Motion Compensation for Multi-receiver Synthetic Aperture Sonar Based on Sub-aperture

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Abstract: Aperture synthesis is a technique for obtaining high cross-range resolution for radar and sonar. High performance synthetic aperture radars (SAR) are now in routine use, both on airborne and space-based platforms. However, despite its conceptual origin from SAR, synthetic aperture sonar (SAS) has received only limited attention, and none of its performance has approached the limits permitted by the underwater environment. This is largely a consequence of the more stringent motion compensation requirements for SAS relative to SAR. As the performance of SAR continues to be improved, processors have been developed that promise to alleviate the difficulties of SAS. The main objective of this work is to apply a recently raised MOCOMP algorithm based on sub-aperture to SAS processor. It performs motion compensation in echo-data before imaging and it can compensate the motion error changing with azimuth angle. Because the configuration of one transmitter and multiple receivers of SAS is a born sub-aperture it is convenient to implement the MOCOMP algorithm in SAS. The performance of the modified MOCOMP algorithm for SAS is demonstrated by experiments with simulated data.

Keywords: synthetic aperture sonar; bi-static; motion compensation; sub-aperture

1 Introduction

In aperture synthetic sonar, coherent data are collected as the platform (towfish or AUV) moves along a linear path. The data are then combined in processing to synthesize an aperture much longer than the sonar's physical aperture. As the case for a real aperture array, synthetic aperture must be linear within a fraction of acoustic wavelength. Since the platform will not follow a linear path to this accuracy, deviations from the ideal linear path must be accurately measured and then compensated during synthetic aperture processing before image formation. This process is known as motion compensation (MOCOMP). Several approaches have been used for MOCOMP in SAR processor[1][2]. The most accurate one is the time-domain approach, which requires very high computational efforts. A new MOCOMP algorithm based on sub-aperture is designed for SAR recently[3][4]. Based on the relation between radar instantaneous illuminate time and Doppler frequency, this method applies segmentation and compensation in cross-range direction and performs motion compensation in echo-data before imaging.

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The main objective of this work is to apply the recently raised MOCOMP algorithm based on sub-aperture to SAS processor. We derive the algorithm from SAS model. The work is organized as follows. The SAS system model analysis is presented in the second Sections and how to fix on sub-apertures in the third. The fourth Section shows the implementation of the MOCOMP algorithm based on sub-aperture. The fifth section is dedicated to the experimental results carried out on simulated SAS data.

2 Geometry model for SAS imaging

For motion compensation the location of the platform with respect to the ground being imaged must be measured very accurately. It is supposed that the velocity wobble is compensated by rectifying the pulse repeat interval (PRI) in real time. If the platform deviates from the ideal linear path during the integration time, the resultant image will be smeared. This is illustrated in Fig.1. The dash dotted line denotes the ideal track of the towfish and the real line denotes the real track. The transmitter locates at $\left(x, y, z\right)$ and $\left(X, Y, Z\right)$ is the location of a point target in the illuminated scene. So the slant range between transmitter and point target is:

$$R_1 = \sqrt{(x-X)^2 + (y-Y)^2 + (z-Z)^2} \qquad (1)$$

Considered that $r = \sqrt{Y^2 + Z^2}$ and look angle α , $Y = -r\sin\alpha$ 、 $Z = -r\cos\alpha$, the slant range could be rewritten as:

