A Wavefront Sensing Method for Synthetic Aperture Sonar Autofocus

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Summary

Synthetic aperture Sonar (SAS) is a technique for improving sonar resolution by using known sonar motion to lengthen the useful sonar aperture. Unfortunately the images formed with a strip-map SAS are rapidly degraded when there is any perturbation from the known flight-path. This paper outlines a new autofocus procedure for improving SAS imagery, based on wavefront sensing techniques from the astronomical imaging field.

We propose an algorithm based on wavefront sensing techniques. The algorithm compares the intensity images generated from the convolving the reconstructed image with a pair of complementary azimuth chirps. Any path deviation becomes apparent in these images and is estimated and removed in an iterative framework.

The main benefit of the proposed algorithm is the ability to use both sea-floor clutter and strong scatterers simultaneously, this is a major advancement over most SAS autofocus schemes which lack this ability. Experimental results using varied sea-floor scenes indicate the algorithm has some promise within an iterative framework. Further research is needed to reduce the computational burden of the algorithm and ideally, remove the requirement of an iterative framework.

1. Introduction

Synthetic aperture sonar (SAS) is a technique for high-resolution seafloor imaging. It allows a reduction in the number of transducers required for a given sonar by using the forward motion of the tow-body to effectively create synthetic transducers. This improvement is most often used to create long (synthetic) apertures for high resolution imaging at relatively low frequencies. SAS offers improved (range independent) resolution over traditional sonar techniques at the cost of increased computation.

The difficulty with achieving diffraction limited imagery with SAS is primarily due to the unknown motion of the sonar from the assumed path. If the unknown sway is of the order of a tenth of a wavelength or more, the reconstructed image is severely blurred. Constraining the motion of a tow-body with the use of a fixed guide or rail has been popular in the past but has limited use. High-drag nose towed towfish have been employed to successfully reduce the sway and Autonomous Underwater Vehicles (AUVs) have been proposed as more stable SAS platforms.

There are two major approaches to solving the blurring caused by the unknown sonar motion. The first is to instrument the sonar platform with an extremely accurate inertial navigation system (INS). However, these instruments are expensive and so the second approach is to try to estimate the sonar motion from the recorded echo data. The techniques that implement this are usually referred to as “micro-navigation” or “autofocus” techniques. Both data-driven micro-navigation and autofocus techniques attempt to solve essentially the same problem, that of estimating the path of the sonar from the data (and correcting the output images, possibly in iterative fashion).

A number of different strip-map SAS autofocus techniques have been proposed in the literature. Essentially these either utilise strong point-like scatterers or the ensemble of weak scatterers that produce the seafloor reverberation. Algorithms in the first category include: CLEAN [4], Phase Curvature Autofocus (PCA) [12], and other variations of the Phase Gradient Autofocus (PGA) algorithm [3]. Not unexpectedly, these algorithms perform poorly whenever there are no prominent point scatterers, such as with bland sea-floor images from mud-bottomed shallow harbours. In these environments, the Shear Average based algorithms [2, 8, 10] perform better, except in the presence of strong scatterers. Hybrid algorithms, such as Phase Matching Autofocus (PMA) [7], and global optimisation techniques based on image quality measures [5, 6, 9] have also been proposed to deal with more general seafloor scenes.

In this paper we cover the detection and estimation of sway in strip-map SAS images using a novel autofocus technique, loosely based on an algorithm for astronomical wavefront sensing [11]. Results demonstrating the possibilities this technique offers are presented, both for point-like and sea-floor clutter based simulated images corrupted by across-track motion errors.

2. Method

The sonar motion affected pulse-compressed echo data $\widetilde{ss}(t,u)$ can be related to the motion free echo data $ss(t,u)$ using

$$\widetilde{ss}(t,u) = \mathcal{M}(ss(t,u); X(u)) \tag{1}$$

where $X(u)$ is the unknown position error as a function of the along-track position, u, t is the time delay related to range, and $\mathcal{M}$ is an operator describing the motion induced transformation. The goal of autofocus algorithms is to estimate $X(u)$ from $\widetilde{ss}(t,u)$ and to recover $ss(t,u)$.

