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ESTIMATING ALONG-TRACK DISPLACEMENT USING REDUNDANT PHASE CENTERS♦

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1 INTRODUCTION

Necessary to the formation of high fidelity synthetic aperture sonar images is the ability to properly compensate the data for platform motion. Redundant phase centers (RPC) are typically used to measure time delays and estimate displacements transverse to the nominal vehicle trajectory.[1-4] This information is combined with inertial measurement unit (IMU) data and used to appropriately compensate the acoustic data for the deviations of the platform from an ideal track. It is often assumed that the vehicle can correctly determine its own speed over the ground (SOG), so that the along-track sampling of the synthetic array is uniformly spaced via synchronizing the ping time interval such that the integration of the SOG with time equals the desired advance per ping (APP). Unfortunately, there are instances when the SOG is not known to the required accuracy. The results for this paper are from the SAS-12 vehicle and, for example, require accuracy in the SOG of 1.5 mm/s to recover an ideal point target response at 150 m cross-track range. Recent SAS-12 sea tests suggest SOG errors in excess of 10.0 mm/s. The error in the SOG measurement results in the actual APP being offset from the ideal APP, and the along track synthetic array no longer being uniformly sampled. A consequence of this is a degraded reconstructed image. This paper will show that RPC can be used to accurately determine the SOG of the vehicle and as a result, be used to measure the APP offset. Accurate along-track information results in improved imagery by correctly compensating data as well as possibly being a useful tool for micro-navigation.

2 TECHNICAL APPROACH

Redundant phase centers are often used to measure time delays that can be related to perturbations in the lateral components of vehicle motion. These range dependent time delays are usually determined by calculating the cross-correlation between the RPC and using various techniques to determine the time delay at sub-sample resolution in the peak of the cross correlation to improve the estimates.

At its present stage, the estimation of along track displacement using RPC solely utilizes the magnitude of the cross correlation of the RPC as well as additional cross correlations between other real and virtual channels. The advance per ping determined using the along-track technique assumes the array is linear along the axis of the vehicle, that there are at least two redundant phase centers, and that the true advance per ping is within half a phase center of the ideal advance per ping. This last assumption is relaxed as the number of overlapping channels increases.

In order to find the value of the advance per ping using this technique, multiple cross correlations are calculated: at the redundant phase center locations, at neighboring phase center locations, and at intermediate virtual phase center locations. The set of along track cross correlations that have

♦ This technology is the subject of a U.S. patent filed by the Navy.

the highest values then determines the actual advance per ping. More precisely, the advance per ping is calculated by finding the location in the peak of along track cross correlation values. This description will be illustrated in the following figures.

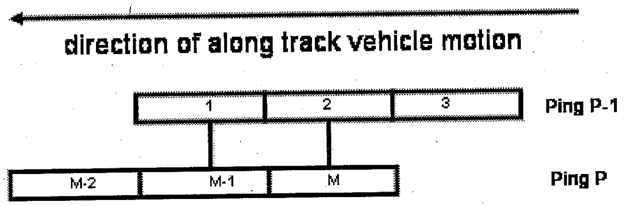

Figure 1. Notional depiction of a two channel redundant phase center overlap with an ideal along track alignment for an acoustic array having M channels.

In Figure 1, the numbered rectangular boxes represent the respective phase centers and the vertical connecting black lines represent the combinations used for the cross correlation calculations. The phase center numbering convention is such that the foremost channel of the array is defined to be channel one, while the rearmost channel is defined to be the Mth phase center, given that the vehicle is moving right to left. This particular along-track configuration represents an ideal advance per ping where the redundant phase centers for channel 1 from ping P-1 and channel M-1 from ping P overlap perfectly.

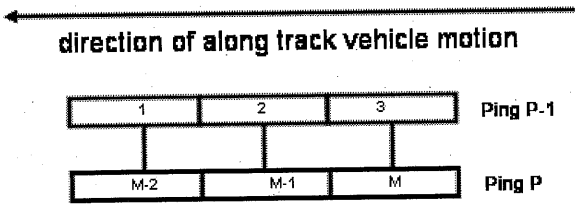

Figure 2. Notional depiction of a two channel redundant phase center overlap with an along track offset of minus one phase center from ideal.

The along-track alignment shown in Figure 2 represents a case where the vehicle has an offset of an entire phase center from the desired advance per ping of two redundant phase centers. In this instance there are three overlapping redundant phase centers that can be used to calculate cross correlations. If the actual advance per ping slipped by an entire phase center, then the magnitude of the cross correlations for the case illustrated in Figure 2 would be larger than the values using the configuration shown in Figure 1.

