.6 cm x 5 cm resolution in range x cross-range and high shadow contrast, up to 170 m range in 20 m water depth.*

Keywords: *Synthetic aperture sonar, navigation, minehunting.*

1. INTRODUCTION

The principle of a synthetic aperture is to displace a physical antenna through the medium and integrate multiple successive transmissions to create a longer virtual antenna. The ratio of the effective length of the synthetic antenna to that of the physical antenna is a measure of the gain of the technique. Both airborne and spaceborne synthetic aperture radars (SARs) have been operational for decades, with gains of the order of 1,000 or more. Synthetic aperture sonar (SAS) has faced much greater challenges, due to order of magnitude differences in the physical parameters involved. The solution to this problem is relatively costly and cumbersome, as it requires the use of a long multi-element physical array, with gains at best of the order of 10-100. Achieving a far range R at a velocity v requires a minimum physical array of length $L = 4vR/c$, where c is the sound velocity. The receiver element spacing has to be less than 4/3 of the required cross-range resolution and, together with the array size, determines the number of receiver channels required, and at the end the complexity and cost of the sonar.

This complexity limited the potential development of SAS systems to military mine countermeasure (MCM) applications. Even in that case, SAS, while still potentially useful, was not a truly enabling technology for the classical Cold War minehunting scenarios, where the task was mainly to detect and classify large mines of fairly simple geometrical shapes (e.g., 2 m long cylindrical objects). Existing sonars on mine countermeasures vessels (MCMVs), or similar sonars forward deployed on unmanned systems, have sufficient resolution to classify these targets under most orientations, and their wide horizontal field of view allows multi-aspect operation for the less favorable cases. The shift of emphasis to expeditionary operations in shallower littoral water and to the countering of smaller, stealthier sea mines and improvised weapons has provided SAS with a real chance of demonstrating its capability and operational value, since for these new tasks the sonar resolution has to be increased by a factor of about 5 to 10 with respect to even the highest resolution classification sonars on MCMVs. The only other practical means of achieving the required performance is to increase the sonar frequency by a similar factor. This dramatically reduces the sonar range, which is a severe operational limitation.

To alleviate this shortfall, the NATO Undersea Research Centre (NURC) started a collaborative joint research programme in early 1998 with the final goal of convincingly demonstrating at sea both the robustness and the operational value of SAS for MCM. Very soon, the research revealed that the available legacy sonars were not well suited for this task, and the design of a new SAS system, optimized for shallow water operations, was planned. An international competition to manufacture the SAS system, according to the NURC high level specification, and integrate it into a commercial off the shelf AUV was held in late 2002. The contract was awarded in January 2003 to Thales Underwater Systems, with subcontractors Bluefin Robotics providing the AUV and IXSEA providing the aided inertial navigation (Fig.1). This paper explains the rationale behind the design of that SAS system and presents some of its experimental results.

2. SHALLOW WATER SAS DESIGN

While SAS in theory achieves constant cross-range resolution determined by the width of the horizontal transmission sector, several factors can impact on the possibility to achieve in practice the nominal resolution.

The first technical issue in SAS is the so-called micronavigation problem, i.e., estimating the acoustic path lengths within the sub-wavelength accuracy required to coherently focus the synthetic aperture. Airborne SAR faced similar challenges as the wavelengths are quite comparable. The problem was solved there by combining inertial navigation systems (INS) with data-driven methods. For SAS, a powerful data-driven technique, which exploits the fact that the physical sonar is a multi-element array rather than the single element airborne radar, was available. It was derived from the known Displaced Phase Centre Antenna (DPCA) technique used in Moving Target Indication radar and its application to SAS had been proposed [1] and subsequently improved upon [2]. A theoretical and experimental analysis of the accuracy of the DPCA technique [3] quantified the limitations that DPCA-based micronavigation has as a stand-alone technique, chiefly in connection with the accuracy of the estimates of the changes in heading of the physical array. Another important result was that gyrostabilized DPCA (G-DPCA) micronavigation, a technique which uses inertial attitude sensor estimates and interferometric measurements together with DPCA slant range sway and surge estimates, offers significant accuracy improvement with respect to DPCA alone [3-4].

Fig.1: AUV-based SAS system developed by Thales Underwater Systems according to a high level SAS design provided by NURC. The SAS is the central mid-section with black acoustically transparent windows. The vehicle is a Bluefin 21 of length 3.5.

A second effect which limits the achievable resolution is the difference in view angle of a target within the SAS integration length can lead to the cross-range blurring of the shadow edges. The effect is also known in physical aperture sonar [5]. A third effect, very important for shallow water operations, was the multipath at large range to water depth ratios [6].

