Modeling and Sensitivity Analysis of Navigation Parameter Errors for Airborne Synthetic Aperture Radar Stereo Geolocation

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Abstract For the high-resolution airborne synthetic aperture radar (SAR) stereo geolocation application, the final geolocation accuracy is influenced by various error parameter sources. In this paper, an airborne SAR stereo geolocation parameter error model, involving the parameter errors derived from the navigation system on the flight platform, has been put forward. Moreover, a kind of near-direct method for modeling and sensitivity analysis of navigation parameter errors is also given. This method directly uses the ground reference to calculate the covariance matrix relationship between the parameter errors and the eventual geolocation errors for ground target points. In addition, utilizing true flight track parameters’ errors, this paper gave a verification of the method and a corresponding sensitivity analysis for airborne SAR stereo geolocation model and proved its efficiency.

Keywords airborne SAR; stereo; sensitivity analysis; parameter error; geolocation

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Introduction

With the rapid development of hardware and software techniques, the stereo positioning technique of synthetic aperture radar (SAR), especially the technique of SAR geolocation, has presented more and more extensive application potential now.[1-4] Usually, the SAR stereo model based on F. Leberl imaging equations is taken as a convenient and classical method of SAR geolocation application. Compared with satellite-borne or space-borne SAR systems, airborne SAR system can provide a higher image resolution but at the same time will produce some serious geometric distortion attributed to the irregular motion of the flight platform caused by atmosphere turbulence.[5] This introduces errors into the on-flight track record parameters and also into the stereo geolocation model, thereby influencing the final three-dimensional positioning accuracy of the ground target points. As far as this point is concerned, the modeling and sensitivity analysis for the airborne SAR geolocation error parameters is very important and can provide us with a kind of quantitative evidence of error propagation regularity, especially when combined with interferometry technique.[6,7] This analysis can also be applied in airborne SAR image processing and other application fields, such as image precision rectification, image mosaicking, SAR stereo photogrammetry,[8,9] information extracting, and SAR change information detection.[10,11]

According to the stereo positioning principle of
SAR images,[12,13] the opposite-side stereo SAR images usually have the best positioning accuracy because they produce a big parallax in data processing. However, simultaneously they present different texture characteristics of ground objects due to the special side-glance imaging mode of SAR. This will cause more difficulties for image interpretation, especially for mapping in mountainous area. Therefore, commonly, the stereo configuration of airborne SAR images is formed with two same-side flight trajectories. The corresponding 3D geolocation model based on F. Leberl imaging equations has been shown as Fig.1. In the uniform ground reference system \((O, X, Y, Z)\), \(S_1\) and \(S_2\) are the sensor position vectors in the ground reference. \(P\) is the ground object point position vector. \(V_1\) and \(V_2\) are the flight velocity vector respectively for the two sensors. \(\theta\) is the stereo intersection angle. \(\tau_1\) and \(\tau_2\) are the azimuth angles for the two radar antennas, respectively. \(B_x\) and \(B_z\) are the components of the baseline. \(\beta\) represents the intersection angle of flight trajectories.

In fact, the 3D geolocation coordinates of ground target point \(P-(X, Y, Z)\) are decided by the intersection process of the four imaging conditional equations of range-Doppler circles of radar imaging process.

![Sketch map of geolocation model from airborne SAR stereo images](image)

Among those error parameter sources of geolocation process inputted into airborne SAR stereo model, the navigation parameters’ errors attracted more attention than those from SAR processors or imaging process, which have been inherited in airborne SAR stereo images for the users. There has been some other research on airborne SAR imaging error parameters model to implement motion compensation and realizing flight path control.[14, 15] In practical surveying and mapping applications, the error covariance relationship between the computation error of the ground target point’s coordinates and the parameter errors is used to review the error propagation in airborne SAR stereo model. One method is to establish an airborne SAR error parameters model through the expression of vector space,[16,17] utilizing an iteration computation and the estimated measurements. Another solution for this problem[7] depends on a kind of arbitrary reference coordinates transformation, from the reference coordinates to the required map projection to realize the direct and simple SAR geolocation.

