Determination of Shift/Bias in Digital Aerial Triangulation of UAV Imagery Sequences

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Abstract. Currently UAV Photogrammetry is characterized a largely automated and efficient data processing. Depicting from the low altitude more often gains on the meaning in the uses of applications as: cities mapping, corridor mapping, road and pipeline inspections or mapping of large areas e.g. forests. Additionally, high-resolution video image (HD and bigger) is more often use for depicting from the low altitude from one side it lets deliver a lot of details and characteristics of ground surfaces features, and from the other side is presenting new challenges in the data processing. Therefore, determination of elements of external orientation plays a substantial role the detail of Digital Terrain Models and artefact-free orthophoto generation. Parallel a research on the quality of acquired images from UAV and above the quality of products e.g. orthophotos are conducted. Despite so fast development UAV photogrammetry still exists the necessity of accomplishment Automatic Aerial Triangulation (AAT) on the basis of the observations GPS/INS and via ground control points. During low altitude photogrammetric flight, the approximate elements of external orientation registered by UAV are burdened with the influence of some shift/bias errors. In this article, methods of determination shift/bias error are presented. In the process of the digital aerial triangulation two solutions are applied. In the first method shift/bias error was determined together with the drift/bias error, elements of external orientation and coordinates of ground control points. In the second method shift/bias error was determined together with the elements of external orientation, coordinates of ground control points and drift/bias error equals 0. When two methods were compared the difference for shift/bias error is more than ±0.01 m for all terrain coordinates XYZ.

1. Introduction

Unmanned Aerial Vehicles (UAVs) equipped with compact digital cameras capable to acquisition images sequences or recording high-resolution video image (HD and bigger). They became an essential imagery tool from the low altitude. UAV photogrammetry became an interesting alternative for surveyors, constructions engineers and scientists worldwide [1]. The number of available solutions of the photogrammetry of the low altitude is growing rapidly. This progress is mainly caused by the development of UAV platforms, cameras installed on their board and the dedicated photogrammetric software [2]. Parallel a research on the quality of acquired images form UAV is being conducted [3] and above the quality of derived products e.g. orthophotos, [4]. Despite so fast development UAV photogrammetry still exists the necessity of accomplishment Automatic Aerial Triangulation (AAT) on the basis of the observations GPS/INS and ground control points. In Aerial Triangulation a network
of control and tie points is observed in photogrammetric block and each image’s orientation is estimated via bundle adjustment [5-9]. In case of classical aerial photogrammetry elements of the external orientation of every image that enters in the complement of block are determined at greater participation of supervision of integrated of GPS/IMU system and at the low number of ground control points. In UAV of photogrammetry in case of application of supervisions of one frequency absolute position and orientation of each image a substantial amount of ground control points measured in the field is required [10].

The approximate elements of external orientation are being delivered by GPS/IMU installed to usually burdened UAV biases in navigation data (e.g. indeterminacy of the phase) which can appear and very often are difficult to detect. It is their possible presence closely is connected with additional modelling - shift and drift parameters at ensuring the substantial amount of ground control points appropriately in the compensation [11].

2. Problem formulation
The use of unmanned aerial vehicle in photogrammetry enables to determinate elements of external orientation in the process of digital aerial triangulation. Elements of external orientation (6 parameters for each image) and ground control points coordinates are final products of digital aerial triangulation in the classical solution. The total number of determined digital aerial triangulation parameter equals, where: \( n_{\text{total}} \) - unknown number for digital aerial triangulation, \( n_{\text{image}} \) - number of images taken for on the needs of photogrammetric study, \( n_{\text{GCP}} \) - unknown number of ground control points coordinates.

Elements of external orientation are determined using 3 line parameters and 3 angular parameters, however ground control points parameters are determined using 3 line parameter . It is worthwhile paying attention to the fact, that the expanded mathematical model of digital aerial triangulation can also take into consideration the determination of shift and drift parameters. The shift/bias error determines translation of images in a single profile and it is constant parameter for digital aerial triangulation model. Therefore drift/bias error is variable parameter in digital aerial triangulation model and describes translation of external orientation for single image profile [4]. It should be noted, that number of appointed shift/bias and draft/bias parameters in digital aerial triangulation equals 6 for single image profile. Use of shift/bias and drift/bias errors models in digital aerial triangulation process influences mainly on precision and accuracy of determination of external orientation elements and the distribution of the residuals for the GPS observations. Moreover it is worth to add, that shift bias error values are greater than drift/bias parameters in digital aerial triangulation process.

