LiDAR DATA ACCURACY: THE IMPACT OF PULSE REPETITION RATE

Nora Csanyi[1,2]
Charles K. Toth[2]
Department of Civil and Environmental Engineering and Geodetic Science[1]
Center for Mapping[2]
The Ohio State University
1216 Kinnear Road, Columbus OH 43212-1154
nora@cfm.ohio-state.edu

ABSTRACT

LiDAR has become a mainstream technology for surface data acquisition for a variety of large-scale mapping applications. Since demand for denser LiDAR data is growing, higher and higher pulse repetition rate LiDAR systems are introduced. The state-of-the-art LiDAR systems are capable of providing as high as 100 kHz or even 150 kHz pulse repetition rate. Due to limitations of the laser power supply on the aircraft, higher pulse repetition rate usually means lower energy of the emitted laser pulse, which in turn can result in the degradation of the accuracy of the measured range. Consequently, it is important to study the effect of increased pulse rate on LiDAR data accuracy. This paper provides an analysis of the effect of pulse repetition rate on the absolute LiDAR data accuracy. To support our investigations, a test flight was carried out with the Optech ALTM 30/70 LiDAR system. A transportation corridor was flown many times with different pulse repetition rates: 33, 50, and 70 kHz. To provide absolute control information in the LiDAR data to facilitate our analysis, 30 LiDAR-specific ground control targets were placed along the two sides of the road. The analysis revealed a noticeable relationship between LiDAR data accuracy and pulse rate. It was also found that using absolute control information the accuracy degradation with higher pulse rates can be compensated.

INTRODUCTION

LiDAR systems have seen significant developments in recent years (Renslow, 2005); the laser ranging accuracy improved to a 2-3 cm level, the availability of intensity signal became common, and the maximum pulse repetition frequency (PRF) increased significantly. Figure 1 shows the increase in the maximum pulse rate of LiDAR systems in recent years. While early systems provided as low as 5 kHz PRF, state-of-the-art LiDAR systems are now capable of working at 100 kHz (Optech ALTM3100) or even as high as 150 kHz (Leica Geosystems ALS50) pulse rate.

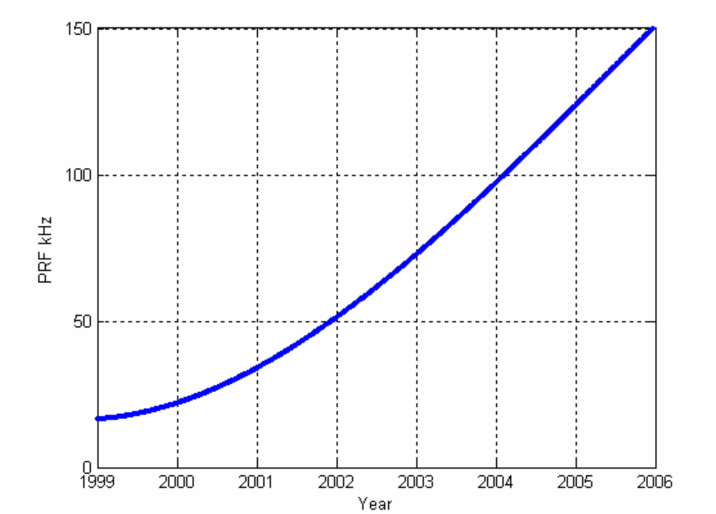


Figure 1. LiDAR pulse rate trend.

The maximum PRF is an important parameter of a LiDAR system since this is the primary factor to determine the point density. An increase in point density has obvious advantages; the denser the data, the better the potential to extract more detailed geospatial information. In addition, this increase in PRF, resulting in significant increase in LiDAR point density, could lead to new application areas of LiDAR. Besides the obvious advantage of using increased PRF, the reduced pulse energy associated with the higher PRF generally also means degradation in accuracy.

