On Stereo Model Reconstitution in Aerial Photogrammetry

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Abstract  This paper describes the operational issues and basic technical requirements of modern aerial photogrammetry. The accuracy of photogrammetric point determination and the $y$-parallax at corresponding model points is analyzed when stereo models are reconstituted by using the exterior orientation elements of aerial images. Real aerial photographs, at image scales from 1:2 500 to 1:6 0000, with DGPS/IMU data taken from various topographies in China were processed by our POS-supported bundle block adjustment program WuCAPS. The empirical results verified that the accuracy of the exterior orientation elements from bundle block adjustment meets the requirements of the specifications of topographic mapping. However, the accuracy of the exterior orientation elements determined by POS fails to meet the requirements of the specifications of topographic mapping.

Keywords  aerial triangulation (AT); GPS (global positioning system); POS (position and orientation system); stereo model reconstitution; ground control points (GCPs); accuracy

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Introduction

Aerial photogrammetry is the science and technology for obtaining 3-dimensional spatial information about the Earth’s surface from aerial images. Photogrammetric point determination, which locates ground objects by using images, is the basis for object recognition in remote sensing. And the key point of this issue is the rapid and accurate determination of an image’s position and behavior at the instant of imaging. This goal was met by aerial triangulation based on well distributed GCPs.

With the development of spatial positioning technology, remote sensing technology, and computer science, aerial triangulation evolved and progressed towards digital mapping without GCPs. In the early 1950’s, photogrammetric scientists began studying how to utilize various auxiliary data to reduce the number of GCPs required. However, the methods haven’t become practical due to technological limitations[1]. Until 1970’s, with the emergence of American Global Positioning System (GPS), people got to adopt carrier phase differential GPS (DGPS) technology to determine an exposure station’s positions (that is three linear elements of aerial photos) during aerial photographic process, which was used to perform aerial triangulation (called GPS-supported AT for short) that can decrease photogrammetric reliance on GCPs, shorten the mapping cycle, and reduce...
production costs, triggering the revolution in the field of photogrammetry[2]. Nevertheless, GPS-supported AT is advantageous for aerial photogrammetric operation primarily over vast and difficult areas, at small and medium mapping scales, not for strip-like zone and urban large-scale mapping[3]. In the 1990s, people started to investigate employing GPS/INS integrated system (also called POS) to acquire a photo’s position and attitude (i.e., to obtain exposure station’s position by GPS, and images’ attitude elements by IMU), for the purpose of photo orientation, and the final goal is to replace block aero triangulation procedure[4-9].

Modern digital photogrammetry will play an important role in automated productions of 4D products (DEM, DOM, DLG, DRG) and updating of spatial databases. This paper will introduce current operational applications of aerial photogrammetry and related technical requirements, in particular, geometric positioning accuracy obtainable in the photogrammetric information chain from photo orientation to stereo-model reconstitution, aiming to investigate their practicability for 4D products production. It is hoped that findings from this study will provide guidance for operational aerial photogrammetry in the context of national land surveying, mapping, and fundamental geographic information acquisition.

1 Current patterns of the modern aerial photogrammetry

Nowadays, there are primarily three patterns for aerial photogrammetry, namely, standard aerial photogrammetry, GPS-supported aerial photogrammetry and POS-supported aerial photogrammetry. Their main procedures are shown as Fig.1.

![Fig.1 Flowchart of the modern aerial photogrammetry](image)

From Fig.1, we can learn that the main difference between these three patterns lies in the ways of aerial photo acquisition and photo orientation. For standard AT, it is through block aerotriangulation with a large number of GCPs to get a model orientation points’ coordinates to complete image orientation. For GPS-supported AT, in aerial photo acquisition process, dynamic GPS positioning is used instead of GCPs to determine the positions of exposure center and meanwhile obtain the model’s orientation points’ coordinates, which are then used to rectify the image’s orientation. For POS-supported AT, images and their corresponding orientation elements (six exterior orientation elements of images) are both acquired, in order to realize geometric inversion of photography by storing their spatial positions and attitude at the moment of exposure.

