ANALYSIS AND ACCURACY ASSESSMENT OF AIRBORNE LASERSCANNING SYSTEM

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ABSTRACT:

Airborne laser scanning technology is impressive in its capability of collecting a tremendous number of points in a very short time and providing a reasonable depiction of complex objects in the scanned areas. So far it has been used in a wide range of applications with promising results. Since it is in a very early stage of development, users are still trying to determine the best ways to collect and analyze the data. The quality of any final product naturally depends on the original data and methods of generating it. Thus the quality of the data should be verified before assessing any of its products. The work described in this paper is aimed at a quantitative accuracy evaluation of the laser data itself. This is an area that has been under-emphasized in much published work on the applications of airborne laser scanning data. The evaluation is done by field surveying, including triangulation and leveling. The results will address both the planimetric as well as the height accuracy of the laser data.

1. INTRODUCTION

With the recent increase in the scope of laser altimetry applications, there is a need for more studies to be conducted on the data quality assessment and on means of improving data quality. Generally, as documented in many LIDAR system vendors' specifications, the accuracy of individual data points is about 5-15cm in height and about 30-50cm in planimetry. However, those values might be degraded if the data collection is carried out in less than ideal conditions (Baltsavias, 1999).

This paper outlines the work that has been done to assess and quantify the quality of the laser scanning data that was collected over Purdue University campus in spring 2001 and used in this research. As an introduction, major sources of errors in laser data are briefly discussed. Then a detailed description of the data will be given. Relative accuracy among the collected data strips will be examined. The absolute accuracy procedure and results are also presented. The procedure starts by selecting an appropriate area with some specific characteristics, as will be discussed later, to conduct a ground topographical survey as a reference for the assessment. Collecting ground points was done using both GPS and typical ground survey methods. A detailed analysis of the laser data over that same area was performed. The results will include both the planimetric as well as the height accuracy of the laser data.

2. ERROR SOURCES IN LASER ALTIMETRY DATA

There are many sources of error and uncertainty that affect the quality of the laser scanning data. They vary in their influence, in the resulting error magnitudes, and in the way they should be corrected or avoided. The resulting errors are an outcome of the laser ranging computation, the scanning system, topography, the atmosphere, positioning and navigation systems, and system integration factors. Some of the major sources will be discussed in brief with the way they should be treated to eliminate or at least minimize their effects.

2.1 Laser unit and scanning system

The misalignment between the sent and the received pulse is one of the error sources in range computation and point positioning. Also the error in coincidence between the platform coordinate system origin and the mirror center is another type of misalignment error. This kind of error is correctable through calibration (Morin and El-sheimy, 2002). Return signal detection, range bin quantization, and the inaccuracies in the pulse travel time measurement are another source of error in range computation. These errors cannot be eliminated totally but can be minimized by increasing the time resolution and improving the synchronization between the clock and the laser system.

2.2 Topography and atmosphere

Many examples can be cited under this category, only the major ones will be mentioned. Vegetation and other objects occluding the terrain introduce systematic error since they do not represent the real terrain surface. Rough terrain and steep slopes can generate artifacts in height measurements especially with large footprints since the elevation error depends on the slope angle and the planimetric position. This error will be more severe when the flight direction is parallel to the slope contour. On the other hand, error in height due to slope is less affected if the flight direction is in the direction of the gradient (Schenk, 1999). Another type of error in terrain can be generated when the laser pulse hits the side of a vertical object, which yields a misleading profile. The return signal amplitude also plays a role in data accuracy. Some gaps in the data might be produced if the returned pulse cannot be detected due to its weakness. Specular reflections may also produce regions of missing data. Uncompensated atmospheric conditions (air pressure, temperature, and humidity) may also influence the accuracy. Those errors are not correctable in a rigorous sense but some of their values can be estimated by interpolation and others can be minimized through careful mission planning and operation.

2.3 GPS and INS positioning and orientation techniques

Unlike photogrammetry, the laser scanning system does not rely on triangulation in exposure station positioning. Rather it depends exclusively on the airborne GPS and INS to provide an accurate position and orientation of the platform. Differential carrier phase positioning (DGPS) in kinematic mode is capable of generating an accurate position with a precision of several centimeters. Satellite geometry, which is quantified by the positional dilution of precision (PDOP), plays a major role in GPS positioning reliability. Poor satellite geometry, high PDOP, generates inaccurate GPS positioning. Poor positioning can be avoided by optimizing the survey time and having at least one visible satellite in each of the four quadrants in order to be well distributed across the sky (Mikhail et al., 2001). On the other hand, a minimum of four visible satellites is needed to position a receiver using the DGPS system. Also, inaccurate orbits might produce significant errors, especially when observing longer GPS baselines.