$$R_1 \approx \sqrt{(x-X)^2 + (r-\Delta r)^2} \qquad (2)$$

wherein

$$\Delta r = -y\cos\alpha - z\sin\alpha \qquad (3)$$

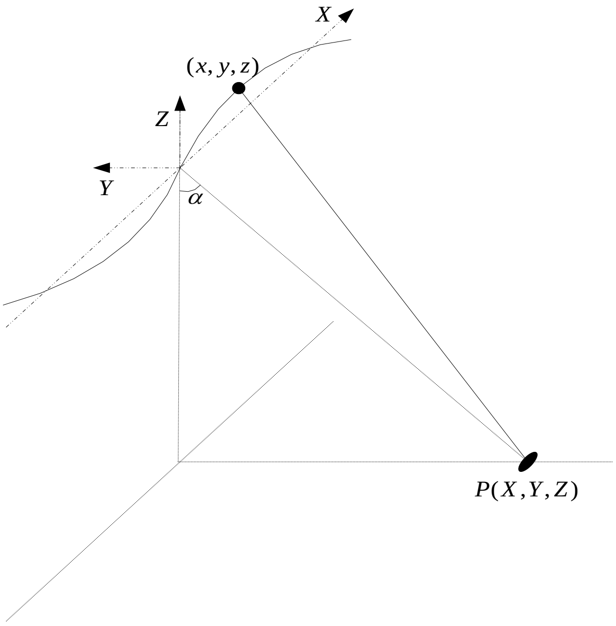

Fig.1 Mapping geometry in geographic coordinates

A notable difference between SAR and SAS is the multi-receiver configuration [5]. So we must take account of yaw angle of the platform in MOCOMP processing. Because of the special configuration the slant range between receiver and point target is different from that between transmitter and point target, as:

$$R_2 = \sqrt{\left[x - X + (u+vt_\delta)\cos\beta\right]^2 + \left[r - (u+vt_\delta)\sin\beta - \Delta_r\right]^2} \quad (3)$$

wherein u is the distance between transmitter and receiver, β is the yaw angle, the term vt_δ denotes the distance that the towfish moved in the interval between pulse transmit and receive because the "stop and hop" hypothesis is no longer reasonable.

3 Partition of sub-aperture

It is necessary to carve up the whole synthetic aperture into several segments, when the sub-aperture idea is applied to SAR. However, the configuration of one transmitter and multiple receivers of SAS is a born sub-aperture. For the convenience in analysis, we convert Descartes coordinate to polar format.

Assuming $x - X + (u+vt_\delta)/2 = -\rho\sin\theta$ 、 $r = \rho\cos\theta$, we find that:

$$R_1 = \sqrt{\left[\rho\sin\theta + (u+vt_\delta)/2\right]^2 + (\rho\cos\theta - \Delta_r)^2} \quad (4)$$

$$\begin{aligned} R_2 = \{&[\rho\sin\theta + (u+vt_\delta)(1/2 - \cos\beta)]^2 \\ &+ [\rho\cos\theta - (u+vt_\delta)\sin\beta - \Delta_r]^2\}^{1/2} \end{aligned} \quad (5)$$

The R_1 and R_2 is approximated by its Taylor series and we get the term ΔR that needs to be compensated based on sub-aperture.

$$\Delta R \approx \delta_1 + \delta_2 + \frac{1}{2\rho}\delta_3 \qquad (6)$$

The term ΔR composes of three parts. One is the constant item marked as δ_1, another is the item that related to the azimuth angle θ marked as δ_2, the third is the item related to slant range marked as δ_3.

$$\delta_1 = -2\Delta_r - \beta(u+vt_\delta) \qquad (7)$$

$$\delta_2 = -2\Delta_r(\cos\theta - 1) \qquad (8)$$

$$\begin{aligned} \delta_3 = &\left[(u+vt_\delta)(1/2 - \cos\beta)\right]^2 + \Delta_r^2 \\ &+ \left[(u+vt_\delta)\sin\beta + \Delta_r\right]^2 \\ &+ \left[(u+vt_\delta)/2\right]^2 \end{aligned} \qquad (9)$$

4 Implementation of motion compensation

The MOCOMP algorithm based on sub-aperture performs motion compensation in echo-data before imaging. Fig.2 shows steps of the MOCOMP algorithm based on sub-aperture.