When, in 2002, NURC faced the task of designing a new high resolution SAS system optimized for shallow water operations, a critically important decision to be made was that of the centre frequency. Three main factors were taken into consideration.

- Higher frequency obviously provides a better physical resolution for a fixed array length and facilitates the obtainment of the desired SAS resolution, since a lower SAS resolution gain is required. For data driven micronavigation techniques, the practically achievable gain does not critically depend on the sonar frequency provided that external attitude sensors and physical interferometry estimates are available.
- The use of narrow vertical beams effectively counters multipath effects at large relative range. At higher frequency the vertical array is shorter, which facilitates the integration into small diameter AUVs.
- The impact of angle view difference on shadow is mitigated by increasing the frequency. The effect is inversely proportional to the square root of the frequency.

All of them suggest the adoption of a relatively high sonar frequency for SAS. A reasonable design criterion is to maximize the sonar frequency under the constraint of achieving robust signal to noise ratio at a desired maximum range and at a minimum grazing angle of 6 deg. Indeed operations at grazing angles lower than 6 deg lead to very long shadows for which differential azimuth effect are a severe limiting factor. In many environmental condition, they could also lead to extensive target masking by the seabed topography. Taking the 6 deg criterion and a typical combination of 20 m water depth and 5 m AUV depth (limited by sea state) we have a maximum effective range of about 150 m. A practical 1.2 m long array operating with a SAS oversampling ratio of 4/3 (useful for robust G-DPCA operation) limits the SAS far range to 170 m for a sonar velocity of 2 m/s. Based on this, a 300 kHz frequency seemed well suited to achieve high signal to noise ratio.

Modern sonar designs for MCMVs achieve multipath rejection by narrowing the vertical field of view. For a side-looking system an additional vertical beam management scheme is required to cover the full swath. NURC opted for a scheme which consists of two receiver arrays with different vertical fields of view, each appropriately narrowed to reject multipath but steered in different directions so as to cover together the full swath, with the exception of the usual gap at high grazing angles, to be covered by overlapped tracks.

The vertical receive element consists of an upper and a lower array which is made up of 19 and 10 vertical sub-elements, respectively. The sub-elements are connected by a shading capacitor-resistor network which allows a degree of flexibility, by hardware modification, in forming the vertical beam pattern of both arrays. For the first experimental tests, the shading network of the most directive vertical array was selected to provide a 3 dB beamwidth of 7 deg and -20 dB sidelobes. The depression angle of the array block is mechanically adjustable. An additional feature was a fully programmable vertical transmit array of 48 channel spaced at half-wavelength, in order to test various vertical beam management schemes on transmission, in particular frequency colored transmission and asymmetrical beams designed to effectively suppressing surface reverberation. Wideband high frequency (270-330 kHz) was chosen for the 36 element array of total length 1.2 m. An addditional interferometric array formed by 12 elements for a total length of 40 cm with an interferometric baseline equal to 19 wavelengths was selected.

3. EXPERIMENTAL RESULTS

The results of a trial conducted in June 2006 in the Marina di Carrara area, show that all the shallow water SAS performance goals specified above have been achieved. In particular, SAS imaging with shadow contrast in excess of 5 dB was achieved by processing at NURC up to 170 m range in 20 m water depth (Fig.2) with 1.6 cm x 5 cm resolution respectively in range and cross-range. This range-to-water-depth ratio of about 8.5 probably exceeds that of all currently available SAS systems capable of shadow classification. In Fig.3 an image obtained with the close range receiver array is shown. Figure 4 shows the signal to noise ratio relative to the two figures, derived from the DPCA ping-to-ping correlation. Although the correlation is significantly lower at long range, DPCA sway estimation was very robust up to 160 m range. Beyond 160 m range excessive electronic noise results in rapid reduction in correlation. The DPCA surge estimation followed the same pattern.

These results were obtained in calm sea state, but strong deviations from the nominal straight trajectory and from constant heading and pitch were observed, due to the vehicle controller not having been optimized. For example, the image in Fig.2 was obtained with a peak-to-peak heading and pitch variation within the SAS integration time of about 3 deg. As a result, both the accuracy of the DPCA sway estimation and the INS synchronization were critical in obtaining focused images. In spite of the challenging large motions, G-DPCA micronavigation and SAS imaging performed robustly.

