Determination of Image Resolution from SAS Image Statistics

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***Abstract*— The quality of a SAS image is affected by the coherence across the synthetic aperture which is directly related to errors in motion estimation, compensation, or physical phenomena (*e.g.* medium instability or acoustic multipath). Operational use of a SAS system can benefit from metrics that estimate image quality and identify areas where sonar imagery is suboptimal. Furthermore, an estimate of the coherence across the synthetic aperture would be necessary to maintain a system calibrated response and use acoustic measurements to determine target or seafloor physical properties. This paper proposes techniques to determine the mean point object response and relates this parameter to image resolution. Unlike previous attempts to determine image resolution that relied on the use of specifically designed targets intended to provide an ideal point response, this technique relies on a statistical approach where the image is assumed to contain many point-like objects. The point objects are identified by comparison with seafloor statistics, and the 3dB peak width is measured for all identified point objects in the image. Analysis of the point object results provides the mean image resolution in two dimensions as well as local variability of resolution across the image. The resolution response provided by this technique was verified by reprocessing samples of SAS imagery while varying the aperture length and bandwidth and determining the resolution of the sample images. Comparison of the predicted and measured resolution response is shown.**

Keywords—Sonar, radar, SAS, SAR, resolution

I. Introduction

Synthetic aperture sonar (SAS) image formation requires proper alignment to maintain signal coherence across the synthetic aperture for optimal imagery characteristics [1-3]. This rarely occurs due to motion estimation or compensation errors which can induce variance in the phase across the synthetic array. Additionally, physical phenomena (*i.e.* medium instability) can limit array coherence when operating over long ranges. Operational use of sonar to perform underwater surveys can benefit from metrics that indicate the data quality of the surveyed area. The methods detailed here propose that the image resolution can be measured from SAS imagery and that the image resolution provides a valuable metric to describe the image quality.

II. Methods

Previous attempts to measure the resolution of sonar imagery often relied on deployment of targets specifically designed to have a point response and data analysis that results in a single resolution measurement. The technique described here uses similar methodologies, but is based on a statistical approach to identify point-like objects of opportunity in the image frame and then determines the width of the point response of the identified objects. While some of these objects will not be truly point like, the statistical approach used here only requires that the selected objects be point-like on average. Experience with data analysis for the system used for the development of the techniques described here has indicated that this is a good assumption. However, careful implementation will be required to ensure that this assumption is valid for all systems and environments.

A simple approach to identify point objects was used for this analysis. In this approach, all points with intensity greater than 6 standard deviations (σ) over the mean image response are labelled as point objects. If one assumes that the background image intensity is Gaussian distributed, 6σ above the mean would produce an insignificant number of points (~1 in 508 million). Therefore, points identified through these criteria include points in the imagery that do not follow a Gaussian distribution and are assumed to be bright point scattering objects. However, the choice of mean + 6σ is somewhat arbitrary and was determined through experimentation by identifying the most point-like responses while still producing a statistically significant number of measurements. Adjustments may be necessary when applying this algorithm to other systems including consideration for the expected gain of point-objects in the surveyed areas.

This list of objects generated from the statistical analysis is further reduced by excluding adjacent points that meet the intensity threshold. The assumption is that point objects that are relatively close may be a single object with a wide peak response. A conservative approach is taken that assumes the brightest point in the cluster of points that meets the intensity threshold is the true point object and the surrounding points are the shoulder of the peak response.

Once a final list of point objects is acquired, slices through the image are taken in the range and cross-range directions to provide the point response. The width of the peak is measured as the distance between the points on each side of the point response peak 3dB from the peak intensity. These values are stored and can be used to determine local- or image-scale resolution by evaluating the mean or median response over a patch of the image or the entire image.

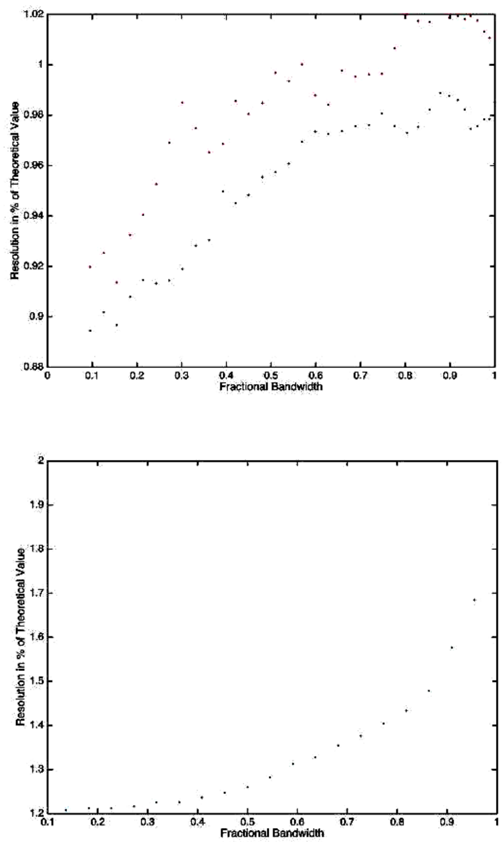

Fig.1: Measured resolution as a function of fractional bandwidth for range axis (upper) and cross range (lower).

