coustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Ten key papers in synthetic aperture sonar

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There are now hundreds of patents and papers on synthetic aperture sonar; some of them of key importance whereas many others are of peripheral or minor interest. Here we take what we consider to be the top ten publications in synthetic aperture sonar and explain why we believe they are important and how they have made a significant contribution to the developing discipline or have made some leap of imagination in the area. This paper is more than a catalogue of the top 10 citations since not all the real advances in the field have been published in academic peer-review journals.

Preamble

This paper is an evaluation of the SAS literature selecting what in our opinion are the ten most influential papers regardless of their citation index. They follow in chronological order.

1 Cutrona, 1975

There is little doubt that the interest in synthetic aperture sonar (SAS) as a separate development from synthetic aperture radar (SAR) started with the first of Cutrona's two benchmark papers. In the first paper, he outlines most of what we now consider accepted practice. He clearly states that the standard SAR properties also apply to SAS viz; the along-track resolution (he calls it "azimuth resolution") is *"...(1) independent of frequency, (2) independent of range, and (3) finer [along-track] resolution is associated with smaller values of projector horizontal aperture D."*

In this first paper he compared the radar equation (usually presented in its non-logarithmic form) to the sonar equation (in its logarithmic form) as given in most of elementary sonar texts. He notes that the noise limit in sonar would be environmental rather than internally generated as is the usual case in radar. Cutrona takes some space describing the mathematical coupling between maximum unambiguous range, pulse repetition frequency (prf) and spatial sampling along the synthetic aperture track. His optimal solution was to have a significantly downward-looking transmitted beam with vertical beam-pattern control and to use a multiplicity of horizontal beams for each ping. The last requirement was somewhat prophetic as at the time all SAR used a single element antenna.

Cutrona notes that *"The media differ significantly with respect to propagation modes and stability. Multi-path, path stability, and refraction are more severe for sonar than for radar. Ultimately these phenomenon limit the resolution achievable."* and he also notes that *"... the motion compensation is much more severe for sonar than radar."*

2 Gilmour, 1978

Although there are a few US patents prior to 1978 that had some relevance to SAS, the first that has all the elements of a workable SAS system was that awarded to Gilmour at Westinghouse Electric. His Fig. 1 has a nose-towed fish with a dynamic depressor, a single aperture projector labeled TX and a keel mounted array of six hydrophone elements. The outputs of the six hydrophone amplifiers are summed with the appropriate delays into some nine separate, slightly overlapping beams, which can be demodulated to baseband and summed to form an image. In his Fig. 10, he clearly demonstrates the concept of adjoining phase centres formed by each transmitter/hydrophone combination can be stitched into one contiguous array. Of course much of the demodulation and "sum-and-delays" are all performed by analogue electronic techniques and these embodiments form a major part of his claims. Regardless of it practical shortcomings, this patent showed the essential elements of most SAS as they exist today.

3 Christoff et al, 1982

Perhaps readers may be puzzled by this choice of key paper since it does not specifically use a SAS but it did address the most critical concern that SAS developers had at that time. Many of the publications prior to 1980 suggested that although SAS may be a credible theoretical possibility, it would not work in practice because the undersea propagation medium was too unstable. To answer this question, the SAS group at Coastal Systems Station of the Naval Surface Warfare Center in Panama City, Fl, built a rail that would hold the transmitting platform steady 48 m out in front of the transmitting projector, and deployed hydrophones at 3, 6 and 9 m elevation off the seafloor. They used a 14 cycle pulse at 100 kHz and reported that at 3 m elevation, the path length from projector to hydrophone caused less than 20° RMS phase variation over some 20 mins. Since the typical synthetic aperture is formed with a 30 s time window, this was proof *"... that the medium stability will not generally impose severe limits on synthetic-aperture performance at these frequencies and ranges."*

4 Huxtable and Geyer, 1993

This paper focused on the necessity for high quality motion compensation (MOCOMP) on the hydrophone data before any SAS processing. They simulated a multi-beam SAS that worked to a maximum unambiguous range of 300 m at 150 kHz and trawled at 3 knots. To measure the position and heading, they simulated a navigation suite with a strap-down inertial navigation system, a Doppler velocity log and a depth gauge all used as input to a Kalman filter to give the best possible estimate of the tow-fish position and heading for each ping. The corrected multi-element hydrophone data was then all processed by the seismic migration algorithm (aka: Stolt mapping, range migration algorithm, Omega-K algorithm) modified to use multi-hydrophone data. *"First, the multi-beam SAS data are transformed*

to equivalent data that would be collected by a fictitious single beam system that collects data at the same phase center locations along the aperture." The output of the processor is the "reconstructed" image which still contains residual positional errors uncorrected by the MOCOMP procedures as well as any errors introduced by medium fluctuations. These residual errors are countered by application of post-processing auto-focus techniques such as the map-drift algorithm and phase gradient auto-focus (PGA) algorithm.

