Generalized ISAR Imaging of Sea Target

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Abstract

A generalized ISAR approach to solve the SAR problem for ship target image reconstruction is considered. A new definition of three dimensional (3-D) SAR scenario is suggested. An analytical geometrical approach to define apparent Yaw, Pitch and Roll angle of the ship target at sea is implemented. The target is presented as an assembly of point scatterers. Mathematical expressions to calculate range distance to each point scatterer are derived. A SAR signal model based on a linear frequency modulated transmitted signal, 3-D geometry and reflectivity function of the target is derived. Image reconstruction procedure includes Fourier transform for range compression and Fourier transform for azimuth compression. To verify the generalized ISAR image reconstruction concept with respect to SAR problem a numerical experiment is carried out.

1. Introduction

SAR imaging is a processing algorithm for mapping of Earth and ocean surface. Motions of the radar platform induce an azimuth resolution, but the accuracy of the processing is dependent on proper autofocusing. When the radar is stationary while the target exhibits relative motion regarding the radar position is called inverse synthetic aperture radar (ISAR) [1]. When both target and carrier are moving, the process can be defined as a generalized ISAR imaging process. It is of particular interest for maritime patrol aircraft missions as it permits long-distance all-weather imaging and recognition of ship targets [2, 3]. In [4, 5, 6, 7] range Doppler technique for two-dimensional (2-D) ISAR target imaging is applied. Joint time-frequency (JTF) processing can also be applied [2].

The problem of airborne side-view generalized ISAR imaging of ship target is explored in the present work. The main objectives are to develop the geometry of ISAR scenario, to determine the basic geometrical characteristic in ISAR imaging, the apparent angles - Yaw, Pitch and Roll of the ship during the observation time, to propose linear frequency modulated ISAR signal model and image reconstruction, and autofocusing procedure. The goal of the processing is to achieve a side view of the target which is of particular interest for further classification purposes. The focus of the analysis is on the movements targeted by the radar system. The main result of this work is adequate 3-D geometry of the ISAR scenario described by analytical geometrical expressions, ISAR signal models with linear frequency modulation, robust image reconstruction processing scheme including, range compression, range alignment, autofocusing phase correction, azimuth compression that allow optimal target shape extraction.

2. Geometry of Generalized ISAR scenario

Assume SAR on board of an aircraft illuminates the target, a ship on sea. The movement of a carrier and a target is depicted in the reference coordinate system $Oxyz$, the origin of which is placed beneath the radar platform. The ship is presented as an assembly of point scatterers, described by 3-D regular grid in coordinate system $O_s XYZ$, placed in the mass center of the ship [8]. The origin O_a of the coordinate system of observation is placed in the mass center of the aircraft and oriented as follows. The $O_a \bar{x}$ axis is oriented to the mass center of the ship. The $O_a \bar{y}$ axis is collinear to a vector velocity of the aircraft. The $O_a \bar{z}$ axis is orthogonal to the plane $O_a \overline{xy}$ (Fig. 1).

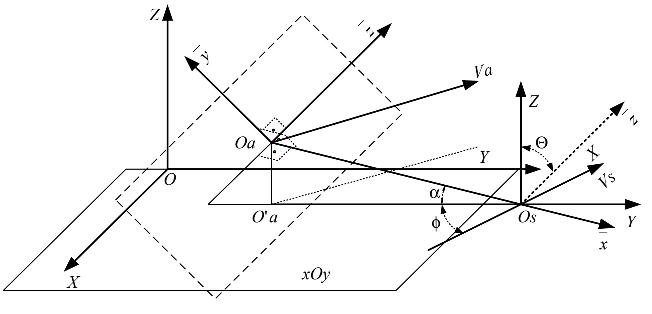

Fig. 1. Generalized ISAR scenario.

