TRIANGULATION OF LH SYSTEMS' ADS40 IMAGERY USING ORIMA GPS/IMU

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ABSTRACT:

The paper describes the mathematical model used for the triangulation of the ADS40. The ADS40 Airborne Digital Sensor is LH Systems' multi-line scanner (Röser, 2000; Sandau, 2000). It is based on the push broom principle and therefore requires more complex mathematical modelling than the collinearity equations used in classical bundle triangulation. Particularly significant is the use of high precision GPS and Inertial Measuring Unit (IMU) technologies, which constrain the bundle adjustment process.

KURZFASSUNG:

Der Artikel stellt das mathematische Modell vor, welches bei der Triangulation von ADS40 Aufnahmen benutzt wird. Der ADS40 Airborne Digital Sensor ist LH Systems' Multi-Zeilen Scanner (Röser, 2000; Sandau, 2000). Er basiert auf dem Push Broom Prinzip und erfordert daher ein komplexeres mathematisches Modell als es durch die klassische Kollinearitätsgleichung der Bündelausgleichung bekannt ist. Von spezieller Bedeutung ist die Benutzung von hochgenauen GPS Positions- und Inertial Winkelmessungen, welche als gewichtete Beobachtungen in die kombinierte Ausgleichung einfließen.

1. INTRODUCTION

ORIMA, LH Systems' orientation management software, manages all aspects for triangulation on analytical plotters and digital workstations. It has been extended to handle the special requirements for the new multi-line sensor ADS40. The ADS40 is a push broom scanner and therefore the triangulation software must use another sensor model than that used for frame photography. The whole workflow of the triangulation process using the ADS40 is fairly different compared to the conventional workflow for frame photography. Triangulation is only one step in the total data processing chain from the sensor to the final product: all processing steps are described by Tempelmann (2000). The overall process includes GPS/IMU data processing and image rectification. These important steps have to be performed prior to the triangulation.

1.1 Motivation for Triangulation with ADS40

The ADS40 is equipped with a GPS/IMU system. This is used to record the motion of the sensor during the flight. The specifications of this system are such that the resultant orientation is suited for certain types of products, but may not meet accuracy requirements for more accurate mapping applications. To obtain the highest possible accuracy plus additional reliability a triangulation is required. The triangulation is further used to calibrate certain system parameters and in combination with control points leads to the best fit to the ground system.

1.2 Essential Pre-Processing before the Triangulation

The GPS/IMU data is first processed in a way that six orientation parameters for each sensor line are given in a local Cartesian co-ordinate system. The CORE module of the SOCET SET®[1] digital workstation software takes care of transformations between the local Cartesian system and the final mapping system. To be able to use SOCET SET's® automatic tie point matching software, the original scenes, which are denoted as Level 0, are rectified to Level 1. This rectification is based on the orientation values that are obtained by the GPS/IMU post processing software. The distortion in the scenes of Level 0, caused by the motion of the sensor, are removed by this rectification and the scenes of Level 1 can be viewed stereoscopically.

Although the scenes used for triangulation are rectified to Level 1 the tie points measured are referred directly to the original Level 0 image. The orientation parameters to be updated by the bundle adjustment will also refer to the orientation of the sensor lines at Level 0. The SOCET SET® ADS40 sensor model is designed in a way that the transformations between Level 0 and Level 1 are performed in real-time.

1.3 Post-Processing after the Triangulation

Once the orientation parameters are updated by the bundle adjustment, the user can proceed with subsequent data extraction tasks using the Level 1 rectified data. This can include feature extraction, DTM extraction, orthophoto production, etc. Optionally, the user can create orthorectified imagery from the raw level 0 imagery. Precisely orthorectified images are referred to as Level 2 images.

[1] SOCET SET is a registered trademark of BAE Systems Mission Solutions Inc.

2. BASIC PRINCIPLES

2.1 Push broom Principle

For triangulation a push broom scanner must have three sensor lines in the focal plane. They are mounted in such a way that one is looking forward, one is looking backward and one is looking in the nadir direction. The distance between the forward and the nadir line and the distance between the backward and the nadir line need not be equal. For the ADS40 the forward and backward views use different angles. The scan of each line is called a scene. The scene of a sensor line is similar to a digital image of a frame sensor.

