Airborne Direct Georeferencing of Frame Imagery: An Error Budget

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ABSTRACT

This paper presents an error analysis for the airborne direct georeferencing technique, where integrated GPS/IMU positioning and navigation systems are used in conjunction with aerial cameras for airborne mapping. The technical specifications for the Applanix POS/AV™ family of airborne positioning and attitude determination systems are used in this study. Two cases are discussed herein, namely the standard stereo model case and the single photo case.

The first example is based upon standard map production - where the aerotriangulation step is ultimately bypassed when using the direct exterior orientation information, measured by the POS/AV™ systems during image data acquisition. The second case is not as widely used, yet provides a more economical alternative. In this example, single photos are processed together with the available DEMs to produce orthorectified quads/images.

The effect of exterior orientation parameter accuracy on the ground point positioning accuracy is discussed in some detail. In addition to the theoretical analysis, an error breakdown is performed to an airborne set of data where the POS/AV™ 510 system was used to directly georeference or to aid the georeferencing of the aerial frame imagery.

Finally, a comparison between the theoretical and practical investigations is presented. The results show that the use of POS/AV enables a variety of mapping products to be generated from airborne navigation and imagery data using ground control only for Q/A purposes.

Key words: Direct Georeferencing, Photogrammetry, Multi-Sensor Systems, GPS/INS.
1. INTRODUCTION

Image direct georeferencing is one of the most important topics currently considered in the photogrammetric mapping industry. Ultimately, the aerotriangulation step can be bypassed when using direct measurements for the exterior orientation parameters of each single image at the moment of camera exposure. Direct georeferencing therefore enables a variety of mapping products to be generated from airborne navigation and imagery data with minimal ground control, mainly used for Q/A.

The achievable, on-the-ground accuracy, of direct georeferencing is studied theoretically for specific applications such as low-cost digital camera systems for small scale mapping (c.f., Mostafa and Schwarz, 1999); or for quality digital cameras used in large scale mapping (c.f., Grejner-Brzezinska, 2000). A number of practical studies were also done for performance analysis purposes (c.f., Cramer et al, 1997; Lechner and Lahmann, 1995; Mostafa et al, 1998; Reid et al, 1998; and Škaloud et al, 1996).

Each of the aforementioned authors studied a specific scenario that implied specific digital/film image acquisition sensor and different GPS/Inertial integrated system configuration. Although, it gives quite a wide background on the subject, the common ground in these studies is the concept, rather than the achievable results, when using standard equipment to apply such a model.

In this paper, a summary of the results of theoretical and practical investigations is presented. The objective for conducting such investigations is to analyze the effect of the exterior orientation parameter accuracy on the ground object positioning accuracy, using standard sensors such as the Applanix POS/AV™ systems and an aerial film camera with 9" x 9" format coupled to a 6" lens cone - such as that of the Zeiss or Leica products.

First, a summary of the theoretical error propagation results are presented. This is followed with an example of practical flight data. The presentation is therefore intended to show the typically achievable accuracies using theoretical and practical investigations and thus, the mathematical treatment is avoided.

2. THEORETICAL ANALYSIS

The standard error propagation technique is used to derive the ground object 3D positioning accuracy as a function of the exterior orientation parameter accuracy. Two cases are presented here.

In the first instance - referred to as The Single Photo Case – the result is a single directly georeferenced photo, that is used along with an available Digital Elevation Model (DEM). This produces an orthorectified image.

The second illustration - referred to as The Model Case - illustrates the typical photogrammetric photo stereo model that is used to do the mapping.
2.1. The Single Photo Case

The determination of ground object position using a single photo is currently done for two reasons. First, this approach makes use of the currently available quality DEMs - especially, those derived by LIDAR. Second, this approach provides a shorter turn-around-time to produce digital orthophotos - making use of the available POS/AV™ derived exterior orientation elements for each single photo.

In traditional photogrammetric mapping, the determination of the 3D position components of a ground object is done using photo stereopairs. This is executed in this way in order to compute the point-based scale factor, using the so-called 3D space intersection concept. However, if the scale factor is provided for each image point by an extra piece of measurement such as a laser range, processing a single photo would be faster and more cost-effective. The other possibility to process single photos is to use an available DEM of the mapped area.

In this model, the computation of the height component of the ground object 3D position is mainly driven by the DEM. Put another way, the image-based 3D space intersection is not needed anymore since the intersection occurs between image ray and the corresponding ground elevation.