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In Fig. 1 the point $O_a(x_{a,}y_a,z_a)$ is the mass center of the carrier, while the point $O_a{}'(x_a,y_a,0)$ is its projection on the plane Oxy. The trajectory of the carrier is described by equations of current coordinates of the aircraft mass center, i.e.

$$x_a = x_a(p) = x_{a0} + V_{ax}pT_p\,;\; y_a = y_a(p) = y_{a0} + V_{ay}pT_p\,,\; z_a = z_a(p) = z_{a0} + V_{az}pT_p \tag{1}$$

where $V_{ax} = V_a\cos\alpha_a$, $V_{ay} = V_a\cos\beta_a$, $V_{az} = V_a\cos\gamma_a$ are components of the vector velocity and V is the module of the vector velocity of the SAR carrier; $\cos\alpha$, $\cos\beta$, $\cos\gamma$ are cosines directions of the aircraft vector velocity; T_p is the pulse reflection period, p is the number of emitted pulses; x_{a0}, y_{a0}, z_{a0} are the initial coordinates of the SAR carrier. The trace of the ship at the sea surface is described by the current coordinates of the mass center of the ship, point $O_s(x_s,y_s,z_s)$. The coordinates of the ship's mass center, point $O_s(x_s,y_s,z_s)$, are defined by the following equations

$$x_s = x_s(p) = x_{s0} + V_{xs}pT_p\,; y_s = y_s(p) = y_{s0} + V_{ys}pT_p\,;\; z_s = z_s(p) = \sin\Omega_z pT_p \tag{2}$$

where $V_{xs} = V_s\cos\alpha_s$, $V_{ys} = V_s\sin\alpha_s$ - the components of the linear vector velocity of the ship; Ω_z angular velocity of the vertical displacement of the mass center of the ship, induced by the sea waves, α_s is the angle between vector-velocity of the ship and Ox axis; V_s - modulus of the ship's vector of velocity.

The relative spatial orientation of the ship and SAR carrier is defined by the following geometrical parameters. The apparent Yaw angle is defined between the lines O_sX and $O_a{}'O_s$, and determined by the expression $\Phi = \mathrm{arctg}\dfrac{V_{ys}(x_s - x_a) + V_{xs}(y_a - y_s)}{V_{ys}(y_a - y_s) + V_{xs}(x_a - x_s)}$. The apparent Roll angle between the lines O_aO_s and $O_a{}'O_s$ is determined by the expression $\alpha = \arccos\sqrt{\dfrac{(x_s - x_a)^2 + (y_s - y_a)^2}{(x_s - x_a)^2 + (y_s - y_a)^2 + (z_s - z_a)^2}}$. The current distance between the SAR carrier and the mass center of the ship - O_aO_s is defined by $R_{as} = \sqrt{(x_a - x_s)^2 + (y_a - y_s)^2 + (z_s - z_a)^2}$. The apparent Pitch angle between $O_a\bar{z}$ and O_sZ axes is defined by $\Theta = \arccos\dfrac{Ab - aB}{\sqrt{C^2b^2 + a^2C^2 + (Ab - aB)^2}}$, where $A = x_s - x_a$, $B = y_s - y_a$ and $C = z_s - z_a$ are the coefficients of the line, $a = z_a(y_a - y_s)$, $b = z_a(x_s - x_a)$, $d = z_ax_a(y_s - y_a) - z_ay_a(x_s - x_a) + z_ax_a(y_s - y_a)$. The coordinates of the ijk th point scatterer of the ship target in the coordinate system of the observation $O_a\bar{x}\,\bar{y}\,\bar{z}$ are determined by the matrix equation

$$\begin{bmatrix} \bar{x}_{ijk}(p) \\ \bar{y}_{ijk}(p) \\ \bar{z}_{ijk}(p) \end{bmatrix} = \begin{bmatrix} R_{as}(p) \\ 0 \\ 0 \end{bmatrix} + A\begin{bmatrix} X_{ijk} \\ Y_{ijk} \\ Z_{ijk} \end{bmatrix} \tag{3}$$

where A denotes the coordinate transformation matrix [9]. $R_{as}(p)$ denotes the range distance between mass centers of the aircraft and the ship respectively and has the form