There are two factors that limit the increase of the maximum PRF: (1) the travel time of the laser pulse, and (2) the limited laser source power related somewhat to aircraft power supply availability. Figure 2 shows the theoretical limits of the pulse rate for the typical flying height range as defined by the signal travel time, ignoring any sensing latency and time delays by hardware. The figure also shows the Optech ALTM 3100 and the Leica Geosystems ALS50 operational envelops. From the curves it is clear that the conventional systems are beginning to run into a technological limit and there is virtually no more room to significantly increase the pulse rate of the current systems, except for very low altitude flights, in which case, however, the area coverage would be very small (Toth, 2004).

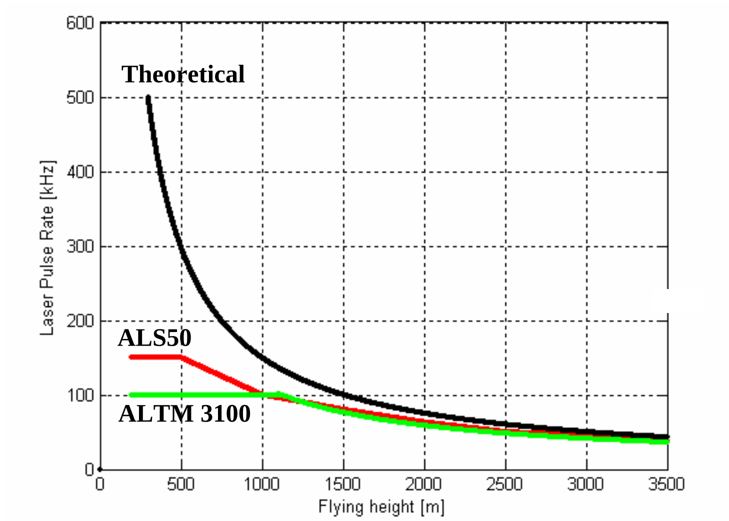


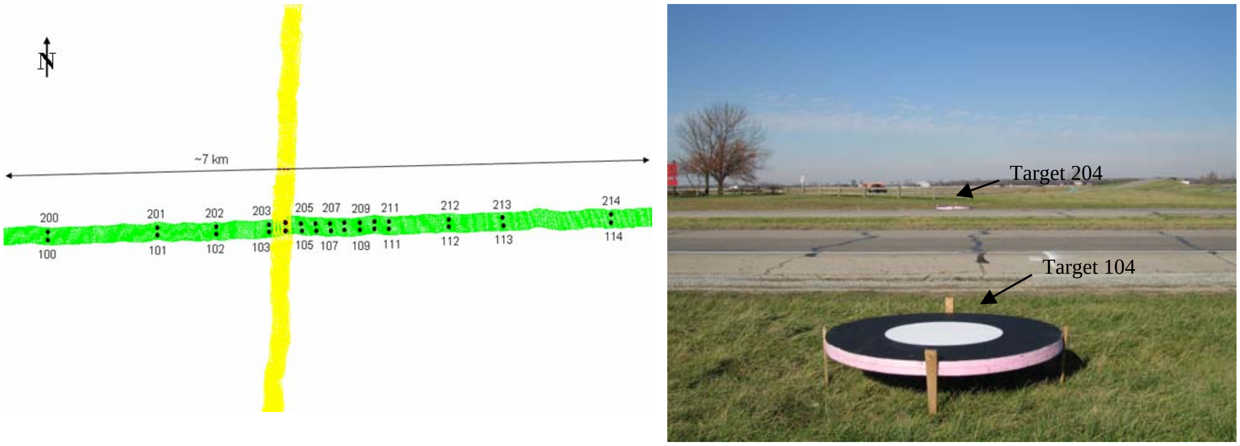
Figure 2. Pulse rate limit due to pulse travel time.