This paper provides a kind of near-direct method for modeling and sensitivity analysis of navigation parameter errors. It will use the union ground reference to obtain the mathematical expression of the error covariance relationship between the parameter errors and the final stereo positioning errors, and the corresponding error analysis results show a direct reference to the user during practical applications for SAR stereo images without more iteration computation. Utilizing true flight track parameters’ errors, this paper gave a verification of the method and a corresponding analysis of the sensitivity of the navigation parameter errors for the airborne SAR geolocation model.

1 Methodology

Corresponding to the 3D geolocation model in Fig.1, there is a vector equation as follows:

\[
|S_i(t_i) - P| = R_i |S_i(t_i) - P| V_i(t_i) = K_i R_i V_i(t_i)
\]

Where \(t_i (i=1,2)\) represents the corresponding imaging time on the two flight trajectories for the same ground object point, respectively. \(K_i (i=1,2)\) denotes the cosine of the azimuth angle of the viewing vector from radar sensor to ground object point, respectively, in the stereo configuration for the same two trajectories. \(K_i\) can be considered polynomial functions of \(t\) as well. In fact, when imaging conditions are ideal enough, \(K_i (i=1,2)\) can be treated as constants, because the radar antenna will keep to a certain direc-
tion during the same flight trajectory, only varying with different flight trajectories or flight time. When the azimuth angle $\tau_i (i = 1, 2)$ is $90^\circ$, this is equal to the situation where the estimated value of the Doppler-centric frequency is zero during the SAR imaging process. $R_i (i = 1, 2)$ is the slant range length from radar sensor to ground target point $P$. $S(t_i) (i = 1, 2)$ is the sensor position vector. $P$ is the ground object point position vector. $V_i(t_i) (i = 1, 2)$ is the instantaneous flight velocity vector at imaging time $t_i (i = 1, 2)$.

As for the solution of the nonlinear simultaneous equations, the usual processing method is to utilize the Taylor’s expansion when measurements have their approximate values or true values, taking only the simple terms and transforming the equations into linear conditional equations; then, they can be solved by the Linear Least Square Adjustment algorithm. Theoretically, this is an approximate processing under two preconditions, i.e., there exist small disparities between the measurements and their approximate or true values, and there is a weak degree of nonlinearity for the simultaneous equations. Detailed discussions about the extent of linearization are possible, and the deduced statistical effects after the linearization processing for the nonlinear simultaneous equations are beyond the scope of this paper.\(^{[18]}\)

For the case of establishing a close to precise parameter error model for airborne SAR geolocation stereo images, this paper adopts a kind of near-direct solution for nonlinear conditional adjustment with unknown parameters to find the true values. It reflects much more the essence of this problem and provides a more reliable analysis. First, the basic adjustment equations should be determined.

Suppose that $P(X, Y, Z)$ is the coordinate of the ground target point $P$ in the ground reference system $(O, X, Y, Z)$, $\zeta (\zeta_1, \zeta_2, \zeta_3, \ldots)$ ($r$ is the error parameters’ sum number) is the error parameter vector of the airborne SAR geolocation stereo model, whose corresponding correction values satisfy

$$\hat{P} = P + V; \quad \hat{\zeta} = \zeta_0 + \Delta \zeta \quad (2)$$

Here, $\hat{\zeta}$ is the approximate value of error parameter vector $\zeta$, and $\hat{P}$ is the measurement vector of $P$ with random error. According to the geolocation stereo model, we can obtain the basic adjustment equations from Eq. (1). The vectors $P$ and $\zeta_0$ can obtain their optimal estimation correction through the simultaneous equations. If we expand the function parts in the basic adjustment equations as Taylor’s series at the true vector values of $P$ and $\zeta_0$, it leads to the following expression:

$$f_i (p, \zeta_0) = f_i^0 + \sum_{j=1}^{3} \frac{f_i^j}{n_p} v_j + \sum_{i=1}^{r} g_i^j \zeta_i + \sum_{p,q=1}^{3} \frac{a_i^{pq} v_p v_q}{2} + \sum_{m,n=1}^{r} b_i^{mn} \zeta_m \zeta_n \quad (3)$$

