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Under Water Imaging by Signal Processing Techniques

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***Abstract*- SONAR is an acronym for sound Navigation And Ranging. The basic principle of sonar is to use sound to detect or locate objects, typically in the ocean. Sonar technology is similar to other technology such as RADAR (radio Detection And Ranging).Basic radar systems use electromagnetic wave reflections from targets to determine the characteristics of the targets. Synthetic Aperture Radar (SAR) systems use the reflections to produce target images as well. SAR and SAS are an imaging system that produces high resolution images of a scene or target by using motion to synthesize the antenna aperture. While Synthetic Aperture Sonar(SAS) is closely resembles to SAR.In this paper we are demonstrating Synthetic Aperture Sonar (SAS) processing for a point target case. The input raw SAS data is generated and the SAS processing is simulated in Matlab.**

***Keywords*- SONAR (Sound Navigation And Ranging), Synthetic Aperture Radar (SAR), Synthetic Aperture SONAR(SAS).**

I. INTRODUCTION

There are a number of applications, both civilian and military, where fine-resolution underwater imaging is of importance. The physical nature of the ocean medium places various limitations upon the ability to image underwater objects. Factors such as sound propagation velocity, attenuation, and reverberation place considerable constraints on various imaging parameters, including, but not limited toresolution, sensor platform velocity, survey coverage rate, and signal-to-noise ratio. There is significant demand for undersea imaging systems that can generate fine-resolution imagery, both in range and cross-range, with the required image fidelity necessary for accurate image interpretation.

Side-looking sonar systems are capable of generating underwater imagery, but the inherent limitation in these systems lies in their inability to maintain fine along-track resolution with increasing range. Fine-resolution side-scan systems require either high frequency operation or very long physical arrays in order to obtain sufficiently narrow illumination beam-widths. SyntheticAperture techniques circumvent this problem, but at the expense of increased signal processing complexity. The primary motivation for using Synthetic Aperture systems centres on their ability to generate very fine along-track (azimuth) resolution, independent of range and frequency, without using excessively large transducers.

Synthetic Aperture Sonar (SAS) combines coherently the backscattered echoes from successive acoustic pulses (pings) for high-resolution seafloor imaging with application in mine countermeasures, underwater archaeology, or inspection of underwater installations. Specifically, an active sonar transmits a short pulse to insonify the seafloor and records the backscattered waves repeatedly while it moves along a predefined (usually linear) path to form a Synthetic Aperture. SAS imaging refers to the inverse problem of reconstructing the seafloor reflectivity by coherently processing the recorded signals from the Synthetic Aperture. The range resolution in SAS imaging is determined by matched filtering, i.e., cross-correlating the recorded and the transmitted signal, hence it is inversely proportional to the bandwidth of the transmitted pulse. The cross range resolution of a real aperture is characterized by a constant angular resolution determined by its beam pattern, resulting in a range and frequency dependent cross-range resolution.While cross range resolution of SAS system is independent of frequency and range, i.e., it is not limited by the physical dimensions of a real aperture.

II. BASIC OF SYNTHETIC APERTURE SONAR (SAS)

A sonar placed on a platform (for example Autonomous Underwater Vehicle [AUV]), which is moving at constant velocity, is transportedover a certain distance known as the synthetic aperture length as shown in Figure2.1. This can be also described as the distance the sensor travels while the target is illuminated by the sonar beam. At sampled times during the platform’s flight, the sonar istransmitting pulses toward a target or targets in the area of interest and receives the reflections from these targets. Every received reflection of the targets is stored in memory, the array of these saved reflections are referred to as raw SAS data.

After the raw data is collected, it then passes through signal processing steps that focus these targets to produce a high resolution image of the area of interest.The output SAS signal (often referred to as raw SAS data) before signal processing, can be interpreted as a two dimensional signal. These dimensions include the fasttime, which refers to range direction and the slow time, which is the azimuth direction.

1. Range Direction(Fast Time)

At a particular point in time, the transmitter sends out a series of pulses, and the sensor's receiver gets reactions shortly after. Note that this does not occur at the same point in time, but by comparing the speed of sound, the distance between the target and sonar, and the speed at which the platform is moving, it is a fair approximation that the wave was sent out and received at the same time.

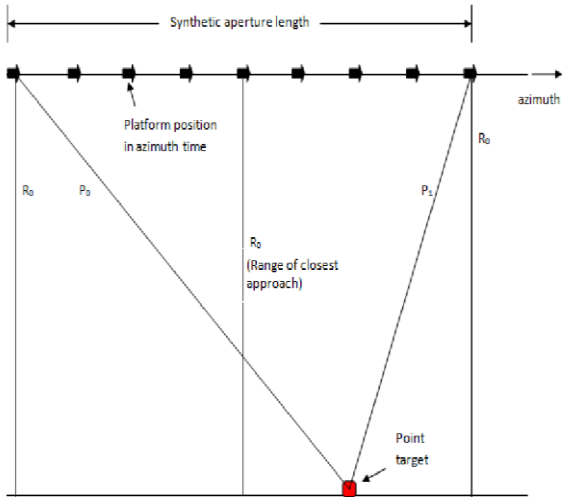

Fig.1 Synthetic Aperture Length.

