EXTERIOR ORIENTATION BY DIRECT MEASUREMENT OF CAMERA POSITION AND ATTITUDE

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ABSTRACT

Airborne attitude and position determination as a means of determining the exterior orientation of an airborne remote sensing system is investigated in this paper. The performance of an airborne data acquisition system consisting of receivers of the Global Positioning System (GPS) and a strapdown Inertial Navigation System (INS) together with an aerial camera is assessed using data of a 1:6000 large scale photogrammetric test. The test was jointly conducted by the Institute for Photogrammetry, Stuttgart and The Department of Geomatics Engineering, Calgary, with aircraft and logistics support by Rheinbraun AG - Department of Photogrammetry, Cologne. Multiple flight lines were flown over a well controlled photogrammetric test field allowing the assessment of position and attitude repeatability, as well as the analysis of gyro drift.

After a brief description of the essential features of the sensor integration design, its practical implementation is described and the error budget of the GPS/INS integration is discussed. The actual position and attitude results obtained from the GPS/INS are then compared to those derived from the independent aerotriangulation bundle adjustment using all available control points. The errors in position determination along the aircraft trajectory are in the decimetre range, those in attitude are varying with standard deviation of 0.03 degree over one hour. To assess the feasibility of using independently determined attitude and position parameters from GPS/INS for the exterior orientation of the photographs, the independent models were directly georeferenced. Preliminary results indicate that aerotriangulation at a photo scale of 1:6000 using independent exterior orientation directly obtained from an integrated GPS/INS can be done with an accuracy of 0.3 m (RMS). It is expected that these results can be improved because there are considerable doubts about the accuracy of the synchronisation between the camera and the GPS/INS in this specific flight.

1. INTRODUCTION

The problem of georeferencing images of aerial photography can be defined as the problem of transforming the image coordinates in the camera frame to the mapping frame. Such a transformation can be written as

$$\begin{pmatrix} X_p \\ Y_p \\ Z_p \end{pmatrix}_m = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}_m + \alpha\, \boldsymbol{R}_p^m(\omega,\varphi,\kappa) \begin{pmatrix} x_p^r \\ y_p^r \\ -f \end{pmatrix}_p \tag{1}$$

where (X_p, Y_p, Z_p) and x_p^r, y_p^r are the point coordinates in the geodetic reference system and the reduced image coordinates in the photo frame, respectively; (X_0, Y_0, Z_0) are the spatial coordinates of camera perspective centre given in the reference frame; α is a point dependent scale factor; f is the camera focal length and $\boldsymbol{R}_p^m$ is three-dimensional transformation matrix which rotates the photo frame into the geodetic mapping frame. In this equation, the vector (X_0, Y_0, Z_0) and the transformation matrix $\boldsymbol{R}_p^m$ are time-variable quantities.

In order to georeference frame based imagery, the parameters of interior and exterior orientation have to be determined. The interior orientation parameters, i.e. coordinates of the principal point x_0, y_0, the focal length f, and the geometric distortion characteristics of the lens, can be measured via laboratory calibration. The six parameters of camera exterior orientation $(X_0, Y_0, Z_0, \omega, \varphi, \kappa)$ are found by correlation between ground control points and their corresponding images. Such a process will be called inverse photogrammetry. Within this method the image coordinates of known control points are measured and related to the ground assuming a perspective projection. Connection between multiple images is formed by measuring points common to adjacent images and by enforcing intersection constraints between them. To be able to resolve the parameters of exterior orientation and to control the error propagation, ground control points have to be established for each block of images. This represents a significant portion of the aerotriangulation budget. Additionally, the evaluation of the images is very time consuming and highly skilled operators are necessary. Moreover, the cost of determining ground control points can be prohibitive for image georeferencing in remote areas.