2 Related technologic requirements

2.1 Aerial photography

In modern aerial photography, in order to improve the quality of obtained images, besides adding flight control systems to aerial camera (such as ASCOT, CCNS4, Aerial TRACKER system), the methods include sticking a GPS receiver with the camera firmly when adopting GPS aerial photography and mounting POS system on the camera in DGPS/IMU aerial photography. According to the different patterns of aerial photography, we can formulate an answerable plan as
shown in Fig.2.

2.2 Ground control plan

In digital photogrammetry workstations, aerotriangulation is carried out by the most theoretically rigorous procedure of bundle block adjustment, but for the sake of obtaining the best pass points’ coordinates and the exterior orientation elements of photos, ground control plan should be designed, as shown in Fig.3, for different patterns of aerial photogrammetry.

![Fig.2 Patterns of the modern aerial photography](image)

![Fig.3 Distribution of GCPs in bundle block adjustment](image)

2.3 Digital mapping

Theoretically, after getting the accurate exterior orientation elements of images, measurable stereo models can be reconstructed using model restoration, by which we can do surveying and mapping of terrain and objects automatically. However, the current process of producing 4D product is: single photo interior orientation → relative orientation of stereo pair → single model absolute orientation → surveying and mapping on stereo models. The method of model restoration is only adopted in the direct georeferencing of POS-supported aerial photogrammetry.

3 Experiments and analysis

There are two ways of aerial photogrammetric positioning. One is called block aerotriangulation, regarding image points’ coordinates, GCPs’ coordinates and/or the exterior orientation elements of images as weighted observed values, and combined bundle block adjustment is performed to solve the images’ orientation parameters and target points’ spatial coordinates, so as to supply orientation control points for stereo model mapping and do highly accurate geometric positioning. For aerial photogrammetry of different scales and topographic types, topographic maps specifications for aerophotogrammetric office operation has defined respective aerotriangulation method, ground control plan, and also concrete standards for pass point accuracy. This method is established and widely used. The other is called direct georeferencing, under the supposition that highly accurate image elements of exterior orientation were available, space intersection is carried out to calculate corresponding object point’s object space coordinates by using photo coordinate system’s coordinates of conjugative image points in stereo pairs. This approach directly determines the object’s position, so 4D products can be produced. Then the paper will mainly discuss how well the positioning accuracy can be achieved and the stereo model Y-parallax when using image exterior orientation elements obtained in various ways.
3.1 Data

Experiments were implemented on 4 groups of actual images from different areas as shown in Table 1. All negatives were scanned with a resolution of 21 m, and in order to get the tie points, POS-supported bundle block adjustment software WuCAPS was used for images of test 1, test 2 and test 4, and homemade JX-4 digital photogrammetry workstation was used for images of test 3. The GCPs are all measured manually in the stereoscopic mode, and the accuracy (RMS) of all image points is statistically better than $\pm 6.0$ m according to the results of relative orientation modual with the function of gross error elimination by WuCAPS. After that, we use Applanix POS/AV system’s postprocess software POSPac\footnote{10} to do test field calibration and the integrated process of DGPS and IMU data, then by applying coordinate system transformation and system error rectification, six exterior orientation elements of each image, which were provided by the POS system, can be obtained.

