THEORETICAL ACCURACY OF DIRECT GEOREFERENCING WITH POSITION AND ORIENTATION SYSTEM IN AERIAL PHOTOGRAMMETRY

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ABSTRACT:

According to the principle of space intersection、collinearity equations and error propagation law, mathematical models of theoretical accuracy of direct georeferencing are proposed in this paper. The validity and feasibility of the mathematical models are tested using four sets of actual photos at different scales and terrains. Results indicate that accuracy of direct georeferencing based on space intersection is in relation to photographic scale and accuracy of exterior orientation elements, while accuracy of direct georeferencing based on collinearity equations is only in relation to projective scale, but both accuracies have not clear relation to terrain. Theoretical accuracy of direct georeferencing based on collinearity equations is better than that based on space intersection, but practical accuracy of both methods are same basically and different from theoretical accuracy. Practical accuracy of direct georeferencing using exterior orientation elements obtained by the POS directly can satisfy the requirements of aerial photogrammetric topographic mapping of corresponding scale.

1. INTRODUCTION

Aerial photogrammetry is one of the most important ways of data acquisition in producing topographical maps of national basic scale. Traditional aerial photogrammetry has obvious disadvantages: long produce cycle, inefficiency, depending on ground control points (GCPs) and so on. Thereby, about 1/5 areas of the western China have not basic topographical maps at present because those areas are inaccessible or lack of GCPs. This is quite disadvantageous to country economy development and development of the west regions (Li, 2005). Direct georeferencing without GCPs becomes possible along with global positioning system (GPS) and inertial measurement unit (IMU) being used in aerial photogrammetry(Wan, 2004). Furthermore, uses of large numbers of active sensors urge the use of direct georeferencing. Direct georeferencing without GCPs becomes the key means of orientation in aerial photogrammetry and has an expansive applied foreground. Accuracy research of direct georeferencing has gained more and more recognition. Experiments of direct georeferencing supported by position and orientation system(POS) has been organised by Europe Organization for Experimental Photogrammetric Research(OEEPE) in 1999, which provides a good guidance to the application of POS(Liu, 2004). Results show that the accuracy of direct georeferencing can't satisfy the requirements of large-scale topographical map in stereo mapping(Li, 2005). Therefore, effect of different errors on direct georeferencing are recalled in theory firstly. Afterwards, mathematical models of theoretical accuracy of direct georeferencing are proposed. Finally, actual data with different mapping scale and terrain are used to analyse the best accuracy direct georeferencing can reach and change rules of theoretical accuracy with change of terrain and mapping scale. The results in this paper provide theoretical bases to the use of direct georeferencing in aerial photogrammetry.

2. ERRORS ANALYSIS OF DIRECT GEOREFERENCING

Direct georeferencing is an orientation means which obtains coordinates of ground points directly using the known exterior orientation elements of photos(Li, 2005). According to the principle that same-name lights are intersectant conjugatedly, 3-D coordinates of ground object points can be computed by corresponding points in photos. So it does, it is sensitive to all kinds of errors(Jacobsen and Helge, 2004). Generally speaking, errors of direct georeferencing are from the following aspects:

2.1 Errors of Interior Orientation Elements

In aerial photogrammetry, interior orientation is determined in laboratories under constant and homogenous temperature conditions. Under actual flight conditions, focal length of camera will change with the temperature and atmospheric pressure(Jacobsen and Helge, 2004). Errors of elevation coordinates Z of object points caused by changing of focal length can't be neglected in direct georeferencing(Meier, 1978). If the calibration field is in actual flight field, it is not necessary to distinguish them because calibration of GPS shift can compensate the error of the focal length(Heipke, 2001). The error caused by the location of principal point is similar to the error of the focal length, which is irrespective to temperature(Meier, 1978).