III. RESULTS

Standard imagery with known resolution was not available, so experiments were conducted to vary the resolution of an image and compared the measured response with the theoretical response. In this experiment, the bandwidth of a dataset was reduced to produce a series of images from in the same environment and motion compensation conditions, but with varying range resolution. Resolution measurements for the sample image with varying bandwidth is shown in Fig. 1 (upper frame, blue points). The figure displays a ratio between the partial and full bandwidth on the x-axis and the measured and theoretical resolution as determined by a relationship outlined in [1-2] (Eqn. 1) on the y-axis. In this relationship, ΔR is the range-axis resolution, c is the speed of sound, and B is the pulse bandwidth.

$$\Delta R = c/(2B) \quad (1)$$

The results in Fig. 1 show that the resolution measurement produces a result suggesting the range resolution is close to a 1:1 relationship, but is less than the theoretical value. This may be caused by the disparate range and cross-range resolutions and that the range-axis measurement is confused by the difference between the range and cross-range characteristics. The same analysis was conducted a second time where the cross-range resolution was reduced to match the range axis resolution and the resulting data shows a relationship that is closer to 1:1 (Fig. 1 upper panel red points). However, the relationship also appears to underestimate the resolution in cases where the bandwidth is severely reduced (<50% original). This underestimation at very low resolutions may be due to an inappropriate window length selection during the point response measurements. The same window length was used for all measurements presented here and may have been too narrow for cases where the resolution is large.

A similar experiment to verify the effect on cross-range resolution was performed by limiting the synthetic aperture length to modify the cross-range resolution of the test image. In this case, the Doppler bandwidth (or equivalent aperture length) was reduced and the resolution response was compared with a theoretical value as described in [2] (Eqn. 2), where ΔR_c is the cross-range resolution, X_0 is the range to the target, λ is the wavelength at the center frequency, and L is the length of the synthetic array.

$$\Delta R_c = X_0\lambda/(2L) \quad (2)$$

The results of the cross-range analysis is shown in Fig. 1 (lower), which shows that the measured resolution approaches twice the theoretical limit at full bandwidth and approaches a 1:1 relationship at very low resolutions. This response could be associated with the horizontal beam pattern, but is more likely associated with subtle errors in motion estimation and compensation causing some reduction of coherence across the synthetic array. As the length of the synthetic aperture is reduced, the likelihood of an error at some point in the synthetic aperture is reduced, resulting in measured resolutions approaching the theoretical values. This effect has been observed previously where apparent motion errors have been removed from imagery by reducing the aperture length and the associated cross-range resolution.

A sample of the spatial variability of the resolution measurement is shown in Fig. 2, which shows two imagery samples formed with differing motion estimation and compensation algorithms and the measured resolution. The bottom left sample image includes errors in motion compensation and the bottom right was formed with a motion estimation solution that improved the image focus. The cross-range resolution for the two image samples is shown in the upper panels of the figure. These resolution maps represent the mean value of cross-range resolution measurements in a $1m^2$ grid across the images. The grid is color-coded to indicate data quality (green is within 2x the theoretical limit, yellow is 2-5x, and red is >5x). Blue areas of the maps indicate areas where an insufficient number of point-objects were identified.

Close inspection of the imagery and the resolution maps indicates good agreement between the measured resolution and the apparent image quality. A large blurred area is present in the bottom third of the left image and is well focused on the right. This feature is also present in the resolution map which shows mixed results for resolution in the same area on the left resolution map and a near solid green area on the right