Multipath, when more than one signal arrives at a receiver via more than one path, affects the vertical component of GPS observations. This can generate a height error of several centimeters based on the multipath configration. More on this issue and its treatment can be found in (Georgiadou and Kleusberg, 1988). An error in resolving the phase ambiguity, the number of integer cycles from the antenna to the satellite, is another source of error in GPS positioning. Signal propagation (troposphere and ionosphere) and uncertainty in calculating atmospheric transmission delays also affect the attainable GPS accuracy. There are many methods to address this problem and they can be found in (Grewal, et al., 2001; Gonzalea, 1998; and Mikhail et al., 2001).

Error in INS attitude data can be described by these factors: misalignment with the platform or the GPS system, biases in the accelerometers, gyrodrift, non-orthogonality of the axes, and gravity modeling error. These factors can accumulate a significant amount of angular error with long mission times

3. TEST DATA SET

The data used in this research was collected using an Optech ALTM 1210 LIDAR sensor operated by Woolpert Consultants on April 2001. It was flown over the Purdue University campus with an approximate area of 3,500,000m^2. It measures approximately 1700m in easting and 2000m in northing with an approximate density of one data point per square meter. The data consists of fourteen strips flown in the north south direction. Each of which has an approximate length of 2000m and width of 200m. The average flying height over terrain was about 600m. Therefore the angular extent of a swath is approximately 19 degrees.

4. RELATIVE ACCURACY OF DATA STRIPS

Airborne laser scanning data are acquired in a strip-wise pattern with a strip width varying depending on the chosen scan angle and the flying height. Usually, those strips are flown in parallel and overlapping until the entire region of interest has been covered. Overlap between strips (as shown in figure 1) provides a mean to evaluate the relative accuracy between them. The imprecision in system positioning, orientation, and ranging may cause the same point to have two different heights if scanned at two different times, which always happen in neighboring overlapping data strips. These points are considered as tie points in strip adjustment to adjust strips and eliminate or at least minimize relative error between them. However, the discrepancy between tie points from adjacent strips gives an indication of the relative offsets without any strong conclusion of the absolute error. In this section, the height discrepancy is examined between adjacent strips.

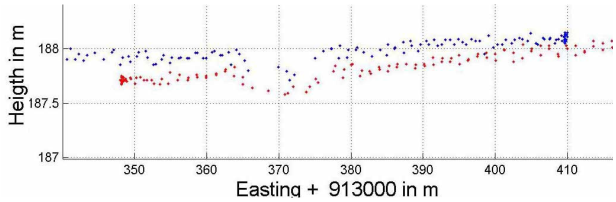

Figure 1: Profile of the overlap region between two adjacent strips.

4.1 Height relative offset

The relative height offsets are obtained by measuring the height discrepancies between overlapping regions from adjacent strips. Height offset can be computed between totally overlapped footprints from the two strips, which hardly exist, or points within a limited distance. Another way is to construct two different horizontal planes in a flat area, one from each strip, and compare these surfaces. Reflectance data can also be used to match features between the two strips (Burman, 2000; Vosselman, 2002), however, this approach is not always successful especially with low-density data and large laser footprints on the ground.

In the test data in this research, the percentage overlap between adjacent strips was designed to be about 30% of the swath width which is about 200m. However, due to the real conditions during the data collection, such as wind, overlap areas between strips ranges from less than 30m to as wide as 100m. The test data the data consists of 14 strips. Therefore, 13 overlap regions were examined in this research to quantify the relative height discrepancy. Each region has a length of 1,500m and they are oriented in the North-South direction as shown in figure 2. The fact that the data is fairly dense (one spot height per square meter) and the overlapped regions included in the testing are large increases the likelihood of having coincident and closeby data points. Therefore, the relative height accuracy was obtained in a straightforward approach by computing the difference between totally or partially overlapped data points.