2.2 Errors of Exterior Orientation Elements

In direct georeferencing supported by POS, exterior orientation elements of each photo are computed through Kalman filter of the observations got by GPS and IMU. The errors of GPS, time synchronization and projection centre deviation between GPS and aerial digital sensor, interpolation of GPS stations and transformation of coordinate system may cause error in linear elements of exterior orientation elements. In the same way, errors of attitude measurement in IMU body and boresight misalignments may also cause error in angle elements of exterior orientation elements (Jacobsen, 2002). Experiments show that the errors of object points caused by angular elements are larger than which caused by linear elements, and error of angular elements is the most important effect factor in direct georeferencing (Cramer and Stallman, 2002).

2.3 Errors of Photo Points Coordinates

There are a great number of factors in process of aerial photogrammetry: flex deformation of photo negative、lens distortion、refraction mistake of atmosphere、hypsography 、earth curvature and so on. These factors are systemic and affect all the photos similarly, so they can be compensated through models of systematic errors. However, there is random error of sub-pixel in the procedure measuring photo point coordinates because the algorithms of auto image correlation are limited.

In conclusion, errors of interior orientation elements, exterior orientation elements and image point coordinates will affect the accuracy of direct georeferencing. When the theoretical accuracy of direct georeferencing is discussed, all the errors should be considered. In order to discuss easily, the errors of exterior orientation elements and photo point coordinates are only detailed here.

3. THEORETICAL ACCURACY MODEL OF DIRECT GEOREFERENCING

3.1 Direct Georeferencing Based on Space Intersection

Space intersection is the most important direct orientation algorithm of stereo mapping in the aerial photogrammetry. Object space coordinates of each object point can be computed by the following formula(Zhang, 2003):

$$\begin{aligned} X &= X_{S_1} + N_1 X_1 \\ Y &= Y_{S_1} + N_1 Y_1 \\ Z &= Z_{S_1} + N_1 Z_1 \end{aligned} \qquad (1)$$

Where

X, Y, Z are object space coordinates of object point respectively;

$N_1 = \dfrac{B_X Z_2 - B_Z X_2}{X_1 Z_2 - Z_1 X_2}, N_2 = \dfrac{B_X Z_1 - B_Z X_1}{X_1 Z_2 - Z_1 X_2}$ are coefficients of point projection of left and right photo respectively;

$B_X = X_{S_2} - X_{S_1}, B_Y = Y_{S_2} - Y_{S_1}, B_Z = Z_{S_2} - Z_{S_1}$ are three components of base line in object space coordinate system respectively;

$X_{S_1}, Y_{S_1}, Z_{S_1}, X_{S_2}, Y_{S_2}, Z_{S_2}$ are the linear elements of exterior orientation elements of left and right image photos coordinates respectively;

$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = \boldsymbol{R}_1 \begin{bmatrix} x_1 \\ y_1 \\ -f \end{bmatrix}$ and $\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \boldsymbol{R}_2 \begin{bmatrix} x_2 \\ y_2 \\ -f \end{bmatrix}$ are spatial coordinate of left and right photo point respectively; $\boldsymbol{R}_1, \boldsymbol{R}_2$ are rotation matrixes composed by angular elements of exterior orientation elements of left and right photo respectively; x_1, y_1, x_2, y_2 are photo point coordinates of left and right photo points respectively; f is focal length.

Regarding exterior orientation elements and photo points coordinates as observations, computing differential coefficient of Eq.(1), then we can get the matrix as follows:

$$d\mathbf{C} = \mathbf{K} \cdot d\mathbf{O} \qquad (2)$$

Where

$d\boldsymbol{C}$ is correction vectors of object space coordinates of object points;

$d\boldsymbol{O}$ are correction vectors of unknowns;

$\boldsymbol{K}$ is matrix of differential coefficients. Their values are computed using exterior orientation elements and of photo point coordinates. Concrete expression form are shown in Eq.(3).