Here, $i$ is the index number of the equations. $j, p, or q$ are the index numbers of the vector component of ground target point $P(X, Y, Z)$. $l, m, or n$ are the index numbers of the error parameters’ vector components ($i = 1, 2, 3, 4; j, p, q = 1, 2, 3; l, m, n = 1, 2, 3, \ldots, r$). And, the coefficients of the terms in Eq. (3) are defined as

$$f_i^j = \frac{n f_i^j}{n_p}; \quad g_i^j = \frac{n f_i^j}{n \zeta_i}; \quad f_i^0 = f_i (P, \zeta_0);$$

$$a_i^{pq} = \frac{1}{2 \frac{n f_i^j}{n_p} \frac{n f_i^j}{n_q}}; \quad b_i^{mn} = \frac{1}{2 \frac{n f_i^j}{n \zeta_m} \frac{n f_i^j}{n \zeta_n}} \quad (4)$$

We can further transform the relationship Eq. (3) into matrix vectors form that is in the form of a more simplified expression, i.e.,

$$AV + \alpha Z + BY + W = 0 \quad (5)$$

Where $V = (v_1, v_2, v_3)^T$, $Z = (AX, AY, AZ)^T$, $Z$ and $Y$ are the parameters’ error vectors; $A, \alpha, B$, and $W$ are coefficient matrices; and $B$ is a block matrix composed of matrix $A_X$ and $B$. They have the mathematical expressions, respectively, of

$$W = \{f_i^0\}; \quad A = \{f_i^j\}; \quad \alpha = \{a_i^{pq}\}; \quad A_{X_0} = \{g_i^j\};$$

$$B = \{b_i^{mn}\}; \quad B = (A_B);$$

$$Y = (\Delta \zeta U) Z = (v_1^2 \ v_2^2 \ v_3^2 \ v_1 v_2 \ v_1 v_3 \ v_2 v_3\ v_1 v_1 \ v_2 v_2 \ v_3 v_3)^T;$$

$$U = (A_{\zeta_1}^2 \ A_{\zeta_2}^2 \ A_{\zeta_3}^2 \ A_{\zeta_2}^2 \ A_{\zeta_3}^2 \ A_{\zeta_1}^2 \ A_{\zeta_1}^2 \ A_{\zeta_2}^2 \ A_{\zeta_3}^2)^T$$

Also, according to the above stereo model all of the matrices have four row vectors. $W$ has only one column; $A, \alpha, A_X$, and $B$ have three, nine, $r$, and $r^2$ columns, respectively. Based on the Least Square Estimator (LSE) algorithm, the corresponding constructional function can be obtained, that is,

$$\psi = V^T V + Z^T Z - 2K^T (AV + \alpha Z + BY + W) \quad (6)$$

Here, $K$ is a constant coefficient matrix. If we compute the partial derivatives on $V, Z$, and $Y$, setting them to be equal to 0, Eq. (7) can be obtained. Their expressions are

$$V = A^T K; \quad Z = A^T K; \quad B^T K = 0 \quad (7)$$
Setting $N = A A^T + a a^T$, the normal equation can be derived as follows:

$$
Y = - (B^T N^{-1} B)^{-1} B^T N^{-1} W;
$$

$$
K = N^{-1} (B (B^T N^{-1} B)^{-1} B^T N^{-1} - E) W
$$

(8)

Eqs.(7) and (8) comprise the near-direct solution for the airborne SAR geolocation stereo model. Compared with the common linear expressions, its coefficients of the normal equation include the simple and quadratic terms. According to research results, this kind of processing method will have fewer computation errors than that of entirely neglecting the quadratic coefficient terms.[18]