If the parameters of exterior orientation can be derived from simultaneously flown on-board sensors with sufficient accuracy, the number of ground control points can be reduced, resulting in obvious economic advantages. The potential of using GPS observations as constraints for the camera perspective centres in bundle adjustment has been proven repeatedly (Friess 1991, Ackermann 1995) and GPS-supported aerial triangulation is by now an accepted procedure. In case of pushbroom imagery, parameters of exterior orientation are required for each scan line. Applying a block adjustment procedure to this problem would require very large numbers of control points. Several rather complicated solutions have been proposed to overcome this problem (Hofmann 1988, Hofmann et al. 1993), but none of them has been accepted in practice. Again, a direct solution

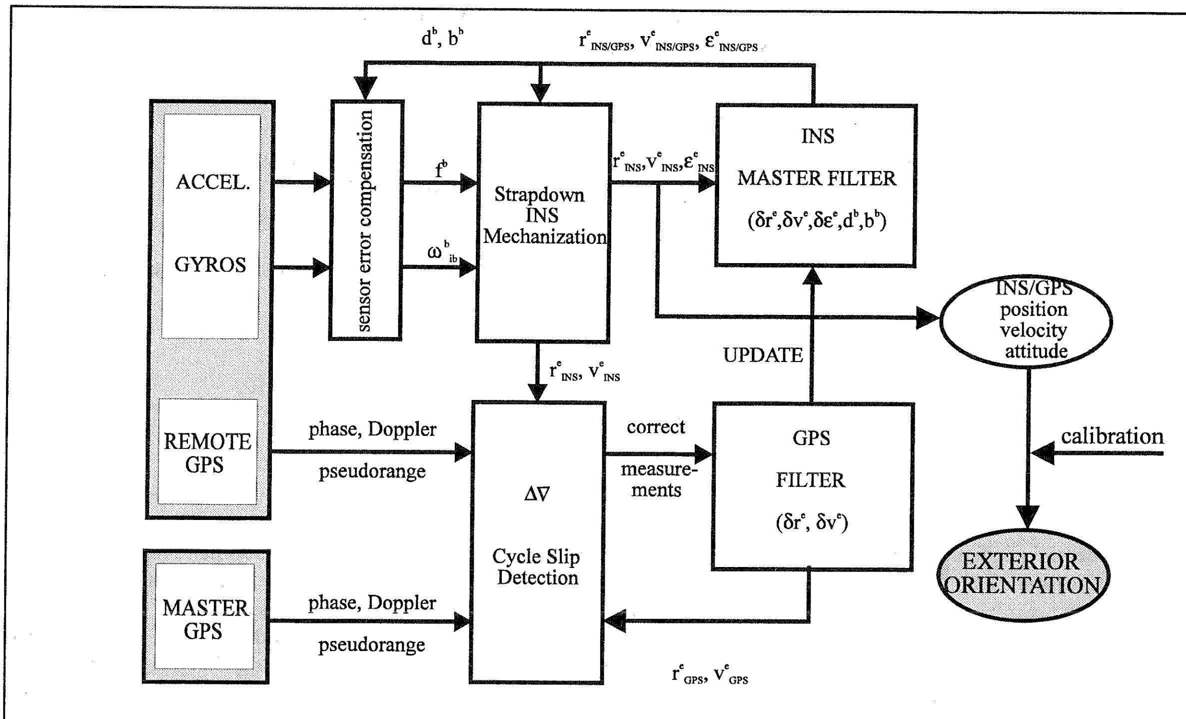

Figure 1: Block Diagram of Sensors Integration

of the problem can be supplied by a precise attitude/positioning system. Furthermore, direct exterior orientation allows the georeferencing of remotely sensed data in near real time (Schwarz et al. 1993).

Position and attitude accuracies needed are application dependent. The horizontal and vertical accuracy on the ground is mainly determined by the accuracy of the cartographic reproduction process and the contourline interval of the maps. The contourline interval is mainly dependent of the scale of the maps and the slope of the terrain and can range from 1 m to several tenths of meters. Assuming that contourlines are not allowed to intersect, the vertical accuracy has to be at least half of the contourline interval (Schwidefsky/Ackermann 1976). The cartographic reproduction quality is determined by the map production facilities and therefore might range from 0.1-0.25 mm. These requirements can be much more stringent if remote sensing is applied for cadastral point determination or engineering tasks. In this case position accuracies better than 10 cm are required in object space. Taking these positioning accuracies into account the

Map Scale / Application	Horizontal Accuracy [m]	Vertical Accuracy [m]	Attitude Accuracy [10^{-3} deg]
1 : 50 000	10	8	35
1 : 25 000	5	4	30
1 : 5 000	1	0.75	15
Cadastral Point Determination	< 0.1	< 0.1	5

Table 1: Required Positioning and Attitude Accuracies (RMS Values)

required accuracies for the attitudes can be calculated. The attitude parameters are mainly dependent on the flying height abouve ground and the focal lenght of the sensor. Assuming a wide-angle aerial camera attitude accuracies as given in Table 1 are necessary for the orientation process.