$$\begin{array}{lll}
\frac{\partial X}{\partial x_1} = -mN_1(Z_1 a_{11} - X_1 c_{11})X_2 & \frac{\partial Y}{\partial x_1} = -mN_1\{Y_1 Z_2 a_{11} - (X_1 Z_2 - Z_1 X_2)b_{11} - Y_1 X_2 c_{11}\} & \frac{\partial Z}{\partial x_1} = -mN_1(Z_1 a_{11} - X_1 c_{11})Z_2 \\
\frac{\partial X}{\partial y_1} = -mN_1(Z_1 a_{12} - X_1 c_{12})X_2 & \frac{\partial Y}{\partial y_1} = -mN_1\{Y_1 Z_2 a_{12} - (X_1 Z_2 - Z_1 X_2)b_{12} - Y_1 X_2 c_{12}\} & \frac{\partial Z}{\partial y_1} = -mN_1(Z_1 a_{12} - X_1 c_{12})Z_2 \\
\frac{\partial X}{\partial x_2} = mN_2(Z_2 a_{21} - X_2 c_{21})X_1 & \frac{\partial X}{\partial x_2} = mN_2(Y_1 Z_2 a_{21} - Y_1 X_2 c_{21}) & \frac{\partial X}{\partial x_2} = mN_2(Z_2 a_{21} - X_2 c_{21})Z_1 \\
\frac{\partial X}{\partial y_2} = mN_2(Z_2 a_{22} - X_2 c_{22})X_1 & \frac{\partial Y}{\partial y_2} = mN_2(Y_1 Z_2 a_{22} - Y_1 X_2 c_{22}) & \frac{\partial Z}{\partial y_2} = mN_2(Z_2 a_{22} - X_2 c_{22})Z_1 \\
\frac{\partial X}{\partial \varphi_1} = mN_1(X_1^2 + Z_1^2)X_2 & \frac{\partial Y}{\partial \varphi_1} = mN_1(X_1 X_2 + Z_1 Z_2)Y_1 & \frac{\partial Z}{\partial \varphi_1} = mN_1(X_1^2 + Z_1^2)Z_2 \\
\frac{\partial X}{\partial \omega_1} = mN_1(X_1 Y_1 \cos\varphi_1 + Y_1 Z_1 \sin\varphi_1)X_2 & \frac{\partial Y}{\partial \omega_1} = -mN_1\{(X_1 Z_1 Z_2 - Y_1^2 X_2 - Z_1^2 X_2)\cos\varphi_1 & \frac{\partial Z}{\partial \omega_1} = mN_1(X_1 Y_1 \cos\varphi_1 + Y_1 Z_1 \sin\varphi_1)Z_2 \\
 & \qquad + (X_1 Z_1 X_2 - X_1^2 Z_2 - Y_1^2 Z_2)\sin\varphi_1\} & \\
\frac{\partial X}{\partial \kappa_1} = mN_1\{X_1 Y_1 a_{13} - (X_1^2 + Z_1^2)b_{13} + Y_1 Z_1 c_{13}\}X_2 & \frac{\partial Y}{\partial \kappa_1} = -mN_1\{(X_1 Z_1 Z_2 - Y_1^2 X_2 - Z_1^2 X_2)a_{13} + (X_1 X_2 + Z_1 Z_2)Y_1 b_{13} & \frac{\partial Z}{\partial \kappa_1} = mN_1\{X_1 Y_1 a_{13} - (X_1^2 + Z_1^2)b_{13} + Y_1 Z_1 c_{13}\}Z_2 \\
 & \qquad + (X_1 Z_1 X_2 - X_1^2 Z_2 - Y_1^2 Z_2)c_{13}\} & \\
\frac{\partial X}{\partial X_{S1}} = -mZ_1 X_2 & \frac{\partial Y}{\partial X_{S1}} = -mY_1 Z_2 & \frac{\partial Z}{\partial X_{S1}} = -mZ_1 Z_2 \\
\frac{\partial X}{\partial Y_{S1}} = 0 & \frac{\partial Y}{\partial Y_{S1}} = 1 & \frac{\partial Z}{\partial Y_{S1}} = 0 \\
\frac{\partial X}{\partial Z_{S1}} = mX_1 X_2 & \frac{\partial Y}{\partial Z_{S1}} = mY_1 X_2 & \frac{\partial Z}{\partial Z_{S1}} = mX_1 Z_2 \\
\frac{\partial X}{\partial \varphi_2} = -mN_2(X_2^2 + Z_2^2)X_1 & \frac{\partial Y}{\partial \varphi_2} = -mN_2(X_2^2 + Z_2^2)Y_1 & \frac{\partial Z}{\partial \varphi_2} = -mN_2(X_2^2 + Z_2^2)Z_1 \\
\frac{\partial X}{\partial \omega_2} = -mN_2(X_2 Y_2 \cos\varphi_2 + Y_2 Z_2 \sin\varphi_2)X_1 & \frac{\partial Y}{\partial \omega_2} = -mN_2(X_2 Y_2 \cos\varphi_2 + Y_2 Z_2 \sin\varphi_2)Y_1 & \frac{\partial Z}{\partial \omega_2} = -mN_2(X_2 Y_2 \cos\varphi_2 + Y_2 Z_2 \sin\varphi_2)Z_1 \\
\frac{\partial X}{\partial \kappa_2} = -mN_2\{X_2 Y_2 a_{23} - (X_2^2 + Z_2^2)b_{23} + Y_2 Z_2 c_{23}\}X_1 & \frac{\partial Y}{\partial \kappa_2} = -mN_2\{X_2 Y_2 a_{23} - (X_2^2 + Z_2^2)b_{23} + Y_2 Z_2 c_{23}\}Y_1 & \frac{\partial Z}{\partial \kappa_2} = -mN_2\{X_2 Y_2 a_{23} - (X_2^2 + Z_2^2)b_{23} + Y_2 Z_2 c_{23}\}Z_1 \\
\frac{\partial X}{\partial X_{S2}} = mX_1 Z_2 & \frac{\partial Y}{\partial X_{S2}} = mY_1 Z_2 & \frac{\partial Z}{\partial X_{S2}} = mZ_1 Z_2 \\
\frac{\partial X}{\partial Y_{S2}} = 0 & \frac{\partial Y}{\partial Y_{S2}} = 0 & \frac{\partial Z}{\partial Y_{S2}} = 0 \\
\frac{\partial X}{\partial Z_{S2}} = -mX_1 X_2 & \frac{\partial Y}{\partial Z_{S2}} = -mY_1 X_2 & \frac{\partial Z}{\partial Z_{S2}} = -mZ_1 X_2
\end{array} \qquad (3)$$