For the case of the SAS-12 vehicle, inspection of the cross correlation coefficients at integer phase center offsets from the actual APP have magnitudes much lower than for those at the correct APP. In fact, often the magnitudes of the cross correlation coefficients adjacent to the actual APP locations are indistinguishable from those more than one phase center away from the APP position, i.e., more than one phase center away from the actual APP puts the magnitudes of the correlation coefficients in the noise. The incorporation of intermediate virtual channels located at half-integer phase center offset locations in the APP provide sufficient signal to noise in the cross correlation coefficients such that the actual APP can be resolved to sub-phase center along-track resolution.

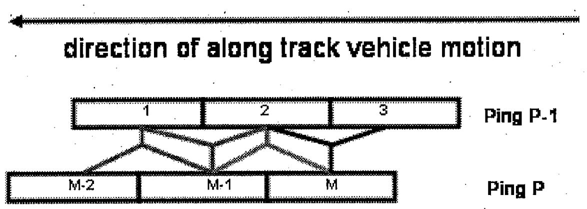

Figure 3. Notional depiction for a two channel redundant phase center overlap with an along track offset of minus one half phase center from ideal. Note the formation of virtual channels by the summation of adjacent channels.

The configuration for the advance per ping with an along track offset of one half phase center is illustrated in Figure 3. In this case, virtual channels are formed by summing adjacent channels and cross correlated with the nearest real channel. For example, in Fig. 3, the signal from channel 1 ping P-1 is cross correlated with the sum of channels (M-2) and (M-1) from ping P. This scheme is repeated across the range of available channels.

Using this technique for the case of a system with two redundant phase centers an along track grid is set up with one half phase center spacing ranging from minus one phase center up to plus one phase center offsets. At each offset location there are various numbers of real and virtual channels that can be used to make cross correlations. Table 1 shows the possible combinations for the case of 2 RPC.

– 1 RPC	-1/2 RPC	0 RPC	+1/2 RPC	+1 RPC
1 ⊕ M-2	1 ⊕ [(M-2)+(M-1)]	1 ⊕ M-1	1 ⊕ [(M-1)+M]	1 ⊕ M
2 ⊕ M-1	[1+2] ⊕ [M-1]	1 ⊕ M	[1+2] ⊕ M	
3 ⊕ M	2 ⊕ [(M-1)+M]	[1+2] ⊕ [(M-1)+M]		
[1+2] ⊕ [(M-2)+(M-1)]	[2+3] ⊕ M			
[2+3] ⊕ [(M-1)+M]				

Table 1. Columns represent the along track spacing in terms of RPC offset for the case of two RPC. ⊕ represents the cross correlation operator. Entries represent the signals to be cross correlated. Signals from ping P-1 are to the left of the ⊕ symbol, and signals from ping P are to the right of the ⊕ symbol.

The cross correlations are typically calculated using a sliding window of width of approximately 1 meter. After calculating the cross correlation of each entry in matrix shown in Table 1, the next step takes the average over a given cross-track range. The range used is usually set by some correlation threshold. Next, the columns of Table 1 are averaged so that there remains one cross correlation value for each offset location. The column with the maximum value and its two nearest neighbors are used to calculate APP. The sub-phase center along-track offset location is determined using a three point interpolator. The actual advance per ping is found by adding the calculated offset to the desired APP. This process is repeated for each successive ping.

It should be noted that this technique is not the most general method to exploit RPC to estimate the APP, but is a straightforward and simple approach. For example, this particular technique utilizes two adjacent channels with equal weights to form a virtual channel, whereas a more general approach might include using more than two real channels with a distributed set of unequal weights. This type of more general approach is the subject of ongoing work at NSWC-PC.

3 RESULTS

Recent sea trials were conducted with the SAS-12 vehicle using a variety of system configurations. The results shown in this paper are from a run having six redundant phase centers. In this case, a table similar to Table 1 was generated. As the number of RPC increases, so does the possible number of discrete half phase center offsets. For the SAS-12 data examined in this paper, it was sufficient to utilize the same number of offsets as given in Table 1. However, as the error in the APP increases, it is necessary to expand the number of offset positions so that the peak in the along track cross correlation technique can be detected and resolved.