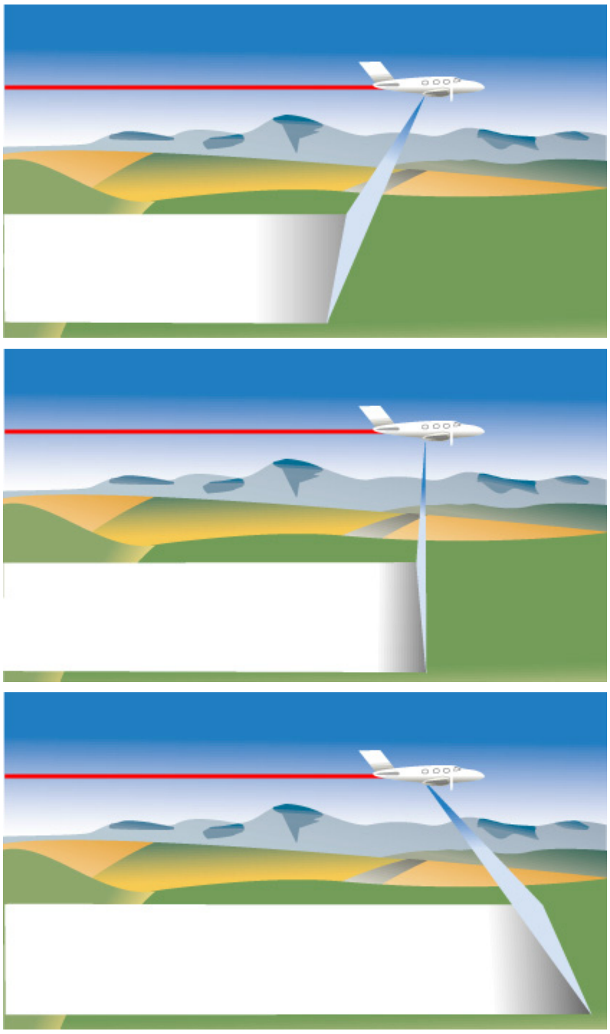


Figure 1: Backward, nadir and forward scenes.

A scene differs from a frame photograph in the way that it is scanned continuously rather than taken at a nearly discrete position. All scenes are scanned synchronously.

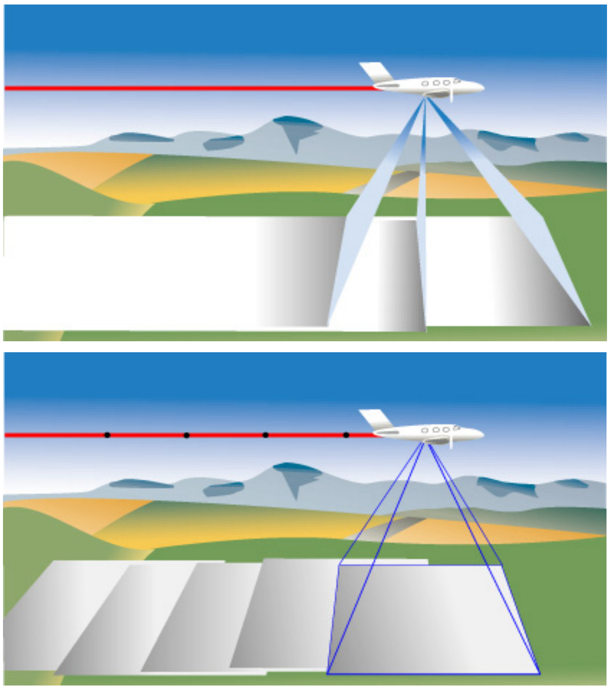


Figure 2: Continuous scan of three scenes compared to discrete photos of a frame sensor.

2.2 Measuring Tie Points in Scenes

To measure homologous points in the scenes the corresponding line and sample must be found. The matching process is very similar to current matching processes. Owing to the complexity of raw aircraft motion in the Level 0 scenes, it is convenient to perform matching on the Level 1 rectified scenes.

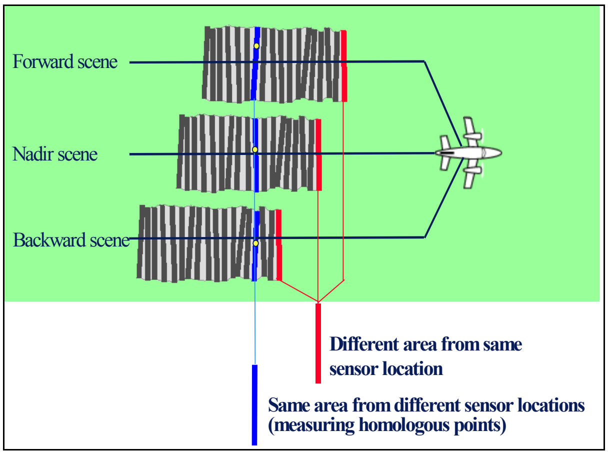


Figure 3: Measuring homologous points in three scenes.