The main factor of the implementation that limits the increase of the PRF is the limited energy of laser source power. Therefore, typically in case of the current systems increasing the PRF results in lower energy of the emitted laser pulse, which, in turn, can result in the degradation of the accuracy of the measured range, and consequently in the accuracy of the acquired data. This aspect of increasing the PRF in order to achieve the desirable higher point density is often overlooked and there have only been a limited number of studies conducted about the effect of increased PRF on the LiDAR data accuracy.

This paper describes the results of a study on the effect of increased PRF on LiDAR data accuracy for an Optech ALTM 30/70 LiDAR system. The first section provides the details of the LiDAR test flight and LiDAR target arrangement to support our analysis. This is followed by the results of the accuracy analysis and discussion.

TEST FLIGHT ARRANGEMENT

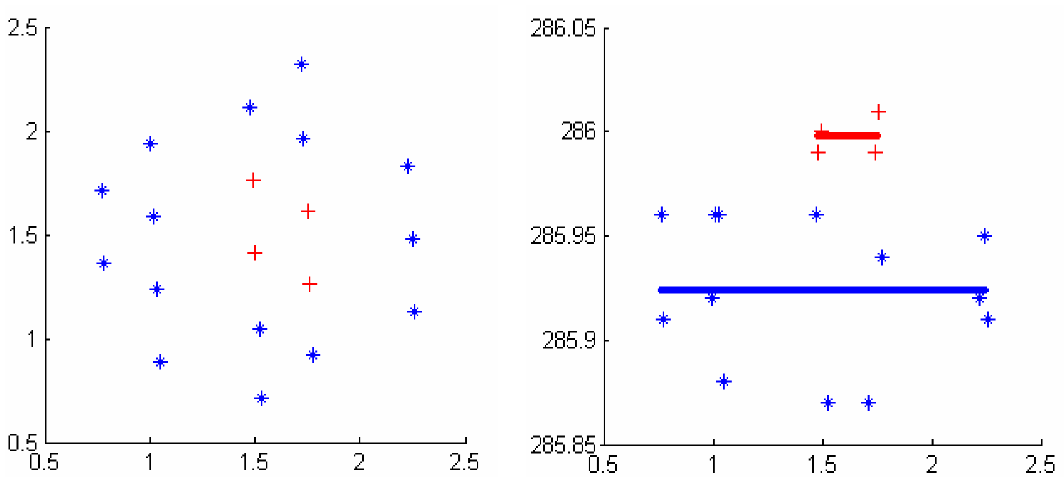
To study the effect of pulse rate on LiDAR data accuracy, data from a test flight, carried out in Madison county Ohio with an Optech ALTM 30/70 LiDAR system was analyzed. During the flight that was supported by the Ohio Department of Transportation, several strips were flown over US Route 40 in both directions and couple of cross strips with various LiDAR settings (33, 50, 70 kHz PRF), each from an about 700 m flying height (AGL). To provide absolute control information in the LiDAR data, 15 pairs of LiDAR targets were placed symmetrically along the two sides of the road with varying alongside distance (130 m, 450 m, and 950 m) between two pairs of targets. The target positioning accuracy in LiDAR data is crucial since that determines the lower boundary for errors in the data that can be detected based on the LiDAR targets. A study was conducted earlier by the Center for Mapping, The Ohio State University to develop an optimal LiDAR-specific target design (more details can be found in Csanyi and Toth, 2006 and Csanyi et al., 2005). Based on that target design, the targets used for this analysis were fabricated by the Ohio Department of Transportation. Figure 3 (a) shows the strips flown and the location of the target pairs, while Figure 3 (b) illustrates the image of one target pair placed along the road. To provide control coordinates, the target centers were GPS surveyed with an approximately 2 cm vertical accuracy.



(a) (b)

Figure 3. Location of target pairs in the LiDAR data (a), and photo of a target pair (b).