To analyze the ground object positioning accuracy, a number of factors have to be considered. These factors are:

1. Exterior orientation accuracy;
2. Image coordinate measurement accuracy;
3. Calibration accuracy;
4. DEM accuracy.

The accuracy of the exterior orientation comes from post-processed accuracy specifications listed in Table 1 for the POS/AV™ 210, 310, 410, and 510, respectively. The POS/AV™ post-processed solutions are generated by the software package POSPac™. The GPS accuracy is assumed to be 0.10 m in the horizontal and 0.15 m in the vertical. Image coordinate measurement accuracy is taken as 5 µm.

The calibration of an integrated imaging/navigation system comes from the combination of individual sensor calibration and overall system calibration. The sensor calibration required for the camera is done in a lab environment, while the inertial sensor errors are calibrated in a closed-loop fashion using an optimal Kalman filter/smooother implemented by the POSPac™ package. The overall system calibration includes the antenna/camera/IMU lever arms and the IMU/camera boresight. In the investigations presented here, these are considered error-free. DEMs can typically be obtained from government organizations such as The US Geological Survey (USGS) or produced using LIDAR. In the simulation presented here, a 0.3 m, DEM accuracy derived by LIDAR, is assumed.
Figure 1 shows the horizontal accuracy (DRMS) of ground positioning for the family of POS/AV™ systems using different image scales. Note that the vertical axis of Figure 1 is logarithmic.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>POS/AV™ 210</th>
<th>POS/AV™ 310</th>
<th>POS/AV™ 410</th>
<th>POS/AV™ 510</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (m)</td>
<td>0.05 - 0.30</td>
<td>0.05 - 0.30</td>
<td>0.05 - 0.30</td>
<td>0.05 - 0.30</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Roll &amp; Pitch (Deg)</td>
<td>0.04</td>
<td>0.013</td>
<td>0.008</td>
<td>0.005</td>
</tr>
<tr>
<td>True Heading (Deg)</td>
<td>0.08</td>
<td>0.035</td>
<td>0.015</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Figure 1. Ground Horizontal Precision (DRMS) – The Single Photo Case
0.3 m DEM Accuracy, 6” Lens Cone

A more detailed insight into the effect of exterior orientation accuracy on ground positioning accuracy can be attained, by isolating the error contributions for the individual positioning and attitude components. Therefore, the exterior orientation parameters are divided into 5 components, namely horizontal positioning accuracy (GPS-Hal), vertical positioning accuracy (GPS-Val) and the three attitude angles, namely roll, pitch and yaw (which represent the aircraft roll, pitch and yaw, respectively). The effect of each of these components on the ground positioning precision ($S_Y$) in the Y-component (across track) for the POS/AV™ 510, is demonstrated in Figures 2, 3, 4, 5, and 6, for image scales 1: 3,600, 1: 7,200, 1: 14,400, 1: 28,800, and 1: 40,000, respectively.
Figure 2. Ground Accuracy for 1:3,600 Photo Scale Vs. 3D GPS Accuracy Using POS/AV™ 510

Figure 3. Ground Accuracy for 1:7,200 Photo Scale Vs. 3D GPS Accuracy Using POS/AV™ 510

Figure 4. Ground Accuracy for 1:14,400 Photo Scale Vs. 3D GPS Accuracy Using POS/AV™ 510

Figure 5. Ground Accuracy for 1:28,800 Photo Scale Vs. 3D GPS Accuracy Using POS/AV™ 510

Figure 6. Ground Accuracy for 1:40,000 Photo Scale Vs. 3D GPS Accuracy Using POS/AV™ 510

Note that the accuracy of ground objects is mainly affected by the GPS accuracy for larger photo scales. Conversely, it is the attitude accuracy that influences the accuracy on the ground for the smaller photo scale. Consequently, the deterioration of the ground positioning precision is more for larger photo scale than for smaller photo scales - especially when the GPS accuracy deteriorates.
If the GPS accuracy deteriorates from 0.05 m to 0.3 m, the ground object positioning precision is more affected for larger photo scales than for smaller photo scales. For example, Table 2 shows the ground point positioning accuracy deterioration factor for different photo scales. This factor is computed by dividing the ground object positioning accuracy corresponding to GPS accuracy of 0.3 m by that corresponding to GPS accuracy of 0.05 m. It is obvious that the larger the photo scale, the more dominant the effect of the GPS positioning accuracy on the ground precision.