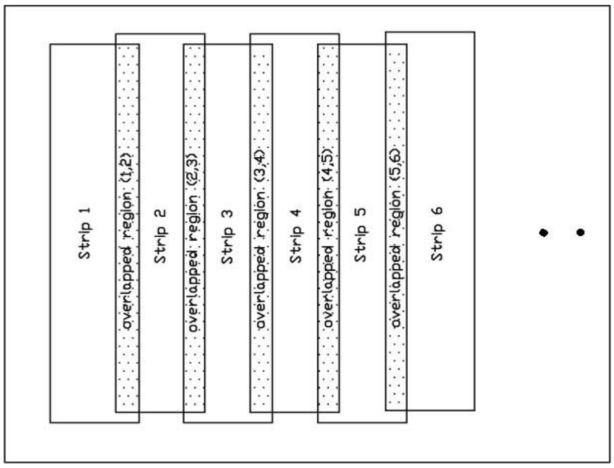

Figure 2: Data strips and overlap regions between them.

On building edges, two points within a few centimeters could have a great height jump since one might be on the ground and the other one is on the roof. Such outliers were detected based on the statistical interpretation of the computed discrepancy and mainly on the computed standard deviation of the discrepancies. Consequently they were deleted from the data set to eliminate their influences. The test started with points within 0.05m or less. Then in order to include more points in the computation and strengthen the results, the planimetric distance constraint was increased to include points within 0.10m and 0.25m. However, changing the planimetric distance and including more points did not change the discrepancy average in all overlapped regions. Figure 3 summarizes the behavior of the computed mean relative height offset between adjacent strips.

As expected, the histograms (for example see figure 4) show that the relative height discrepancy between adjacent strips has a random normal distribution. However, the mean of discrepancies is not stationary and does not equal zero. In the first four overlapped regions the discrepancy was within ±0.04m. Then the average discrepancy between strips (5-6, 6-7, 7-8, 8-10, 10-11, and 11-12) seems to increase up to 0.10m with a negative sign since the discrepancy was computed by subtracting the height of the right strip from the height of the left strip. Then in the last two overlapped regions (12-13 and 13-14) the discrepancy dropped to –0.06m. Therefore the discrepancy shows a systematic behavior. It shows a trend with time (North-South direction) since the strips where ordered on the time they were scanned (strip 1 was the first one to scan and strip 14 was the last). This trend was observed in all the 13 overlap regions that were tested. Figure 5 shows the relative height discrepancy along the North-South direction in the overlapped region between the 1st and the 2nd strip. It also shows the short period variation overlaid on the trend which is the long period variation. In general those offsets are not purely as a result of height differences at exactly correspondening points in the two strips since they are not error free in planimetric positioning. Consequently, due to this planimetric uncertainty the compared points might not have the same exact planimetric position and this miss correspondence may contribute to the height offsets. This correlation between height and planimtric offsets is more significant in sloping surfaces.

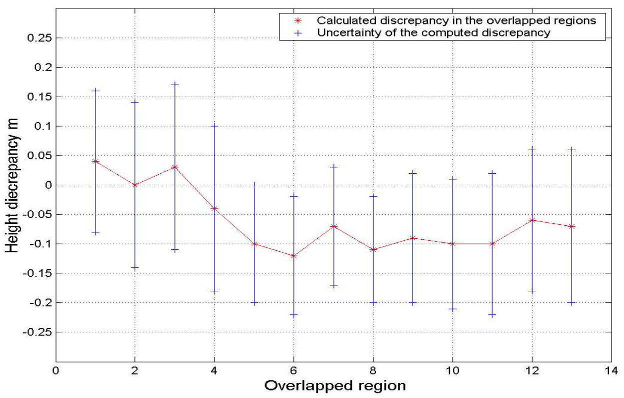

Figure 3: Mean Relative discrepancy behavior between adjacent strips, where the x-axis represents the overlap region (where 1 is the overlap region between strip 1 and 2)

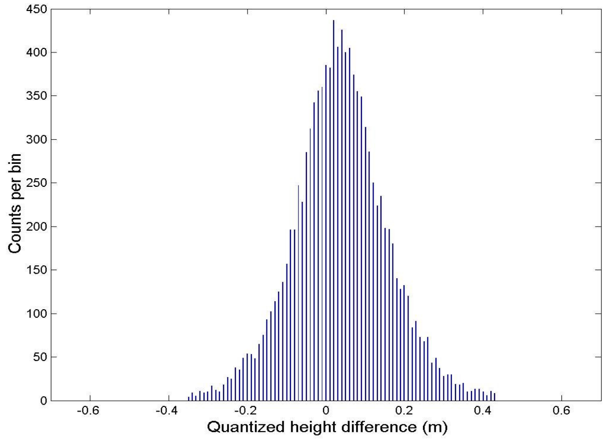

Figure 4: Histogram of the relative height discrepancy between the 1st strip and the 2nd strip.