The aim of the article is to present the methods for determination shift error in digital aerial triangulation process using image data from unmanned aerial vehicle. Two methods were used to determinate shift bias error value:

I) In first method shift/bias error was determined along with elements of external orientation drift bias error and ground control points coordinates,

II) In second method shift/bias error was determined along with elements of external orientation and ground control points coordinates where drift/bias error equals 0.

The experiment was conducted for block of 250 images sequences, taken by SONY Nex5R Trimble UX-5 Aerial Imaging Rover. Photogrammetric flight was conducted on 2015 in test area (small village) , whereas aligning of the block of images was carried out in the UASMaster software. The article was divided into five sections: introduction, mathematic model for determination shift error, experiment, results with discussion and conclusions.

3. Mathematical formula for designation shift/bias in aerial triangulation
Digital aerial triangulation enables to relation between the terrain coordinate frame of ground control points and system of a photogrammetric camera by terms of the, as below [12]:
\[
x_k - x_0 = -c_k \left[ \frac{r_{11}(X_T - X_{k'v}) + r_{21}(Y_T - Y_{k'v}) + r_{31}(Z_T - Z_{k'v})}{r_{13}(X_T - X_{k'v}) + r_{23}(Y_T - Y_{k'v}) + r_{33}(Z_T - Z_{k'v})} \right]
\]

\[
y_k - y_0 = -c_k \left[ \frac{r_{12}(X_T - X_{k'v}) + r_{22}(Y_T - Y_{k'v}) + r_{32}(Z_T - Z_{k'v})}{r_{13}(X_T - X_{k'v}) + r_{23}(Y_T - Y_{k'v}) + r_{33}(Z_T - Z_{k'v})} \right]
\]

(1)

where:
- \((x_k, y_k)\) - image coordinates,
- \((x_0, y_0)\) - principal point of image coordinates,
- \(c_k\) - focal length,
- \((X_T, Y_T, Z_T)\) - coordinates of ground control points in terrain frame,
- \((X_{k'v}, Y_{k'v}, Z_{k'v})\) - the coordinates of projection center, expressed in terrain frame,

\[
R = \begin{bmatrix}
    r_{11} & r_{12} & r_{13} \\
    r_{21} & r_{22} & r_{23} \\
    r_{31} & r_{32} & r_{33}
\end{bmatrix}
\]

- \(R\) - orthogonal matrix, matrix contains angular elements of external orientation, \(R = R(\omega, \varphi, \kappa)\),
- \((\omega, \varphi, \kappa)\) - angular elements of external orientation.

During the adjustment processing of GPS observations, expanded mathematical model of digital aerial triangulation can take into consideration shift/bias error and drift/bias error determination, as in equation below (2) [12], [13]:

\[
x_k - x_0 = -c_k \left[ \frac{r_{11}(X_T - X_{k'v}) + r_{21}(Y_T - Y_{k'v}) + r_{31}(Z_T - Z_{k'v})}{r_{13}(X_T - X_{k'v}) + r_{23}(Y_T - Y_{k'v}) + r_{33}(Z_T - Z_{k'v})} \right] + \delta_{shift} + (t - t_0) \cdot \delta_{drift}
\]

\[
y_k - y_0 = -c_k \left[ \frac{r_{12}(X_T - X_{k'v}) + r_{22}(Y_T - Y_{k'v}) + r_{32}(Z_T - Z_{k'v})}{r_{13}(X_T - X_{k'v}) + r_{23}(Y_T - Y_{k'v}) + r_{33}(Z_T - Z_{k'v})} \right] + \delta_{shift} + (t - t_0) \cdot \delta_{drift}
\]

(2)

or shift bias error only, as in equation (3):

\[
x_k - x_0 = -c_k \left[ \frac{r_{11}(X_T - X_{k'v}) + r_{21}(Y_T - Y_{k'v}) + r_{31}(Z_T - Z_{k'v})}{r_{13}(X_T - X_{k'v}) + r_{23}(Y_T - Y_{k'v}) + r_{33}(Z_T - Z_{k'v})} \right] + \delta_{shift}
\]

\[
y_k - y_0 = -c_k \left[ \frac{r_{12}(X_T - X_{k'v}) + r_{22}(Y_T - Y_{k'v}) + r_{32}(Z_T - Z_{k'v})}{r_{13}(X_T - X_{k'v}) + r_{23}(Y_T - Y_{k'v}) + r_{33}(Z_T - Z_{k'v})} \right] + \delta_{shift}
\]

(3)

where:
- \(\delta_{shift}\) - shift bias error,
- \(\delta_{shift} = [\delta x_{shift}; \delta y_{shift}; \delta z_{shift}]^T\).
\(\delta_{\text{drift}}\) - drift bias error,

\[
\delta_{\text{drift}} = \left[ \delta x_{\text{drift}} ; \delta y_{\text{drift}} ; \delta z_{\text{drift}} \right]^T,
\]

\(t\) - measuring epoch, describes the interval of time to take the image from one block,
\(t_0\) - beginning measuring epoch for take the photographs from one block.