Although this paper mainly described the results of a simulated SAS system, there were some strong statements made that showed the way ahead. *"... off-the-shelf MOCOMP sensors are not adequate for motion compensation. However, auto-focus algorithms are capable of performing the needed residual motion compensation..."* They finally pointed out that the auto-focusing could also correct for medium phase fluctuations which were likely to be *"..smaller than phase errors caused by [the] residual motion [errors]"*

5   Griffiths et al, 1994

A common desire for many SAS research groups was the combination of high resolution SAS imagery (i.e, an optical picture of the backscattered strength of every resolution cell in the along-track, cross-track plane) with a bathymetric map (estimating the depth to some datum of every resolution cell). Unfortunately estimating the depth of every cell (assuming the system is not wildly oversampled) is not possible since the depth can be only measured by interferometry over a group of cells. Given two vertically displaced hydrophone [arrays], it is possible to determine the angle of arrival of some part of the seafloor by time correlation (or phase estimation) which can only be done from group of scatterers covering many adjacent resolution cells. Thus there is a trade-off between height accuracy and image plane resolution for the bathymetric map. This paper on interferometric SAS (InSAS) outlines some of the aspects involved (including some discussion of autofocus techniques which clearly apply equally to standard SAS). The tank-based experimental results were convincing but it was at that stage unclear how this would work in the open sea.

6   Châtillon et al, 1999

The SAMI (Synthetic Aperture Mapping and Imaging) project was the result of a European multi-institution cooperative venture under the MAST2 (MArine Science and Technology) programme to deploy a working SAS mainly designed for long-range geological work rather than near-range imaging at close to glancing angles. The centre frequency was only 8.5 kHz with a normal slant range up to 750 m. They designed the four metre long tow-fish to have four 1 m by 26 cm hydrophone elements stacked two upper and lower with some 25 cm of vertical separation. The front lower element also worked as the transmitting projector. The tow-fish also housed a inertial measurement unit for relative position and heading

estimation.

The images produced by this SAS were impressive and the "large scale images" were hard to interpret since they used a large depression angle more akin to that used by a satellite-borne SAR. Like a SAR they could have multiple pings in flight at any one time and could be receiving echoes from a ping transmitted many pulse periods earlier. Since they had hydrophones with vertical separation, they could try to estimate the bathymetry and claimed to have a 1 m by 1 m by 1 m voxel out to 2.5 km although the ground truth would have been been hard to verify. Their Fig. 10 of a side-by-side of a bathymetric map and SAS image of the Canyon du Var is particularly interesting. Sadly at the end of the project the component parts contributed by each institution were retrieved and the SAS disassembled.

7   Lurton, 2000

Although InSAS had been demonstrated in a tank and at sea, some of the limiting factors were not well understood. This theoretical and simulation paper by Lurton investigated all the significant factors that influence the quality and resolution of swath bathymetry using phase differences. He does clearly specify that he excludes surface multipath effect which have a significant impact on shallow water systems. Lurton does a good job explaining the sliding footprint effect which is the result of the wide transmission bandwidth producing a range resolution smaller than the differential range cell shift between the vertically displaced hydrophone arrays. *"This implies performing a first approximate estimation of bathymetry, then applying an artificial delay between the two receivers depending on the raw estimation of the instantaneous impact point angle, and, finally computing the final phase differences with a minimised sliding footprint effect."*

8   Bellettini and Pinto, 2002

Although there were earlier publications of the use of overlapping phase centres from sequential pings for micro-navigation (i.e., relative position to sub-wavelength accuracy as well as relative heading), the best paper in the SAS field is probably that in 2002 from Bellettini and Pinto of the NATO SACLANT Undersea Research Centre (now called NURC). Here they laid out the analysis that leads to the Cramér-Rao lower bound of the displaced phase-centre antenna (DPCA) measurement technique. The comparison with the experiments using a high frequency 100 kHz SAS showed that when using two overlapping phase centres, the results were somewhat poorer than that predicted but at least were consistent with their theoretical bounds.

9   Hansen et al, 2006

Although little in this paper was completely original, this is perhaps the first complete example of a fully

working non-tethered system as described in the open literature. It had everything needed. A comprehensive suite of position sensors were employed to get rough position, orientation and velocity. This was used to implement coarse motion compensation and this was combined with DPCA to get fine scale position and orientation errors which could be applied to any fine motion compensation algorithms. As a final touch, the reconstructed image went through phase gradient autofocus to correct any residual errors. The sonar had two horizontal hydrophone arrays stacked vertically with a common projector located in between the arrays. With the AUV well stabilized to roll, these two arrays could produce interferometric images and subsequent baythmetric sea-floor height estimates. Since they worked in deep water (well deep defined as ¿ 100m), their phase estimates were not influences by surface multi-path. The sonar images of the partly buried U-boat is as fine an image as has been seen at that depth and range.

10   Mitchell et al, 2006

When a complex reflecting target is illuminated from a limited range of aspect angles, the resulting image often appears to be collection of corner reflectors. But what if we could encircle the target of interest and use all available aspect angles to contribute to a coherent image? In this paper Mitchell et al describe two circular SAS experiments where they placed a target on a rotating turntable so as to collect the backscattered data from all 360° to demonstrate the superb quality of the properly processed coherent image. But perhaps more exciting was the second experiment where they navigated a surface platform in a near-circular track around a stationary target measuring the backscatter over all possible angles. Their Fig. 11 is a remarkable image with various mine-like objects clearly identifiable; truncated cone, wedge, cylinder lying on its side, etc.

Postamble

SAS has now gone from a good idea to a useful operational tool with commercial off-the-shelf systems now available. Although the marginal cost of a SAS over a simple side-scan is still high, the combination of resolution constant with range and independent of centre frequency as well as bathymetry now make SAS part of the mainstream.

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