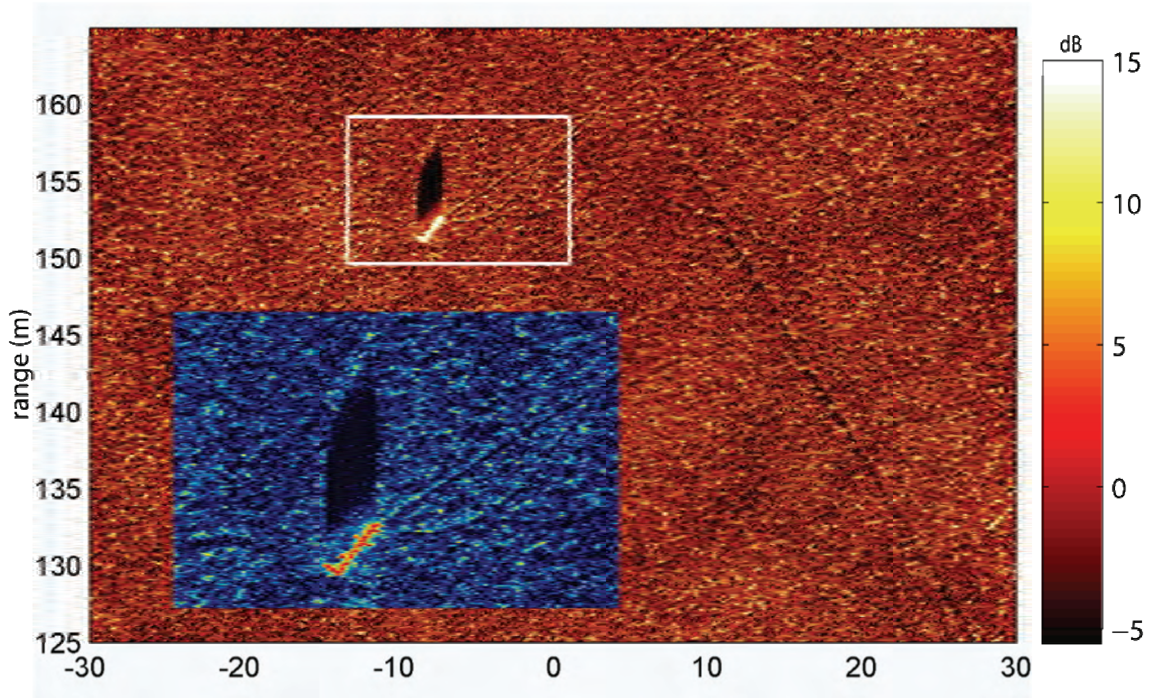

Fig.2: Large scale and detailed SAS images of a 2 m x 0.5 m cylindrical dummy target. Resolution is 1.6 cm x 5 cm, water depth 20 m, sonar altitude 15 m, bottom type: mud. The detailed SAS image is displayed with a different color map to represent clearly the full dynamic range of the image (33 dB).