Two accuracy classes will be considered in the following. For cadastral or precise engineering projects, accuracies have to be at the sub-decimetre level for position and at the level of five milli-degrees or better for attitude. For mapping applications at the scale of 1:10000 and smaller and for many resource mapping applications with multi-spectral scanners, accuracies at the level of one metre or less for position and of a few tenths of a degree for attitude are sufficient. In this paper the potential of integrated GPS/INS systems is evaluated for the direct determination of the exterior orientation parameters for these levels of accuracy.

In the described test, the feasibility of directly determined exterior orientation parameters is evaluated in two steps. First, the in-flight orientation accuracy and position of the integrated GPS/INS is assessed by comparing it to orientation parameters independently determined by inverse photogrammetry, i.e. by using a large number of accurate ground control points to determine position and attitude parameters at aircraft level from the image measurements. Second, coordinates of pre-surveyed check points on the ground are determined by georeferencing independent models whose exterior orientation has been derived from the integrated GPS/INS system.

2. THE SENSOR INTEGRATION

In order to obtain the best positioning/attitude performance, the INS data are integrated with GPS double differential measurements in a decentralized Kalman filter configuration (Figure 1). The GPS filter is independent of the INS filter and its output is used to update the INS error states. The double difference pseudorange, carrier phase and phase rate observations form the measurement vector in the GPS filter. Its output (i.e. position and velocity) is taken as a set of pseudo-measurements which are used to update the INS master filter. The noise in these 'pseudo-measurements' is determined by the GPS filter covariance matrix. Updated error states in the INS master filter are fed back to correct INS raw measurements. The output of the strapdown mechanization therefore contains GPS/INS integrated position, velocity and attitude information. This information is used to check the validity of GPS measurements and to help resolve the carrier phase ambiguities in the event of cycle slips or serious loss of lock in the GPS measurements. The INS error model has 15 states including navigation errors (attitude, position, velocity) and correlated sensor noise terms (gyro drift, accelerometer biases). The timevarying nature of gyro drifts and accelerometer biases is modelled by Gauss-Markov processes. The GPS error state model includes position and velocity errors. In addition, the state is augmented by double difference ambiguity parameters. The detailed equation describing the 15 state error model as well as strapdown INS mechanization in the earth-fixed frame can be found in Schwarz and Wei (1994).

Since the GPS antenna and the INS system are physically displaced from the perspective centre of the imaging sensor, a constant displacement vector $\boldsymbol{dr} = (dx, dy, dz)^T$ has to be added to the GPS/INS integrated position to obtain the position of the camera perspective centre in the GPS reference frame. The components of the translation vector are measured by using conventional surveying techniques before the flight mission.

Similarly, a constant misorientation $d\boldsymbol{R}_p^b = f(\delta_1, \delta_2, \delta_3)$ exists between INS and the imaging sensor and has to be taken into account to obtain correct orientation parameters of the camera perspective centre. Determining the misorientation matrix $d\boldsymbol{R}_p^b$ is more complicated since the sensor axes in either device cannot be physically observed. However, a solution can be obtained by implementing an in-flight calibration. This is possible for either frame cameras (Škaloud et al., 1994) or push-broom scanner imagery (Cosandier et al., 1994). A key assumption for in-flight calibration is that no changes in relative position and orientation between the imaging device, INS and GPS antenna will occur. This can be achieved by hard-mounting the GPS antenna and INS on a rigid platform in the aircraft and by locking the imaging device, e.g. the aerial camera, down to the same platform.

The measurements of the integrated system have to be interpolated at the exposure times of the imaging sensor. This can be done using the high rate navigation output of 64 Hz. Combining the GPS/INS derived position $(X_0, Y_0, Z_0)^T$ and attitude with the spatial displacement $dr=(dx, dy, dz)^T$ and the misorientation matrix $\boldsymbol{dR}$ between the INS and the imaging sensor, Equation 1 takes the form

$$\begin{pmatrix} X_p \\ Y_p \\ Z_p \end{pmatrix}_m = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}_m + \boldsymbol{R}_b^m \begin{pmatrix} dx \\ dy \\ dz \end{pmatrix}_b + \boldsymbol{R}_b^m \, d\boldsymbol{R}_p^b \begin{pmatrix} x_p^r \\ y_p^r \\ -f \end{pmatrix}_p \qquad (2)$$

Thus, after supplying GPS/INS derived position and attitude together with sensor calibration, all terms on the right hand side of the Equation 2 are known and reduced image points coordinates x_p^r, y_p^r can be represented in object space by this simple transformation.