$$R_{as}(p) = \sqrt{(x_a - x_s)^2 + (y_a - y_s)^2 + (z_a - z_s)^2}\,. \tag{4}$$

3. SAR Transmitted Pulse and GISAR Signal Model

The SAR transmits a series of electromagnetic waves to the ship target, which are described analytically by sequence of N linear frequency modulated (LFM) or chirp pulses each of which is described as follows

$$\dot{S}(t) = \mathbf{rect}\frac{t}{T}\mathbf{exp}\left\{-j\left[\omega t + bt^2\right]\right\} \tag{5}$$

where $\omega = 2\pi\frac{c}{\lambda}$ is the signal angular frequency, φ_0 is the initial phase of a LFM pulse; $c = 3.10^8$ m/s is the speed of the light. The bandwidth $(2\Delta F)$ of the transmitted pulse provides for the dimension of the range resolution cell, i.e. $\Delta R = c/2\Delta F$, t is the fast time, $b = \frac{2\pi\Delta F}{T}$ is the LFM rate, T is the time duration of a LFM pulse, $k = \overline{1,K}$ is the sample number of a LFM pulse; $K = \frac{T}{\Delta T}$ is the number of samples of the LFM pulse, ΔT is the time duration of a LFM sample. The deterministic component of the SAR signal, reflected by all point scatterers can be determined by the expression [10]

$$\dot{S}(p,k) = \sum_{ijk} a_{ijk}\,\mathbf{rect}\frac{t-t_{ij}}{T}\,\mathbf{exp}\left\{-j\left[\omega(t-t_{ijk})+b(t-t_{ijk})^2\right]\right\} \tag{6}$$

where a_{ijk} is the reflection coefficient (intensity) of the point scatterer of the ship; $t_{ijk} = 2\overline{R}_{ijk}(p)/c$ is the time delay of the signal from the ijkth point scatterer of the ship target; $\overline{R}_{ijk}(p)$ is the module of the range distance vector to the point scatterer of the ship target, defined by coordinates (3). The discrete fast time t can be calculated by the expression $t = [k_{ijk\,\min}(p)+(k-1)]\Delta T$, where $k = \overline{1, L(p)+K}$, $k_{ijk\,\min}(p) = \mathrm{int}[t_{ijk\,\min}(p)/\Delta T]$ is the number of the range bin where the signal, reflected by nearest pint scatterer of the target is detected, $t_{ijk\,\min}(p) = 2\overline{R}_{ijk\,\min}(p)/c$ is the minimal time delay of the SAR signal reflected from the nearest point scatterer of the target, $L(p) = k_{ijk\,\max}(p) - k_{ijk\,\min}(p)$ is relative time dimensions of the target, $k_{ijk\,\max}(p) = \mathrm{int}[t_{ijk\,\max}(p)/\Delta T]$, $t_{ijk\,\max}(p) = 2\overline{R}_{ijk\,\max}(p)/c$ is the maximum time delay of the SAR signal reflected from the farthest point scatterer of the target.

4. GISAR Image Reconstruction

a. Range alignment: The autofocusing procedure consists of both coarse range alignment and precise phase correction. The operation of range alignment is performed over the SAR signal registered for pth emitted pulse by renumbering the range bin addresses in the interval from $k = k_{ijk\,\min}(p)$ to $k = k_{ijk\,\max}(p)+K$ where SAR signal is placed, by new numbers, from $k=1$ to $k = L(p)+K$.

b. ISAR Image Reconstruction Procedure: By implementing both range compression and azimuth compression the image reconstruction from LFM ISAR data can be performed. Range compression of ISAR signal data demodulated by multiplication with complex conjugated transmitted signal can be implemented by applying Fourier transform procedure in accordance with the expression

$$\xi(p,q) = \sum_{k=1}^{K+L} S(p,k)S^*(t)\,\mathbf{exp}\left(-j\frac{2\pi kq}{K+L}\right), \text{ where } \dot{S}^*(t) = \mathbf{exp}\left\{j\left[\omega t + bt^2\right]\right\},\ q = \overline{1,(K+L(p))},\ k = \overline{1,K+L(p)}. \tag{7}$$

Azimuth compression of the ISAR signal for each qth row can be implemented by Fourier transform over the range compressed ISAR data, i.e.

$$\overline{\xi}(\overline{p},q) = \sum_{p=1}^{N} \xi(p,q)\,\mathbf{exp}\left(-j\frac{2\pi p\overline{p}}{N}\right), \text{ where } \overline{p} = \overline{1,N},\ q = \overline{1,(K+L)}. \tag{8}$$

The final image of a target can be retrieved by the module operation over azimuth compressed data, i.e.