According to covariance propagation law(Ge, 2005), co-factor matrix of object coordinate of direct georeferencing Q_{CC} can be obtained by co-factor matrix of point coordinates and exterior orientation elements $\boldsymbol{Q}_{OO}$:

$$\boldsymbol{Q}_{CC} = \boldsymbol{K}\boldsymbol{Q}_{OO}\boldsymbol{K}^{\mathrm{T}} \tag{4}$$

If there are *n* object points in a stereo pair, the total horizontal and vertical accuracy can be computed through the following formula:

$$\begin{aligned} m_{XY} &= \sigma_0 \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{XX}^{i} + Q_{YY}^{i})} \\ m_{Z} &= \sigma_0 \sqrt{\frac{1}{n}\sum_{i=1}^{n} Q_{ZZ}^{i}} \end{aligned} \tag{5}$$

Where

σ_0 is the root mean square error of unit weight, here is the measurement accuracy of photo point coordinates;

$Q_{XX}^{i}, Q_{YY}^{i}, Q_{ZZ}^{i}$ are the diagonal elements of co-factor matrix Q_{CC} of the *i*th object point.

If one object point is projected on *n* photos, the theoretical accuracy of object point in each stereo pair can be computed according to Eq. (5). Regarding the accuracy of each stereo pair as independent observation, the total theoretical accuracy of object point can be computed by error propagation law.