Total number of unknown parameters in the expanded model of digital aerial triangulation determinate with equation (2) equals:

\[
n_{\text{total}} = 6 \times n_{\text{image}} + 3 \times n_{\text{GCP}} + 2 \times 3 \times n_{\text{Block}} \tag{4}
\]

or accurately based on equation (3):

\[
n_{\text{total}} = 6 \times n_{\text{image}} + 3 \times n_{\text{GCP}} + 3 \times n_{\text{Block}} \tag{5}
\]

where:

\(n_{\text{Block}}\) - number of image profiles.

Based on equation (2) number of unknown parameters for determination has been expanded by shift error and drift error, which number equals 3 for each images profile. However in equation (3) number of unknown parameters in digital aerial triangulation has been expanded by shift error only, assuming that drift/bias parameter equals 0 for whole developed profile.

4. Research experiment

The flight mission was conducted on test area in September 2015. Shooting conditions were good and average wind speed equals 3,4 m/s. The Trimble UX-5 equipped in SONY NEX-5R camera was used to obtain the data. The region of test area (small village), located 110 km to the north-west from Bydgoszcz in Poland was chosen as the site for the test area. The area covered 2.5 km² flat, partially wooded terrains and photogrammetric flight was conducted in the direction of the north - south. Tested block contains 250 images obtained from altitude 450 m, located in 9 profiles (see Fig. 1).

**Figure 1.** The geometry of adjustment block [6]
Final GSD pixel size for developed orthophotomap equals 0.14 m. The 16 signalised ground control points were calculated by GNSS RTK technique with accuracy about 0.03 m.

Aerial triangulation for block of low altitudes was conducted in UASMaster software based on the algorithm of equalization by the method of independent bundles. The tie points were generated in an automatic method based on algorithm of fitting by the area (Area Based Matching), fitting by the features (Feature Based Matching), also algorithm based on minimization of the function of the costs (Cost Based Matching).

Adjustments were made for operator measurement points on images after equalization and points were eliminated about the number of connections smaller than 3 for the purpose of the increase of the reliability of the network [4].

| Coordinate system       | PUWG 2000/5 |
|------------------------|-------------|
| Number of profiles     | 9           |
| Number of images       | 250         |
| Digital camera/ focal length [mm] | NEX 5 / 15.51 |
| Average overlap[\%]    | 75 / 75     |
| Altitude height [m]    | 450         |
| Number of GCPs         | 11          |
| Number of check points | 5           |
| GSD [m]                | 0.14        |
| A priori accuracy of coordinates of the projection center based on GPS/INS data | 10 m for each coordinate XYZ |
| A priori accuracy of ground control points coordinates | 0.014 m for horizontal coordinate, 0.043 m for vertical coordinate |

5. Results and discussion

Values of shift/bias error in extended digital aerial triangulation model were designated by use of the equations (2) and (3). In method from equations (2), shift/bias parameter was determined along with drift/bias error, elements of external orientation and ground control points coordinates. In case of research method from equations (3), shift/bias parameter was determined along with elements of external orientation and ground control points coordinates. One should be underline, in research method from equations (3) drift/bias error is constant and equals 0 for each profile of images. Results for shift/bias error in research method from equations (2) are marked with symbol (I), where in research method from equation (3) accordingly with symbol (II). The Table 2 presents results for shift bias parameter in both methods (I) and (II), with the regard number of the profiles and individual coordinate XYZ in the terrain frame.

In the case of X coordinate, values of shift/bias error in method I and II are positive in profile number 2, 6 and 9. The dispersion of positive results of shift bias error for X coordinate refers to profile number 2 and 8, and equals between 0.487 m and 1.259 for method I and 0.487 m to 1.256 for method II, respectively. Negative values of shift error for X coordinate are in profile number 1, 3, 4, 5 and 7. The dispersion of negative results of shift/bias error for X coordinate refers to profile number 7 and 5 and equals -0.587 m to -0.057 for method I and -0.589 m to -0.057 for method II respectively. Values of shift/bias error along Y axis are positive for all profile numbers based on method I and II. One
should underline, that the dispersion of shift/bias error results along Y axis is noted for profile number 5 and 8. Values of shift/bias error along Y axis equals 0.477 m to 3.085 m for method I and 0.474 m to 3.079 m in method II, respectively.