The transmitted pulsesent out by the sonar is an FM pulse represented by

$$S_{pul}(\tau) = w_r(\tau)\exp(j2\pi f_i \tau) \qquad (1)$$

or the real part

$$S_{pul,re}(\tau) = w_r(\tau)\cos(j2\pi f_i \tau) \qquad (2)$$

Where

$f_i = f_o + K_r\tau$is the instantaneous frequency

τ = range time, referenced to the centre of the pulse

$w_r(\tau)$ = the pulse envelope, a rectangular function with a pulse duration of T_r that is$w_r(\tau) = rect\frac{\tau}{T_r}$

K_r = FM rate of the range pulse

A positive sign of $K_r$represents an up-chirp while a negative sign represents a down-chirp. To avoid aliasing problems, the demodulatedreceived signal must be sampled with a rate,$F_r$that should be higher than the pulse bandwidth, which is given by$|K_r|T_r$According to the Nyquist criterion, the sampling rate must be a least twice the pulse bandwidth. After transmission, the pulse received by the sensor from a point reflector that is$R_a$meters away will be a scaled and shifted version of the original pulse, which could be represented by,

$$S_{rec}(\tau) = AS_{pul}\left(\tau - \frac{2R_a}{c}\right) \qquad (3)$$

$$S_{rec}(\tau) = Aw_r\left(\tau - \frac{2R_a}{c}\right)\cos\left(2\pi f_i\left(\tau - \frac{2R_a}{c}\right)\right) \qquad (4)$$

Where $f_i = f_o + K_r\left(\tau - \frac{2R_a}{c}\right)$is the instantaneous frequency and A represents the scale/reflectivity of the target. An important quality/performance evaluator of sonars is the resolution. This is defined as the ability of the sonar to differentiate between two targets that are closely located either in range or azimuth. The range resolution is given by

$$\rho_r = \frac{c}{2B} \qquad (5)$$

where$c$=1500 m/s, is the speed of sound,
B is the signal bandwidth.

2. Azimuth Direction (Slow Time):

The second dimension in the SAS signal comes about due to the motionof the platform. Consider Equation 4 now $R_a$is a function of the motion of the platform (that is, the slant range between the sonar, and the target changes as the platform moves). From 4,$R_a$now becomes dependent on slow time variable η, therefore,R_a is replaced as R_η. From Figure 1 the distance from the point P_o[or R_{η_B}] to the target and pointP_1[or R_{η_A} to the target is different. The motion of the platform has two major implications, the first of which is a phase modulation from pulse to pulse, and also range cell migration (RCM) due to one target showing up at multiple resolution cells during the duration of the platform motion.

The slant range at a particular point in azimuth time can be modelled using the Pythagorean Theorem;

$$R(\eta)^2 = R_0^2 + X^2 \qquad (9)$$

Assume that the slant range model is that the target is stationary. $R_0$is the slant range when the sonar is closest to the target. After demodulation the received signal is of the form;

$$S(\tau,\eta) = Aw_r\left(\tau - \frac{2R(\eta)}{c}\right)w_a(\eta-\eta_c)\times\exp\left(-j4\pi f_o\frac{R(\eta)}{c}\right) \times\exp\left\{\pi K_r\left(\tau-\frac{2R(\eta)}{c}\right)^2\right\} \qquad (10)$$

Where $\eta_c$is the beam centre crossing time andw_a is the azimuth window. The azimuth window is applied as a result of varying signal strength due to the beam pattern. Themaximum signal strength is received when the sonar is placed directly over the target,i.e., when slant range is minimum (range of closest approach). As the sonar eitherapproaches or moves away from this point, the target is no longer illuminated fully by the sonar pulse hence the strength of the received signal is lower.

The beam pattern is approximated as;

$$p_a(\theta) \approx sinc\left(\frac{0.886\theta}{\beta_{bw}}\right) \qquad (11)$$

Where θ is the angle the slant range makes with the range of closest approach, and $\beta_{bw} = {0.886\lambda}/{L_a}$ represents the azimuth bandwidth and L_a is the length of the antenna.

The received signal is represented by the square of the beam pattern, $w_a = p_a^2(\theta)$ that θ varies as the platform moves, hence it is a function of, η azimuth time. It is also important to note that, there is an effect of attenuation for media with losses. This received data right before the signal processing stage is continuous in range time domain but already sampled in the slow time domain due to the transmit and receive times of the sensor. Generally, the azimuth resolution of a sonar is dependent on the beam width in the sense that if two targets are located in the beam width then it is difficult to tell the difference between them from the reaction obtained. For the synthetic aperture sonar, just like in the range direction, there is a phase modulation in the azimuth direction but this is due to the motion of the platform.