The two-concentric-circle target design with black and white coating not only provided a tool for reliable accuracy analysis but also for the analysis of the effect of reflectivity on the range measurement. This phenomenon is a well-understood by LiDAR vendors. In general, targets with low reflectivity appear lower, while targets with high reflectivity appear higher in LiDAR data if intensity-based correction is not applied. LiDAR vendors provide intensity-based calibration tables that are routinely applied at LiDAR data processing to correct for this effect. The LiDAR targets due to their two-circle-design with substantially different reflectivity provided an excellent tool to check this effect as well as the effectiveness of the provided intensity-based correction tables. Figure 4 shows LiDAR points fallen on a LiDAR target in top view (a) and in side view (b) before the intensity-based correction was applied to the data.



(a) (b)

Figure 4. LiDAR points on target in top view (a) and side view (b) before correction.

Figure 4 clearly shows that LiDAR points on the inner white circle of the target with high reflectivity have an about 7cm higher mean elevation than the mean elevation of points fallen on the black outer ring with low reflectivity, even though the target has a flat surface. After applying the intensity-based correction table to the LiDAR data, shown in Figure 5 for 70 kHz PRF as provided by the vendor, the mean elevation difference between inner white circle points and outer black ring points decreased to 1 cm as shown in Figure 6.

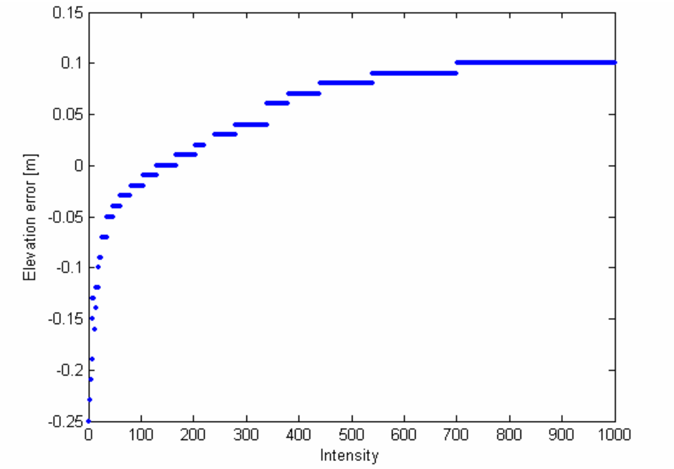


Figure 5. Intensity calibration table for Optech ALTM 30/70 for 70 kHz PRF.

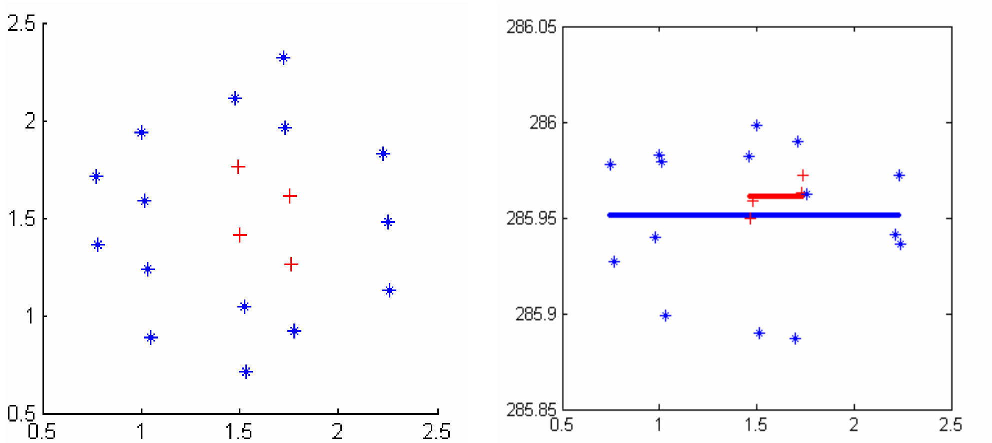


Figure 6. LiDAR points on target in top view (a) and side view (b) after correction

EFFECT OF PRF ON LiDAR DATA ACCURACY

To analyze the effect of the pulse repetition frequency on LiDAR data accuracy as well as to see if there is any remaining effect of reflectivity on the accuracy after the intensity-based correction was applied, the following method was applied. All LiDAR points on all LiDAR targets in all strips flown with 33 kHz, 50 kHz, and 70 kHz PRF were automatically identified (details of target identification method can be found in Csanyi and Toth, 2006) and the elevations for each point were compared to GPS-measured control coordinates. Figure 7 shows the differences found as a function of the intensity value of the points. The figures also show fitted lines to the point clouds.