The proposed autofocus algorithm operates on regions of the distorted reconstructed image $\widetilde{ff}(x,y)$,

$$\widetilde{ff}(x,y) = \mathcal{A}\{\widetilde{ss}(t,u)\}, \tag{2}$$

where $\mathcal{A}\{\}$ is an operator that represents the azimuth compression.

The first step of the algorithm convolves the distorted reconstructed image $\widetilde{ff}(x,y)$ with a pair of conjugate chirps,

$$\begin{aligned} qq_1(x,y) &= \int_{\infty}^{\infty} \widetilde{ff}(x, y-u) w(u) \exp\left(jKu^2\right) du, \\ qq_2(x,y) &= \int_{\infty}^{\infty} \widetilde{ff}(x, y-u) w(u) \exp\left(-jKu^2\right) du, \end{aligned} \tag{3}$$

where K is the chirp rate and $w(y)$ is an amplitude weighting function, to produce two new 'chirped' images $qq_1(x,y)$ and $qq_2(x,y)$. The process of chirp convolution is to spread the distorted images in the along-track direction (conversely to some implementations of the Range-Doppler reconstruction algorithm where chirp convolution is used for along-track focusing [1]).

To reduce the effects of coherent speckle in the chirped images, we compute their along-track cumulative intensity images

$$\begin{aligned} cc_1(x,y) &= \int_{\infty}^{y} |qq_1(x,y_1)|^2 \, dy_1, \\ cc_2(x,y) &= \int_{\infty}^{y} |qq_2(x,y_1)|^2 \, dy_1, \end{aligned} \tag{4}$$

which in practice we normalise for each cross-track position x. Finally we compute a similarity measure, by summing (or averaging) the absolute difference between the cumulative intensity images

$$\eta = \iint_{-\infty}^{\infty} |cc_1(x,y) - cc_2(x,y)| \, dx \, dy. \tag{5}$$

When there is no sonar sway ($X(u) = 0$), the chirped images should be identical in intensity, and thus the similarity measure η should be zero. With a simple linear sway over the aperture ($X(u) = \sigma u$),

$$\widetilde{ff}(x,y) \approx ff(x - \sigma y, y + \sigma x), \tag{6}$$

and the chirped images are displaced relative to each other, and thus the similarity measure is no longer zero. It can be shown that the displacement Δy is proportional to σ,

$$\Delta y = \frac{\sigma \omega_0 / c}{K}, \tag{7}$$

where ω_0 is the centre frequency. So in theory, if the displacement can be estimated, the linear sway component can be derived. Note that higher order sway components spread the chirped images by different amounts.

3. Results

To determine the efficacy of the technique as a image quality metric for a global optimisation method [5, 6], echo data from a bland seafloor was simulated using a large number of point scatterers and with a sonar speed of 1.0 m/s. The scene was then reconstructed many times from the echo data, while varying the sonar speed parameter, and the quality measure given by Eq. (5) was plotted as a function of

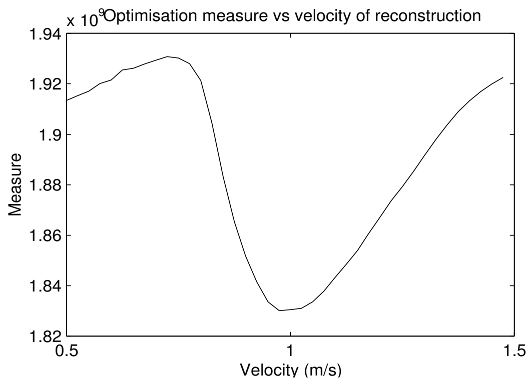

Figure 1: Optimisation measure as a function of varying the sonar speed employed in the reconstruction process. The data set is a bland clutter floor simulated at $v = 1.0$ m/s.

the sonar speed. Figure (1) shows that the minimum measure occurs at the correct speed of 1.0 m/s.

A known sway error was then introduced to the sonar path using a fifth-order polynomial. Figure (2) shows the distorted image that results from the reconstruction with the unknown motion while Figure (4) shows the diffraction limited image reconstructed with the known motion removed. An iterative optimisation technique was then employed to estimate the parameters of the sonar path using Eq. (5) as an image quality measure. This was found to slowly converge to the correct path as shown by Figure (5) giving the resultant image shown in Figure (3) which is a good approximation of the ideal image shown in Figure (4).