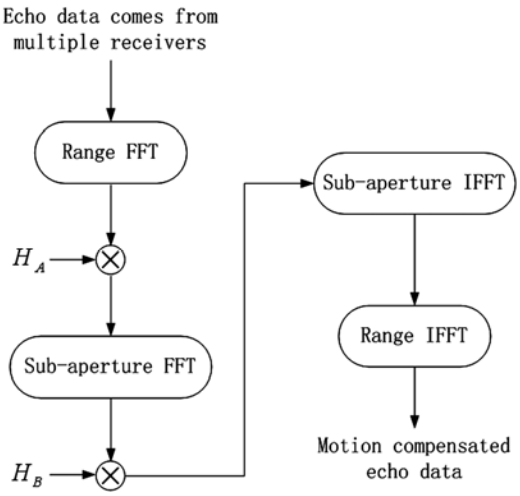

Fig.2 Diagram of the MOCOMP algorithm

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The signal backscattered by a point target at (X,r) is given by:

$$SS(x,u,t,r)=\sigma(X,r)W^2(x-X,r)\cdot p\{t-(R_1+R_2)/C\} \quad (10)$$

wherein W is related to the array pattern and it is squared because it is supposed that the same array to operate in both transmit and receive mode. For simplicity and without loss of generality, the array pattern W is often omitted during derivations and we suppose $\sigma(X,r)=1$. $p(t)$ denotes the transmitted signal waveform.

Step A transforms the received signal into frequency domain along the range direction.

$$S\hat{S}(x,u,k,r)=P(f)\exp\{-j(k+k_0)(R_1+R_2)\} \quad (11)$$

wherein $k=2\pi f/C$ and $k_0=2\pi f_0/C$ denote the wave-number along the range direction. $P(f)$ is the Fourier spectrum of the transmitted signal $p(t)$, so we can multiply $S\hat{S}(x,u,k,r)$ with the conjugate term of $P(f)$ to complete pulse compress along the range direction. This step performs the first order motion compensation at the reference range ρ_0 by the phase angle function H_A.

$$H_A=\exp\left\{j(k+k_0)\left[\delta_1+\frac{1}{2\rho_0}\delta_3\right]\right\} \quad (12)$$

The crucial problem is how to compensate the item related to the cross range. In order to kick the problem, the multiple-receiver echo-data which comes from a pulse is looked upon a sub-aperture and is transformed to the Doppler domain along every sub-aperture to obtain a coarse image in polar coordinates. So the second order motion compensation is performed by multiplying the coarse image with a phase angle function H_B.

$$H_B=\exp\{-j(k+k_0)[2\Delta_r(\cos\theta-1)]\} \quad (13)$$

wherein $\theta=\mathrm{a}\sin(C k_u/f_0)$.

Finally, the echo-data approximatively without motion error is obtained by a 2-D IFFT of the coarse image. Then we rearrange the echo data to an equivalent from a mono-static SAS and put it into imaging algorithm.

4 Simulation trials

The Range Doppler Algorithm (RDA) is the oldest and still a most popular algorithm used in digital processing of SAR and SAS data. Several modification of the algorithm exist in [6], and detailed comparison of them is given in [7]-[8]. For SAS imaging, MOCOMP algorithm is always necessary and most of current MOCOMP algorithms are based on RDA. We choose the RDA algorithm to analysis the performance of the MOCOMP algorithm based on sub-aperture.

Tab.1 Operating parameters in simulation

Transmitted signal:	LFM signal
Signal bandwidth:	20 KHz
Carrier:	150 KHz
Length of receiver:	0.08 m
Number of receiver:	10
Sampling frequency:	300 KHz
PRI:	0.4 s
Velocity:	1 m/s

In order to validate the presented theory, some simulation results are presented in this section. The nominal operating parameters used in the simulation are shown in Tab.1. Furthermore, there exist an ideal point targets in the scene centered at 100m from the sonar track. The transmitter and receivers are collected in the cross range direction.

