Lorentzen, Ole J., *Effects of snaking for a towed sonar array on an AUV, Proceedings of the 38th Scandinavian Symposium on Physical Acoustics, Geilo February 1 - 4, 2015. Editor: Rolf J. Korneliussen, ISBN 978-82-8123-015-6.*

Effects of snaking for a towed sonar array on an AUV

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Abstract

Autonomous underwater vehicles are dynamic systems that don't move perfectly straight through the water. When attaching a towed antenna, the antenna misalignment relative to the desired straight antenna may cause reduced performance in both direction of arrival estimation and resolution performance. In this study, curved and snaking antenna perturbations are simulated and their performance reviewed with regards to how large offsets can be tolerated. An intuitive bearing vs. time record plot illustrates the effects caused by these perturbations.

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1 Introduction

The Norwegian Defence Research Establishment (FFI) has been working with many aspects of autonomous underwater vehicle (AUV) technology for more than 25 years, particularly with development of the HUGIN AUV, shown in Figure 1. Recently we have acquired a towed sonar array for use with HUGIN, and started to work on signal processing for this application.

Figure 1: The HUGIN HUS AUV.

In this study we consider the effects of how such a towed array moves through the water. AUVs are small compared to surface vessels and manned submarines, and they are dynamic systems that never move perfectly straight. At FFI we have worked on accurate estimation of the AUV navigation, e.g. for the special case of active synthetic aperture sonar (SAS) imaging [1]. In this study we explore how large perturbations of the array position that can be allowed without compensation, which in turn indicates how well the element positions have to be estimated. We use simulations of various array perturbations and review the effect on classic signal processing performance, specifically direction of arrival (DOA) estimation and resolution. We consider arrays with curved and snaking (sinusoidal) shapes in the horizontal plane, as shown in Figure 2.

(a) Curved array illustration.

(b) Snaking array illustration.

Figure 2: Illustrations of investigated array perturbations in the horizontal plane.

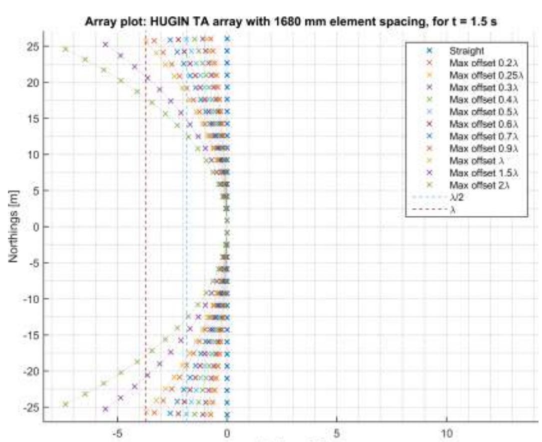
2 Method

A geometric direct path (no scattering) sonar simulator supporting any array and source geometries was developed and used in this study. A continuous wave (CW) point source at 440 Hz was simulated in the far-field at 2500 meters from the receiver array. It was positioned at 1 degree off the array broadside. The receiver array was a 32 element array with 1.68 meter element spacing, corresponding to 0.5λ for 440 Hz, where λ is the wavelength under assumed speed of sound $c = 1480$ m/s.

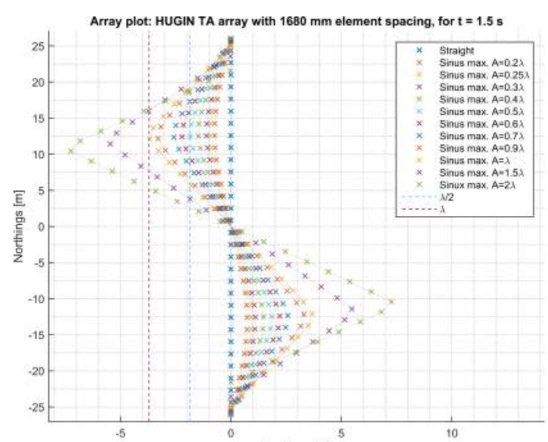
Simulations were run both with a straight array, and then also with perturbed array element positions. 20 realisations of zero-mean, white noise were applied on each case so that the SNR is 10 dB before array gain. Classic time domain spline-interpolating delay and sum beamforming[2] was performed with an azimuthal sampling of 0.05°. The beamforming algorithm was given the straight array configuration in all cases.

