Research of the Aeroplane Intelligent Localization Methods Based on Synthetic Aperture Radar Imagery

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Abstract—**Synthetic Aperture Radar (SAR) presents prominent advantages, such as working in all-time and all weather condition, which makes it locate the aeroplane more advantageous. First, the article discusses the effect on aircraft location caused by factors such as topographic relief while SAR imaging. Then, proposes a method that calculates the areoplane's spatial position based on the multi-angular cone model after images matching are finished between different SAR images. The experiments verify the high-precision location of aircraft with more than 4 matching points provided, which spells itself the fitting tool in positioning aircraft with scarce image matching points.**

Keywords-Circuit scanning SAR imagery; scene match; aircraft localization; multi-angular cone method

I. INTRODUCTION

In recent years, with the development of sensor technology, SAR has already become an important tool in earth observation. For working in all-time and all weather condition, it can reveal the topographic structure and ground camouflage effectively, which means itself a useful tool in target detection and imagery matching. Because of the limited information for the real-time images taken from aircrafts and simultaneous process of images into account, the localization of aircraft must consider impacts of factors, such as imaging principles of sensors and topographic relief [1]. So, the localization of aircraft with least corresponding image points is becoming a hot issue in the field of imagery matching.

Now, a few achievements have been made in image matching and aircraft localization using SAR sensor imaging. In early days, researches focused on the impact of topographic relief and relevant rectification for us [2]. Gao Xiangwu discussed how position of targets can been obtained by solving distance equations and doppler equations, with single one point coordinates in SAR image and position of aircraft as variables, but this method arrived at short precision results [3]. Shi Lihui researched in unmanned vehicle localization, which carried minitype SAR sensor, and studied positioning ability in distance direction and orientation direction using distance equations and doppler equations respectively [4]. Yet the results saw location errors remarkably increased with slant range more large. Yue Xijuan mainly studied targets localization based on difference GPS and INS (Inertial Navigation System) [5]. Li Tianchi proposed a SAR positioning method based on parametric estimation, which can get the high-precision position of the aeroplane [6]. The experiments verified that relatively high-precision localization relied much on adequate corresponding image matching points, usually more than 6. Qin Yuliang put forward a airframe positioning method, using distance-Doppler data from missile-borne SAR, together with missile altitude measured by flying speed and altimeter from INS [7]. And his emphasis was analyzing the main factors affecting precision on the basis of simulation computers. Detailed research of Luo, H.B covered locating errors of SAR distance model [8]. Gierull, C.H analyzed localization of moving targets via orientation and distance data from SAR [9]. In this article, after analyzing effect of topographic relief on aircraft's positioning, we propose a solution of aircraft's spatial localization based on a multi-angular cone model, and its high-precision results need just over 4 dependable image matching points.

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II. ANALYSIS OF LOCALIZATION ERRORS OF SAR IMAGING AIRCRAFT

The geometric errors of SAR images mainly include systematic error of radar, position and speed errors of platform, as well as errors of signal processor. These error sources determine accuracy of the aircraft location carrying SAR sensor. Therefore, we need to analyze the error sources of SAR images firstly in order to study and improve the locating accuracy of SAR image producer.

The geometric errors of SAR images can be decomposed into orientation direction errors and distance direction errors, in which the orientation direction errors caused by frequencies in the Doppler centre can be solved by high-precision parametric estimation. So this issue chiefly discusses distance direction errors.

A. Error of echo delay

Position of target in distance direction measured by SAR is determined by the known angle of incidence and slope distance between surveying platform and target. The slope distance can be calculated through surveying the total time delay between transmitting signal and receiving echo signal. Yet the error of echo delay is one of the major elements affecting position

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accuracy of the target in distance direction. The relation between slope distance and time delay is below

$$R = 0.5c(\tau - \tau_e) \tag{1}$$

In the formula, C is light speed; τ_e are time delays of radar transmitter and receiver; τ includes transmitter time delay τ_1 、 electromagnetic wave propagation delay τ_2 、 setting time τ_3 of echo signal receiving aperture、 forward time error $\Delta\tau$ of echo signal receiving aperture.

τ_1、 τ_2 and τ_3 are parameters calibrated. Wave interval in serial pulses is the fixed time interval $\Delta\tau$, which contributes the positioning error in distance direction as below

$$\Delta R = c\Delta\tau / 2\sin\theta \tag{2}$$

In the formula, θ is side-looking angle of imaging radar.