2.3 Orientation Fixes

The GPS and IMU data, which is measured at high rates during image acquisition, yields a continuous position and attitude of the ADS40. During the triangulation process, we want to update this continuous stream of data based on the principles of least squares bundle adjustment. In this case we are using "orientation fixes" at regular intervals along the flight path of the push broom scanner.

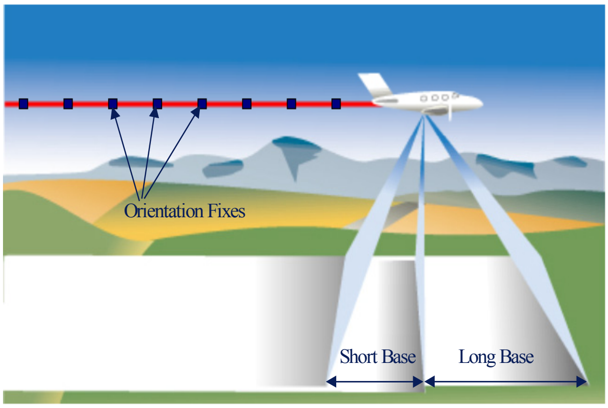


Figure 4: Definition of orientation fixes and short and long base.

Orientation fixes are characterized by:

- An orientation fix is the orientation of the sensor at a certain time
- Geometrically best conditions are obtained when the distance between two fixes equals the short base
- The time interval between two fixes depends on the gyro (IMU) quality
- The six orientation parameters for each fix are updated by the triangulation process; each fix is identified by the unique time
- One scene (image) has multiple orientation fixes

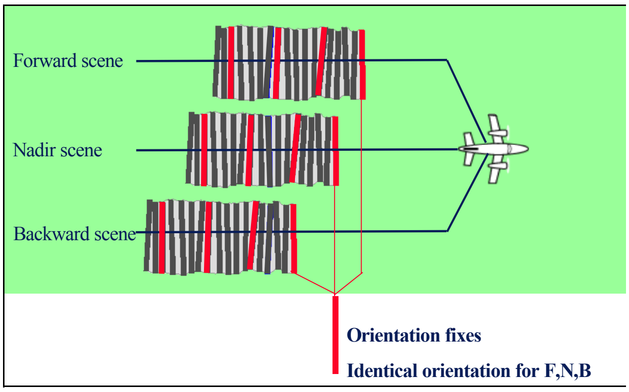


Figure 5: Orientation fixes at predefined fixed intervals.

3. THE MATHEMATICAL MODEL

3.1 Ground to Sensor Transformation

The mathematical model describes the transformation of a point from the ground system to the orientation fixes.

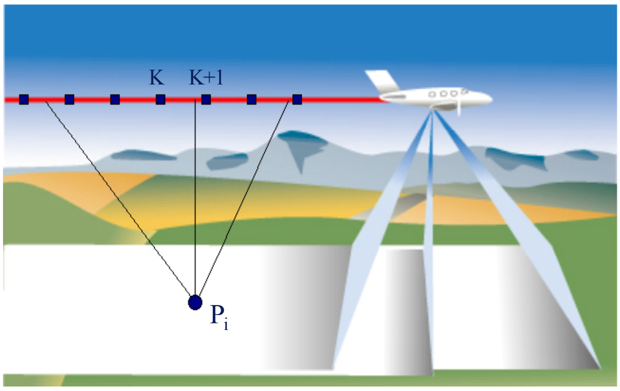


Figure 6: Point projection between orientation fixes.