In the next part, we will deduce the error covariance relationship between the error vectors—$V$ and $\Delta \zeta$. Substitute the coefficient matrix $K$ into Eq. (7), and set

$$
M = (A^T N^{-1} B); L = (A^T N^{-1} W)
$$

(9)

We will call this result Eq. (10), which, given the error propagation regularity of variance and covariance matrices, is

$$
D_{yy} = E \{M (YY^T) M^T + MLY^T + LYM^T + LL^T \}
$$

(10)

Given the hypothesis condition that the parameter error vectors are independent of each other and satisfying the normal distributions with a mean value of zero and a variance of $\sigma_i^2$, which is common sense, we can eventually find the expressions for the expectation of $Y$, $Y^T$, and $YY^T$ eventually. We may find that the random vector $A^T \zeta_i / \sigma_i^2$ satisfies the chi-square distribution with one degree of freedom, and it is easy to deduce the final results as follows:

$$
E (A^T \zeta_i) = \sigma_i^2; \quad D (A^T \zeta_i) = 2 \sigma_i^4; \quad E (A^T \zeta_i) = 0
$$

(11)

Here, $i$ denotes the index number of the error parameters ($i = 1, 2, 3, \cdots, r$). After expanding the nonlinear simultaneous equations at the true values, we can eventually obtain the error variance-covariance matrix relationship between the parameter errors and the positioning errors of ground target point $P$, i.e.,

$$
D_{yy} = ME \{(\Delta \zeta U)(\Delta \zeta^T U^T)^T\} M^T
$$

(12)

Therefore, the sensitivities or influence of independent parameter errors on airborne SAR geolocation from the stereo positioning model can be estimated using Eq.(12). In addition, the coefficient matrix $M$ depends only on the derivatives of nonlinear simultaneous equations. Considering the influence of quadratic partial derivatives, it is convenient to implement this in computer programs.

2 Test and results

2.1 Test

According to the above parameter error covariance relationship of the airborne SAR geolocation stereo model, this paper chooses the navigation parameter vector $(X_s, Y_s, Z_s, X_v, Y_v, Z_v, V_x, V_y, V_z, \tau_s, \tau_v)$, which has a direct influence on the final geolocation errors for airborne SAR stereo images. These error parameters are mainly involved the record data of velocity, position, and attitude angles on the flight trajectory.

The test dataset derives from practical flight data of Zigong area, Sichuan Province, in southwestern in China, including DGPS, INS, and airborne SAR image data. The test site has a rough terrain with an average height of 360 m, with no more than 1500 m. In addition, the surface covered with several kinds of vegetation with height, such as bamboo, shrubs, and so on. The original airborne image data in the test is shown as in Fig. 2.

| Number | Parameter               | Value (m) |
|--------|-------------------------|-----------|
| 1      | Azimuth space           | 0.5       |
| 2      | Slant range space       | 0.667     |
| 3      | Mapping swath(Ground range) | 5500     |
| 4      | Near range              | 15024     |
| 5      | Flight height           | 5600      |

Table 1 System parameters of airborne SAR data

For the case of analyzing quantitatively the error parameters’ sensitivity to the geolocation positioning error of airborne SAR stereo model under approximately ideal imaging conditions, we first adopted the iterative algorithm to find out the optimal estimation values for the corresponding record data of flight...
tracks, and a simulation test was been taken to review the effect of the model\textsuperscript{[19]} The work parameters of the airborne SAR system are listed in Table 1.

For the purpose of obtaining intuitive results, this paper utilized the reference values to show the quantities of the parameter errors’ sensitivity to the final geolocation errors. For example, some parameters’ values in the specification of navigation and orientation system (POS AV 610, absolute accuracy, PP) have been taken as the reference values to inspect the sensitivity of the parameter errors.\textsuperscript{[20]} The test results are listed in Table 2.