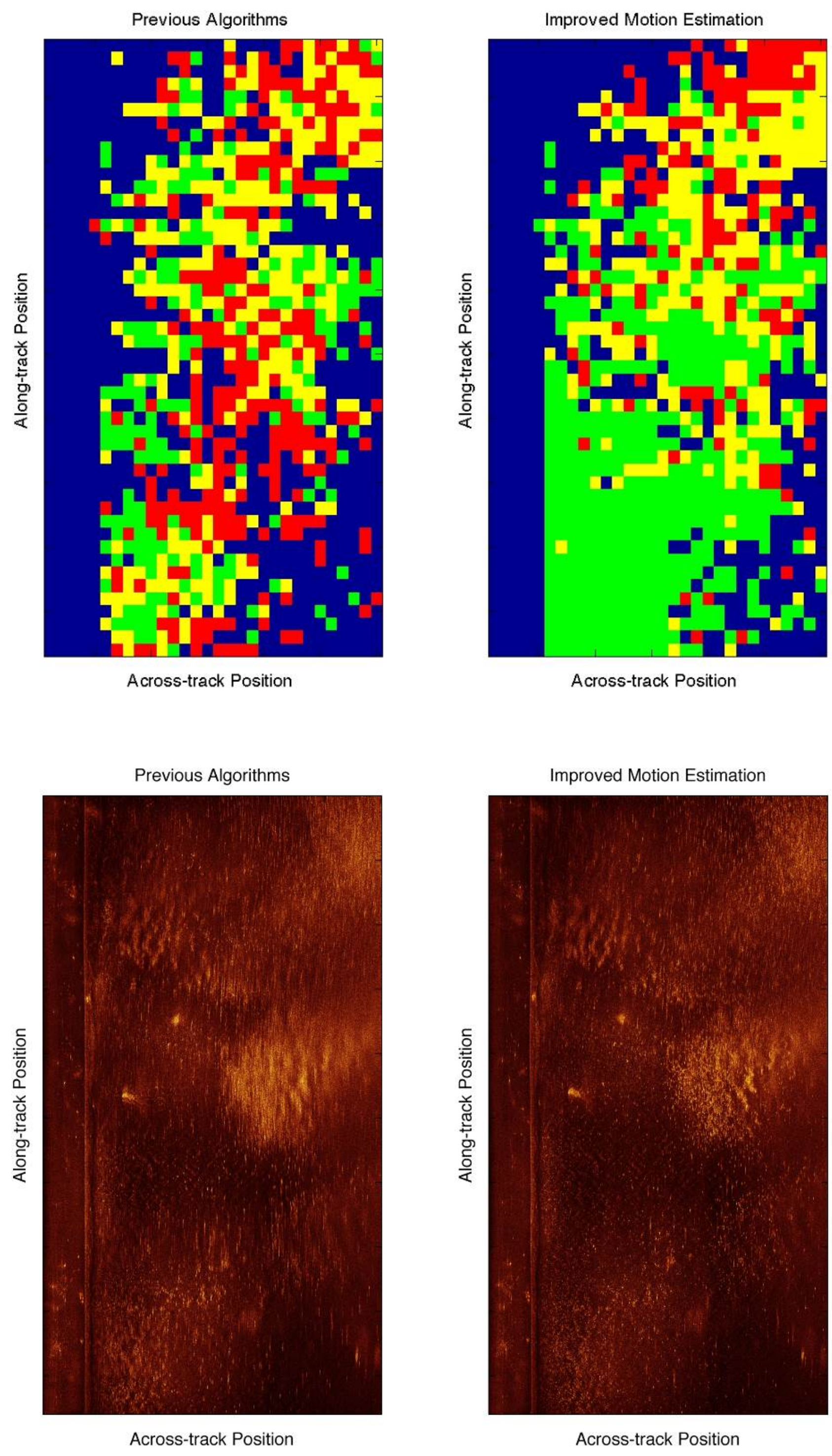

Fig.2: 2D image resolution analysis for a SAS frame with (left) and without (right) inherent motion errors. The resolution measurement is made over 1m^2 pixels and is color mapped to indicate system performance (green within 2x theoretical limit, yellow within 5x and red >5x theoretical limit). Imagery used for resolution analysis is included (lower panels).

indicating that the motion errors have been eliminated. The top of the improved image still includes some blurring and this is also evident in the resolution map which indicates that results are more consistent than the left example, but still includes some motion induced blur. The differences between the quality of these two images and their resolution maps indicate that this technique can be used to compare the performance of competing motion estimation and compensation algorithms.

Areas where no measurements are returned also provide useful data for analysis of sonar imagery as it indicates areas with few point-like objects. These areas often have some other phenomena limiting image quality (nulls in beam patterns or areas with excessive noise, or reduced performance due to multipath effects [4]). These areas need to be accounted for in analysis to evaluate the quality of the survey data and to identify areas where no imagery is present. This effect is present in Fig. 2 which shows no measurement in the water-column of the left side of the measurements and a reduction of coverage for the measurements at the far right side of the imagery where multipath is limiting the quality of the imagery.

IV. DISCUSION

The quality of SAS imagery is directly related to the coherence across the synthetic arrays used for image formation and ideal coherence is altered by system motion and environmental factors. A thorough analysis of SAS surveys will require some estimate of system performance to ensure that systems accurately compensate for unwanted motion or environmental effects and are operating within specification. Further, efforts to relate image intensity to absolute physical values (*i.e*. calibration of SAS imagery) will require precise knowledge of the gain produced in the SAS process. The resolution measurement presented here appears to provide a good indication of image quality and could be used as a metric for automated image analysis or estimation of system performance for surveys. However, further research is needed to relate this measurement to array coherence and determine the impact of incoherence on resolution and image intensity.

While these measurements show good agreement with theoretical expectations in general, the cause for deviations from expectations are not fully evaluated and warrant further research. Particularly the cross-range case is of interest where the effect is most likely related to a loss in coherence across the synthetic array. Experiments should be conducted to determine how the response of an object affects the ability to resolve the object (i.e. how does the directivity of the objects response or the physical dimensions of the object alter the coherence across the array used to resolve the object). Further research in this area may provide insight into techniques that may be used to identify objects with a particular frequency-aspect response. Additionally, if phenomena that contribute to incoherence across synthetic apertures are understood, techniques may be developed to compensate for the phenomena and improve the resulting image resolution.

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