The ground to sensor transformation is characterized by:

- Points can be measured at any location
- Each projected point falls in between two orientation fixes
- The transformation from ground to sensor is expressed as a function of the two neighbouring orientation fixes

The image coordinates are expressed as a function of the ground point (**P**$_i$) and the orientation parameters of the two neighbouring orientation fixes (k) and (k+1). The mathematical model is given in full detail by Müller (1991).

$$x_{ij} = F_{ij}(X_i, Y_i, Z_i, X_k, Y_k, Z_k, \omega_k, \varphi_k, \kappa_k, \\ X_{k+1}, Y_{k+1}, Z_{k+1}, \omega_{k+1}, \varphi_{k+1}, \kappa_{k+1}) \qquad (1)$$

$$y_{ij} = G_{ij}(X_i, Y_i, Z_i, X_k, Y_k, Z_k, \omega_k, \varphi_k, \kappa_k, \\ X_{k+1}, Y_{k+1}, Z_{k+1}, \omega_{k+1}, \varphi_{k+1}, \kappa_{k+1}) \qquad (2)$$

The orientation parameters ($X_j..\kappa_j$) are computed from their neighboring orientation fixes plus a correction term ($\delta X_j..\delta\kappa_j$)derived from the GPS/IMU observations. The interpolation coefficients (c_j) are a function of the time differences from the neighboring orientation fixes. The basics of this mathematical model go back to Otto Hofmann (Hofmann, 1982)

$$\boxed{\begin{aligned} X_j &= c_j X_k + (1-c_j) X_{k+1} - \delta X_j \\ &\dots \\ \kappa_j &= c_j \kappa_k + (1-c_j)\kappa_{k+1} - \delta\kappa_j \end{aligned}} \qquad (3)$$

$$c_j = \frac{t_{k+1} - t_j}{t_{k+1} - t_k} \qquad (4)$$

$$\begin{aligned} \delta X_j &= c_j X_k^{GPS} + (1-c_j) X_{k+1}^{GPS} - X_j^{GPS} \\ &.... \\ \delta\kappa_j &= c_j \kappa_k^{IMU} + (1-c_j)\kappa_{k+1}^{IMU} - \kappa_j^{IMU} \end{aligned} \qquad (5)$$

Finally the orientation parameters ($X_j..\kappa_j$) are introduced into the well known collinearity equations to transform the point from the ground system to the sensor system.

$$\begin{bmatrix} x_{ij} \\ y_{ij} \\ -f \end{bmatrix} = \lambda_{ij}\mathbf{R}(\omega,\varphi,\kappa)_j \begin{bmatrix} X_i - X_j \\ Y_i - Y_j \\ Z_i - Z_j \end{bmatrix} \tag{6}$$

By dividing equations one and two by equation three in (6) above, the unknown scale λ_{ij} cancels out. These equations are the collinearity equations as used for frame sensors.

$$x_{ij} = -f\,\frac{r_{11_j}(X_i - X_j) + r_{12_j}(Y_i - Y_j) + r_{13_j}(Z_i - Z_j)}{r_{31_j}(X_i - X_j) + r_{32_j}(Y_i - Y_j) + r_{33_j}(Z_i - Z_j)} \tag{7}$$

$$y_{ij} = -f\,\frac{r_{21_j}(X_i - X_j) + r_{22_j}(Y_i - Y_j) + r_{23_j}(Z_i - Z_j)}{r_{31_j}(X_i - X_j) + r_{32_j}(Y_i - Y_j) + r_{33_j}(Z_i - Z_j)} \tag{8}$$

The mathematical model used is very flexible. In areas without sufficient measurements of tie points, e.g. lakes or forests, the orientation parameters are primarily or exclusively determined by the GPS/IMU measurements. On the other hand, if GPS/IMU data cannot be used or is not available, the orientation can be determined by tie point measurements only. In the latter case the definition of the orientation fixes interval and the tie point distribution must be chosen very carefully to avoid known singularities of the mathematical model, as they are described in the analysis of Müller (1991).
The figure below illustrates graphically the relation between the orientation parameters, the orientation fixes and the GPS/IMU observations.

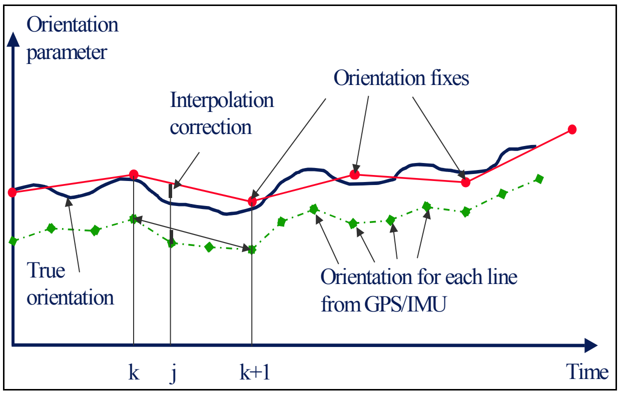


Figure 7: Example of one orientation parameter over time.