### Table 2 Test results of sensitivity of airborne SAR geolocation error parameters

| Parameter error (σ) | Reference value | σX(m) | σY(m) | σZ(m) |
|---------------------|-----------------|-------|-------|-------|
| τ                   | 2°              | 0.125605 | 0.120951 | 69.410823 |
| Vx                  | 0.005 m•s\(^{-1}\) | 0.395785 | 0.096263 | 264.070217 |
| Vy                  | 0.005 m•s\(^{-1}\) | 0.025269 | 0.006172 | 16.882122 |
| Vz                  | 0.005 m•s\(^{-1}\) | 0.169923 | 0.041633 | 113.211169 |
| Xs                  | 0.05 m          | 0.309325 | 0.002274 | 28.529131 |
| Ys                  | 0.05 m          | 0.184518 | 0.00938  | 28.529131 |
| Zs                  | 0.05 m          | 0.134242 | 0.001   | 0.009643 |

#### 2.2 Discussion

From the results, we can see that the error parameter \(V_s\) has an apparent effect on the positioning error in height direction \(Z\). According to the performance specifications of the POS AV navigation system, if the error in \(V_s\) is 0.005 m•s\(^{-1}\), the influence on the horizontal positioning accuracy can be neglected completely. Unfortunately, the absolute error in the direction of \(Z\) will then be close to 265 m, although this may still be considered to satisfy the horizontal accuracy requirement of geolocation for 1:50000-scale and 1:10000-scale topographic mapping tasks at least.

As far as the error parameter \(V_r\) is concerned, it has no big influence on the 3D geolocation accuracy of the ground target point \(P\). When adopting the reference navigation system’s precision referred to in the above part, the biggest positioning error in the direction of \(Z\) is still no more than 17 m. It can be concluded that the sensitivity of \(V_r\) to the final positioning accuracy of \(P\) is very small and is enough to satisfy the geolocation requirement for some scale (e.g., 1:50000) of topographic mapping.

Just as \(V_s\) and \(V_r\), the error parameter \(V_z\) has little influence on the horizontal positioning accuracy of the ground target point \(P\), with an error of no more than 0.2 m. When the error in this parameter is 0.005 m•s\(^{-1}\), it will produce an error around 113 m in the direction of height \(Z\). Even then, the horizontal requirement of mapping some large-scale topography with airborne SAR geolocation technique can still be met with.

Among the in-flight spatial position errors, parameters of the radar sensor, \(X_s\), produce much more influence on the positional error on the \(X\)-axis for the airborne SAR geolocation than on the other two axes. In particular, the smallest positional error that on the \(Y\)-axis is just at millimeter level. Actually, as one of the flight status parameter components, it has little influence on the final geolocation accuracy of point \(P\) when it has an error of 0.05 m for airborne data and is enough to fulfill large-scale topographic mapping missions.

Nevertheless, the direction that is mostly influenced by the effects of the error in parameter \(Y_s\) on the positional accuracy is the \(Z\)-axis. Even if there is only an error of 0.05 m in the radar sensor instantaneous spatial position, parameter \(Y_s\) along the flight direction, the final height positional error in the height for the ground target point \(P\) will be about 28.5 m or so. However, the horizontal positional error on the \(Y\)-axes can be neglected entirely.

Compared with the other positional parameters of the radar sensor, \(Z_s\) produces the smallest error in the final geolocation positional accuracy for the ground point \(P\). When the reference error value is 0.05 m, the effect will be at centimeter level.

The error of parameter \(τ\) reflects directly whether the stereo configuration condition in airborne SAR geolocation model is strong or weak and the reliability and stability of the model. Although ostensibly attributed to one of the geometric imaging conditioning parameters, it has one important error source, i.e., the SAR imaging factor \(f_d\). According to the test result, the main influence on the final positioning accuracy from error parameter \(τ\) is on the vertical direction of \(Z\), with little horizontal positioning errors. Only when the error is about 2°, the height error of the final geolocation can decrease to about 69.4 m.

