

STRIP ADJUSTMENT OF LIDAR DATA

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ABSTRACT:

Light Detection And Ranging (LIDAR) is a technique, which allows for measuring a huge amount of object point coordinates with accuracies up to some centimeters in short time. Their conversion into a highly accurate **Digital Terrain Model (DTM)** requires a careful handling of the single processing steps, from the flight planning until the manual revision of the generated DTM, considering the different error sources. In addition it must be ensured, that the LIDAR system maintains correctly calibrated during all the flight sessions.

This paper describes a simple adjustment approach, which compensates for the mayor part of systematic vertical errors, mainly originating from the GPS, and it allows for almost automatic processing also of huge amounts of laser data. The approach was developed and applied in the framework of a real project, whose objective was to generate a highly accurate DTM of the Eastern Ter river. The obtained results of two selected sub-blocks are presented, which are also verified by independent check points.

1. INTRODUCTION

LIDAR is affected by many error sources, contaminating the laser data with random and systematic errors. The analysis and the adequate modeling of those errors in the data processing is a mayor issue of research since LIDAR has become a recognized and widely used mean to generate high quality DTMs. A comprehensive survey of those errors e.g. can be found in [Schenk, 2001]. There also exist quite a series of approaches to reduce systematic errors in laser strips (see e.g. [Crombaghs et al. 2000], [Maas 2000] or [Vosselman and Maas, 2001]), which partly have already been implemented in commercial software packages [Burman 2002]. The approaches are quite complex, either non-automatic or limited to small data samples, which poses problems to a time- and cost-effective compilation of that large amount of data, that modern 25- or 50-kHz LIDAR-Systems are able to collect.

This paper describes a rather simple approach, which is almost fully automatic and allows for accurate DTM generation of wide areas in reasonable time. It was developed and applied in the framework of the “Ter-project”, whose objective was to generate a highly accurate DTM of the Eastern Ter river, an area of approximately 200 km². Since the accuracy requirements were high in altitude, but low in planimetry, the approach concentrates on the modeling of height errors and neglects horizontal errors in a first approximation.

The entire data set is subdivided into 4 sub-blocks (Central, West, North and South). In the following the approach is described and the results, which have been obtained in the project, are outlined and discussed. Since the results for the 4 sub-blocks came up quite similar, this paper only refers to the Central and the Western sub-blocks (in the following called block A and B), for which also two check-sites with additional independent check points were available.

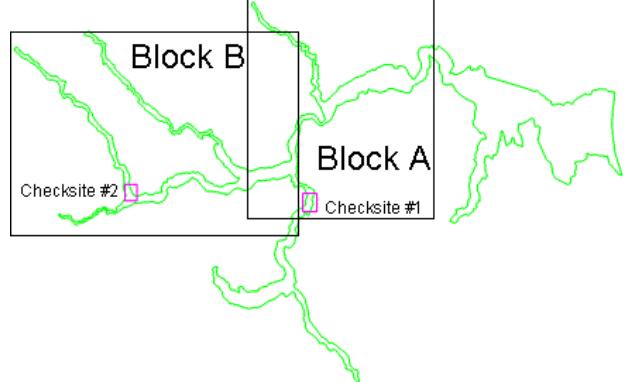


Figure 1: Location of blocks A and B of the Ter-project

2. PREPARATION

The approach implies a special block design and, of course, it also requires a well calibrated LIDAR system

2.1 Block design

The modified block design employs additional crossing flight strips and control areas (CAs). Their numbers depend on the size and the shape of the block. Each data strip must be covered by at least one crossing strip, i.e. for a regular block with all parallel flight strips one crossing strip and one CA is sufficient, while in case of more complicated block shapes more crossing strips may be required. To increase redundancy and confidence of the later adjustment it is recommended, that CAs are covered by a crossing flight strip and longer data strips are crossed by

more than one strip. The latter will reduce errors, introduced by GPS accuracy variation, which might occur during long strips. If the block consists of a series of different regular sub-blocks, as it is the case in the example shown in Figure 2, isolated sub-blocks should be fixed by an additional CA.

As CAs usually soccer fields are selected, which are plane and thus, a possible horizontal error in a laser point would not affect its vertical component. As an example, Figure 2 shows the design of block A, containing 5 CAs and 50 data strips. In this project more than 20 control points were measured within each CA by field survey.