3.2 Direct Georeferencing Based on Collinearity Equations

If the positions of the projection centre and attitude information of the photo are known, the ground coordinates of object point can be computed by least squares adjustment according to the photo coordinates of the corresponding point in the stereo pair. The common formula of collinearity equations is(Zhang, 2003):

$$\begin{aligned} x &= -f\,\frac{a_1(X - X_S) + b_1(Y - Y_S) + c_1(Z - Z_S)}{a_3(X - X_S) + b_3(Y - Y_S) + c_3(Z - Z_S)} \\ y &= -f\,\frac{a_2(X - X_S) + b_2(Y - Y_S) + c_2(Z - Z_S)}{a_3(X - X_S) + b_3(Y - Y_S) + c_3(Z - Z_S)} \end{aligned} \tag{6}$$

Regarding the photo point coordinates as observations and regarding ground coordinates of object as unknowns, the error equations are obtained as follows:

$$\begin{aligned} v_x &= \frac{\partial x}{\partial X}\Delta X + \frac{\partial x}{\partial Y}\Delta Y + \frac{\partial x}{\partial Z}\Delta Z - (x - x^0) \\ v_y &= \frac{\partial y}{\partial X}\Delta X + \frac{\partial y}{\partial Y}\Delta Y + \frac{\partial y}{\partial Z}\Delta Z - (y - y^0) \end{aligned} \tag{7}$$

For any object point in a stereo pair, 4 error equations can be listed like Eq. (7), whereas there are just 3 unknowns, thereby, there is 1 redundant observation. So the ground coordinates *X*,*Y*,*Z* of object points can be computed according to least squares adjustment. The matrix type of error equations can be expressed by:

$$\boldsymbol{V} = \boldsymbol{AC} - \boldsymbol{L} \tag{8}$$

Where

C is the vector of ground coordinates of object points;
V is correction vector of photo point coordinates;
L is residual vector of photo point coordinates;
A is coefficient matrix.

In photogrammetry, theoretical accuracy of the unknowns can be computed by the covariance matrix $\mathrm{D}(\boldsymbol{C}) = \sigma_0^2\boldsymbol{Q}_{CC}$ obtained in the process of least square adjustment (Yuan, 2001). Generally, the theoretical accuracy of the *i*th unknown is expressed by:

$$m_i = \sigma_0\sqrt{Q_{CC}^{i}} \qquad (i = X, Y, Z) \tag{9}$$

Where

σ_0 isroot mean square error of unit weight observation;

Q_{CC}^{i} is diagonal element of co-factor matrix Q_{CC} of the *i*th ground object point.

If one object point is projected on *n* photos, 2*n* error equations can be obtained according to Eq. (7). Then, the ground coordinates *X*,*Y*,*Z* of object points can be computed by least squares adjustment and the theoretical accuracy can got by Eq. (9). If there are *n* object points in one stereo pair, the total horizontal and vertical theoretical accuracy of direct georeferencing can be computed by Eq. (5) too.

4. EXPERIMENTS AND RESULTS ANALYSIS

4.1 Introduction of Test Data

In this article, four sets of actual data taken from experimental projects which are different in terrain and photographic scale are selected and used to experiment. They were taken in Nov. of 2004,Jan. of 2005,Sep.and Oct. of 2005 respectively. Table 1 shows all the technical parameters of the experimental photos.

Item	Test 1	Test 2	Test 3	Test 4
Photo Negative	Kodak 2442	Kodak 2442	Kodak 2402	Kodak 2402
Focal Length (mm)	153.84	303.64	154.06	153.53
Frame (cm^2)	23 ×23	23 ×23	23 ×23	23 ×23
Photographic Scale	1:2500	1:3000	1:32000	1:60000
Longitudinal overlap	61%	63%	64%	64%
Lateral overlap	32%	33%	33%	30%
Number of Strips	9	10	8	4
Number of photos	255	377	160	48
Maximum terrain undulation (m)	38.60	181.81	729.28	107.50

Table 1. Technical data of the empirical photos

After all negatives are scanned with a resolution of *21μm* to digital images, the WuCAPS system is used for automatic point transfer. The corresponding image coordinates of all GCPs are measured manually in the stereoscopic mode. The root mean square error (RMSE) of all image coordinates is statistically better than ±6.0μm according to the results of the consecutive relative orientation with conditions for model connection and the function of gross errors eliminated by WuCAPS.