In this paper, we have made an in-depth discussion on the discrepancies between the sensitivity degrees
on the final geolocation accuracy from the error parameters on the neighboring flight trajectories. In fact, for the airborne SAR geolocation stereo model, the same error parameter on the two neighboring trajectories has an approximate sensitivity to the final positioning error of the same coordinate axis of the ground reference system. There still are discrepancies between them, which is investigated in this paper using the following sensitivity ratio factor:

\[ \hat{S}_i = \frac{\sigma_i}{\sigma_{i2}}, \quad i = X, Y, Z \]  (13)

Where 1 and 2 represent the neighboring flight trajectories in the geolocation stereo model, and \( i \) is the direction of the ground reference coordinates’ axes-\( X, Y, \) or \( Z \). Generally, the closer the value of \( \hat{S}_i \) to 1, the smaller the discrepancy between the same error parameter on the neighboring flight trajectories. The test results are shown in Fig. 3 and Table 3.

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**Fig. 3** Sensitivity ratio of the same parameter error on the neighboring flight trajectories in the stereo test model
Table 3  Sensitivity discrepancies of error parameters on the neighboring flight trajectories

| Parameter error ($\sigma$) | Reference value | $\delta_\sigma$ (m) | $\delta_\sigma$ (m) | $\delta_\sigma$ (m) |
|---------------------------|-----------------|--------------------|--------------------|--------------------|
| $\tau$                    | $2^\circ$       | -0.005366          | -0.091716          | 10.815198          |
| $V_x$                     | 0.005 m s$^{-1}$| 0.004105           | -0.280057          | 48.102591          |
| $V_y$                     | 0.005 m s$^{-1}$| -0.000522          | -0.002334          | -0.004026          |
| $V_z$                     | 0.005 m s$^{-1}$| -0.030269          | -0.150566          | 2.876907           |
| $X_s$                     | 0.05 m          | 0.050015           | 2E-06              | 0.000231           |
| $Y_s$                     | 0.05 m          | -5.2E-05           | -0.041202          | -0.017888          |
| $Z_s$                     | 0.05 m          | -3.7246E-06        | 1.1E-06            | -0.03048115        |

In Fig. 3 and Table 3, we can find that the sensitivity discrepancies of error parameters on the neighboring flight trajectories vary little around their reference values. Most of them vary by no more than 0.1 m, except the simulation test results for error parameters $V_x$, $V_z$, and $\tau$. As shown in the table, when the same error parameter has the same reference value, the sensitivity discrepancy will be different for different ground reference axes. Also, in general, the ground positioning error on the $Z$-axis is worse than that of the other axes especially for the velocity vector components. Otherwise, the position vector of radar sensor will show very little variation between the neighboring flight trajectories for the final 3D geolocation positioning accuracy of the ground target point.

### 3 Conclusion

A kind of near-direct solution method for nonlinear conditional adjustment with unknown parameters has been adopted in this paper to produce the airborne SAR geolocation stereo model. It provided a variance-covariance matrix relationship between the parameter errors and the geolocation errors, which established a close to precise parameter error model for airborne SAR geolocation stereo images.

According to the error parameter model proposed in this paper and the test results, we can draw the following conclusions for the navigation error analysis in airborne SAR geolocation processing. First, almost all of the selected navigation parameter errors inputted directly into the airborne SAR geolocation stereo model have little influence on the horizontal positioning accuracy for the ground target points. Also, they all have apparent errors in the direction of height. The error parameters having the most influence on $Z$-axis are the in-flight velocity vector components and imaging angle factor $-\tau$. As for the error discrepancies of the geolocation for the error parameters on the neighboring flight trajectories, the in-flight velocity vector components have much more variation than that of the position vector of the radar sensor in the simulation test results of the error analysis on the single flight trajectory. This reveals the fact that the radar position vector is more reliable in the geolocation processing of airborne SAR stereo images than the velocity vector. There exists apparent influence on the final position accuracy from the velocity vector parameter and imaging azimuth angle, even under the condition of there being few random recording or measurement errors.

The above results have provided a positive relevance to the airborne SAR applications of geolocation mapping, equipment requirement analysis, flight planning, system designing, etc.