Typically, the GPS/IMU sensors will have a systematic offset to the actual sensor head. This systematic offset between the true orientation and the GPS/IMU observations is compensated and computed by additional parameters within the self-calibration process of the triangulation.

After the adjustment, the orientation of the GPS/IMU is updated by piecewise interpolation from the orientation fixes, which were computed in the bundle adjustment.

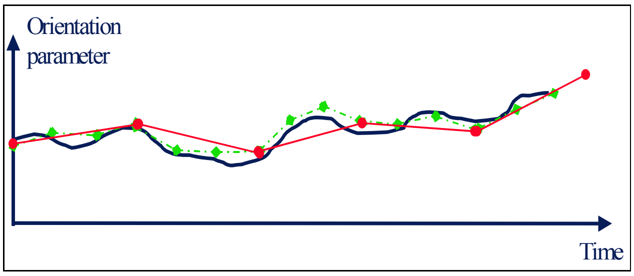
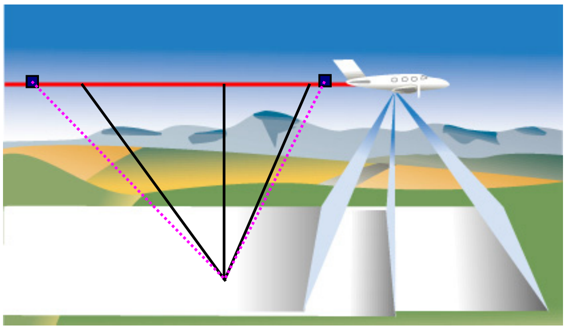


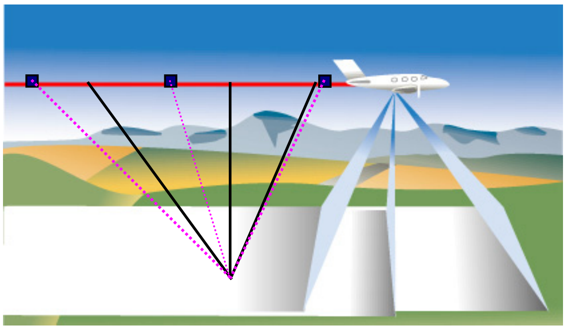
Figure 8: Precise orientation for each line of Level 0.

3.2 Spacing of Orientation Fixes

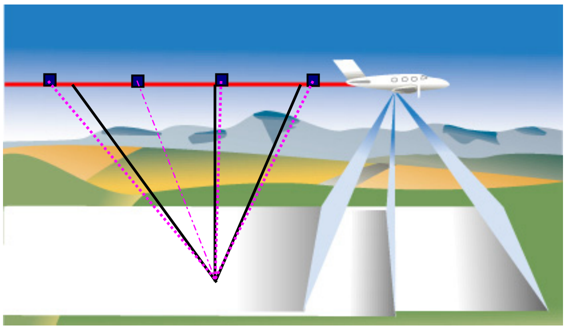
The spacing of the orientation fixes has a strong impact on the determinability of all parameters. Therefore it must be defined carefully.



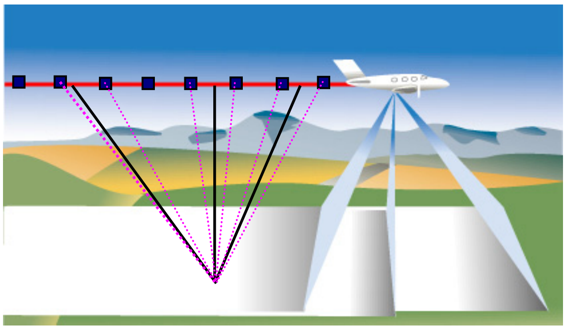
a) This example shows a very large spacing. The solid black lines indicate the three observations in forward, nadir and backward scenes. The dashed purple lines indicate the effect of the rays in the adjustment. Although the point is observed in three scenes the geometric effect is reduced to two rays. If the fixes were even further apart from each other the effect of the three observations could approach a single ray point. This is due to the mathematical model. The effect of an observation depends on the distance to the fixes. If the spacing is defined to be too wide, the adjustment becomes singular.



b) This example shows a medium spacing. As two observations, nadir and backward, fall into one interval, the geometry is not truly comparable with a three ray point. The weight of the dashed purple lines should indicate the influence of each ray on the point determination.



c) This example shows a spacing that corresponds to the short base. This leads to a geometrically very stable solution. Each observation falls into a separate pair of orientation fixes. This corresponds to a true three ray point.



d) This example shows a dense spacing of the orientation fixes, shorter than the short base, which can result from the time limit of the gyro quality. The math model handles this configuration as long as sufficient tie points are measured.

