Range-segment Motion Compensation based on Integrated INS for Wide-swath Synthetic Aperture Sonar

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Abstract. Motion errors have severe effect on synthetic aperture sonar (SAS) imagery if worse than a fraction of a wavelength along the entire aperture. Not only currents, but vehicle instability randomly causes periodic motion errors in the synthetic aperture and grating lobes in the SAS images as well. Displaced phase center antenna referred to as micro-navigation has been developed with multiple-receiver SAS for a long time, but still has challenges against larger motion errors. The integrated inertial navigation system comprising an inertial navigation system (INS) and other aided sensors such as a Doppler Velocity Log (DVL) and a surface ship’s Global Position System (GPS) is an unavoidable and trade-off solution to the problem of motion estimate, which is definitely more robust and reliable with the application of the multi-sensor data fusion. Besides, the motion error is variant along the slant range. For a better resolution of the wide-swath SAS, a range-segment motion compensation method based on the integrated inertial navigation system is presented in the paper. This method relies on the multi-sensor data fusion of the integrated inertial navigation system via Kalman filter and is found to significantly outperform the conventional method.

1. Introduction

Synthetic aperture sonar is an effective technique to obtain high-resolution images of the seafloor, which artificially increases the length of the aperture by the ideal uniform straight movement of the imaging platform. Unfortunately, it has to suffer from several challenges related to the ocean environment [1]. One of the severest is platform’s nonstraight trajectory usually caused by turbulence and currents that may inevitably result in distorted SAS images.

A wide variety of motion compensation methods have been developed for the purpose of the improvement of the SAS image quality [2]. The most common methods are DPCA and improved DPCA often referred to as micro-navigation. Segment DPCA [3] as an improved one is presented to deal with the problem of the range-variant motion error in wide-swath SAS application, which indeed gets a better performance in eliminating the influence of range-variant motion error than DPCA. However, neither DPCA nor Segment DPCA have the same limitations: at least two receivers are overlapped between two successive pings, motion information can’t be estimated completely and motion error could not be too large. Based on some earlier experimental results, it appears that the integrated inertial navigation system...
is potentially the basis of the source to estimate the motion error, especially for towed systems which usually have larger fluctuations than those of AUV systems. Thus, it is more reliable to use the data about the motion error from the integrated inertial navigation system consisting of a high-grade INS, a low drift DVL and a surface ship’s GPS [4]. In addition, compensating segment by segment is also needed for wide-swath SAS because of the range-variant motion error in slant range plane. Based upon the analysis above, a range-segment motion compensation method based on integrated inertial system is proposed for wide-swath SAS in this paper.

The paper is organized as follows: firstly, the SAS system geometry is presented and the motion errors are analyzed in Section 2; Secondly, the procedure of range-segment motion compensation is elaborated in detail in Section 3; Finally, simulation and experimental results are given to verify the method.

2. System geometry and motion error model

A sonar with the imaging geometry is shown in Figure 1. According to the stop-hop model and phase centers approximation [5], the recorded sonar echo as a function of time $t$ may be expressed as [6]

$$s(t) = \text{rect}(\frac{t - \tau}{T}) \cdot \exp\left\{jK(t - \tau)^2 - 2j\pi f_c \tau\right\}$$

(1)

where, $T$ is the pulse width, $K$ is the chirp rate, $f_c$ is the carrier frequency, and the time delay $\tau$ is given by

$$\tau = \frac{2\sqrt{r^2 + (vt)^2}}{c}$$

(2)

for a given medium sound speed $c$, the platform velocity $v$ and the nearest slant range $r$ between the antenna and the target with respect to nominal trajectory, which can be represented by

$$r = \sqrt{x^2 + h^2}$$

(3)

where, $x$ is ground range and $h$ is the height of the sonar relative to the target.

It is worth noting that for simplicity, the stop-hop model neglects temporal Doppler effects and the image skew due to motion during echo reception. And the phase centers approximation treats a projector-receiver pair as a pair of virtual transducers collocated midway between the actual transducers.