The results were reviewed by examining the error and variance in the direction of arrival estimate and the resolution by means of the half power width, i.e. the -3 dB main lobe width in the steered response. The direction of arrival is estimated both directly by peak value, and by performing a parabolic fit using peak value and the -3 dB intersection values.

The array perturbations used were curved shapes with radii giving maximum element offsets from the straight array of 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.9, 1, 1.5 and 2 wavelengths ($\lambda \approx 3.36$ m. at 440 Hz) as shown in Figure 3a and sinusoidal snaking shapes as shown in Figure 3b, with amplitudes as for the maximum element offsets used with the curved arrays.



(a) Curved array perturbations.



(b) Snaking array perturbations.

Figure 3: Perturbed array shapes.

3 Results

For the curved array scenario, the direction of arrival and resolution estimates are shown in Figure 4.

The direction of arrival estimate only suffers slightly until the maximum element offset is greater than 0.5λ, where it gives more than 2° error. This is apparently due to signal splitting, i.e. we get a dip in the steered response so that it looks like two signals, and the highest peak is picked. Because the curved shape appears fairly symmetrical for a source located close to broadside, the parabolic fit method performs slightly better until the maximum element offset becomes greater than 1.5λ, after which it fails because the signal splitting has a dip lower than -3 dB in between the two apparent signals. This is the point at which we would define that there are two resolved signals at different DOA. The same effect is present intermittedly at 0.7λ.

For both the direct and parabolic fit estimates, the variance increases significantly at the same values because the added noise causes variability on which one of the peaks is selected after the signal splitting. For a target directly in the broadside direction, we would expect the mean estimate to be in the broadside direction, but in this case with the target 1° away from broadside, a skewed result seems reasonable.

The resolution only suffers slightly by less than 0.5° up until a maximum element offset of about 0.3λ, when the rate of degradation increases significantly. Compared to the limits of good DOA estimates, the resolution is about four times worse at a maximum element offset of 0.5λ. This means that even though the DOA estimate is good at a maximum element offset of 0.5λ, the resolution has suffered significantly, which may be critical in an extension to a multiple signal case. The apparent increased resolution at maximum element offset of 0.7λ is due to the signal splitting and is considered a measurement technicality.