3. TEST FLIGHT SCENARIO AND REFERENCE TRAJECTORY ACCURACY

A well-defined photogrammetric test field close to Cologne, Germany was used to asses the accuracy of an actual airborne data collection system. The geodetic receivers selected for the test are pairs of dual frequency receivers Trimble 4000 SSE and Ashtech Z12. Two of them were used at the base stations located close to the network origin in the middle of the block (Ashtech Z12) and at the airport (Trimble 4000 SSE) about 30 km away from the test field. The inertial navigation system to be tested is a Litton LTN-90 strapdown system with gyro drift rates of about 0.03 deg/hour. The photogrammetric camera installed in the twin-engine Partenavia P68C aircraft is a Zeiss RMK A aerial camera with a precise shutter pulse output being recorded by the receiver (Trimble 4000 SSE) in GPS time. The time synchronisation with other on-board sensors is realized via a data collection computer receiving raw INS output and GPS data (Ashtech Z12) together with a receiver provided precise 1 pulse per second (PPS) signal.

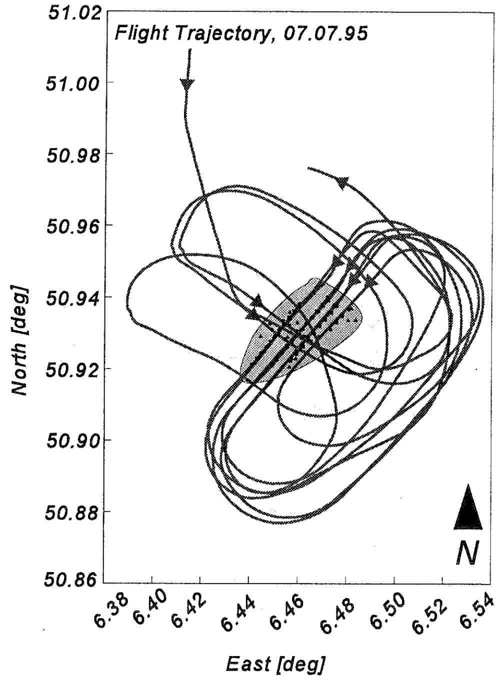

Figure 2: Test Flight Scenario

The test area has an extension of about 4 x 2 km and is normally used to determine the ground movement of the overburden dump "Sophienhöhe" in the open pit mining area. Therefore, about 160 points are marked permanently on the ground and their coordinates are measured in regular time intervals using GPS supported aerial triangulation. For this test flight a subset configuration of 47 ground control points in the flight test area has been chosen in such a way that camera orientation parameters can be derived with highest possible accuracy by inverse photogrammetry. The 3-D coordinates of 16 control points were determined by adjusting a network of GPS static baselines with a relative positioning accuracy of 1 part per million. Additionally, 31 vertical control points were established and their ellipsoidal heights were determined by levelling and computation of geoid undulation.

Nine photogrammetric strips, three of them repetitive, were flown over the test area in early July 1995 (Figure 2). The length of the strips differs from approximately 1 to 4 km. From the total number of 168 photographs a subset of 77 centre located images was chosen. Together, they form a photogrammetric block with 80% forward and 60% side overlap. The average flying height of about 900 m and the 15 cm camera focal length resulted in a photo scale of 1:6000.