B. *Error caused by target altitude*

On the SAR image, topographic relief in imaging region, resulted from topographical changes, directly leads to image point displacement. Assume that H is the altitude of imaging radar, $h(x)$ is the elevation of ground point A. x is A 's image matching coordinate on the image, namely corresponding horizontal coordinate in distance direction on the SAR image. R is slope distance measured by SAR echoes, and r is radial distance from sensor nadir point to the projection of target at $h(x)$ altitude on the average surface elevation. The image point coordinate displacement caused by topographic relief $h(x)$ can be expressed as below

$$\begin{aligned}\Delta r &= \sqrt{R^2 - (H - h(x))^2} - \sqrt{(H - h(x))^2 + r^2 - H^2} \\ &= x - \sqrt{(H - h(x))^2 + x^2 - H^2}\end{aligned} \tag{3}$$

Formula (3) tells us the displacement of the imaging position of target towards photo nadir point increases as $h(x)$ increases, which means its effect needs to be considered in high-precision matching and positioning of images.

III. PRINCIPLES OF AIRCRAFT LOCALIZATION IN MULTI-ANGULAR CONE MODEL

As for imaging of circuit scanning SAR, the scanning beam rotates in a circle with radial scanning of radar antenna together. And the area within the inner circle is called radar blind area, which is resulted from time delay between the start of radial scanning and the antenna's receiving echo from the nearest object. In this area, radar image is totally blank. As a result, such SAR imaging forms the annulation image. As figure 1 shows, 3-4 homologous image points well distributed on the annulation image compose a multi-angular cone model, on which based the accurate localization of aircraft is realizable [10].

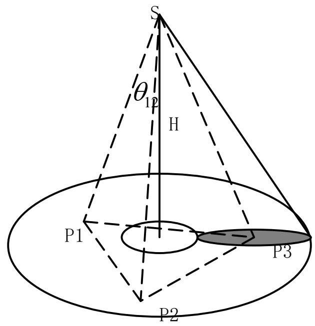

Figure 1. Principles of circuit scanning SAR imaging

A. *Calculation model*

As Fig. 1 shows, S is aircraft's position, H is the radar's altitude, P_1、P_2、P_3 are corresponding image points in the imaging region obtained through image matching, which simultaneity provide their image coordinates. And their spatial coordinates are derived from the reference image. θ_{ij} is separation angle of corresponding beams. In the imaging relation of circuit scanning SAR, angle between vector $\overrightarrow{SP_1}$ and $\overrightarrow{SP_2}$ in object space is equal to the corresponding one between vector $\overrightarrow{SP_1}$ and $\overrightarrow{SP_2}$ in image space. Then

$$\frac{\overrightarrow{Sp_1}\cdot\overrightarrow{Sp_2}}{\left|\overrightarrow{Sp_1}\right|\left|\overrightarrow{Sp_2}\right|} = \frac{\overrightarrow{SP_1}\cdot\overrightarrow{SP_2}}{\left|\overrightarrow{SP_1}\right|\left|\overrightarrow{SP_2}\right|} = \cos\theta_{12} = C_1$$

Obviously, it can be calculated by the image coordinates of control points. As for a discretional pair of points *i* and *i+1*

$$C_{i0} = \frac{(x_i - x_0)(x_{i+1} - x_0) + (y_i - y_0)(y_{i+1} - y_0) + f^2}{\sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + f^2}\sqrt{(x_{i+1} - x_0)^2 + (y_{i+1} - y_0)^2 + f^2}} \tag{4}$$

In the formula, f is equivalent focal length, of which the solution is described afterward.

Then we come to observation equation

$$C_i = \frac{(X_i - X_s)(X_{i+1} - X_s) + (Y_i - Y_s)(Y_{i+1} - Y_s) + (Z_i - Z_s)(Z_{i+1} - Z_s)}{S_i S_{i+1}} \tag{5}$$

Where,

$$\left.\begin{aligned} S_i &= \sqrt{(X_i - X_s)^2 + (Y_i - Y_s)^2 + (Z_i - Z_s)^2} \\ S_{i+1} &= \sqrt{(X_{i+1} - X_s)^2 + (Y_{i+1} - Y_s)^2 + (Z_{i+1} - Z_s)^2} \end{aligned}\right\}$$

Formula (4) and (5) comprise the solving model of aircraft spatial position $S(X_S, Y_S, Z_S)$.