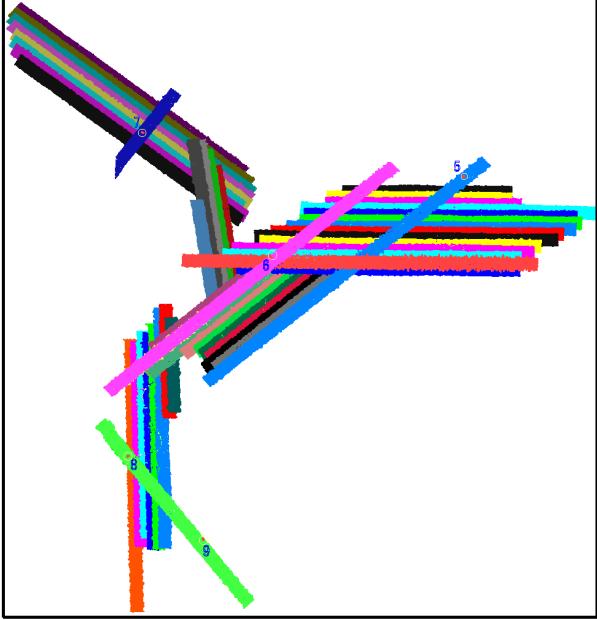


Figure 2: Data strip configuration of block A including five control areas #5-#9. The size of the circumscribing rectangle is 20x21km.

2.2 Flight and system parameters

The applied flight and system parameters are listed in Table 1. For eye safety reasons the flying height is 2,300 m. Adjacent strips were flown with a side-overlap of 50%, resulting in a mean point density of almost 2 points/m².

| | |
|------------------------|---------------------------|
| Airplane | Partenavia P-68C Observer |
| LIDAR system | ALTM 2025-E |
| Flying speed | 222 km/h |
| Flying altitude | 2,300 m (above ground) |
| GPS frequency: | 1 Hz |
| INS frequency: | 200 Hz |
| Laser repetition rate: | 25,000 Hz |
| Scan frequency: | 42 Hz |
| Scan width: | ± 5° |
| Swath width: | 402 m |
| Strip side-overlap | 50% |
| Beam divergence: | 0.2 mrad |
| Foot print size: | 0.46 m |

Table 1: Flight and system parameters

According to the accuracy requirements our concerns mainly concentrate on the reduction of the height errors, rather than the

horizontal errors of the LIDAR points. A narrow scan angle of ±5° keeps the effect of the attitude and the mirror angle errors on the measured height values small. Their bigger horizontal effects are considered to be still small enough to be neglected.

The same way we care only for GPS height errors (rather than horizontal errors), which probably constitute the major error source in the DTM generation process. Due to the spatial distribution of the visible GPS satellites the GPS height errors are normally larger than the horizontal errors.

The data collection was restricted to GPS windows with at least 6 visible satellites and a PDOP of 4 or less at a maximum distance to the GPS ground station of 30 km. Although the trajectory of the sensor has been computed to an estimated accuracy of 10 cm we obtained poor absolute accuracy of the LIDAR data with systematic errors up to 20 cm [Ruiz et al. 2002]. These large shifts have also been found by other investigators [Huisings et al. 1998], [Crombaghs et al. 2000].

The LIDAR system is calibrated by calibration flights over a large building of known coordinates and over a flat surface (airport runway). The calibration results obtained over the past year show more or less stable values for the roll and pitch correction, while the scale factor and also the height offsets show a considerable variation over time. Therefore the calibration parameters, especially the scale factor, are checked regularly at the beginning and the end of a project. The height offsets are a consequence of the GPS errors and will be corrected by the described method.

3. BLOCK ADJUSTMENT

The block adjustment is based on the assumption that each data strip is affected only by a constant shift in height. The following gives a brief description of the observations entered in the adjustment, the adjustment model and the results, which have been achieved.

3.1 Generation of the observations

The following three observation groups enter in the block adjustment:

1. height differences between crossing data strips,
2. height differences between data strips and CAs,
3. pseudo-observations for the heights of the CAs.

For the generation of the first observation group, first, the locations of the strip crossings are detected. For this task the program reads the output of the CCNS-4 navigation system (it could also be done using the LIDAR data themselves) and computes a ground DTM with a regular grid from the laser points for each strip at each crossing area. The height differences between corresponding grid points are statistically analyzed, outliers are eliminated and the mean height difference observation is calculated. The a priori weight of the observation is defined as a function of the calculated standard deviation.

In case of the second observation group also a ground DTM is generated and the mean difference between the heights of all control points and the respective interpolated DTM heights within the CA is computed. The a priori weight is defined as a function of the calculated standard deviation of the mean height difference and the standard deviation of the control points.