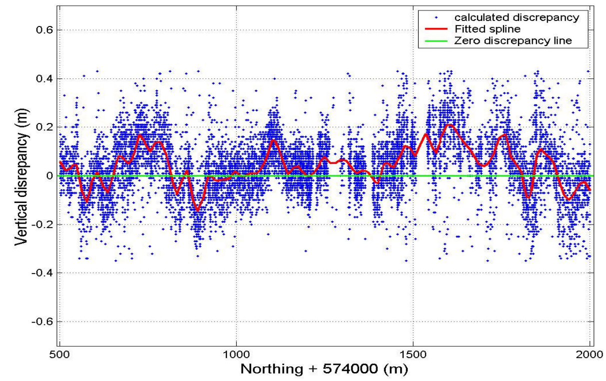

Figure 5: Relative height discrepancy in North-South direction (overlap region between the 1st and the 2nd strip).

5. DATA ABSOLUTE ACCURACY

Firms that work in collecting data usually publish a fixed number for the uncertainty of their data. However, these numbers are usually not verified by the users. This is due to the fact that this is not a simple task. Correspondence between laser data points and ground points is not a straightforward matter. The absolute offsets can be found by measuring the location on the ground of a point or feature of a known coordinates in the data set and compare the two measurements. So in order to evaluate the data set used in this research, a ground survey was conducted on an area with particular specifications. A large tennis field, which contains 10 tennis courts, and a flat football field adjacent to it represent the selected test area, as shown in figure 6. The selected area has two main useful characteristics. First, area is flat and horizontal with almost no significant slope over the tennis courts. This enables the examining of pure height accuracy since the flatness of the surface rules out any planimetric uncertainty effects. Second, the presence of drainage ditches around the field facilitates the computation of the planimetric accuracy. The selected area covers a full swath. An intensive control network over the test area was established using static Differential Global Positioning System (DGPS). This network was designed to serve the typical topographic survey over the test area. After establishing the necessary control around the selected test area, an intensive topographical survey was conducted. More than 400 points were collected over that area. Collected points were concentrated mostly at the critical features such as ditches surrounding the tennis courts. Figure 6 shows the collected ground points over the test area. Those points were then used to establish the correspondence with the laser data based on the spatial positions and consequently the absolute planimetric accuracy was determined.

5.1 Absolute height accuracy

A buffer zone (with a width of one meter) was constructed around each ground data line and the corresponding laser data points inside that buffer zone were identified. Then for each laser data point that lies within a meter or less from two ground data points, the corresponding height point with the same planimetric position was interpolated from the surrounding ground-surveyed points. Since the points are near by and the surface is flat, a linear interpolation was used. In order to minimize the effect of the planimetric uncertainty of the laser data, the interpolation was limited to totally flat areas. The slope of those areas was restricted to not exceed 10%. Direct differencing is then applied to compute the offset between the two data points from the laser and ground (the laser height was subtracted from the ground interpolated height). More than a thousand differences were computed. Figure 7 shows the histogram of those differences. The histogram shows a bias in the differences of -0.088m with a standard deviation of ±0.082m. That means that the average height of the laser data points included in the test are higher than the surveyed ground by 0.088m. The total computed RMSE of the test data from the ground reference was about 12cm.. This number represents the real standard deviation of the LIDAR data heights.

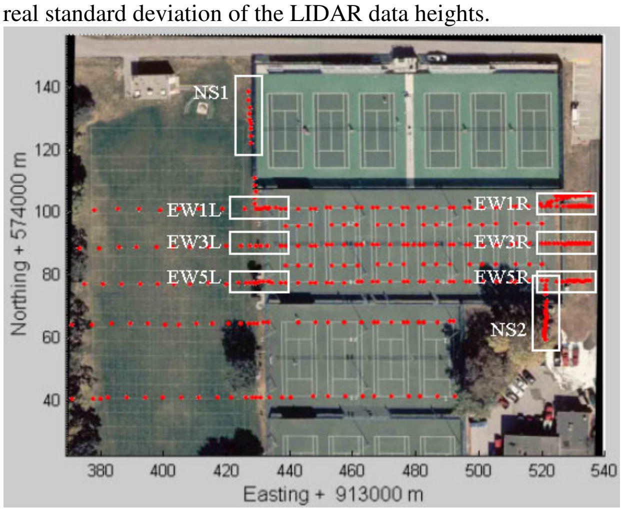

Figure 6: Surveyed ground points over the test area and Selected locations for the planimetric accuracy computation.