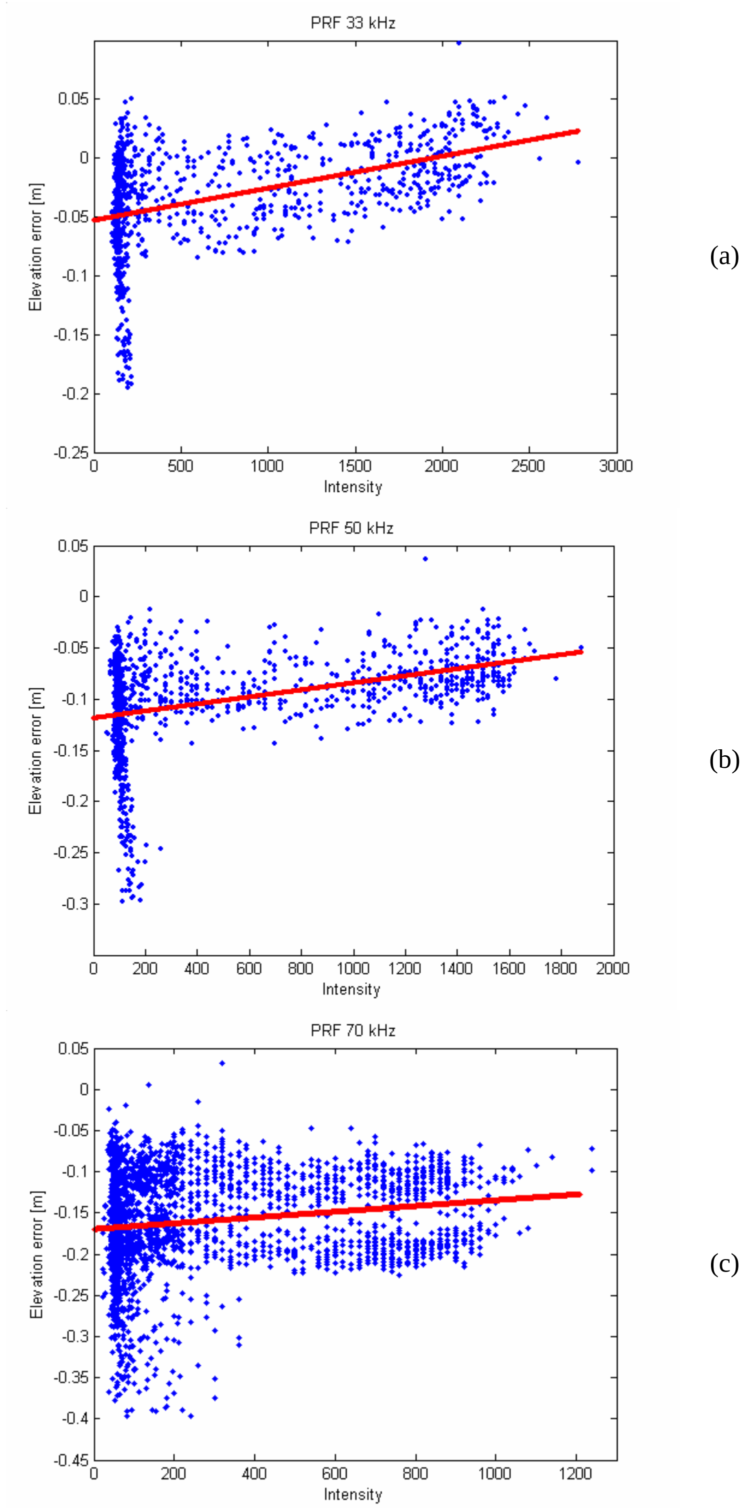


Figure 7. Vertical differences at target points, all targets in all strips flown with 33 (a), 50 (b), and 70 kHz PRF (c).