Figures 9(a-d): Impact of spacing of orientation fixes.

3.3 Tie Points

The distribution of the tie points depends on the interval of the orientation fixes. The interval should not exceed the short base length. Furthermore the interval depends on the quality of the gyros used. For the ADS40 the specifications define gyros that deliver a very high precision over an interval of at least 8 seconds. The typical number of tie points is very similar to traditional triangulation.

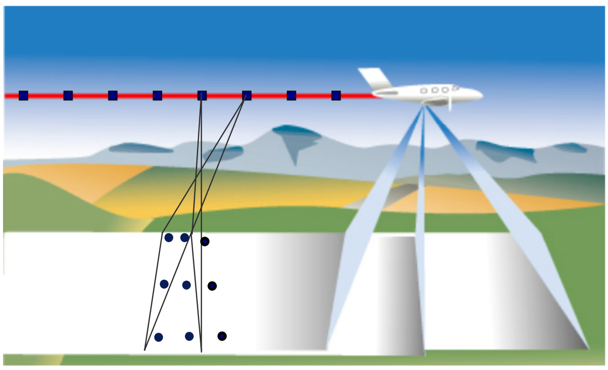


Figure 10: Minimum number of tie points for a photogrammetric determination of orientation fixes.

To find the minimum number of tie points one can count the number of observations and unknowns. Assuming the scenario where the orientation fix spacing equals the short base the following calculation holds true.

- 4 orientation fixes times 6 parameters = 24 unknowns
- 8 tie points times 3 co-ordinates = 24 unknowns
- 8 tie points in 3 scenes times 2 co-ordinates = 48 observations

This simple calculation does not account for the GPS/IMU observations and the necessary datum definition, but it shows fairly well that the demands are similar to frame photography.

3.4 Control Points

Ground control can be limited to a minimum to define the datum. Each strip is geometrically very stable owing to the GPS/IMU information used. Control points should be placed in the corners of the block similar to traditional airborne GPS-supported triangulation projects. The coordinate transformation functions of ORIMA transform the given control points from the mapping system to the local Cartesian system.

3.5 Calibration by Bundle Adjustment

3.5.1 Misalignment

To utilize the orientation values which are derived from GPS/IMU directly without triangulation, the coordinate transformation between the GPS/IMU system and the photogrammetric system must be known. The axes of the gyro system which represent the axes of the IMU cannot be perfectly aligned with the axes of the photogrammetric system. The remaining misalignment is determined by the bundle adjustment.

The misalignment is modelled by the following equation:

$$\boxed{\mathbf{R}_{IMU_k} = \mathbf{R}_{Misalign}\mathbf{R}_{OriFix_k}} \tag{9}$$

Every rotation matrix can be described by 4 algebraic parameters:

$$\mathbf{u} = \begin{bmatrix} d \\ a \\ b \\ c \end{bmatrix} \quad \text{with:} \quad d^2 + a^2 + b^2 + c^2 = 1 \tag{10}$$

Two orthogonal 4x4 matrices are used:

$$\mathbf{P}_{\mathbf{u}} = \begin{bmatrix} d & a & b & c \\ -a & d & c & -b \\ -b & -c & d & a \\ -c & b & -a & d \end{bmatrix} \tag{11}$$

$$\mathbf{Q}_{\mathbf{u}} = \begin{bmatrix} d & -a & -b & -c \\ a & d & c & -b \\ b & -c & d & a \\ c & b & -a & d \end{bmatrix} \tag{12}$$

$$\mathbf{P}_{\mathbf{u}}^{\mathrm{T}}\mathbf{P}_{\mathbf{u}} = \mathbf{Q}_{\mathbf{u}}^{\mathrm{T}}\mathbf{Q}_{\mathbf{u}} = \mathbf{I} \tag{13}$$

$$\mathbf{P_u Q_u} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & & & \\ 0 & & \mathbf{R} & \\ 0 & & & \end{bmatrix} \tag{14}$$

with:

$$\mathbf{R} = \begin{bmatrix} d^2 + a^2 - b^2 - c^2 & 2(ab + cd) & 2(ac - bd) \\ 2(ab - cd) & d^2 - a^2 + b^2 - c^2 & 2(bc + ad) \\ 2(ac + bd) & 2(bc - ad) & d^2 - a^2 - b^2 + c^2 \end{bmatrix} \tag{15}$$