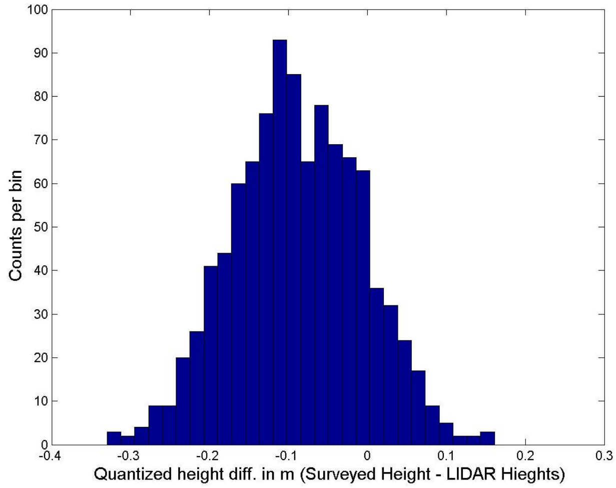

Figure 7: Height differences histogram between the laser height and the ground height.

5.2 Absolute planimetric accuracy

Planimetric offsets are more complicated to determine since they require especially significant features to establish the correspondence between the two data sets. Such features and locations for estimating the offsets may not be available or when they exist are usually limited. Moreover, identifying these locations is costly in time and requires great care in order to be reliable. Drainage ditches, terrain curvature, and building gable roofs are some examples of such features.

Eight locations as shown in figure 6 were identified and successfully used in obtaining the planimetric accuracy. Six of those locations were used to compute the offset in the X (Easting) direction and the other two were utilized to compute the offset in the Y (Northing) direction. Offsets in the X direction were given more attention since they coincide with the scanning direction. In each of these locations the data points from both data sets, LIDAR and ground, were identified as shown in figure 8(a). From each set, an estimated curve using least squares fitting was constructed (green solid line for the LIDAR points and red solid line for the ground points) representing the available data as shown in figure 8(b). The idea here is to match these two curves and obtain the shift that will maximize the match. Prior to that, the height bias should be removed in order exclude its effect in the matching. In figure 8(b) the green dashed curve represents the LIDAR data after removing the height bias between the two data curves.

To get the best match between the two curves, the LIDAR data curve will be shifted gradually around the ground data set in the direction of the computed offset (X as in figure 8). The shift ranged from –2m to +2m with an increment of 0.01m. At each increment, the offset (in the intended direction X or Y) of each ground point and its interpolated-correspondence point from the LIDAR curve data is computed. The sum of the squares of these offsets is considered as the matching cost at each location. Figure 8(c) shows the matching cost function behavior with respect to different shift values. At the minimum matching cost, which is associated with the best match between the two curves, the correspondence shift is obtained. Figure 8(d) shows the original data curves, after removing the height bias, and after the planimetric shift.

than two seconds of the scanning time which contains about 19,000 data points. Although the size of the test sample (1008 points) is sufficient to represent the sample, the distribution of the test points across the time span (the two seconds) was not ideal. Figure 9 shows the behavior of the absolute height error with respect to the time they were scanned.

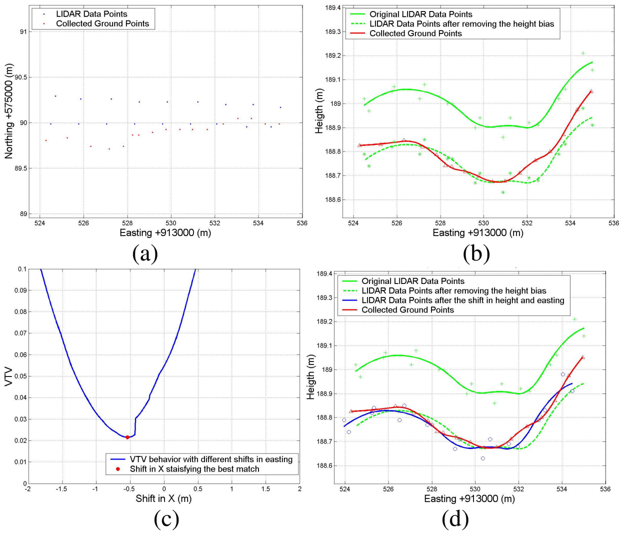

Figure 8: Planimetric offset in (X) direction at location EW3R.