Table 2. The results of shift bias based on research method I and II

| Number of profile | Shift bias error for X coordinate [m] | Shift bias error for Y coordinate [m] | Shift bias error for Z coordinate [m] |
|-------------------|--------------------------------------|--------------------------------------|--------------------------------------|
|                   | Solution I | Solution II                           | Solution I | Solution II                           | Solution I | Solution II |
| 1                 | -0.163     | -0.164                                | 0.906      | 0.904                                 | 1.445      | 1.446       |
| 2                 | 0.487      | 0.487                                 | 1.810      | 1.807                                 | -0.855     | -0.854      |
| 3                 | -0.189     | -0.189                                | 1.576      | 1.573                                 | 0.718      | 0.721       |
| 4                 | -0.197     | -0.198                                | 1.375      | 1.372                                 | -2.262     | -2.260      |
| 5                 | -0.057     | -0.057                                | 0.477      | 0.474                                 | 0.577      | 0.580       |
| 6                 | 0.535      | 0.534                                 | 1.937      | 1.932                                 | -1.399     | -1.395      |
| 7                 | -0.587     | -0.589                                | 2.551      | 2.546                                 | 1.775      | 1.780       |
| 8                 | 1.259      | 1.256                                 | 3.085      | 3.079                                 | -1.861     | -1.857      |
| 9                 | 0.985      | 0.982                                 | 2.844      | 2.836                                 | 2.149      | 2.156       |

The difference of shift/bias error value for Y axis between profiles 5 and 8 equals 2.608 m in method I and 2.605 m for method II. Values of shift bias parameter for Z coordinate are positive for profile numbers 1, 3, 5, 7 and 9. The dispersion of positive results of shift/bias error for Z coordinate refers to profile number 5 and 9, and equals 0.577 m to 2.149 m for method I and 0.580 m to 2.156 m for method II, respectively. The difference for shift bias error value along Z axis between profiles 5 and 9 equals 1.572 m in method I and 1.576 m for method II. Negative values of shift bias error for Z axis are in profiles 2, 4, 6 and 8. The dispersion of negative results of shift/bias error for Z coordinate refers to profile number 2 and 4 and equals -2.262 m to -0.855 m for method I and 2.260 m to -0.854 m for method II, respectively. The difference of shift error value for Z axis between profiles 2 and 4 equals 1.407 m in method I and 1.406 m for method II, respectively.

Figure 2. Difference of shift/bias value for X axis

Figure 3. Difference of shift/bias value for Y axis
The Figures 2, 3 and 4 present difference of shift/bias error values based on I and II research methods. The difference of shift/bias error values for each coordinate axis was obtained, as below:

\[
\begin{align*}
\Delta \delta x_{\text{shift}} &= \delta x_{\text{shift}}^I - \delta x_{\text{shift}}^II \\
\Delta \delta y_{\text{shift}} &= \delta y_{\text{shift}}^I - \delta y_{\text{shift}}^II \\
\Delta \delta z_{\text{shift}} &= \delta z_{\text{shift}}^I - \delta z_{\text{shift}}^II
\end{align*}
\]  

(6)

where:

\((\delta x_{\text{shift}}^I, \delta y_{\text{shift}}^I, \delta z_{\text{shift}}^I)\) - the value of shift/bias error obtained in research method I (see Table 2),

\((\delta x_{\text{shift}}^II, \delta y_{\text{shift}}^II, \delta z_{\text{shift}}^II)\) - value of shift/bias error obtained in research method II (see Table 2).

Figure 4. Difference of shift bias value for Z axis

The parameter \(\Delta \delta x_{\text{shift}}\) equals 0.000 m to 0.003 m, with average value and median equal 0.001 m for whole image bundle. One should underline, that values of the \(\Delta \delta x_{\text{shift}}\) parameters for the profiles 2, 3 and 5 equals 0, and for profiles 1, 4, 6, 7, 8 and 9 are greater than 0. Values of \(\Delta \delta y_{\text{shift}}\), parameter for Y axis are positive for all blocks in worked out bundle of images. The average value for \(\Delta \delta y_{\text{shift}}\) parameter equals 0.004 m with range between 0.002 m and 0.008 m. Value of median for \(\Delta \delta y_{\text{shift}}\) parameter for Y axis is 0.004 m. It is necessary to mark, that values of \(\Delta \delta y_{\text{shift}}\) parameter are greater for research method I then for method II. Values of \(\Delta \delta y_{\text{shift}}\) parameter for Z axis for all blocks in worked out bundle of images. The average value for \(\Delta \delta z_{\text{shift}}\) parameter and statistical value of median equals -0.003 m for whole bundle of images. Moreover numerical range of results for \(\Delta \delta z_{\text{shift}}\) parameter equal between -0.007 m do -0.001 m. It is worthwhile paying attention, that values of \(\Delta \delta z_{\text{shift}}\) parameter are smaller for research method I than method II.