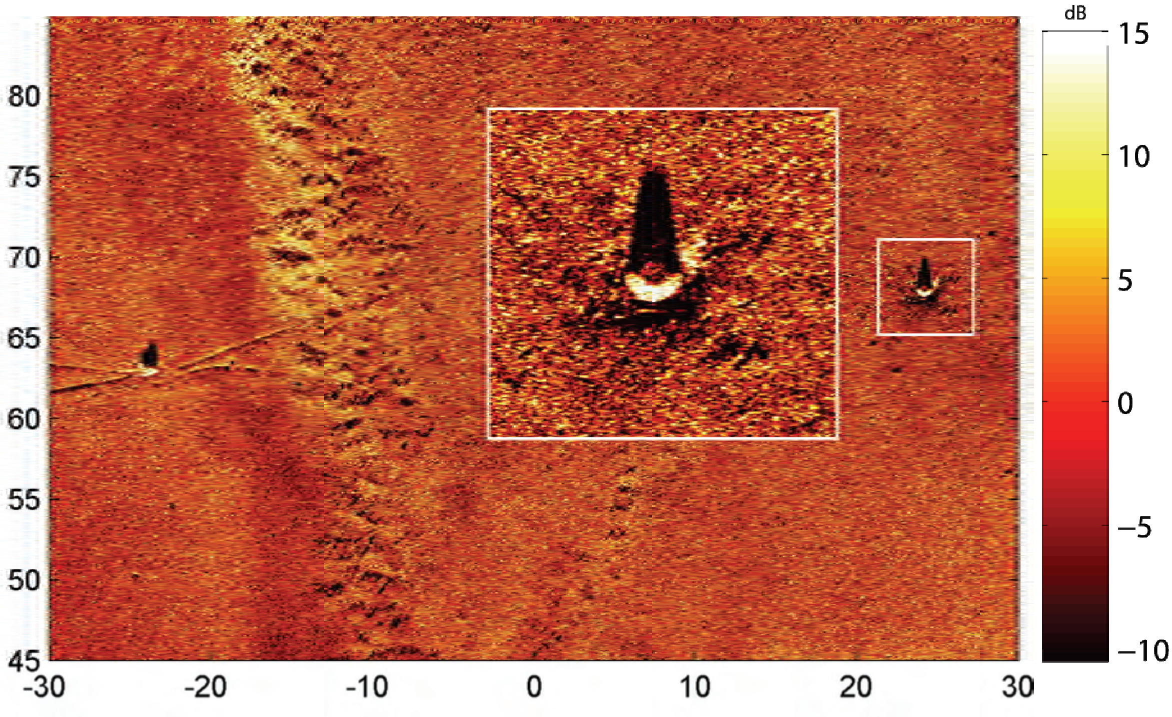

Fig.3: Large scale and detailed SAS images of a slightly buried dummy target shaped like a truncated cone of 1 m diametre and 45 cm height. Resolution is 1.6 cm x 5 cm, 20 m water depth, 10 m sonar altitude. Bottom type: mud (mainly).

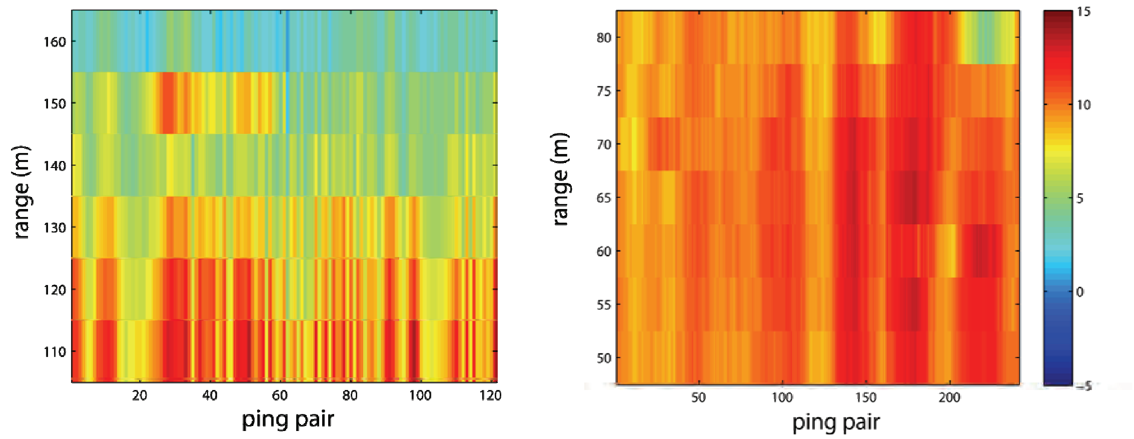

Fig.4: Signal to noise ratio (in dB) derived from the DPCA ping-to-ping correlation coefficient of the data producing the SAS image in Fig.2 and 3.

4. ACKNOWLEDGEMENTS

The authors would like to acknowledge the essential contributions of the staff from the NURC team with P.A. Sletner as Engineering Coordinator, and the Thales Systems and Trial Team, led by A. Sawyer in collecting the raw data used to produce the SAS images. This raw data is the joint property of Thales Underwater Systems and of NURC.

REFERENCES

[1] **R.S.Raven**, Electronic stabilization for displaced phase center systems, U.S. Patent 4 244 036, Jan. 6, 1981.

[2] **M.Pinto**, Procédé de recalage d'images sonar au moyen de sous-antennes, French Patent 9700487, Jan.17, 1997 (U.S. Patent 6 240 050 B1, May 29, 2001).

[3] **A.Bellettini and M.A.Pinto**, Theoretical accuracy of synthetic aperture sonar micronavigation using a displaced phase centre antenna, *IEEE J. Oceanic Eng.*, volume (27), pp. 780-789, 2002.

[4] **A.Bellettini, M.Pinto, L.Wang and R.Hollett**, Synthetic aperture sonar micronavigation using a gyrostabilized displaced phase centre antenna, *SACLANTCEN REPORT SR-378,* La Spezia, 2003.

[5] **F.Florin and S.Bozinoski**, Effets d'echoes et d'ombres differentiels sur les antennes de sonar actif en champ de Fresnel, Proc. Quatorziéme Colloque Gretsi, Juan-les-Pins, 13-16 Septembre 1993, pp.1155-1158.

[6] **A.Bellettini, M.Pinto and L.Wang**, Effect of multipath on synthetic aperture sonar, In *Proc. of WCU 2003*, Paris, 2003.

Document Data Sheet

Security Classification		*Project No.*
Document Serial No.	*Date of Issue*	*Total Pages*
NURC-PR-2007-015	November 2007	6 pp.

Author(s)

Bellettini, A., Pinto, M., Evans, B.

Title

Experimental results of a 300 kHz shallow water synthetic aperture sonar

Abstract

.

Keywords

Issuing Organization

NURC
Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
NURC
(New York) APO AE 09613-5000]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@nurc.nato.int