As stated above, eight locations were tested to obtain the planimetric shift. In fact the number of these locations was limited since the area that was covered by the topographical survey does not contain many suitable features for that purpose. Table 1 summarizes the results at those selected locations. Regarding the offset in X (Easting) direction, which is across the flight direction and coincide with the scanning direction, six locations were selected, three at the edge of the swath width of strip 2 (EW1R, EW3R, and EW5R) and the rest at the middle of the strip (EW1L, EW3L, and EW5L). As expected at the strip edge, the offset in the scanning direction (-0.60m as an average) was larger than at the middle of the strip (-0.30m as an average). However, those shifts were in the same direction. The same thing could be said for the height bias, height offsets seem to be larger in magnitude at the edge of the strip. Unfortunately there were no significant features at the other end of the strip to have a complete idea of the planimetric accuracy behavior along the whole swath width. On the other hand, two locations were selected to test the accuracy along the flight direction Y (Northing), one at the middle of the strip (NS1) and the other one at the edge (NS2). The two locations show an offset of –0.55m and –0.40m, respectively, in the same direction.

Location	Height bias(m)	Direction	Plan. Offset (m)	Location in swath width
EW1R	-0.12	Easting X	-0.67	Right edge
EW1L	-0.03	Easting X	-0.28	Middle
EW3R	-0.23	Easting X	-0.54	Right edge
EW3L	-0.07	Easting X	-0.20	Middle
EW5R	-0.23	Easting X	-0.62	Right edge
EW5L	-0.08	Easting X	-0.43	Middle
NS1	-0.04	Northing Y	-0.55	Middle
NS2	-0.07	Northing Y	-0.40	Middle

Table 1: Planimetric accuracy results.

6. RESULTS, ANALYSIS, AND STATISTICAL CONCLUSIONS

To show the error behavior with respect to time, the LIDAR data points over the test area were sorted based on the time they were scanned. Then the calculated height differences (1008 biases) were sorted accordingly. The test area covered only less

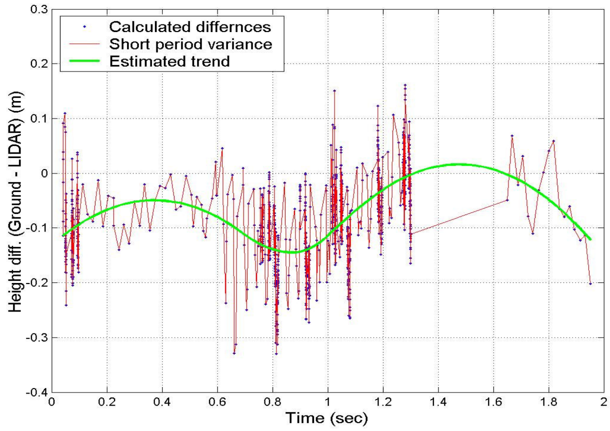

Figure 9: Height accuracy (Ground – LIDAR) versus time.

The height differences between the LIDAR points and their corresponding ground-surveyed points show two types of variations. The first type of variation is called short period variation. This variation has a high frequency as we can see in figure 10. This variation between two consecutive points could reach 0.30m as a maximum within 0.001sec. This short variation of the uncertainty of LIDAR heights gives an indication of the system precision since the consecutive points are so close to each other in the time domain and the test was conducted on a flat surface where the height is very nearly the same. On the other hand, as shown in figure 9, a data driven trend of the differences is observed which is the second form of the variation. A "trend" is defined in (Mikhail, 1976) as "it is that component of a random phenomenon which has a period larger than the recorded data sample", which can be seen clearly in figure 9. Although the test data represent only a small sample, this trend is very noticeable. The planimetric relative accuracy between data strips, see figure 5, ascertain this conclusion regarding the two forms of the random variation since the computation of the relative accuracy covers most of the data.