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However, platform often has motion errors in six degrees of freedom in practice where the errors have any impact on the time delay. Thus, taking into consideration the motion error $\Delta r$, mainly resulting from sway $\Delta x$ and heave $\Delta h$, the time delay has a new expression as follows:

$$\tau' = \frac{2\sqrt{(r + \Delta r)^2 + (vt)^2}}{c}$$

(4)
Provided that the high frequency imaging system is narrowbeam enough with $|vt| \ll r$, the difference of time delay between the actual and nominal trajectory is

$$
\Delta \tau = t' - t \approx \frac{2\Delta r}{c} \frac{2r \cdot \Delta r + \Delta r^2}{(r + \Delta r)^2 + (vt)^2 + \sqrt{r^2 + (vt)^2}} \approx \frac{2\Delta r}{c} \cdot \frac{\Delta x \cdot \sqrt{r^2 - h^2 + \Delta h \cdot h}}{r}
$$

From the equation (5), we can see that $\Delta \tau$ is obviously depend on the slant range $r$, which means that motion error is variant in slant range. The distorted echo signal may be written as

$$
\tilde{s}(t) \approx s\left(t - \frac{2\Delta r}{c} \cdot \frac{\Delta x \cdot \sqrt{r^2 - h^2 + \Delta h \cdot h}}{r}\right) \cdot \exp\left(-j2\pi f_c \cdot \frac{2\Delta x \cdot \sqrt{r^2 - h^2 + \Delta h \cdot h}}{r}\right)
$$

3. Range-segment motion compensation

The sonar has to be positioned with accuracy better than a fraction of a wavelength along the synthetic aperture. This is very difficult underwater where GPS is not available. Because it is not realistic in general to assume that the sonar travels along a straight track at constant speed. In practice, the motion is perturbed randomly from this ideal trajectory due to the combination of variable driving forces, such as towing from a cable by a surface ship, surface waves and the unstable and non-homogenous nature of the ocean currents [7]. Thus, high accuracy motion estimate is necessary for high resolution SAS.

3.1. The Integrated Inertial Navigation System

The preferred solution to motion estimate is using the sensor itself for navigation, in combination with aided inertial navigation [7-10]. A very promising sensor data-driven technique is DPCA micro-navigation, which is exploring the temporal and spatial correlation of received reverberations from the seabed between adjacent transmissions [11]. However, DPCA has some undesirable limitations: at least two receivers are overlapped between two successive pings, motion information can't be estimated completely and motion error could not be too large. A lot of difficulties have been met in our field experiments when applying DPCA for motion compensation. Large Yaw and sway may have severe effects on the performance of this technique. Thus, the achievable performance of DPCA is still to be assessed, which may be confined to small motion errors.

Hence, a combination between inertial navigation and sensor data-driven technique is chiefly based on the measurements from inertial navigation system (INS) since the latter is limited by larger motion errors. It is found that a very high standard integrated inertial navigation system could provide a reliable and robust solution for positions update of SAS, whose main components are the inertial measurement unit, the Doppler velocity logger and a surface ship’s GPS, in combination with a Kalman filter. Obviously, DVL gives a relatively rough estimate of the sonar velocity and are not able to provide any detailed information on small movements of the system. So, there is a need to fuse INS acceleration and DVL estimation to increase measurement quality by choosing to use a Kalman smoother to merge the sensors’ information. Even though the integrated inertial navigation system is generally still not met the high requirements of accuracy, it could provide the relative accurate results that are beyond the reach of the data-driven technique. Figure 2 shows a conventional schematic overview of the integrated inertial navigation system.
Figure 2. Integrated inertial navigation system structure

An INS consists of three accelerometers measuring specific force and three gyros measuring angular rate. A DVL and a surface ship GPS are the aiding sensors. A Kalman filter will, in a mathematically optimal manner, utilize a wide variety of navigation sensors for aiding the INS. The Kalman filter is based on a physical state model and provides a much higher total navigation performance than is obtained from the independent navigation sensors [4]. State and measurement equations are respectively expressed as (7) and (8).