B. Establishment of error equations

Error equations of the solving model derive from linearization of equation (5)

$$v_i = \left(\frac{2X_s - X_i - X_{i+1}}{S_i S_{i+1}} + \left(\frac{X_i - X_s}{S_i^2} + \frac{X_{i+1} - X_s}{S_{i+1}^2} \right) C_i \right) \Delta X_s + \left(\frac{2Y_s - Y_i - Y_{i+1}}{S_i S_{i+1}} + \left(\frac{Y_i - Y_s}{S_i^2} + \frac{Y_{i+1} - Y_s}{S_{i+1}^2} \right) C_i \right) \Delta Y_s + \left(\frac{2Z_s - Z_i - Z_{i+1}}{S_i S_{i+1}} + \left(\frac{Z_i - Z_s}{S_i^2} + \frac{Z_{i+1} - Z_s}{S_{i+1}^2} \right) C_i \right) \Delta Z_s - (C_i - C_0) \tag{6}$$

At least, 3 control points are needed to calculate aircraft's spatial position. Given n control points, we can deduce *n(n-1)/2* equations ,among which only *(2n-3)* ones are independent.

In the least squares procedure, error equations are as below

$$\underset{(2n-3)\times 1}{v} = \underset{(2n-3)\times 3}{A} \cdot \underset{3\times 1}{\delta S_{XYZ}} - \underset{(2n-3)\times 1}{C} \tag{7}$$

The corresponding solution is

$$\underset{3\times 1}{\delta S_{XYZ}} = (\underset{3\times(2n-3)}{A^T} \underset{(2n-3)\times 3}{A})^{-1} \underset{3\times(2n-3)}{A^T} \underset{(2n-3)\times 1}{C} \tag{8}$$

Now, the sensor imaging position *(X_s, Y_s, Z_s)* can be gained from typical least squares adjustment of the equations set.

C. Equivalent focal length f

Equivalent focal length f can be computed from the ratio of radar altitude H to imaging scale parameter. The scales m_x、m_y are fitted in affine transformation, in which coordinates on the reference image after image matching and corresponding real-time image coordinates are used. The model is as below

$$\begin{cases} x_i - x_0 = a_0 + a_1(X_i - X_0) + a_2(Y_i - Y_0) \\ y_i - y_0 = b_0 + b_1(X_i - X_0) + b_2(Y_i - Y_0) \end{cases} \tag{9}$$

Where,

$$x_0 = \sum_{i=0}^{n} x_i / n \qquad y_0 = \sum_{i=0}^{n} y_i / n$$

$$X_0 = \sum_{i=1}^{n} X_i / n \qquad Y_0 = \sum_{i=1}^{n} Y_i / n$$

In the above formula, x_0, y_0 can also be represented by the centre of circuit scanning SAR. X_0, Y_0, corresponding with x_0, y_0 can be obtained after matching real-time image and reference image together.

Image scale denominator can be computed with $a_0, a_1, a_2, b_0, b_1, b_2$ given by least squares adjustment of formula (9).

$$\begin{cases} m_x = \sqrt{1/(a_1^2 + b_1^2)} \\ m_y = \sqrt{1/(a_2^2 + b_2^2)} \end{cases} \qquad m = \sqrt{m_x^2 + m_y^2}$$

Namely,

$$f = H / m \tag{10}$$

Now, the equivalent focal length f in the multi-angular cone model is obtained, and can be used to locate the aircraft position with formula (6).

IV. EXPERIMENT AND RESULT ANALYSIS

Adequate accurate image matching points are vital to locate aircraft position with circuit scanning SAR images. Since more large real-time images region made during aircraft's flight reduces the efficiency, more small image region limits the target information and leads to scarce image matching points, keeping image matching points to a minimum is significant to achieve aircraft's position.

To test the multi-angular cone model, we assume that image points are matched correctly in each sub region, which can help the analysis and verification. The selected matching points in the image have been matched correctly, so image matching methods need no further description. Fig. 2 shows the distribution of the selected image matching points on the circuit scanning SAR image.

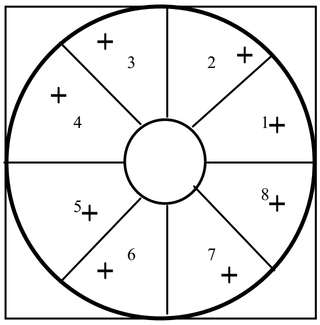

Figure 2. Distribution of image matching points

Locating aircraft via image matching, the corresponding reference images should have been labeled the geocoding, which provides the spatial position of the corresponding homologous image points. Thus, the areoplane's spatial position can be calculated by formula (8).