From the above relationships, the misalignment transformation can be rewritten as:

$$\boxed{\mathbf{u}_{IMU_k} = \mathbf{Q}_{Misalign} \mathbf{u}_{OriFix_k}} \tag{16}$$

The four algebraic rotation parameters (d, a, b, c) are not independent. Within the adjustment process only three linear independent rotation parameters are estimated. After the adjustment process the algebraic parameters are transformed into the conventional rotation parameters (ω, φ, κ). For more information about algebraic rotation parameters please refer to Pope (1970 and Hinsken (1988).

3.5.2 Offset

Typically the offset between the GPS antenna centre and the projection centre is surveyed with sufficient accuracy. Within the GPS/IMU post-processing the co-ordinates of the GPS antenna are reduced to the projection centre.
On the other hand it is also possible to estimate the constant offset vector in the sensor system within the bundle adjustment. The offset is computed for each orientation fix based on the following math model.

$$\begin{bmatrix} X_{GPS} \\ Y_{GPS} \\ Z_{GPS} \end{bmatrix}_k^{Ground} = \begin{bmatrix} X_{OriFix} \\ Y_{OriFix} \\ Z_{OriFix} \end{bmatrix}_k^{Ground} + \mathbf{R}^{Ground}_{Sensor\ OriFix_k} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{Offset}^{Sensor} \tag{17}$$

To resolve the linear dependency between the offset and the orientation fixes parameters, the block must have strips with different kappa angles, preferably by 180 degrees. The linear dependency in Z can hardly be resolved.

To account for a potential datum difference between the observed, GPS-based orientation fixes and the estimated orientation fixes, an optional set of datum transformation parameters can be used.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_k^{GPS} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_0^{GPS} + \lambda \cdot \mathbf{R}^{GPS}_{Ground} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_k^{Ground} \tag{18}$$

These datum transformation parameters are project specific.

4. IMPLEMENTATION

The implementation of the ADS40 sensor model into ORIMA was done in such a way that users familiar with the software for the classical frame sensor can use their knowledge for projects based on the ADS40 as well. When ADS40 scenes are inserted into an ORIMA project the type of sensor is detected automatically. Measurement of tie points is performed in the same way as for frame sensors. The user can start the automatic tie point measurement (APM) process in SOCET SET to obtain the necessary tie points to compute the orientation fixes. The APM process requires a tie point pattern, which guides the tie point distribution within the scene. Here the software was modified to account for the new sensor model. The tie point pattern is no longer limited to a 2-D pattern for the whole image format. It is now possible to define a pattern across the line and a repetition frequency. The repetition frequency is computed from the known gyro quality and short base length. The new 1-D pattern with repetition frequency approach allows the user to handle scenes of varying lengths, not only images with a fixed format. Furthermore the pattern need no longer be applied to all images, but to user-defined scenes only. Typically it is sufficient to define the pattern for the nadir scenes only. In contrast to frame sensor images, ADS40 projects require no set-up prior to the APM measurements. Since good initial values for the exterior orientation of each line exist from the GPS/IMU, the matching process can be started directly.

Manual measurements of tie or control points are performed exactly the same way as with frame sensors.

The required number and location for the orientation fixes is computed automatically prior to the start of the bundle adjustment. After the tie and optional control point measurements are finished, the bundle adjustment can be started directly. All the familiar features from the adjustment program (CAP-A) are also available for ADS40 projects. These include automatic blunder detection and removal by robust estimation, variance component estimation for GPS and IMU observations, computation of confidence ellipses and internal and customized external reliability values and last but not least self-calibration parameters can also be used with ADS40 data. For further details on CAP-A please refer to Hinsken (1999). The graphical user interface of ORIMA has not been changed for ADS40 data. Error analysis after the bundle adjustment is performed in exactly the same way as for frame images. The analysis is performed in a highly interactive manner. Points flagged as blunders by the bundle adjustment can be manually inspected for remeasurement. After the user selects a group of points which are of interest for manual inspection, the related scenes will be loaded into multiple windows one point after another and the user can visually judge and remeasure a point if desired.