To improve the resolution, the principle of pulse compression could also be applied. Since modulation has already been done as a result of the platform motion, a matched filter will be applied in the azimuth direction to complete the application of pulse compression (pulse compression involves modulation and matched filtering). Using a similar idea to that used in the rangedirection, the azimuth resolution is the inverse of the bandwidth multiplied by 0.866, $\rho_a = \frac{0.866}{BW_a}$ where azimuth bandwidth is represented as BW_a. In distance units this is multiplied by the speed with which the beam moves on the ground and the squint angle at the beam centre. This results in

$$\rho_a = \frac{0.866 V_g cos\theta_{r,c}}{BW_a} \qquad (12)$$

The azimuth bandwidth is

$$BW_a = 0.866\left(\frac{2V_s cos\theta_{r,c}}{L_a}\right) \qquad (13)$$

The azimuth resolution calculated here is indeed the cross range resolution but since low squint is assumed, the cross range and azimuth vectors are assumed parallel; the cross range vector is the direction perpendicular to that of the sonar's line of sight. The resulting azimuth resolution of the SAS system is given by

$$\rho_a = \left(\frac{L_a}{2}\right) \qquad (14)$$

Where L_a is the antenna length in the azimuth direction. The locus of energy in memory for a point target, this is the cause of range cell migration and the purpose of SAS signal processing is to focus the energy to a point.

III. SIGNAL PROCESSING OF SAS DATA

The SAS differ from basic Sonar in two ways.

- Motion of the sonar/platform on which it is placed.
- Signal processing involved to transform the received data into an image.

SAS data obtained in 2D function dependent on range and azimuth time. Processing of data involves different algorithm. They are Range Doppler Algorithm (RDA), Chirp Scaling Algorithm (CSA), Omega K Algorithm, SPECAN Algorithm or Back projection. In this paper we use Range Doppler Algorithm (RDA)

1. Range Doppler Algorithm (RDA):

Range Doppler Algorithm is used in transforming raw SAS data into a more useful SAS image.

Figure.2 Flow chart of Signal Processing of SAS

2. Range Compression:

Range Compression consists of three steps

- Performing range Fourier Transform.
- Applying matched filtering (multiplying the received data with time reversed complex conjugate of a range signal template.
- Range inverse Fourier Transform.

3. Azimuth FFT:

Azimuth FFT is to transform the range compressed signal to the range Doppler domain.

4. Range Cell Migration Correction (RCMC):

Sonar motion seems a good solution to increase the sonar resolution by the effect of a larger aperture. Motion causes problem in the signal processing such as migration of Range Cells. RCMC is an interpolation algorithm that corrects the cell migration. For point target which are in the same range but are separated in azimuth, when transformed to the range Doppler domain the energy of each of these target become collocated . This makes computation easier because the migration can be applied once for all targets.

5. Azimuth Compression and Azimuth IFFT:

In Azimuth compression the matched filter is applied to the RCM corrected signal. As the input signal to the matched filter is in range and azimuth frequency domain Fourier Transform is not required. The matched filter output is applied to Inverse Fourier transform is then taken to transform the signal back to the time domain both in range and azimuth. So the output of the matched filter is the SAS image.

IV. SIMULATION & RESULTS

The generation of point target in MATLAB using below parameters

Parameters	Values
Centre frequency	100000Hz
Velocity of sound	1500m/s
Velocity of Platform	3m/s
Length of Aperture	1m
Bandwidth	30000Hz
Elevation	10m
Pulse Width	0.1
PRF	110Hz

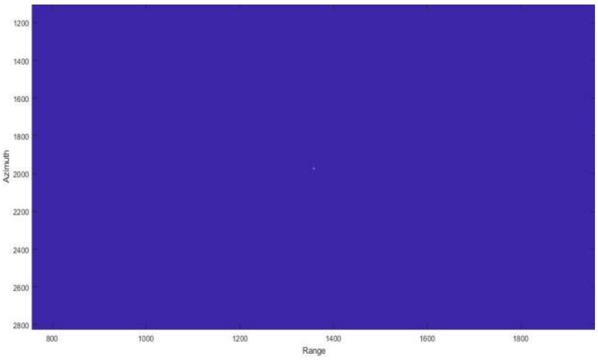

Figure.3 Generated Point target of raw data.

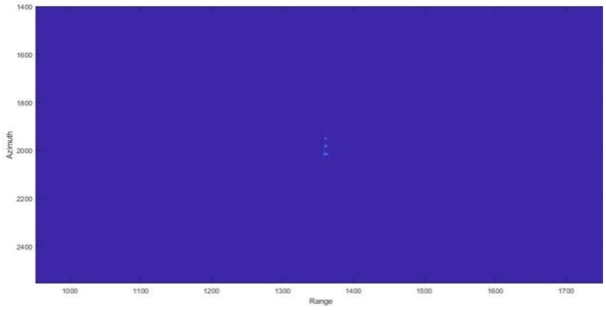

Figure.4 Generated Extended target from raw data.

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