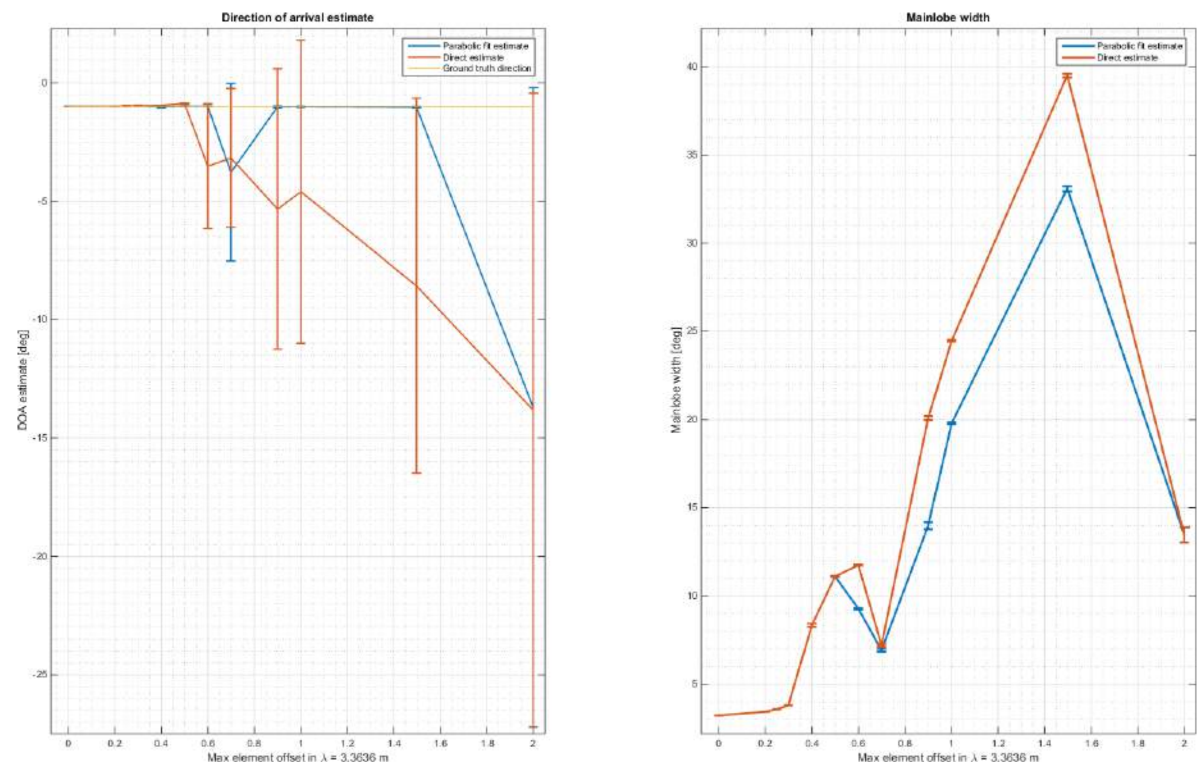


Figure 4: Direction of arrival estimates and resolution estimates for curved array perturbation.

Looking at an example steered response in Figure 5, it is obvious from the upper panel how the signal splitting can cause erroneous DOA estimates. In the lower panel, it is demonstrated how the parabolic fit can perform better than the direct estimate in this particular case.

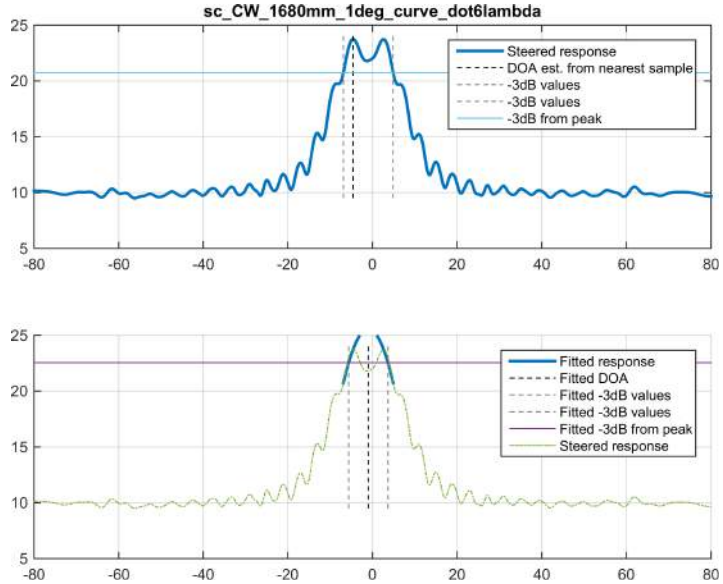


Figure 5: Steered response for a curved array with maximum element offset of 0.6λ.

For the snaking array scenario, the direction of arrival and resolution estimates are shown in Figure 6.

The direction of arrival estimate suffers by an error of two degrees already at 0.3λ, an error which is an order of magnitude greater than for the curved array with similar maximum element offset. The DOA estimate has inconsistencies at 0.4λ, 0.9λ, 1.5λ and 2λ, which is similar to what we found with the curved array perturbation; A different peak is selected, but the main signal peak is larger again in the following perturbation. At this point the error is already large, so this effect is not important.