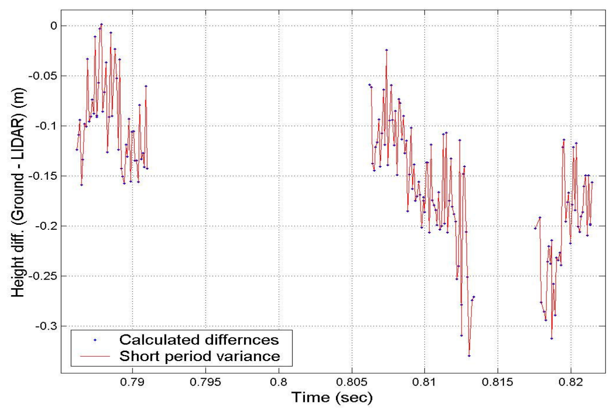

Figure 10: Short period variation of the height biases.

To conclude, the results will be summarized. A height offset of 0.08m was found between the surveyed ground points and the LIDAR data in the test area. The computed uncertainty of the

LIDAR heights over the test area is about ±0.20m which is slightly larger than the published height standard deviation of the system (±0.15m). Regarding the planimetric accuracy, the computed offsets in the scanning direction over the test area show two main outcomes. First, the planimetric uncertainty is larger (almost double) at the end of the swath than at the middle. So in general, the planimetric accuracy seems to vary based on the location along the swath width. At the end of the swath width the average offset was about 0.60m, while at the middle it was about 0.30m. The second outcome is that the whole strip seems to be shifted in the easting direction since all the computed offsets have the same direction.

Both accuracies, relative and absolute, show two types of variation. The first variation form is the short period random variation which has a high frequency with time. This random variation seems to represent the actual precision of the LIDAR system. The other variation form is the long period variation or "a trend". This trend has a much lower frequency and seems to be as a result of the error in the positioning system. If this trend is modeled and the data is adjusted accordingly, the accuracy of data will be improved. Testing more samples that cover different parts with a longer period of time is needed to verify these conclusions.

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REFERENCES

Baltsavias, E.P., 1999. Airborne laser scanning: Existing systems and firms and other resources. *ISPRS J*, vol. 54, pp. 164-198.

Burman, H., 1999. Adjustment of laserscanner data for correction of orientation errors. *In International Archives of Photogrammetry and Remote Sensing*, vol. 33, part B3/1, pp.125-132.

Casella, V., Spalla, A., 2000. Estimation of planimetric accuracy of laser scanning data. Proposal of a method exploiting ramps. *IAPRS* proceeding, Vol XXXIII, Part B3/1, Amsterdam, 16-23 Luglio 2000, pp. 157-163.

Georgiadou, Y., Kleusberg, A., 1988. On carrier signal multipath effects in relative GPS positioning. *Manuscripta Geodaetica*. Volume 13: 172-179.

Gonzalea, A., 1998. Horizontal Accuracy Assessment of The New Generation of High Resolution Satellite Imagery for Mapping Purposes, Master's Thesis, The Ohio State University, pp. 67-70.

Grewal, S., Weill, R., Andrews, P., 2001. *Global Positioning System, Inertial Navigation, and Integration*. A John Wiley & Sons, Inc, ISBN: 047135032X.

Mikhail, E. M., Gracie, G., 1976. *Observations and least squares*. IEP-A Dun-Donnelley, New York. ISBN: 0-7002-2481-5.

Mikhail, Edward M., Bethel, James S., McGlone, J. Chris., 2001. *Introduction to Modern Photogrammetry*., John Wiley & Sons, Inc, ISBN: 0-471-30924.

Morin, K., El-Sheimy, N., 2002. Adjustment of LIDAR Data. FIG Paper the *FIG XXII International Congress*, April 19-26, 2002, Washington, D.C., USA

Schenk, T., 1999. Photogrammetry and Laser Altimetry. In *International Archives of Photogrammetry and Remote Sensing*, 32(3W14).

Vosselman, G., 2002. On the estimation of planimetric offsets in laser altimetry data. In *International Archives of Photogrammetry and Remote Sensing* 34 (3A), pp. 375-380.

Wehr, A., Lohr, U., 1999. Airborne laser scanning - an introduction and overview. *ISPRS J*, vol. 54 (2/3), pp. 68-82.