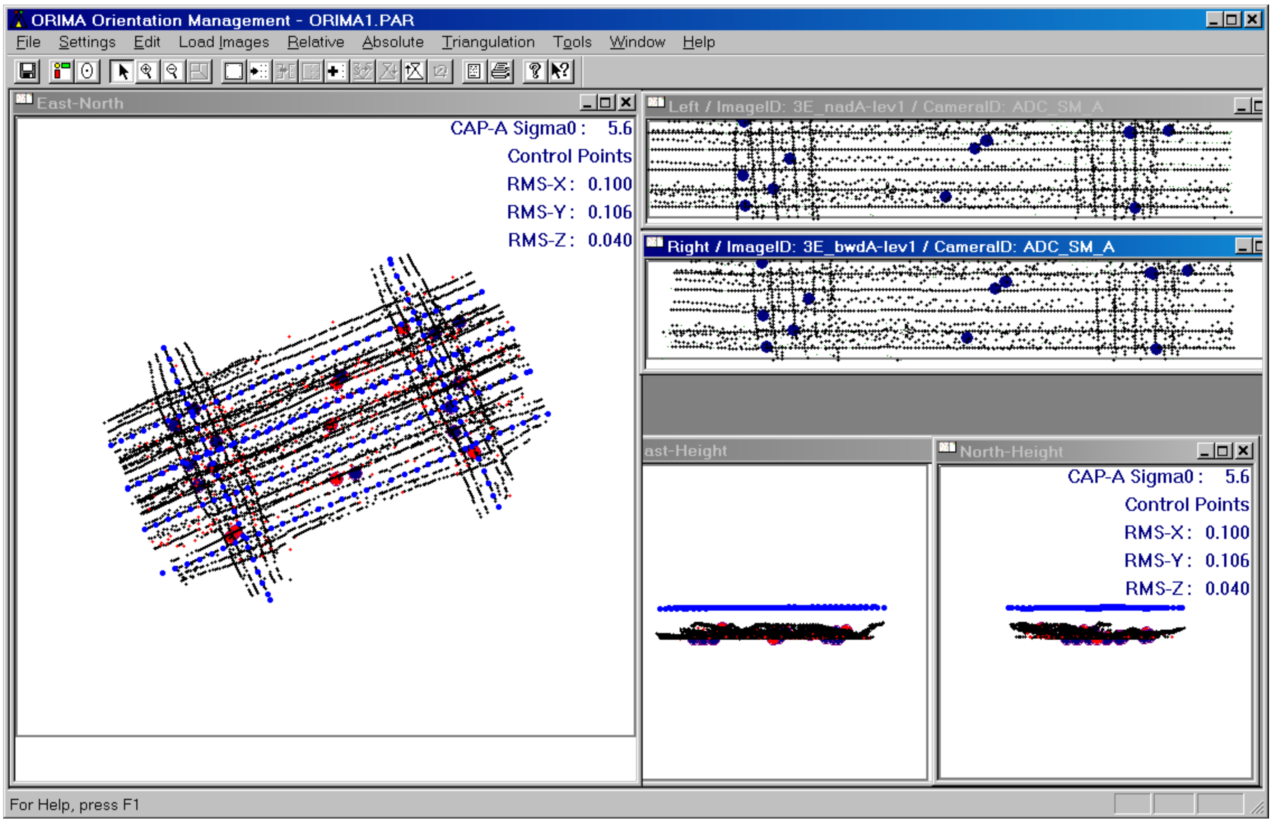


Figure 11: ORIMA user interface showing ADS40 block.

Once the analysis is finished and final parameters are obtained from the bundle adjustment, a new set of orientation files is generated by ORIMA. Within this process the precise orientation values for each sensor line at Level 0 are computed based on the adjusted orientation fix parameters and the observed GPS/IMU values. The photogrammetric mathematical model is updated with these precise orientation values and more accurate measurements can be made. The user is now ready to produce features, DTM, orthophotos, etc.

5. SUMMARY

In this paper we have detailed how a traditional least squares bundle adjustment process has been augmented to support a push broom scanner with GPS/IMU data completely. The use of high precision GPS and IMU data combined with traditional triangulation techniques gives rise to a robust and very flexible system. The adjustment process can determine calibration, datum deficiencies, and errors in GPS, and more precisely register the imagery to ground control. It should be noted that very little ground control is required. Owing to the GPS/IMU data, ground control is essentially unnecessary. For typical issues of local datum knowledge and quality control, some ground control is recommended.

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