Figure 4 shows the APP as a function of run time. The blue line represents the vehicle's estimated APP, which for this figure is calculated by using the vehicle's estimated SOG (Vspeed) multiplied by the difference in ping time. The red line represents the APP as determined by using the cross correlation technique (Cspeed). There is a noticeable difference in the APP between the two results. In this instance, the APP using Cspeed appears to track the upper envelope of the Vspeed estimated APP and also appears to have less noise than the Vspeed APP. In fact the, the mean difference between the two techniques is 1.7 mm. A 1.7 mm APP bias is sufficient to degrade the along track resolution of the SAS image, especially at longer ranges where more pings are required in order to form a synthetic aperture. The longer the synthetic aperture, the more the APP error builds up over time. This effect will be illustrated later on in this paper. The APP measured using the cross correlation technique readily lends itself to measure the vehicle SOG.

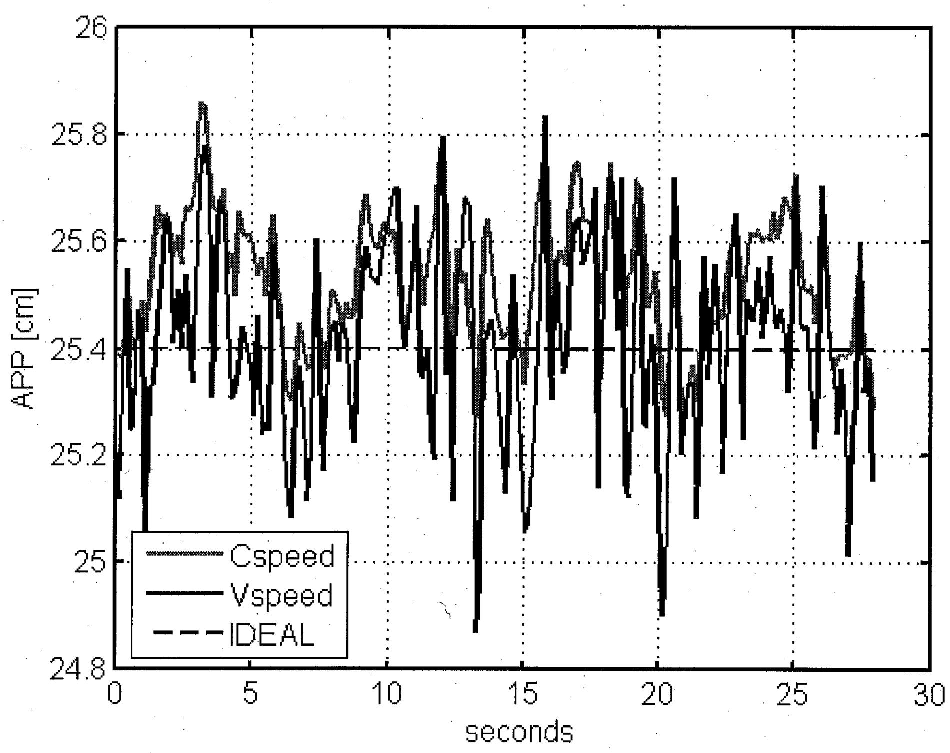

Figure 4. Advance per ping of SAS-12 vehicle calculated using six RPC's. The cross correlation technique output, denoted by Cspeed in the figure legend, is shown in red. Vspeed denotes the vehicle's estimate of speed over ground that is used to calculate the APP and is shown in blue. The desired APP in this case is 25.4 cm, while the estimated APP bias is 1.7 mm.

The vehicle SOG measured using the cross correlation technique (red) and the vehicle's own estimate (blue) using a commercial DVL and a proprietary inertial navigation system (INS) package are shown in Fig. 5. Compared to the APP results in Fig. 4, the SOG for the cross correlation technique shows a nice smoothly varying estimate. In fact, this result is much more likely to be representative of actual vehicle motion. This is to be contrasted with the vehicle's estimated SOG. Also noteworthy is that the Cspeed estimate appears as an upper envelope of the Vspeed output.