### References

[1] Gonçalves J A (2004) Analysis of SAR image geolocation accuracy for mapping[C]. SAR Image Analysis, Modeling, and Techniques VI, Barcelona, Spain

[2] Hennig T A, Kretsch J L, Pessagno C J, et al. (2001) The shuttle radar topography mission[C]. Digital Earth Moving: First International Symposium, DEM 2001, Manno, Switzerland

[3] Karathanassi V, Iossifidis C H (2003) A SAR geocoding method for evaluating geodetic coordinates and improving indirect geocoding accuracy[C]. Remote Sensing for Environmental Monitoring, GIS Applications, and Geology II, Agia Pelagia, Crete, Greece

[4] Oleksandr O B, Ievgeniia V D, Volodymyr V V, et al. (2007) Retrieving 3-D topography by using a single-antenna squint-mode airborne SAR[J]. IEEE Transactions on Geoscience and Remote Sensing, 45(11): 3574-3583

[5] Perlant F (2001) Using stereo images for digital terrain modeling[J]. Surveys in Geophysics, 21: 201-207

[6] David A Y, Charles V, Jakowatz Jr (2007) Shift–scale complex correlation for wide-angle coherent cross-track SAR stereo processing[J]. IEEE Transactions on Geoscience and Remote Sensing, 45(3): 576-583
[7] Sansosti E (2004) A simple and exact solution for the interferometric and stereo SAR geolocation problem[J]. IEEE Transactions on Geoscience and Remote Sensing, 42(8): 1625-1634

[8] David A Y, Daniel E W, Charles V J (2004) Terrain elevation mapping results from airborne spotlight-mode coherent cross-track SAR stereo[J]. IEEE Transactions on Geoscience and Remote Sensing, 42(2): 301-308

[9] Ka M H, Kim M J (2001) Digital elevation map generation using SAR stereo technique with RADARSAT images over Seoul area[J]. Korean Journal of Remote Sensing, 17(2): 155-164

[10] Michaelsen E, Thiele A, Cadario E, et al. (2008) Building extraction based on stereo analysis of high-resolution SAR images taken from orthogonal aspect directions[J]. Pattern Recognition and Image Analysis, 18 (2): 231-235

[11] Chang B, Fang Y (2002) The principles of positioning with space-borne SAR images[C]. 2002 IEEE International Geoscience and Remote Sensing Symposium, Toronto, Canada

[12] Hoonyol L, Morgan J V, Warner M R (2003) Radargrammetry of opposite-side stereo magellan synthetic aperture radar on venus[C]. 2003 IEEE International Geoscience and Remote Sensing Symposium, Toulouse, France

[13] Bamler R (2001) Principles of synthetic aperture radar[J]. Surveys in Geophysics, 21: 147-157

[14] Madson S N, Hensley S, Wheeler K, et al. (2005) UAV-based L-band SAR with precision flight path control[C]. Enabling Sensor and Platform Technologies for Spaceborne Remote Sensing, Honolulu, Hawaii, USA

[15] Cantalloube H, Nahum C (1999) Accurate geometric model for airborne synthetic aperture radar[C]. SPIE : SAR Image Analysis, Modeling, and Techniques II, Florence, Italy

[16] Cantalloube H (2000) An accurate geometrical error model for airborne SAR: a design example[C]. ESA SP 2000: SAR Workshop: CEOS Committee on Earth Observation Satellites, Toulouse, France

[17] Liu Guolin (2002) Non-linear least square and mapping adjustment[M]. Beijing: Surveying and Mapping Press (In Chinese)

[18] Nocera L, Dupont S, Berthod M A (1996) Simulation-based validation of some improvements in automatic stereo-radargrammetry[C]. Geoscience and Remote Sensing Symposium, IGARSS ’96, Lincoln, Nebraska, USA

[19] Applanix company (2008) POS AV™ Specification[OL]. http://www.applanix.com/media/downloads/products/specs/POSAV%20Specs.pdf