| Table 1 | Parameters of images in experimental projects |
|---------|---------------------------------------------|
| Time    | test 1 | test 2 | test 3 | test 4 |
| Airplane| Yun-12 | Yun-12 | Yun-8  | Aviation-II |
| Camera  | Leica RC-30 | Leica RC-30 | Leica RC-30 | Leica RC-30 |
| Flight control system | Track Air | Track Air | CCNS 4 | CCNS 4 |
| POS system | POS AV 510 | POS AV 510 | POS AV 510 | POS AV 510 |
| Negatives | Kodak 2 444 | Kodak 2 044 | Kodak 2 402 | Kodak 2 402 |
| Principle distance /mm | 153.84 | 303.64 | 154.06 | 153.53 |
| Frame /cm×cm | 23×23 | 23×23 | 23×23 | 23×23 |
| Photographic scale | 1:2 500 | 1:3 000 | 1:32 000 | 1:60 000 |
| Forward overlap /% | 61 | 63 | 64 | 64 |
| Side overlap /% | 32 | 33 | 33 | 30 |
| Strip number | 9 | 10 | 9 | 4 |
| Control strips | 2 | 2 | 2 | 0 |
| Photos | 255 | 377 | 244 | 48 |
| GCPs | 73 | 160 | 34 | 29 |
| Densification points | 3 631 | 5 442 | 2 951 | 712 |
| Area /km×km | 4×5 | 5×8 | 47×52 | 40×57 |
| Maximum terrain undulation | 38.6 | 181.6 | 729.3 | 109.3 |
| /m (flat ground) | (mountain) | (high mountain) | (lowland) |
| GPS refresh rate /s | 2 | 0.5 | 1 | 1 |
| GPS initialize time /min | 10 | 10 | 5 | 5 |
| GPS static /min | 5 | 5 | 5 | 5 |
| GPS lever arm /m | 0.303, 0.110, -2.029 | 0.303, -0.110, -2.002 | -2.015, -0.030, 3.102 | 2.034, -0.520, 1.320 |
| IMU lever arm /m | 0.000, 0.200, -0.559 | 0.000, 0.200, -0.710 | 0.000, -0.201, 0.427 | -0.006, -0.202, 0.430 |

3.2 Performance of exterior orientation elements

In order to analyze the performance of exterior orientation elements obtained by different methods, standard AT with dense GCPs on the border and GPS-supported AT with four full GCPs in corners were firstly implemented, the six exterior orientation elements of each image can be obtained, and their theoretic accuracy can be estimated. Then we assumed the results of standard AT as the “truth” and estimated the performance of exterior orientation elements provided by POS. The results are shown in Table 2.

From Table 1, we see that the images of test 1, test 2 can be used for producing 4D product at the scale of 1:500~1:2 000, and images of test 4 for that at the scale of 1:5 000~1:10 000. In the principle of Topographic Maps Specifications for Aerophotogrammetric Office Operation\footnote{11-13}, test 1, test 2, test 3, and test 4 belong to flat land, mountain land, high mountain land, and lowland, respectively. From the results in
Table 2, some conclusions can be summed up as follows.

| Images method | \( \sigma_0 \) /µm | GCPs | Check Pts | RMS of check pts’ residual/m | Theoretical accuracy of EO |
|---------------|-----------------|------|-----------|-----------------------------|---------------------------|
| test 1 Std.   | 5.7             | 23   | 39        | 49 33                      | 0.09 0.06 0.104 0.079 0.028 0.030 0.019 12.1 13.1 4.4 |
| GPS           | 7.0             | 4    | 67 67     | 0.10 0.09 0.137 0.105 0.030 0.034 0.029 9.2 11.9 5.9 |
| POS           |                 |      |           | 0.123 0.112 0.104 0.079 0.028 0.030 0.019 12.1 13.1 4.4 |
| test 2 Std.   | 4.9             | 39   | 69 116 86 | 0.06 0.06 0.087 0.128 0.097 0.104 0.039 22.6 24.4 4.1 |
| GPS           | 6.7             | 4    | 151 151   | 0.10 0.10 0.143 0.153 0.080 0.138 0.068 21.3 25.8 12.1 |
| POS           |                 |      |           | 0.224 0.294 0.165 0.153 0.080 0.138 0.068 21.3 25.8 12.1 |
| test 3 GPS    | 7.6             | 4    | 30 30     | 0.74 0.76 1.061 0.503 0.203 0.240 0.232 9.7 10.9 9.9 |
| POS           |                 |      |           | 1.064 1.414 1.781 35.9 31.8 31.9 |
| test 4 Std.   | 7.6             | 15   | 19 10 14 13.0 12.9 1.830 1.454 0.920 0.946 0.675 18.8 18.5 6.9 |
| GPS           | 7.0             | 4    | 25 25     | 1.55 2.33 2.798 1.275 0.878 0.988 0.658 17.9 19.6 6.5 |
| POS           |                 |      |           | 1.324 2.849 2.817 61.8 57.1 67.3 |