The characteristics of appointed values for shift bias error difference for each XYZ coordinates with using the linear trend, were presented into Figure 2, 3 and 4. Model of the linear regression was obtained, as below [14]:

\[R = a \cdot Q + b\]  

(7)

where:

\(R\) - difference of shift bias error value for each XYZ axis i.e. accordingly \((\Delta \delta x_{\text{shift}}, \Delta \delta y_{\text{shift}}, \Delta \delta z_{\text{shift}})\) parameters,

\((a,b)\) - determined linear factors,

\(Q\) - profile number.

Line parameters in equation (7) are determined separately for each parameters \((\Delta \delta x_{\text{shift}}, \Delta \delta y_{\text{shift}}, \Delta \delta z_{\text{shift}})\) with the use of the method of least squares. Apart from that, the parameter of standard deviation the determinant error of the fitting of the function of linear regression with regard to obtained values of the parameters are determined \((\Delta \delta x_{\text{shift}}, \Delta \delta y_{\text{shift}}, \Delta \delta z_{\text{shift}})\) , as below:
where:

\( m_0 = \sqrt{\frac{\sum v^2}{r-k}} \)  \hspace{1cm} (8)

where:

- \( m_0 \) - standard deviation appointed for the linear regression along each XYZ,
- \( v \) - residuals,
- \( v = a \cdot Q + b - R \),
- \( r \) - number of measuring, in this meaning profile line, \( r = 9 \),
- \( k \) - number of unknown parameters.

| Table 3. Characteristics of the coefficients of the linear regression |
|------------------|------------------|------------------|
| Parameter        | \( \Delta \delta_{x_{app}} \) | \( \Delta \delta_{y_{app}} \) | \( \Delta \delta_{z_{app}} \) |
| Value of coefficients | a = 0.00035 | a = 0.00065 | a = 0.00065 |
| Standard deviation [m] | b = -0.00053 | b = 0.00097 | b = 0.00008 |

Table 3 shows total comparison of value of certain linear factors \((a, b)\) and standard deviation parameter \(m_0\). The character of the results for the parameters changes \((\Delta \delta_{x_{shift}}, \Delta \delta_{y_{shift}})\) is positive, what is proved by value of line factor „a”, which is greater than 0. Moreover factor „b” is positive for parameter \(\Delta \delta_{y_{shift}}\) and negative for parameter \(\Delta \delta_{x_{shift}}\). Positive value of factor „b” testifies about, that increase of value \(\Delta \delta_{y_{shift}}\) parameter increase much faster than \(\Delta \delta_{x_{shift}}\) parameter. Values of „a” and „b” factors are negative for \(\Delta \delta_{z_{shift}}\) parameter, what cause the negative line regression trend for this factor. Moreover the error of the adjusting of linear regression with regard to the parameters \((\Delta \delta_{x_{shift}}, \Delta \delta_{y_{shift}}, \Delta \delta_{z_{shift}})\) is identical and equals about 0.001 m.

6. Conclusions

In this article, results of research relating to determination of shift error in the process of the digital aerial triangulation for images profile acquired from low altitudes by the unmanned aerial vehicle are presented. The image data from the Trimble UX-5 were used in this research experiment. Photogrammetric flight was conducted in September 2015 in test area. Digital aerial triangulation process was conducted in UASMaster software for block of 250 images sequences located in 9 profiles. Shift/bias error was determined in digital aerial triangulation process with two research methods:

I) shift/bias error was determined along with drift/bias error, elements of external orientation and ground control points coordinates in method I,

II) shift/bias error was determined along with elements of external orientation, ground control points coordinates and drift bias error equals 0 in method II.

Determined values of shift parameter along each axis XYZ for methods I and II were presented in this paper. The difference between results for shift parameter proposed in method I and II equals no more than ±0.01 m for each XYZ coordinates. Moreover linear regression model for determining the changes for differences of shift/bias parameter values for each XYZ axis was used in this article.

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