The GCPs are determined by combined static GPS net surveying, and the planimetric coordinates are transformed to the Xian geodetic coordinate system 1980 under Gauss-Kruger projection, while the elevation coordinate system takes national height data. The GCPs were measured by two surveying and mapping companies and the planimetry accuracy is better than ±0.1 mm on the map compared with national high-grade GCPs in two empirical blocks. In Tests 1 and 2, elevation is measured by a leveling survey, and the accuracy is higher than ±0.1 m. In Tests 3 and 4, elevation is measured by a GPS geoid fitting method with an accuracy better than ±0.5 m.

4.2 The Best Accuracy of Direct Georeferencing with the POS

In order to analyze whether the exterior orientation elements obtained by the POS can be used to stereo map in photogrammetry or not, the accuracy of image points coordinates are supposed to $\pm 6.0\mu m$ in this article. According to the analysis in front section, the best accuracy of direct georeferencing by the POS can be obtained through Eqs.(5) and (9) when accuracy of exterior orientation elements adopts $m_{Xs}=m_{Ys}=m_{Zs}=0.05\text{m}$, $m_{\varphi}=m_{\omega}=18'', m_{\kappa}=36''$. The best accuracy of direct georeferencing by the POS can be seen in Table 2.

	Orientation way	Theoretical accuracy (m)			
		X	*Y*	*XY*	*Z*
Test1	Space intersection	0.094	0.058	0.097	0.159
	Collinearity equations	0.039	0.037	0.054	0.057
Test2	Space Intersection	0.108	0.071	0.114	0.357
	Collinearity equations	0.057	0.055	0.079	0.177
Test3	Space Intersection	0.845	0.486	0.870	1.354
	Collinearity equations	0.324	0.289	0.434	0.668
Test4	Space Intersection	0.926	1.585	1.636	2.586
	Collinearity equations	1.058	0.878	1.375	2.256

Table 2. The best accuracy of direct georeferencing by POS

In Table 1, images in test 1 and test 2 can be used to produce 4D production at scale of 1:500~1:2000, images in test 3 can be used to produce 4D production at scale of 1:5000~1:10000 and images on test 4 can be used to produce 4D production at scale of 1:50000. It can be seen from Table 1 and Table 2 that:

1) The accuracy of direct georeferencing based on space intersection is lower than which based on collinearity equations. The reason is that spatial location of object point is computed by geometry intersect of two rays, so errors of image points coordinates and exterior orientation elements transfer to projection coefficient of points directly, and transfer to point location ultimately. On the other hand, there is one redundant observation condition when the corresponding points of left and right image in the stereo pair can satisfy the Eq. (6). It has a strong constraint conditions and collocates the errors of image points coordinates and exterior orientation elements obtained by POS properly, so the accuracy of direct georeferencing are improved a lot.

2) For test 1, accuracy of direct georeferencing can satisfy the requirement for flat topographic mapping at scale of 1:500 (GB 7930-87, 1998). For test 2, accuracy of direct georeferencing can satisfy the requirement for hill topographic mapping at scale of 1:500 (GB 7930-87, 1998). For test 3, accuracy of direct georeferencing can satisfy the requirement for hill topographic mapping at a scale of 1:5000 (GB/T 13990-92, 1993)For test 4, accuracy of direct georeferencing can satisfy the requirement for upland topographic mapping at scale of 1:50000 (GB 12340-90, 1998).

3) In conclusion, no matter what the terrain and mapping scale is, no matter what the way of orientation is, the exterior orientation elements obtained by a POS can be used to implement stereo mapping and the accuracy of the orientation results can satisfy the accuracy request of topographic mapping in theory.