The Figure 7 illustrates that even after applying the intensity-based correction to the data, there is still some dependency of the LiDAR point elevation error on the reflectivity for all strips flown with various PRF settings. Significantly higher errors were found at points with low intensity values than for points with high values suggesting that the currently used intensity calibration tables do not completely compensate for the effect of reflectance on elevation error.

Analyzing the effect of PRF on LiDAR data accuracy, as Figure 7 illustrates, the major findings based on these test results can be summarized as (1) the mean elevation error is smallest for the 33 kHz strips, for the 50 kHz strips it is larger, and it is the largest for the 70 kHz strips; (2) the standard deviation of the LiDAR points fallen on a flat surface is increasing with increasing PRF, although the increase is not significant. By comparing Figure 7 (a), (b) and (c), it was also found that as expected, higher PRF setting results in smaller intensity range of the LiDAR points as the signal gets weaker (Ahokas et al, 2006). For better comparison between the 33, 50, and 70 kHz LiDAR strips, Figure 8 shows the above three figures together and Table 1 summarizes the major differences found after analyzing the LiDAR strips flown with different PRF settings. The coefficients *a* and *b* in Table 1 refer to the intercept and gradient of the fitted line to each point cloud as:

$$elev\_error = a + b \cdot Intensity$$

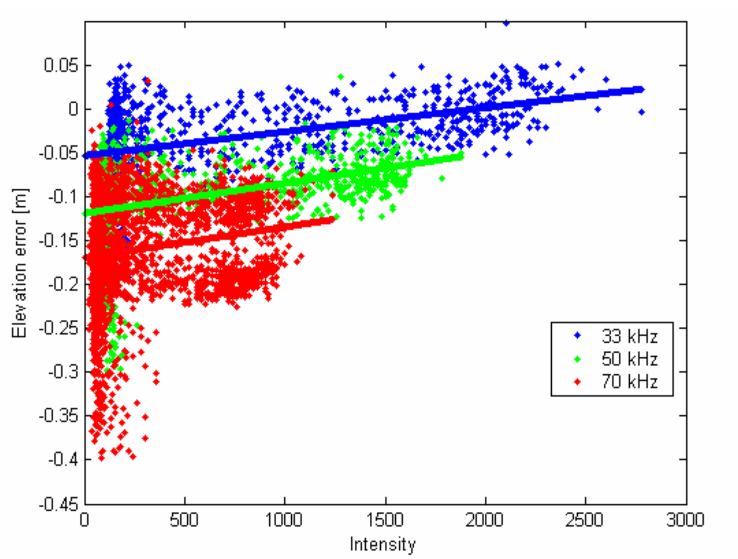


Figure 8. Vertical differences at all target points in all strips.

Table 1. Comparison summary of LiDAR strips flown with different PRF.

PRF [kHz]	Std [m]	Intensity range	a	b
33	0.045	104-2780	-0.053	0.0027
50	0.048	55-1880	-0.119	0.0034
70	0.062	21-1240	-0.170	0.0035

The intercept values of the fitted lines clearly show an increase in mean elevation error for strips flown with higher PRF. Furthermore, the gradients of the fitted lines being different from zero clearly suggest a dependency of the point elevation on the reflectivity of the target.

Besides the effect of PRF, many other error sources contribute to the errors found at the target locations, and therefore, the errors were also analyzed separately for each LiDAR strip (more details can be found in Csanyi, 2006; and on common errors in Baltsavias, 1999). Table 2 shows the mean elevation errors at the target locations together with the standard deviation of the errors for each LiDAR strip separately. The table also shows the number of targets identified in each strip, and the pulse rate, scan frequency, and the scan angle settings for the strip. It should be noted that the strips where only 2-4 targets were identified are cross strips. The standard deviation values of the average target elevation errors within each strip are 1-3 cm, which indicates that the errors found at the target locations are consistent within each strip. The strips are grouped by pulse rate frequency since a noticeable relationship was found between the pulse rate frequency setting for the strips and the mean elevation error found at the targets.