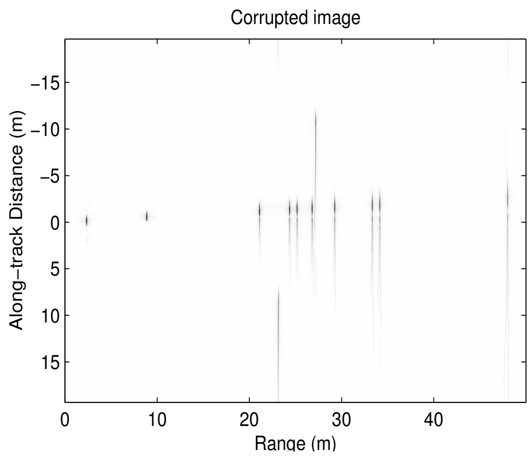

Figure 2: Reconstructed simulated scene showing the blurring to a number of point targets caused by a polynomial path distortion.

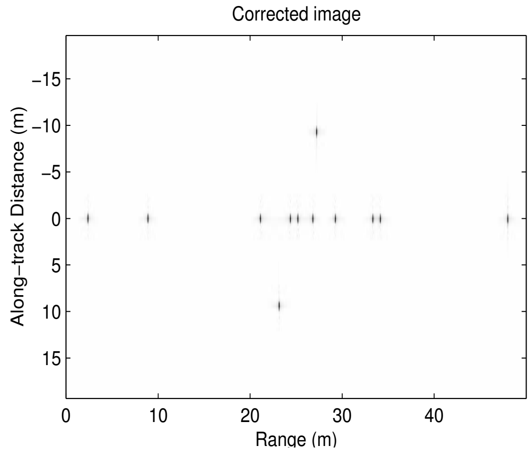

Figure 3: Reconstructed simulated scene after autofocus using optimisation over polynomial basis set. This image is similar to the ideal image.

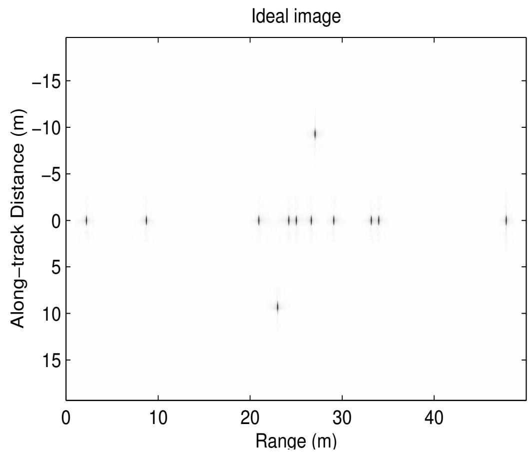

Figure 4: Ideal reconstructed image of a number of simulated point targets.

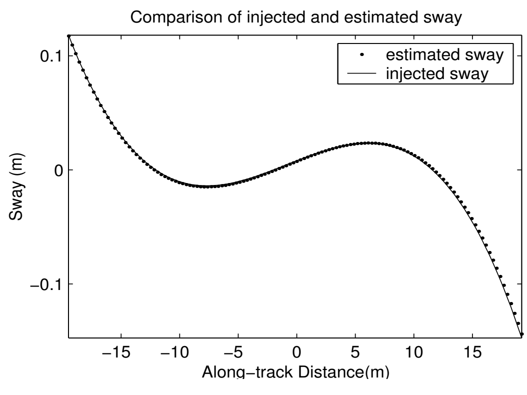

Figure 5: Comparison of estimated and injected fifth-order polynomial path distortions. The maximum estimation error $\approx 3.5\,\mathrm{mm} \equiv \lambda/14$.

4. Conclusions

In this paper we have demonstrated a new image quality measure using the difference of cumulative intensity functions of chirped images. With no residual sway the two images are identical. A linear sway introduces a displacement between the two images and higher order sways tend to over-focus one of the images and under-focus the other.

Preliminary work shows that the new measure works with a global optimisation procedure to estimate both unknown sonar speed and sway, using both prominent point and clutter based scenes. Currently the iterative nature of the technique is computationally expensive when compared with some of the less general direct path estimation techniques such as PCA and PMA. Direct path estimation (in a non-iterative framework) should be possible with this technique, although further research is required to verify that possibility. Further work is also required to compare the new measure with standard image contrast measures used in global autofocus methods.

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