4.3 Total Accuracy of Direct Georeferencing by POS

The theoretical accuracies of direct georeferencing based on space intersection and collinearity equations can be evaluated using the practical accuracy of exterior orientation elements obtained by the POS. Exterior orientation elements obtained by POS is measured directly in the process of photography, so the relativity among them are small and can be ignored. In addition, the image points and exterior orientation elements are measured separately, the relativity among them are ignored. According to the Eqs.(5) and (8), the total theoretical accuracy

	Orientation Way	Theoretical accuracy (m)				Practical accuracy (m)			
		X	*Y*	*XY*	*Z*	*X*	*Y*	*XY*	*Z*
Test1	Space Intersection	0.361	0.133	0.389	0.736	0.145	0.187	0.237	0.699
	Collinearity equations	0.039	0.037	0.054	0.057	0.095	0.179	0.203	0.689
Test2	Space Intersection	0.310	0.210	0.379	1.038	0.098	0.239	0.258	0.198
	Collinearity equations	0.057	0.055	0.079	0.177	0.076	0.201	0.215	0.173
Test3	Space Intersection	1.252	2.151	2.531	3.733	1.261	0.749	1.466	1.119
	Collinearity equations	0.324	0.289	0.434	0.668	0.887	0.705	1.134	1.217
Test4	Space Intersection	3.798	2.396	4.600	7.035	2.129	2.771	3.494	3.104
	Collinearity equations	1.058	0.878	1.375	2.256	1.280	2.386	2.708	2.261

Table 3. Total theoretical accuracy and practical accuracy of direct georeferencing

of ground points coordinates can be computed. Practical accuracy of ground coordinates can be obtained by differences between observations and computing values of ground points. The total theoretical accuracy and practical accuracy are displayed in Table 3.

The following conclusions can be taken from Table 3:

1) The theoretical accuracy of direct georeferencing based on space intersection depends on accuracy of exterior orientation elements, the higher the accuracy of exterior orientation elements is, the higher the accuracy of object points is, and vice versa; accuracy of direct georeferencing based on collinearity equations has not clear relation to accuracy of exterior orientation elements.

2) Although the accuracy of direct georeferencing based on collinearity equations is higher than that based on space intersection in theory, there is no material difference between these two orientation ways in practice. This fact reveals that errors of exterior orientation elements are effect factors on direct georeferencing, but they are not the only factor. Errors of image points coordinates and check points can’t be eliminated in direct georeferencing, so even the most rigorous orientation way like direct georeferencing based on collinearity equations can’t get good results, this fact incarnates the limitation of direct georeferencing.

4.4 Relations Analysis Between Accuracy of Direct Georeferencing by POS andTerrain Undulation

In order to research the relationship between accuracy of direct georeferencing by POS and hypsography, change curves of accuracy of direct georeferencing along with altitude difference are plotted in Figure.1. On the case of a single model, terrain of test 1 is flat, test 2 is flat and upland, test 3 is flat、upland、hill and mountain, test 4 is flat and upland.

In Figure.1, theoretical accuracies of direct georeferencing based on both space intersection and collinearity equations advance along with the augment of scale; theoretical accuracy of direct georeferencing fluctuates with the changing of direct of hypsography but has not obvious rules.

5. CONCLUSIONS

Based on space intersection and collinearity equations, theoretical accuracy models of direct georeferencing by exterior orientation elements are educed according to error propagation law. Four sets of actual data obtained by POS which are different in scale and terrain are used to test the theory provided in this paper. Results show that the theoretical accuracy of direct georeferencing based on space intersection is in relation to scale and accuracy of exterior orientation elements, while theoretical accuracy of direct georeferencing based on collinearity equations is in relation to scale only, but both have not clear relationship to terrain. Theoretical accuracy of direct georeferencing based on collinearity equations is better than which based on space intersection, but practical accuracy of both methods are same basically and different from theoretical accuracy. Practical accuracy of direct georeferencing of exterior orientation elements obtained by POS directly can reach to mapping accuracy request of corresponding scale. On the basis of results, the author suggests that ground object points can be made certain through direct georeferencing based on collinearity equations when exterior orientation elements obtained by POS system are used to stereo mapping, further more, all points in the test area may be computed together as possible as we can.