Note: 1) Std., GPS and POS stand that the exterior orientation elements are obtained by the method of standard AT with dense GCPs on the border, GPS-supported AT with 4 full GCPs on the corners and POS system, respectively (same to the following tables).
2) Because the distribution of GCPs cannot meet the requirement of standard AT, for test 3 we cannot carry out the bundle block adjustment with dense GCPs on the border (same to the following tables).
3) RMS of check points’ residual is calculated from the error \( \Delta (i=X,Y,Z) \) between the adjusted coordinates and the ground measured coordinates of \( n \) check points, that is \( \mu_i = \sqrt{\sum \Delta^2 / n} ; \mu_{x,y,z} = \sqrt{\mu_i^2 + \mu_i^2} \).
4) Theoretical accuracy of EO is obtained from the unknown covariance matrix calculated according to the law of error propagation, \( m_i = \sigma_i \sqrt{\sum \Delta (i = X,Y,Z,\phi,\omega,\kappa)} \).

1) For test 1, densified points’ horizontal accuracy and vertical accuracy are better than 0.15 meter, totally meeting the accuracy requirement: 0.25 meter in planimetry and 0.30 meter in height\(^{[11]}\) of 1:500 Topographic Maps Specifications for Aerophotogrammetric Office Operation for flat land.
2) For test 2, densified points’ horizontal accuracy is better than 0.15 meter and vertical accuracy better than 0.20 meter, totally meeting the accuracy requirement: 0.35 meter in planimetry and 0.40 meter in height\(^{[11]}\) of 1:500 Topographic Maps Specifications for Aerophotogrammetric Office Operation for mountain land.
3) For test 3, densified points’ horizontal accuracy is better than 1.1 meters and vertical accuracy better than 1.0 meter, totally meeting the accuracy requirement: 2.5 meters in planimetry and 2.0 meters in height\(^{[12]}\) of 1:5 000 Topographic Maps Specifications for Aerophotogrammetric Office Operation for mountain land.
4) For test 4, densified points’ horizontal accuracy is better than 3.0 meters and vertical accuracy better than 1.5 meters, totally meeting the accuracy requirement: 17.5 meters in planimetry and 3.0 meters in height\(^{[13]}\) of 1:50000 Topographic Maps Specifications for Aerophotogrammetric Office Operation for high mountain land.

It can be seen from Table 2 that for the images of different land types at different scales, the densified points obtained from standard AT and GPS-support AT both satisfied the requirement of 4D product, and that the accuracy of exterior orientation elements obtained by these two methods are generally similar. The larger the photo scale is, the higher the accuracy of the photo’s linear elements we can get; but the accuracy of the photo’s angular elements has nothing to do with the photo scale but is related to the focal length of the camera, so the shorter the focal length is, the higher the photo’s angular elements accuracy is. Additionally, by comparing the data in Table 2, it can be found that the exterior orientation elements provided by POS system perform are worse than that of analytic aerotriangulation, and also obviously worse than the POS nominal accuracy \( m_x = m_y = m_z = 0.1 \text{m}, m_\phi = m_\omega = 18^\circ, m_\kappa = 36^\circ \).

### 3.3 Accuracy of direct georeferencing

Currently, 4D product commonly uses the densified points acquired by aerotriangulation as the model orientation points instead of reconstructing the stereo...
model directly from the image exterior orientation elements. So the accuracy requirement of exterior orientation elements is not defined in the current norm. Generally speaking, so long as enough densification points meet the error threshold limit for each model can we get, by performing absolute orientation, a measurable model which can be reconstructed. Then we can acquire satisfying spatial information. We analyzed the accuracy of direct georeferencing by using different exterior orientation elements, which is calculated by the approach that firstly employ forward intersection\cite{14}, by using the six exterior orientation elements with different accuracy obtained in the above section, to compute the ground coordinates, and calculate the RMS of ground coordinates of object points (seeing Table 3 for detail) by comparing the ground coordinates with those of most GCPs.