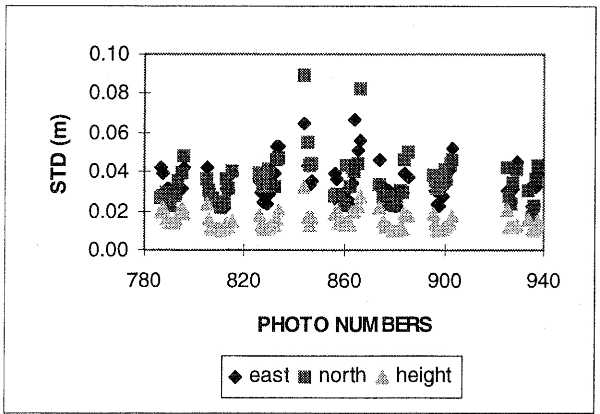

Figure 3: Predicted Positioning Accuracy of Reference Trajectory

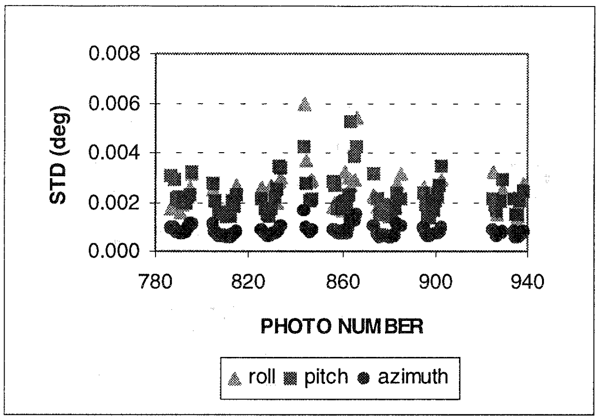

Figure 4: Predicted Orientation Accuracy of Reference Trajectory

Due to the large overlaps the photogrammetric block is of a high redundancy. The accuracy of the perspective centres of the photographs is estimated by traditional block adjustment using all ground control points. The position accuracy of the perspective centres is about 3 cm (STD) in horizontal and 2 cm (STD) in vertical direction (Figure 3). The standard deviations (STD) of the orientation angles are depicted in Figure 4. Their mean values are about 2 milli-degree (mdeg) in roll and pitch and 1 mdeg in azimuth. Hence, the parameters of exterior orientation are determined with an accuracy which is two to four times better than that expected from the tested attitude/positioning system. They can therefore be used as a reference.

4. ACCURACY OF GPS/INS EXTERIOR ORIENTATION

The GPS/INS data has been processed according to the methodology discussed in Section 1 by using KINGSPAD (KINematic Geodetic System for Position and Attitude Determination), an integration software package developed by The University of Calgary. This program has been recently extended to employ direct integer ambiguity search (DIAS) in either static or kinematic mode (Wei and Schwarz 1995).

Problematic GPS data, containing either a number of cycle slips, or having more than one loss of lock or poor satellite geometry, was processed first in wide-lane mode with frequent kinematic OTF ambiguity search. By using the two frequencies for widelaning, a noisy but unbiased flight trajectory could be established, which then served as a reference for final single frequency processing. During periods of time when only the same four satellites were visible, the INS data was the only source to assist in cycle slip detection. The 64 Hz program navigation output was linearly interpolated to obtain position and attitude for the camera exposure time.

After correcting for the spatial offsets between sensors, a comparison between parameters of exterior orientation derived from GPS/INS and from the photogrammetric bundle adjustment could be made. The position differences reflected in Figure 5 have RMS values of 15 cm horizontally and 20 cm vertically. Since the separation between the rover and master station receivers was within 10 km, these rather large differences are most likely due to the small number of observable satellites and the poor satellite configuration. In order to achieve reasonable geometry, low elevation satellites had to be included into the processing. Even with an elevation mask as low as 10 degrees, only 4 to 5 satellites were simultaneously tracked by both receivers.