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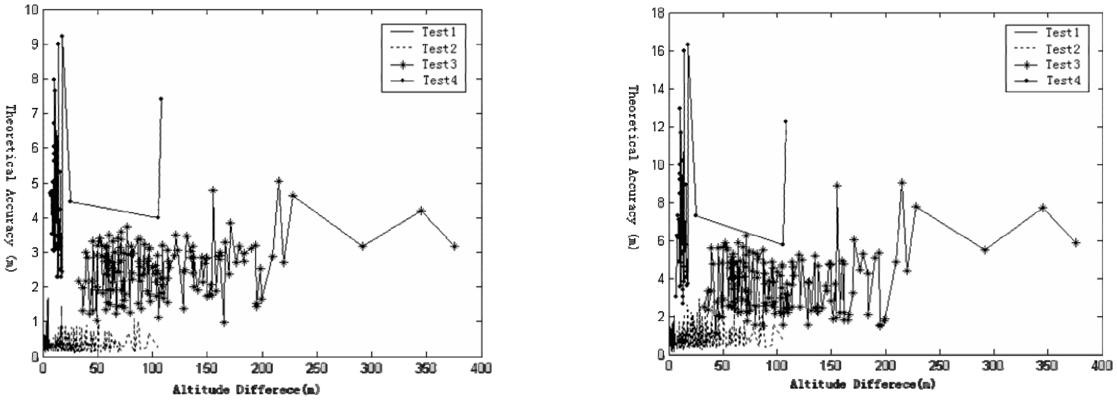
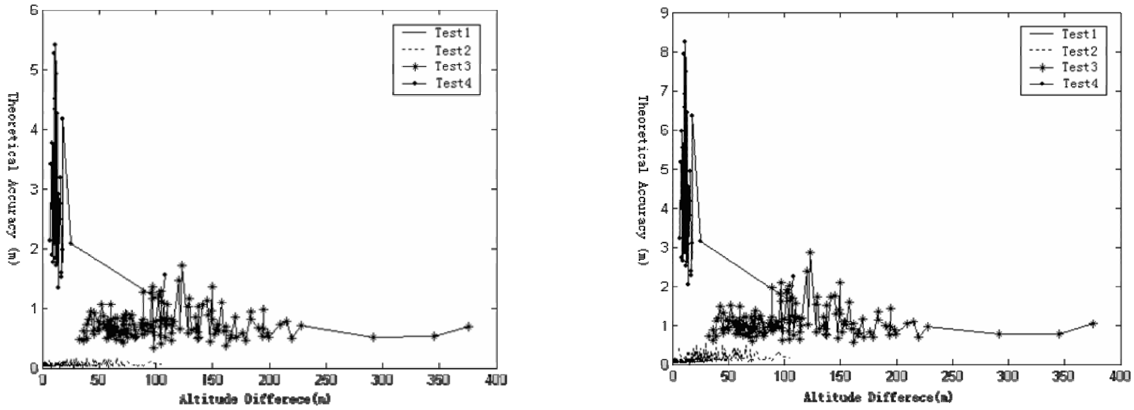


(a) Changing curves of horizontal theoretical accuracy of direct georeferencing based on space intersection with terrain undulation

(b) Changing curves of vertical theoretical accuracy of direct georeferencing based on space intersection with terrain undulation



(c) Changing curves of horizontal theoretical accuracy of direct georeferencing based on collinearity equations with terrain undulation

(d) Changing curves of vertical theoretical accuracy of direct georeferencing based on collinearity equations with terrain undulation

Figure1. Theoretical accuracy curves of direct georeferencing with terrain undulation

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