<table>
<thead>
<tr>
<th>POS/A VTM 510</th>
<th>Image Scale</th>
<th>0.05 m (1Φ) GPS Accuracy</th>
<th>0.30 m (1Φ) GPS Accuracy</th>
<th>Across Track Ground Precision ((S_y))</th>
<th>Accuracy Deterioration Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:3,600</td>
<td>0.07</td>
<td>0.22</td>
<td></td>
<td>3.14</td>
<td></td>
</tr>
<tr>
<td>1:7,200</td>
<td>0.13</td>
<td>0.25</td>
<td></td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>1:14,400</td>
<td>0.25</td>
<td>0.33</td>
<td></td>
<td>1.32</td>
<td></td>
</tr>
<tr>
<td>1:28,800</td>
<td>0.5</td>
<td>0.54</td>
<td></td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>1:40,000</td>
<td>0.69</td>
<td>0.72</td>
<td></td>
<td>1.04</td>
<td></td>
</tr>
</tbody>
</table>

2.2. The Model Case

This case represents the classical ‘model set-up’ scenario - a pair of photos or digital frame images can be used to determine the 3D object point coordinates using the space intersection concept. Using POS/A VTM data, the aerotriangulation step is bypassed. This results in immediate map production from raw image data and post-processed POS/A VTM data. Such an approach significantly reduces the time and cost of the mapping process.

Using the standard error propagation technique, the effect of exterior orientation accuracy on ground positioning accuracy is studied. The same assumptions made in Section 2.1 are made here. Figure 7 shows the ground point accuracy in horizontal (DRMS) for different POS/A VTM systems and for different image scales. Figure 8 shows the ground point height accuracy for different POS/A VTM systems and for different image scales.
Figure 7. Ground Horizontal Accuracy (DRMS) - The Model Case - 6” Lens Cone

Figure 8. Ground Object Height Accuracy (RMS) - The Model Case - 6” Lens Cone

In the model case, the POS/AV™ 210 and POS/AV™ 310 satisfy the ground positioning accuracy for some applications. However, they may produce a non-satisfactory y-parallax in the model that would make stereovision more difficult than that when using a POS/AV™ 410 or POS/AV™ 510. This topic is the subject of an ongoing study at Applanix.
Note that the vertical accuracy at larger scales converges to the same value regardless of the model of the POS/AV™. This indicates that at the larger scales the vertical ground accuracy is limited by the GPS accuracy, not the angle accuracy. Hence when using direct georeferencing at larger scales it is absolutely critical that the proper mission planning and base station layout be used in order to ensure maximum possible accuracy in the GPS solution.

As previously mentioned, some calibration issues have not been considered in the theoretical study presented herein. Two calibration parameters are important, those being camera and boresight calibration. The former is the determination of the camera interior geometry (principal point offsets and focal length) as well as lens distortion parameters (which are calibrated in a lab). The latter is the orientation offset between the image coordinate system and the IMU coordinates system (which is done using a ground target field). Residual errors of these two calibration parameter sets are kept to a minimum by checking on a regular basis - especially the boresight.

3. ANALYSIS OF AIRBORNE DATA

In order to verify the theoretical error analysis presented in Section 2, an airborne data set provided by HJW of Oakland, California is presented here. It includes image data, precisely surveyed GCPs, POS/AV™510 GPS/IMU raw observables and a post-processed GPS-assisted aerotriangulation reference.

For this flight, the POS/AV™ 510 system was used, coupled with a Zeiss RMK Top camera. A 1:6000 scale, four-strip flight was flown with minimum banking angles (to avoid GPS cycle slips) and resulting in a block of 4 strips of 11 images each (a 44-image block). The flight lines were flown in opposite directions in order to achieve good boresight calibration. A total of 27 well-distributed GCPs were included in the block.

Using the POSPac™ post-processing package, a smoothed best estimate trajectory was produced. Then, using the POSEO™ package the interpolated camera exposure station position and image orientation angles, at the moment of each camera exposure, were extracted for each photo from the trajectory, coordinated in the US state-plane mapping frame.