\[
\begin{bmatrix}
\dot{v}_x \\
\dot{v}_y \\
\dot{v}_z \\
\tilde{a}_x \\
\tilde{a}_y \\
\tilde{a}_z
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & \delta t & 0 & 0 \\
0 & 1 & 0 & 0 & \delta t & 0 \\
0 & 0 & 1 & 0 & 0 & \delta t \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
v_x \\
v_y \\
v_z \\
a_x \\
a_y \\
a_z
\end{bmatrix}
+ \begin{bmatrix}
W_{DVLx} \\
W_{DVLy} \\
W_{DVLz} \\
W_{INSx} \\
W_{INSy} \\
W_{INSz}
\end{bmatrix}
\tag{7}
\]

\[
\begin{bmatrix}
v_x \\
v_y \\
v_z \\
a_x \\
a_y \\
a_z
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\tilde{v}_x \\
\tilde{v}_y \\
\tilde{v}_z \\
\tilde{a}_x \\
\tilde{a}_y \\
\tilde{a}_z
\end{bmatrix}
+ \begin{bmatrix}
V_{DVLx} \\
V_{DVLy} \\
V_{DVLz} \\
V_{INSx} \\
V_{INSy} \\
V_{INSz}
\end{bmatrix}
\tag{8}
\]

where, \(v_x, v_y, v_z\) denote the DVL measured velocity of three-axis, \(W_{DVLx}, W_{DVLy}, W_{DVLz}\) denote the State and measurement noise of DVL respectively. \(a_x, a_y, a_z\) denote the INS measured acceleration of three-axis, \(W_{INSx}, W_{INSy}, W_{INSz}\) denote the State and measurement noise of INS respectively. \(\delta t\) is the time interval. \(\tilde{v}_x, \tilde{v}_y, \tilde{v}_z, \tilde{a}_x, \tilde{a}_y, \tilde{a}_z\) denote the state variables.

3.2. Motion Error Estimation and Range-segment Compensation

In [12], sway and heave are estimated by segment DPCA and least square fitting that usually introduce estimate errors making results far away from the real values. Whereas the Inertial Navigation System (INS) outputs position, velocity and attitude using high frequency data from an Inertial Measurement Unit by which variable sway, surge and heave can be directly calculated. For simplicity, we only consider sway and heave errors in this paper. Taking range-variant motion error into consideration, the range-segment motion compensation method proceeds as follows:

Step1. Rotate the INS measurements from body coordinate into geographic coordinate.
\[
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix} =
\begin{bmatrix}
  \cos \alpha & -\sin \alpha & 0 \\
  \sin \alpha & \cos \alpha & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  \cos \beta & 0 & -\sin \beta \\
  0 & 1 & 0 \\
  0 & \cos \varphi & \sin \varphi \\
\end{bmatrix}
\begin{bmatrix}
  x_p \\
  y_p \\
  z_p
\end{bmatrix}
\]  

(9)

where, \( x_p, y_p, z_p \) denote the body coordinate of the transducer element, \( x, y, z \) denote the geographic coordinate of the transducer element, \( \alpha, \beta, \varphi \) are respectively referred to as heading, pitch and roll, which can be measured by the integrated inertial navigation system.

Step2. Obtain ideal track by least square fitting.

According to the X and Y coordinates of transducer element in the geographic coordinate system, the ideal track is obtained using the least square fitting method in the horizontal plane. For simplicity, choose the mean value of Z coordinate as the ideal track in vertical direction, expressed as \( \bar{z} \).

Step3. Calculate the sway and heave relative to the real track.

\[
\Delta x = \frac{y - kx}{\sqrt{1 + k^2}}
\]
\[
\Delta h = z - \bar{z}
\]

(10)

where, \( k \) denote the slope ratio of the ideal track calculated by least square fitting, \( \Delta x, \Delta h \) are respectively sway and heave in geographic coordinate.