Table 2. Mean vertical target elevation errors and their standard deviation values in the different strips.

Strip ID	PRF [kHz]	Scan Freq [Hz]	Scan Angle [deg]	Point Density [pts/m^2]	Mean Target Elevation Difference [m]	Std Elevation Difference [m]	Number of Targets in Strip
4	**70**	70	10	**7.7**	**-0.20**	**0.02**	30
2b	**70**	70	10	**7.7**	**-0.20**	**0.02**	30
4b	**70**	70	10	**7.9**	**-0.11**	**0.01**	29
5b	**70**	70	10	**8.9**	**-0.13**	**N/A**	2
8b	**70**	70	10	**7.2**	**-0.15**	**N/A**	2
7	**70**	50	20	**4.2**	**-0.12**	**0.02**	29
8	**70**	50	20	**4.2**	**-0.12**	**0.01**	25
15	**70**	50	20	**3.7**	**-0.11**	**0.03**	3
19	**70**	50	20	**4.7**	**-0.13**	**0.02**	4
				Mean	**-0.14**		
				Std	**0.04**		
11	**50**	63	10	**5.6**	**-0.10**	**0.02**	28
18	**50**	63	10	**5.8**	**-0.10**	**N/A**	2
10	**50**	44	20	**3.2**	**-0.12**	**0.02**	19
13	**50**	44	20	**3.0**	**-0.10**	**0.02**	22
14	**50**	44	20	**3.0**	**-0.07**	**0.02**	20
17	**50**	44	20	**2.8**	**-0.08**	**N/A**	2
				Mean	**-0.10**		
				Std	**0.02**		
2	**33**	51	10	**3.8**	**-0.05**	**0.02**	23
5	**33**	51	10	**3.4**	**-0.03**	**0.02**	19
12	**33**	51	10	**4.3**	**0.00**	**0.02**	27
9	**33**	36	20	**1.8**	**-0.06**	**0.01**	11
				Mean	**-0.04**		
				Std	**0.03**		

Table 3. Mean residual vertical target elevation errors and their standard deviation values in the different strips after 3D similarity transformation.

Strip ID	PRF [kHz]	Scan Freq [Hz]	Scan Angle [deg]	Point Density [pts/m2]	Mean Target Elevation Difference [m]	Std Elevation Difference [m]	Number of Targets in Strip
4	**70**	70	10	**7.7**	**0.00**	**0.02**	30
2b	**70**	70	10	**7.7**	**0.00**	**0.02**	30
4b	**70**	70	10	**7.9**	**0.00**	**0.01**	29
5b	**70**	70	10	**8.9**	**0.00**	**N/A**	2
8b	**70**	70	10	**7.2**	**0.00**	**N/A**	2
7	**70**	50	20	**4.2**	**0.00**	**0.02**	29
8	**70**	50	20	**4.2**	**0.00**	**0.01**	25
15	**70**	50	20	**3.7**	**0.00**	**0.03**	3
19	**70**	50	20	**4.7**	**0.00**	**0.02**	4
11	**50**	63	10	**5.6**	**0.00**	**0.02**	28
18	**50**	63	10	**5.8**	**0.00**	**N/A**	2
10	**50**	44	20	**3.2**	**0.00**	**0.02**	19
13	**50**	44	20	**3.0**	**0.00**	**0.02**	22
14	**50**	44	20	**3.0**	**0.00**	**0.02**	20
17	**50**	44	20	**2.8**	**0.00**	**N/A**	2
2	**33**	51	10	**3.8**	**0.00**	**0.02**	23
5	**33**	51	10	**3.4**	**0.00**	**0.01**	19
12	**33**	51	10	**4.3**	**0.00**	**0.01**	27
9	**33**	36	20	**1.8**	**0.00**	**0.02**	11