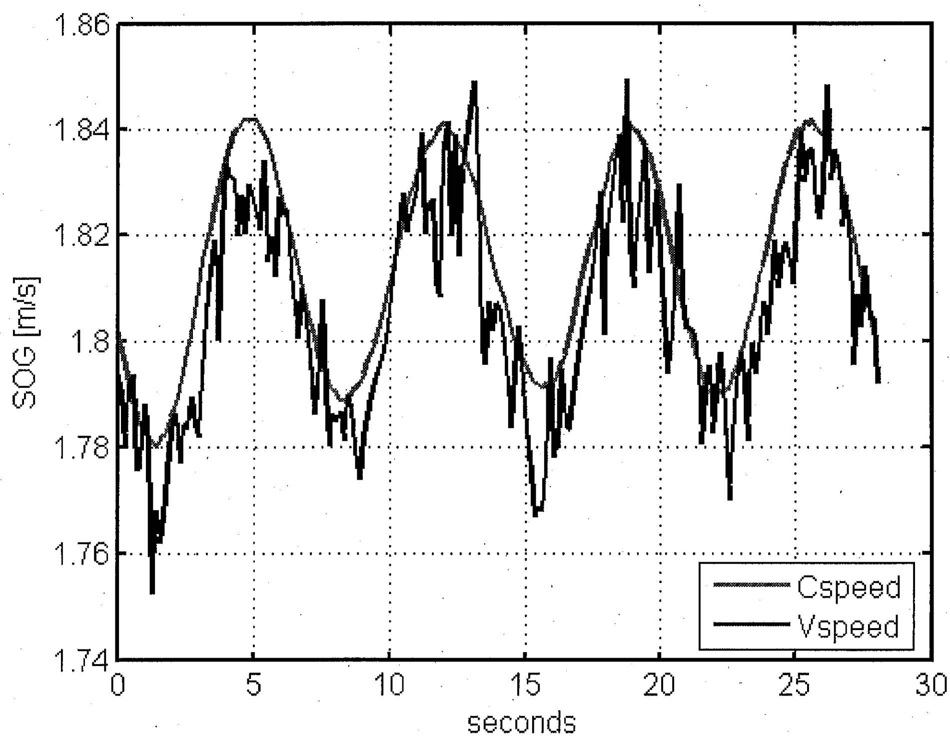

Figure 5. Vehicle SOG verses run time for the data in Figure 4. using Cspeed (red) and Vspeed (blue). Vehicle Vspeed SOG bias from Cspeed = 8.9 mm/s.

The six to seven second oscillation present in the SOG estimates of Fig. 5 likely reflects surface wave effects on the AUV.

The data shown in Fig. 5 are put through a high-pass filter with a 1.0 Hz cutoff, in order to compare the higher frequency jitter between the two methods of determining the SOG. Figure 6 is a plot of the high-pass filter outputs. In this case, the noise in the SOG using the Cspeed method is better than an order of magnitude over the Vspeed method. The noise in the Cspeed technique of the SOG, defined as the standard deviation of the high-pass result is 0.4 mm/s. This compares favorably when compared to the SOG noise using Vspeed which has a value of 6.3 mm/s.

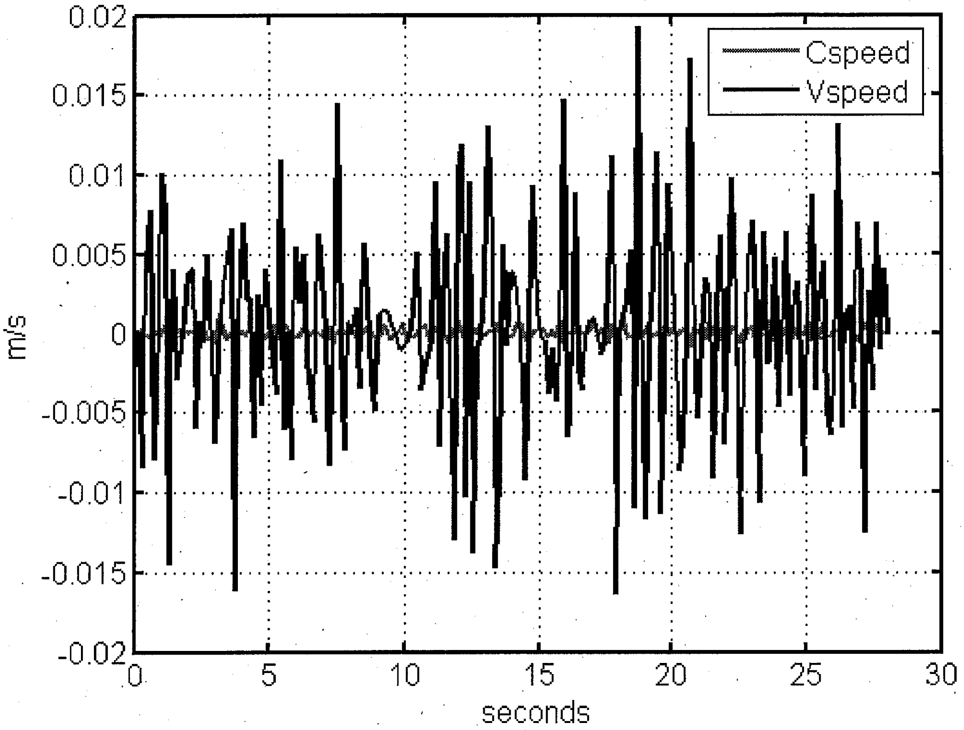

Figure 6. SOG noise verses run time from Cspeed (red) and Vspeed (blue). The high pass filter (1 Hz cutoff) result in Cspeed and Vspeed standard deviations of 0.4 and 6.3 mm/s, respectively.