The resolution suffers with increasing maximum element offsets, at a rate that increases significantly around a maximum element offset of 0.25λ. The improvement in resolution for maximum element offsets of 0.4λ and 0.9λ coincides with a change in the DOA estimate, and is due to a different lobe in the steered response being selected as the direction. While this lobe is more narrow, it no longer indicates the actual DOA estimate resolution. The snaking and curved array perturbations have similar, small resolution losses for maximum element offsets less than 0.4λ.

Comparing curved and snaking array shapes, the snaking shape has reduced DOA performance at smaller maximum element offsets than with the curved array shape. One of the reasons for this could be that the offset between the outer elements in the snaking array is two times the amplitude. Even when considering this, the curved array still has better DOA performance than the snaking array with only half the maximum element offset as amplitude. This indicates that this type of signal processing is more sensitive to the snaking array shape.

The results from both the curved and snaking array perturbations are presented as bearing versus time record (BTR) plots in Figure 7. The increasing defocus and eventually split signal directions occurring with increasing curvature is clearly seen in Figure 7a. For the snaking BTR in Figure 7b, the increasingly strong multiple DOA estimates with increasing sinusoidal amplitude can be observed.

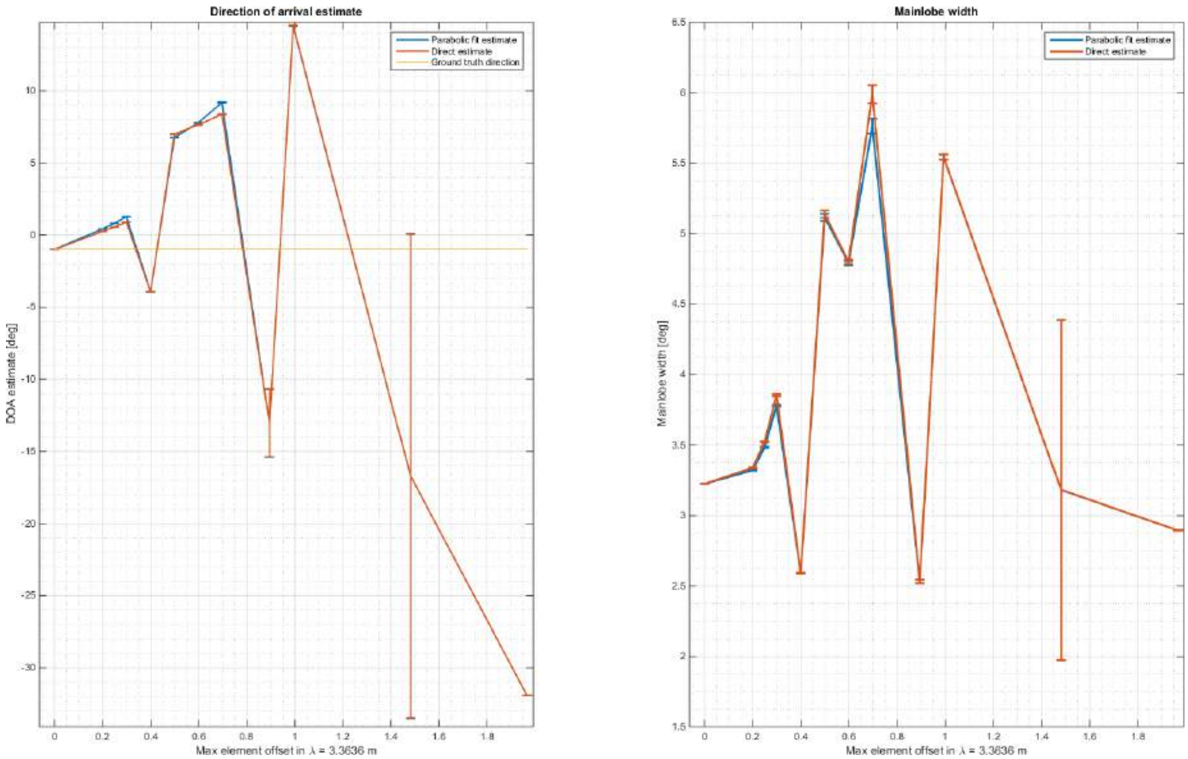
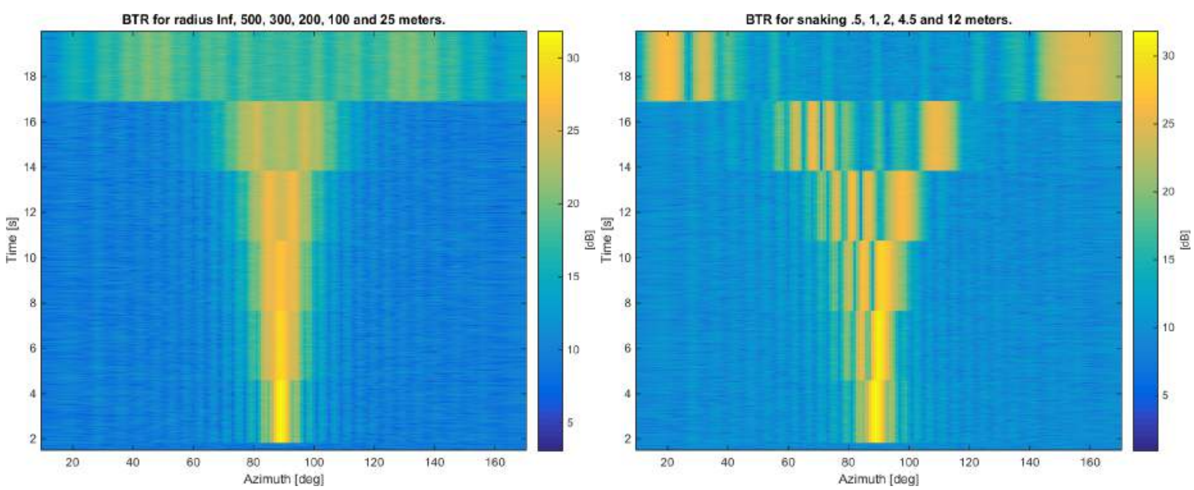