In the experimentation, the different points in various quadrants are used to locate aircraft position in multi-angular cone model. Table 1 lists the results through different counts of image matching points. Without GPS information at imaging time, the areoplane's position is unavailable. So the mean value of results from four groups is assumed to be the real value for comparing.

TABLE I. COMPARISON OF LOCALIZATION RESULTS VIA DIFFERENT COUNT OF IMAGE MATCHING POINTS

Using point 1,3,5 (unit: meter)			**Using point 1,3,5,7 (unit: meter)**		
XS	***YS***	***ZS***	***XS***	***YS***	***ZS***
92878.1	56230.5	3770.3	92850.4	56256.1	3775.7
$\delta XS =$ 17.6	$\delta YS =$ -21.9	$\delta ZS =$ -5.1	$\delta XS =$ -10.1	$\delta YS =$ 3.7	$\delta ZS =$ 1.6
Using point 1,2,3,4,5,7 (unit: meter)			**Using all the points 1-8 (unit: meter)**		
XS	***YS***	***ZS***	***XS***	***YS***	***ZS***
92857.7	56259.2	3775.6	92855.8	56263.6	3774.9
$\delta XS =$ -2.8	$\delta YS =$ 6.8	$\delta ZS =$ 1.5	$\delta XS =$ -4.7	$\delta YS =$ 11.2	$\delta ZS =$ 0.8

Tab. 1 shows that the position error is larger when 3 points used. Because 3 points means no redundant observation, each error of the matching points contributes to the uncertain result. The error band is smaller 10 meters after adjustment compensation when over 4 points are used. Yet the error band doesn't decrease further when more points are used. The results prove that over 4 reliable points mean relatively high-precision location of aircraft.

Since correct image matching points are hard to get in the real-time image, request for less image matching points proves to be significant to locate aircraft via circuit scanning SAR images, which enhances the reliability of image matching navigation in a certain extent. The method proposed here needs less image matching points to guarantee the locating accuracy, which proves to be applicable in image matching navigation based on circuit scanning SAR images.

REFERENCES

[1] Weiss, M.; Marino, G.. Position and orientation estimation of two airborne platforms towards each other. Geoscience and Remote Sensing Symposium, 2007. IGARSS 2007. IEEE International 23-28 July 2007:115-118.

[2] Shao Yongshe, He Xiangchen, Chen Ying, Ge Chiqiang. Research of the influence of terrain modulation on the aeroplane location and its correction.Systems Engineering and Electronics,2006,28(3): 403-406.

[3] Gao Xiangwu, Huang Guangming, Yang Ruliang. Study on a Fast Target Location Method for Airborne SAR and Location Precision Analysis. Modern Radar, Vol.26(9), 2004:4-7.

[4] Shi Lihui. Capability Analysis of Target Separtion and Location of the Minitype SAR on UAV, Modern Radar, Vol.28(2), 2006:21-23.

[5] Yue Xijuan, Huang Guoman, Zhao Zheng. Research on the mathematic model of direct geolocation with airborne SAR image. Science of Surveying and Mapping, Vol.34(Special Issue), 2009:181-183.

[6] Li Tianchi, Zhou Yinqing, Ma Haiying, He Xiangchen. SAR position method based on parameter estimation.Systems Engineering and Electronics, 2007, 29(3):372-374.

[7] Qin Yuliang, Li Hong, Wang Hongqiang, Li Xiang. Missile location based on SAR seeker.Systems Engineering and Electronics, Vol.31(1), 2009:121-124.

[8] Luo, H.B.; He, X.F.; He, M.; Error analysis of pixel positioning accuracy of SAR images based on R-D location model. Synthetic Aperture Radar, 2007. APSAR 2007. 1st Asian and Pacific Conference on. 5-9 Nov. 2007:580-583.

[9] Gierull, C.H.; Azimuth positioning of moving targets in two-channel SAR by direction-of-arrival estimation. Electronics Letters. Vol.40(21),2004:1380–1381.

[10] Chen Ying. Digital photogrammetry for remote sensing image. Shanghai: Tongji University Publishing House, 2004.