Step4. Divide the baseband echo data into \( N \) segments along the slant range and calculate time error \( \Delta r_i \) corresponding to \( \Delta r_i \) in the \( i \)th segment.

\[
\Delta r_i = \frac{2\Delta r_i}{c} = \frac{2}{c} \frac{\Delta x \cdot \sqrt{r_i^2 - h^2} + \Delta h \cdot h}{r_i}
\]

(11)

where, \( N \) is the number of the segments, \( 1 \leq i \leq N \), \( r_i \) is the slant range of the \( i \)th segment, \( h \) is the height of the transducer element from the sea floor, generally given by DVL.

Step5. Compensate the motion error segment by segment.

\[
s'(t) = \sum_i \delta_i(t) \odot \delta(t + \frac{2\Delta r_i}{c}) \cdot \exp(j2\pi f_i \frac{2\Delta r_i}{c})
\]

(12)

motion error comprises the time delay and phase compensation, \( s'(t) \) denote the motion compensated signal, \( \delta_i(t) \) denote the distorted signal of the \( i \)th segment.

There is another more efficient way to compensate motion error in the frequency domain,

\[
s'(t) = \sum_i \text{ifft}(\text{fft}(\delta_i(t)) \cdot \exp(j2\pi(f + f_c) \frac{2\Delta r_i}{c}))
\]

(13)

where, \( f \) is the frequency with respect to \( t \).

4. Results from simulation system and field experiments

Simulation and field experiments have been designed to verify the effectiveness of the proposed method. For reference purposes, the conventional method is also run with one whole swath compensation. Reconstruction of the echo data is performed via wavenumber algorithm [6].

4.1. Simulation results

Three rows of point targets are set in the imaging area with a total of 51 in Figure 3. Sway and heave errors are also introduced as cosine function, as shown in Figure 3(b), which means that the track of SAS is not straight. The swath is 80m, and the distorted signal has been divided into three segments. The results of different method are displayed as follows:
6

(a) Simulation result without motion compensation        (b) Added sway and heave errors

(c) Simulation result with conventional method       (d) simulation result with proposed method

Figure 3. Simulation results

From figure 3(a), it can be easily found that if the sway and heave referred to figure 3(b) are not compensated, the point targets spread severely in the azimuth direction. Figure 3(c) and 3(d) show that the targets get noticeably more focused and the image quality gets improved after motion compensation. It means that motion compensation is of vital importance for non-straight trajectory. Compared with figure 3(c) and figure 3(d), we can see that the proposed range-segment method has a better performance than conventional method, especially in the near and far region.

4.2. Field experiment results

The field experiment was conducted in August, 2018 in central China. SAS system was towed from a cable by a surface ship. The swath is 260m long that the range-variant of motion error is obvious. The echo data has been divided into 3 segments.

The field experiment results are the same with the simulation. The object that has a ghost image in the middle of the figure 4(a) gets more focus after motion compensation. But a bit of blur about the ditch still exists in the right of the figure 4(b). From the figure 4(c), the ditch is clearer than ever. The range-variant motion error can be compensated properly by proposed method.
5. Conclusion
Motion error is the main factor that effects the quality of SAS images, and it is variant along the slant range especially for wide-swath SAS. The integrated inertial navigation system is the basis of source to estimate the motion error in contrast with several limitations of DPCA. The range-segment method based on the integrated inertial navigation system could provide a robust and reliable solution and a full swath high resolution image for SAS motion compensation. Simulation and field experiment results have confirmed the effectiveness of the proposed method.

It should be noted that there is still a little defocusing existing in some parts of the image. Whereas DPC has an advantage in dealing with this problem of residue motion errors. Therefore, a combination of both the integrated inertial navigation system and DPC is an attractive solution for SAS imagery, which is under development now.

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