Figure 6: Direction of arrival estimates and resolution estimates for snaking array perturbation.



(a) Increasingly curved array.

(b) Increasingly snaking array.

Figure 7: Bearing time record (BTR) plots showing the steered response for curved and snaking arrays, with similarly increasing maximum element offsets.

4 Conclusions

The curved array shape gives a fairly symmetrical steered response for a source close to broadside. The DOA estimate is accurate to within 1° for maximum element offsets up to 0.5λ, while the resolution increases by less than 1° for maximum element offsets up to 0.3λ. At a maximum element offset of 0.4λ the resolution is almost three times worse than for the straight array.

The snaking array shape gives a steered response with three apparent DOAs. The DOA estimate is off by more than 1° for a maximum element offset of 0.2λ, with an increasing error for greater maximum element offsets. The resolution is only about 1° worse at a maximum element offset of 0.3λ.

Comparing curved and snaking array shapes, the results indicate that this type of signal processing is more sensitive to the sinusoidal perturbation.

For approximately symmetric array perturbations, like the curved array, symmetric estimation techniques like parabolic fitting can improve DOA estimation performance.

Note that these results are valid for the given case of a single source in white noise with a critically sampled array, and not in general for multiple signals in colored noise cases. The results could be extended and give an indication on the results for more complex scenarios.

Acknowledgements

The author would like to acknowledge Roy E. Hansen, Torstein O. Sæbø and Stig A. V. Synnes for their input and guidance.

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