| Image | Method to acquire EO | Num of check points | Maximum discrepancy/m | Minimum discrepancy/m | RMS/m |
|-------|----------------------|---------------------|------------------------|------------------------|-------|
|       |                      |                     | X | Y | XY | Height | X | Y | XY | Height |
| test 1 | Std. | 188 | 0.18 | -0.25 | 0.295 | -0.276 | 0.00 | 0.00 | 0.009 | 0.000 | 0.08 | 0.07 | 0.107 | 0.081 |
|        | GPS  | 196 | -0.28 | -0.28 | 0.334 | 0.254 | 0.00 | 0.00 | 0.014 | -0.001 | 0.13 | 0.08 | 0.156 | 0.100 |
|        | POS  | 196 | -0.31 | 0.39 | 0.390 | 0.310 | 0.00 | 0.01 | 0.055 | 0.000 | 0.11 | 0.18 | 0.210 | 0.127 |
| test 2 | Std. | 412 | -0.22 | -0.14 | 0.222 | -0.317 | 0.00 | 0.00 | 0.007 | -0.001 | 0.06 | 0.05 | 0.083 | 0.121 |
|        | GPS  | 419 | -0.29 | 0.21 | 0.322 | -0.428 | 0.00 | 0.00 | 0.006 | 0.000 | 0.11 | 0.06 | 0.131 | 0.166 |
|        | POS  | 419 | 0.26 | -0.49 | 0.497 | 0.487 | 0.00 | 0.00 | 0.003 | 0.001 | 0.09 | 0.24 | 0.257 | 0.182 |
| test 3 | GPS  | 68  | 2.34 | 1.92 | 2.540 | -2.660 | 0.02 | 0.02 | 0.146 | -0.030 | 1.00 | 0.83 | 1.299 | 1.325 |
|        | POS  | 64  | -2.95 | -2.43 | 3.399 | 2.330 | -0.03 | 0.04 | 0.298 | 0.082 | 1.20 | 0.78 | 1.435 | 1.051 |
| test 4 | Std. | 46  | -3.63 | 3.01 | 3.884 | 4.374 | -0.03 | 0.05 | 0.174 | 0.028 | 1.40 | 1.33 | 1.930 | 1.880 |
|        | GPS  | 46  | 4.43 | 4.75 | 4.832 | 4.359 | 0.00 | 0.02 | 0.108 | 0.033 | 1.45 | 1.50 | 2.215 | 1.912 |
|        | POS  | 46  | 5.29 | 4.47 | 5.447 | 5.947 | -0.14 | -0.02 | 0.584 | -0.058 | 2.55 | 1.79 | 3.115 | 3.711 |

From Table 3, such conclusions can be summed up as follows:

1) For test 1, the horizontal accuracy of direct georeferencing is better than 0.25 meter and vertical accuracy better than 0.15 meter, which well meet the requirement specified in 1:500 flat land terrain mapping standards: 0.3 meter in plane and 0.2 meter in elevation\cite{11}.

2) For test 2, the horizontal accuracy of direct georeferencing is better than 0.3 meter and vertical accuracy better than 0.2 meter, which well meet the requirement specified in 1:500 mountain terrain mapping standards: 0.4 meter in plane and 0.5 meter in elevation\cite{11}.

3) For test 3, the horizontal and vertical accuracy of direct georeferencing are both better than 1.5 meters, which well meet the requirement specified in 1:5000 terrain mapping standards: 3.75 meters in plane and 2.5 meters in elevation\cite{12}.

4) For test 4, the horizontal accuracy of direct georeferencing is better than 3.15 meters and vertical accuracy better than 3.75 meters, which well meet the requirement specified in 1:50 000 downland terrain mapping standards: 25.0 meters in plane and 4.0 meters in elevation\cite{13}.

It can be learned from Table 3 that the aerotriangulation approach performs better than POS in obtaining exterior orientation elements when direct georeferencing is applied to images with different land types and scales. This result indicates that using the exterior orientation elements acquired by the aerotriangulation method to perform direct georeferencing can satisfy the accuracy standards of topographic surveying. So it can be deduced that so long as aerotriangulation meets the accuracy standards, the exterior orientation elements derived from that can be used absolutely for producing 4D product.

### 3.4 Y-Parallaxes in reconstituted stereo models

In the work of photogrammetry, another issue we should pay attention to is the feasibility of directly reconstructing the stereo model for terrain mapping with Y-parallaxes in the stereo image pair.
with exterior orientation elements used, that is Y-parallax of model point is not beyond 20 m\[^{11-13}\]. So three stereo pairs depicting different terrain types are chosen from four tests respectively to reconstruct stereo model using the obtained exterior orientation elements\[^{15}\], and Table 4 is the Y-parallax on stereo model’s corresponding points.