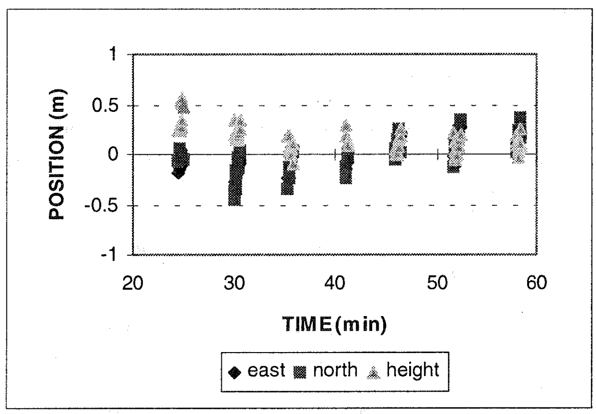

Figure 5: Variation in GPS/INS-Camera Position

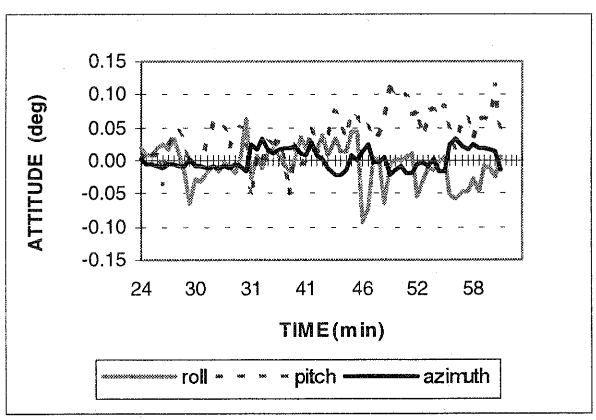

Figure 6: Variation in GPS/INS-Camera Orientation

The differences between the orientation parameters are depicted in Figure 6 by means of the three Euler angles roll, pitch and azimuth. The time scale of this figure is not uniform due to the fact that comparisons can only be made during the short time periods when flying over the test field. The errors in azimuth are randomly distributed with standard deviations (STD) of 0.015° over the whole mission. This implies that the dominant systematic errors in INS-derived attitude have been almost completely eliminated by frequent GPS updates. These updates should be theoretically more effective in roll and pitch, see Škaloud 1995 for a theoretical explanation, but this does not seem to be the case for either pitch or roll. Both are at a level of about 0.03° (STD), and show a small drift in pitch and some rather systematic features in roll. This could be due to several reasons: unmodelled errors due to aircraft dynamics; time synchronization errors between GPS/INS and camera; large gyro noise due to aircraft vibration; residual errors in the photogrammetrically derived parameters of exterior orientation due to the strong correlation between position and attitude. Most likely, a mixture of all these sources contributed to the larger than expected attitude errors. Further analysis is planned to better explain some of the unexpected features.

5. DIRECT GEOREFERENCING

Target points in the imagery can be directly georeferenced, once all unknowns in the modified collinearity Equation 2 have been determined. In this case, the parameters of interior orientation as well as the offsets between on board sensors are known from calibration and the parameters of exterior orientation are resolved via GPS/INS integration. To evaluate the overall performance of direct georeferencing, coordinates of 50 control points were recomputed by means of Equation 2 and compared to their reference values. Practically, the computation was done by using the calibration parameters of interior orientation to correct the measured image coordinates and running the bundle adjustment with no ground control and fixed parameters of exterior orientation as derived from GPS/INS. The three dimensional position residuals on all 50 check points are depicted in Figure 7. The error distribution has a standard deviation of 30 cm horizontally and 50 cm vertically. Additionally, the points are shifted towards South by a mean value of 35 cm.

Since the camera position and orientation were considered as known parameters in the adjustment, errors in their determination are directly propagated into the derived ground coordinates. Considering the errors shown in Figures 5 and 6 at a flight height of 900 m, the resulting position errors on the ground could even be larger. This might indicate that the reference values derived by inverse photogrammetry are not as reliable as indicated by their standard deviations, due to the high correlations between them.

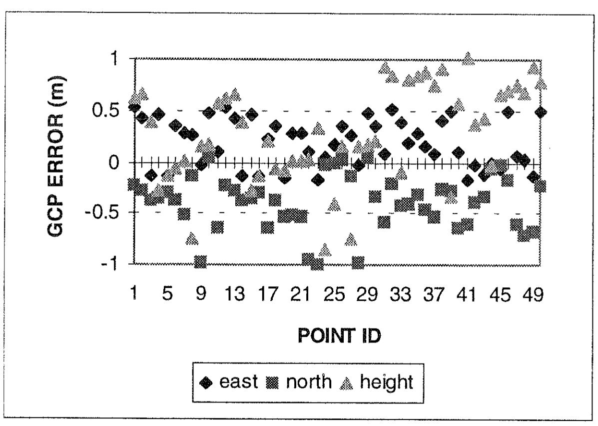

Figure 7: Check Point Residuals-Direct Georeferencing

6. CONCLUSIONS

The performance of an airborne data acquisition system for precise attitude and position determination in support of airborne remote sensing has been evaluated by means of aerotriangulation. Due to poor satellite geometry, the positioning errors along the aircraft trajectory were larger than usual, and reached several decimetres. The attitude errors from the integrated GPS/INS showed some unexpected features. While the azimuth error behaves randomly, as expected, with a standard deviation of 0.01 degree, the errors in pitch and roll are larger, about 0.03 degree, and seem to be systematic in nature. They need to be further investigated. Direct image georeferencing at 1:6000 using the measured GPS/INS attitude was better than 1 metre (absolute), when compared to 50 presurveyed control points. This accuracy is sufficient for many of the intended mapping applications.

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