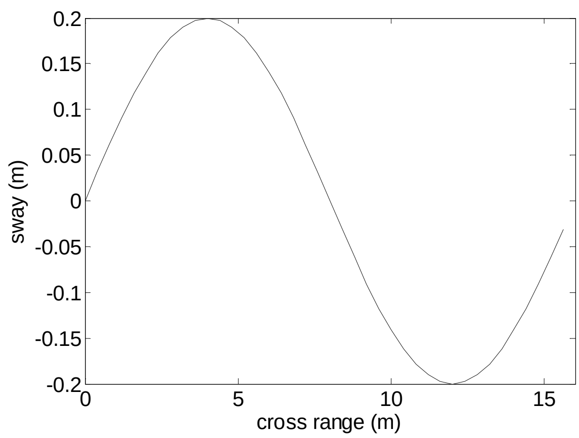

Fig.3 Sway errors in simulated echo-data

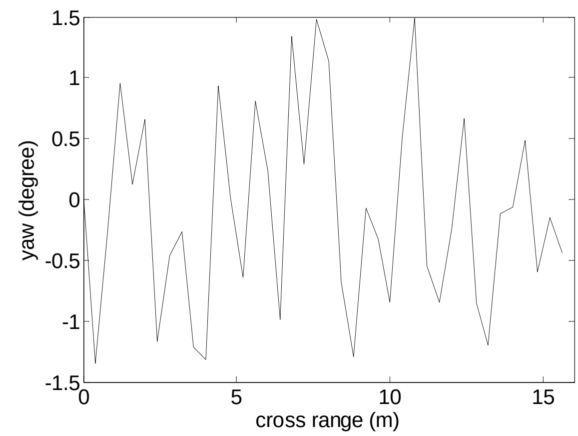

Fig.4 Yaw errors in simulated echo-data

In Fig.5, the imaging result of the simulated point target is shown. This result is obtained from a set of simulated data affected by sine sway and yaw motion errors demonstrated in Fig.3 and Fig.4. In order to depict the performance of MOCOMP algorithm based on sub-aperture, there is no widow function added to both range and cross range direction. Fig.6 depicts the cutaway view along cross range direction. The results show that most of the motion errors have been successfully compensated by the MOCOMP algorithm based on sub-aperture. The dashed denotes the imaging result only compensated by the first order compensation and the real line denotes the imaging result compensated by the first and the second order compensation. The width at -3dB narrows apparently, that is to say, resolving power is improved.

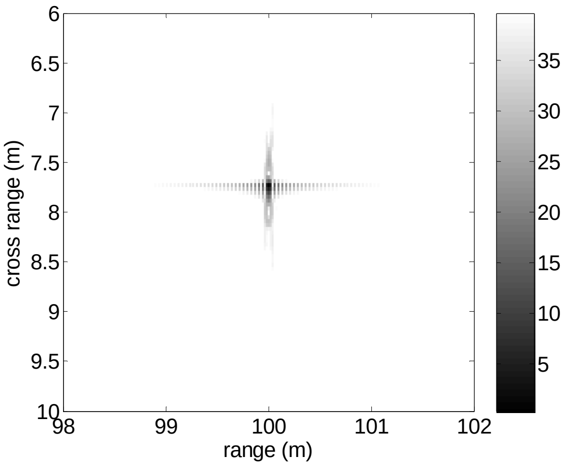

Fig.5 Imaging result of the simulated point

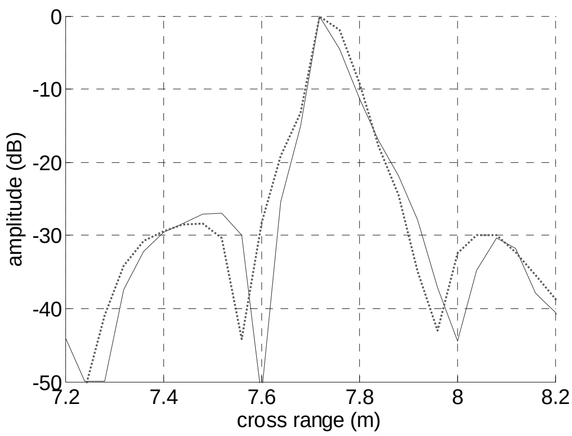

Fig.6 Cutaway view along cross range

5 Conclusions

A recently raised MOCOMP algorithm based on sub-aperture is modified for SAS processor. It can compensate the motion error related to cross range angle. Because it performs motion compensation in echo-data before imaging, the MOCOMP algorithm could combine with all kinds of imaging algorithm.

The performance of the MOCOMP algorithm has been demonstrated using simulated echo-data with sway and yaw motion error. It was shown that it is possible to focus bi-static SAS data with motion error without signification degradation of geometry resolving power. The computational efficiency of the proposed algorithm is very high. Therefore the algorithm seems to be well suited for processing bi-static SAS data in real time.

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Biographies

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