From Table 4, it can be seen that when using the exterior orientation elements obtained by the method of aerotriangulation to reconstruct stereo model, no matter what type of terrain is applied and how much the scale is, the model points’ maximum Y-parallax lies in one pixel and the RMS of that is below half a pixel, which satisfies the accuracy requirement of terrain mapping that vertical parallax’s RMS of each model should not be beyond 20 m. But when we use the exterior orientation elements provided by POS, the vertical parallaxes of each model point are all slightly larger, and the smaller the photo scale, the larger the vertical parallax, completely not meeting the requirement.

| Image | Model | Pts | Maximum height difference/m | Minimum Y-parallax/μm | RMS |
|-------|-------|-----|-----------------------------|----------------------|-----|
|       |       |     | Regular GPS POS Regular GPS POS Regular GPS POS |                     |     |
| test 1 | 282/281 | 23  | 0.57 14.2 16.2 | 17.7 -0.3 0.3 0.0 | 8.0 8.8 12.9 |
| 274/273 | 32  | 17.87 -11.2 14.5 -28.6 0.2 -0.3 -0.2 | 5.8 6.7 12.9 |
| 343/344 | 27  | 36.38 -13.1 15.7 38.1 0.2 -1.3 0.3 | 6.8 7.3 18.0 |
| test 2 | 14/13  | 26  | 26.41 -15.0 11.7 -31.2 -0.1 -0.1 -1.6 | 5.9 5.7 18.1 |
| 29/28  | 47  | 68.27 -10.9 -17.8 19.6 0.0 0.2 0.2 | 4.0 7.2 10.3 |
| 275/274 | 34  | 105.74 -14.3 16.1 -24.5 -0.3 0.7 -0.8 | 6.4 10.0 12.8 |
| test 3 | 1017/1018 | 31 | 26.00 18.7 44.9 -1.0 -4.8 | 10.0 22.9 |
| 1013/1014 | 22 | 91.60 17.5 35.6 -0.2 2.5 | 7.9 17.8 |
| 234/233 | 54  | 192.90 -18.0 36.2 -0.5 -0.9 | 8.2 12.9 |
| 238/237 | 23  | 375.76 17.0 49.2 0.1 0.0 | 8.1 17.7 |
| test 4 | 1076/1075 | 32 | 7.48 -18.7 19.1 -36.8 0.4 1.8 0.6 | 12.3 12.9 21.3 |
| 1115/1114 | 28 | 17.45 14.8 -17.2 -39.0 -0.2 -0.2 -1.3 | 6.9 7.3 22.0 |
| 1105/1104 | 28 | 109.55 11.6 12.9 -25.2 0.1 0.6 -1.0 | 6.5 6.3 14.0 |

4 Conclusion

It can be shown from the experiment that, if the elements of the exterior orientation obtained from aerotriangulation meet the accuracy standards, they can be used directly for image orientation and stereo model reconstitution. However, because of systematic errors in POS exterior orientation elements, it is currently difficult to meet the standards of photogrammetry, especially when extracting 3D spatial information. It was found that, in the time of digital photogrammetry, much work can be done automatically by computers, with the reliance on GCPs lessened gradually, thus simplifying operational photogrammetry. On the whole, standard AT, which is the most established and widely-used approach to obtain image orientation parameters, is still the main body of photogrammetry; GPS-supported AT is the easy-to-operate and low-cost method and corresponding standards have been drafted for it; POS direct georeferencing is one of the important cutting-edge techniques in photogrammetry. The basic spatial information acquisition should take advantage of this, and design good plans to gain maximum financial benefits. We propose that, for large-scale mapping of flat areas with good transportation, standard AT should be employed primarily; for difficult areas, non-charted areas or areas that are not accessible, GPS-support AT without GCPs can be adopted to acquire the basic spatial information for producing national base maps; POS photogrammetry can be used for the production
of orthophotos and update of 4D products in small regions. However, POS has a promising prospect in the field of large-scale urban mapping, LIDAR, and digital aerial photogrammetry. We should promote the integration technology of POS system and other sensors by undertaking large-scale experiments, thus providing technical support for economical and rapid gathering of geospatial information.

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