The constant boresight angles between the camera and the IMU were removed so that the practical error analysis could be compared with the theoretical one presented in Section 2. This was done by processing the POS/AV™ derived position and orientation angles along with the image measurements in the POSBST™ software package. After removing the boresight angles, the camera station positions and image orientation produced independently by aerotriangulation were differenced with the exterior orientation generated by the POS/AV™510. The camera exposure station position differences are shown in Figure 9, while the image orientation angle differences are shown in Figure 10. Their statistics are shown in Table 3. The results are consistent with the POS/AV™ 510 system specifications listed in Table 1.
Figure 9. Camera Exposure Station Position Difference Between Aerotriangulation and POS/AV\textsuperscript{TM} 510

Figure 10. Camera Attitude Difference Between Aerotriangulation and POS/AV\textsuperscript{TM} 510
Table 3. The Difference between Aerotriangulation and POS/AV™510

<table>
<thead>
<tr>
<th>Stats.</th>
<th>dX (m)</th>
<th>dY (m)</th>
<th>dZ (m)</th>
<th>dOmega (ArcSec)</th>
<th>dPhi (ArcSec)</th>
<th>dKappa (ArcSec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.064</td>
<td>-0.029</td>
<td>-0.034</td>
<td>-39.2</td>
<td>-22.7</td>
<td>-68</td>
</tr>
<tr>
<td>Max</td>
<td>0.040</td>
<td>0.031</td>
<td>0.070</td>
<td>33.1</td>
<td>25.2</td>
<td>61</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.004</td>
<td>0.000</td>
<td>0.000</td>
<td>-1.4</td>
<td>-0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.026</td>
<td>0.017</td>
<td>0.023</td>
<td>19.1</td>
<td>11.9</td>
<td>33.1</td>
</tr>
<tr>
<td>RMS</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>19.2</td>
<td>11.9</td>
<td>33.1</td>
</tr>
</tbody>
</table>

To determine the absolute ground accuracy of the direct georeferencing approach using POS/AV™ exterior orientation without GCPs, 36 models were processed individually using only one image point (with known ground coordinates) per model. In each model, the exterior orientation data derived by POS/AV™ were used, along with the image point coordinates on both model photos, to determine the conjugate ground point position using the space intersection concept. The determined ground coordinates were then compared to the reference land-surveyed values. The checkpoint residuals are shown in Figure 11, while their statistics are depicted in Table 4. It is obvious from the checkpoint residuals that the accuracy of direct georeferencing using POS/AV™ 510 is consistent with the theoretical accuracy presented in Figures 7 and 8 for the model case, thus validating the analysis.

Table 4. Statistics of Checkpoint Residuals

<table>
<thead>
<tr>
<th>Stats.</th>
<th>East (m)</th>
<th>North (m)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.19</td>
<td>-0.08</td>
<td>-0.24</td>
</tr>
<tr>
<td>Max</td>
<td>0.18</td>
<td>0.14</td>
<td>0.36</td>
</tr>
<tr>
<td>Mean</td>
<td>0.02</td>
<td>0.01</td>
<td>0.09</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.07</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>RMS</td>
<td>0.08</td>
<td>0.05</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Figure 11. Check Point Residuals Derived Using Individual Models
SUMMARY AND OUTLOOK

In this paper both a theoretical and practical error analysis were presented.

The main objective of the theoretical error analysis is to extrapolate the POS/AV\textsuperscript{TM} system accuracy capabilities in the mapping industry, under variable conditions, for the different POS\textsuperscript{TM} systems and for different image scales. The airborne data error analysis was used to verify the theoretical one.

Hence, the theoretical accuracy plots presented herein can be used as guidelines for designing a multi-sensor system for data acquisition. However it should be noted that additional error sources such as boresight and camera calibration will degrade the overall integrated system accuracy. Since overall integrated system calibration and individual sensor calibration are very important in the direct georeferencing approach, the effect of residual calibration errors is currently under investigation.

ACKNOWLEDGMENT

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REFERENCES


**BIOGRAPHICAL NOTES**

Mohamed Mostafa is responsible for R&D in Airborne Applications at Applanix. He obtained a Ph.D. in Geomatics Engineering from The University of Calgary in 1999. His research interests are in the field of kinematic geodesy and digital photogrammetry.

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Erik Lithopoulos obtained a Master of Applied Science in Electrical Engineering from the University of Toronto in 1981. He is responsible for exploring and developing new markets for Applanix’s GPS/Inertial products and technology. He has been with the company since 1991 as Manager of Business Development.