After analyzing the errors found at the target locations, a 3D similarity transformation, applied to each strip separately, was found to be adequate to correct for errors in the strips. Table 3 shows the mean residual elevation errors at the target locations for each LiDAR strip. As the table illustrates, after the 3D similarity transformation, errors found were corrected and even for the 70 kHz strips where originally larger errors were found. After the correction the mean elevation error decreased to zero for each strip. Out of the seven parameters of the 3D similarity transformation, typically the shift parameters are significant, the rotation angles are usually insignificant, and the scale is practically always 1.

CONCLUSIONS

In this paper the impact of pulse repetition rate on LiDAR data accuracy was analyzed using data collected by an Optech ALTM 30/70 LiDAR system operated with 33, 50, and 70 kHz PRF settings. The LiDAR-specific ground control targets with their two-concentric-circle-design used for the accuracy analysis also provided an excellent tool for analyzing the effect of reflectivity on range measurement and for evaluating the quality of the current intensity-based calibration for the Optech ALTM 30/70 system.

The analysis revealed a noticeable dependency of LiDAR point accuracy on the PRF. After analyzing several strips flown with 33, 50, and 70 kHz PRF settings, the smallest elevation errors at target locations were found in the strips flown with 33 kHz PRF, for strips flown with 50 kHz PRF the elevation errors were larger, and the largest elevation errors were found in strips flown with 70 kHz PRF. The elevation errors at the 30 target locations were found to be consistent within each strip. Even for the 70 kHz strips where the relatively larger errors were found, the errors could be easily corrected by applying appropriate transformation to each LiDAR strip using the targets. The analysis also revealed an increase in standard deviation of the LiDAR points with increasing PRF but it was found to be small.

The dependency of elevation error on reflectance was also analyzed and the results suggest that the intensity-based calibration does not entirely account for the effect of reflectivity. Our test inidicated that the effect of reflectivity on elevation error was the largest for LiDAR points with very small intensity values. These results indicate that the current intensity calibration could be further refined.

REFERENCES

Ahokas, E., S. Kaasalainen, J. Hyyppa, J. Suomalainen, 2006. Calibration of the Optech ALTM 3100 laser scanner intensity data using brightness targets, Proceedings of ISPRS Commission I Symposium.

Baltsavias, E.P.,1999. Airborne laser scanning: basic relations and formulas. ISPRS Journal of Photogrammetry & Remote Sensing Vol. 54, pp. 199-214.

Csanyi N, C. Toth, 2004. On using LiDAR-specific ground targets, ASPRS Annual Conference, Denver, CO, May 23-28, CD-ROM.

Csanyi N, C. Toth, D. Grejner-Brzezinska, and J. Ray, 2005. Improving LiDAR data accuracy using LiDAR-specific ground targets, ASPRS Annual Conference, Baltimore, MD, March 7-11, CD-ROM.

Csanyi N, 2006. Precision LiDAR Mapping of Transportation Corridors Using LiDAR-Specific Ground Targets, Geospatial Information Systems for Transportation Symposium, March 27-29, 2006, http://www.gis-t.org/yr2006/Proceedings/csanyi-Submission.pdf .

Csanyi, N., and C. Toth, 2006. Improvement of LiDAR Data Accuracy Using LiDAR-Specific Ground Targets, Accepted for publication in Journal of Photogrammetric Engineering & Remote Sensing.

Renslow, M., 2005. The Status of LiDAR Today and Future Directions, 3D Mapping from InSAR and LiDAR, ISPRS WG I/2 Workshop, Banff, Canada, June 7-10, CD-ROM.

Toth, C. 2004: Future Trends in LiDAR, Proc. ASPRS 2004 Annual Conference, Denver, CO, May 23-28, CD-ROM.