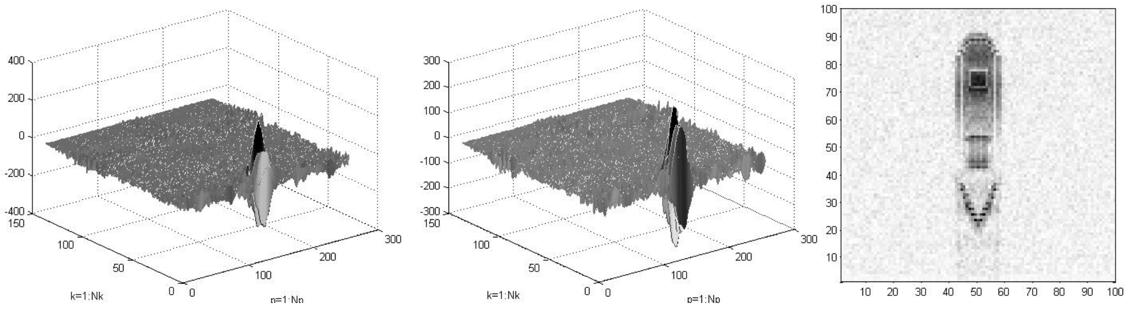
$$Q(\overline{p},q) = \left|\overline{\xi}(\overline{p},q)\right| \tag{9}$$

c. Autofocusing Phase Correction Algorithm

Autofocusing phase correction can be performed by multiplication of the matrix $\dot{S}(p,k)$ by phase correction term $\exp[-j\Phi(p)]$, where $\Phi(p) = a_1(pT_p)+a_2(pT_p)^2+a_3(pT_p)^3+a_4(pT_p)^4+....a_m(pT_p)^m$ is a polynomial of m-th order. The polynomial coefficients a_m, where $m = 1,2,...$ can be calculated iteratively using contrast image cost function [4].

5. Numerical Experiment

To prove the properties of the generalized 3-D SAR signal model with linear frequency modulation and to verify the correctness of developed digital signal generalized ISAR image reconstruction procedures. It is assumed that the ship target is moving rectilinearly in a 3-D Cartesian coordinate system of observation $Oxyz$ and the geometry of the target is depicted in 3-D coordinate system $O_S XYZ$. The real part and imaginary part of the GISAR signal, and the final image of a ship target after 2-D FFT range and azimuth compression and module operation presented in Fig. 2.



(a) (b) (c)

Fig. 2. Real part (a), imaginary part (*b*) of the GISAR signal, and final image (*c*) of a ship target after 2-D FFT range and azimuth compression and module operation.

6. Conclusion

In the paper a generalized ISAR approach to solve the SAR problem with respect to ship target recognition and image reconstruction has been suggested. A mew coordinate definition of 3-D SAR scenario has been addressed. An analytical geometrical approach to define apparent Yaw, Pitch and Roll angle of the ship target at sea has been applied. Mathematical expressions to determine range distance from SAR to point scatterers of the target have been derived. The model of the GISAR signal return is composed by a linear frequency modulated transmitted signal, geometry and reflectivity properties of point scatterers of the object. GISAR image reconstruction procedure includes Fourier transform range compression and azimuth compression. To verify the GISAR signal model and image reconstruction concept with respect to the SAR problem a numerical experiment has been carried out. As can be noticed from the extracted image of the ship target the quality of the image is satisfactory. GISAR geometry, extracted equations and models of GISAR signals can be used for ship target identification.

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7. References

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