It should be noted however that in terms of image degradation, that the jitter in the APP offset is not as critical as the APP bias. In order to quantify the effects of the APP offset on image quality, a point target simulation was run using the Cspeed calculated APP for the data already presented. Figure 7 shows the results of the point target simulations. Plotted are the along track point target responses for a point target placed at a range of 150m. The first simulation ran with an ideal motion configuration file; the point target response for ideal motion is shown in Fig. 7 with the dashed black line. The along track resolution at the 3dB down point is approximately 3 cm. This is to be compared with the result with using the actual APP of Fig. 4 in the point target simulation, shown in blue line with circles. The -3dB along track resolution here is nearly 12.5 cm, indicative of serious image degradation. However, knowledge of the actual APP allows the acoustic data to be appropriately compensated. The result of the compensated point target response is shown with the red line with squares and indicates that properly estimating the APP and compensating the acoustic data results in near full recovery of the ideal point target response.

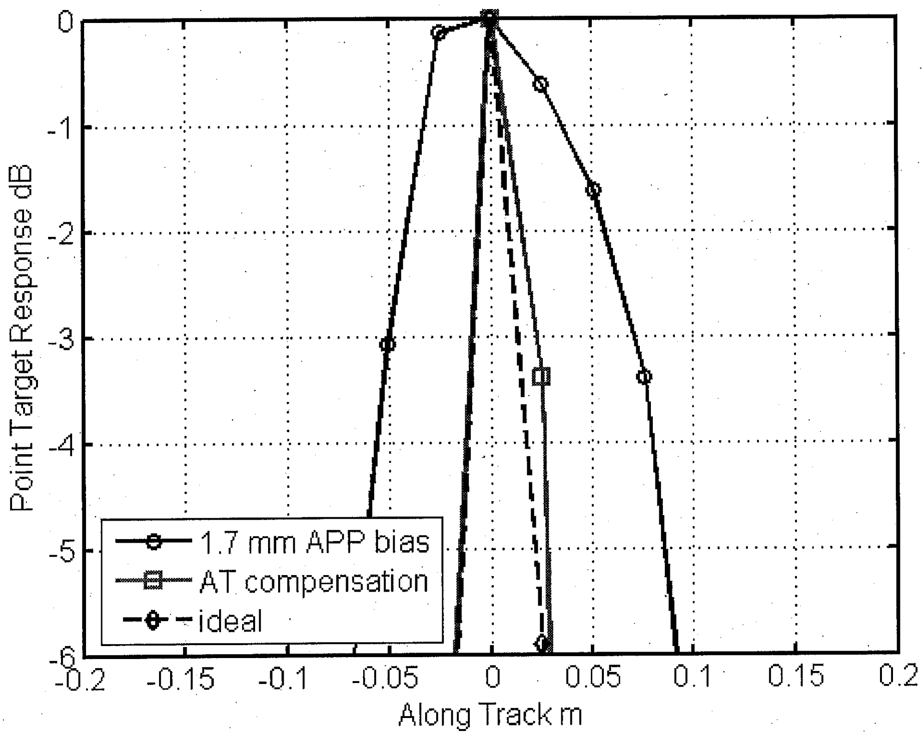

Figure 7. Along track point target response using Cspeed calculated APP at range of 150 m.

4 CONCLUSIONS

SAS image quality is directly related to the quality of the motion estimation and the ability to correctly apply the motion compensation to the acoustic data. Until recently the along-track displacement, or advance per ping, has been assumed to be negligible. However, the SAS-12 AUV at NSWC-PC has presented the opportunity to examine the effect of along-track motion errors and to investigate ways to measure the along-track offset. It has been shown that a redundant phase center-like technique can be utilized in order to estimate the along-track advance per ping and speed over ground of the SAS carrying vehicle. In fact, the data suggest that the along-track algorithm described in this paper could easily be applied in a real-time system and be used to as a supplementary input into an INS package. In addition, the along-track technique does not require knowledge of any environmental parameters, such as the speed of sound at the platform or throughout the water column, as inputs in order to determine the APP offset.

5 REFERENCES

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