Very simple models were computed as ground DTMs. Regular grid models of 2 m grid step were generated for each strip by selecting the lowest point in each grid cell. With this method buildings and, in some cases, vegetation are not properly filtered but it was enough for the purposes of the block adjustment. The artefacts that could appear in one strip usually appear also in the others and their effect in the results is negligible.

The pseudo-observations of the third group establish an absolute height reference at each CA, which is set to 0.0 m. Their a priori weight is a function of the control point measurement accuracy (in our example between 1 and 3 cm), which is supposed to be significantly higher than the expected laser point accuracy.

3.2 Functional model

The functional model is quite simple and employs one unknown for each data strip, representing its vertical deviation from the reference height, and also one unknown for each CA (reference) height, fixed at 0.0 m by highly weighted pseudo-observations (third observation group). Thus, a possible deviation of the mean data strip height from that reference height is expressed in its corresponding unknown, which later can directly be applied to correct the laser point heights of the respective strip. All the processing steps from the generation of the observations up to the final correction of the laser point heights run fully automatically.

3.3 Results

Besides the results of the block adjustments, which are discussed in the following section, the final DTM has also been verified using additional independent check points, measured by field survey (see 3.3.2).

3.3.1 Results of adjustment

Table 2 lists the statistic values of the residuals for the observation groups #1 and #2. The standard deviations of group #1 are below 2 cm with a maximum value of 5 cm. Compared to the laser point accuracy, specified by the manufacturer with < 25 cm at 2000 m flying altitude, these values are small and confirm the good performance of the applied adjustment.

| | Block A | | Block B | |
|-------------------|---------|--------|---------|--------|
| Group | #1 | #2 | #1 | #2 |
| # of observations | 140 | 10 | 208 | 27 |
| Min [m] | -0.031 | -0.026 | -0.029 | -0.086 |
| Max [m] | 0.050 | 0.018 | 0.049 | 0.032 |
| Sigma [m] | 0.014 | 0.014 | 0.011 | 0.029 |

Table 2: Statistics of estimated residuals. Group #1 refers to height differences between data strips, #2 between data strips and CAs

The higher residuals of group #2 in block B indicate still some problems in the control point measurements in at least one CA, i.e. here, the entered standard deviations of the third observation group (pseudo-observations) might have been chosen as too optimistic. However, the maximum value of 8.6 cm is even far within the expected accuracy range.

In Figure 3 the estimated height corrections for the single data strips are graphically represented, day-wise and in chronological order. It shows clearly, that the corrections are affected by systematic errors, which depend both on the day and on the time during the single data session. The zig-zag-characteristic of the curves might indicate remaining calibration errors affecting the laser point heights in the order of a few centimeters.

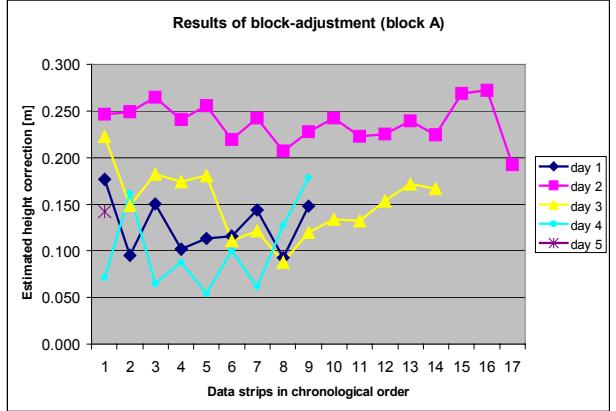


Figure 3: Estimated height corrections for the single data strips of block A

Table 3 contains the statistics of the estimated height corrections. The daily effect is expressed as the respective mean correction (*Mean*), which varies between 10.2 and 18.4 cm. Besides this global effect there also exist variations (*Range*) within the single data sessions of the same order of magnitude. The major part of those errors is assumed to be caused by the GPS.

| Day | #1 | #2 | #3 | #4 | #5 | all |
|-------------|-------|-------|-------|-------|-------|-------|
| Block A | | | | | | |
| # of strips | 9 | 17 | 14 | 9 | 1 | 50 |
| Min [m] | 0.093 | 0.192 | 0.088 | 0.054 | 0.142 | 0.050 |
| Max [m] | 0.177 | 0.272 | 0.223 | 0.179 | 0.142 | 0.270 |
| Range [m] | 0.084 | 0.080 | 0.134 | 0.125 | 0.000 | 0.220 |
| Mean [m] | 0.126 | 0.237 | 0.138 | 0.102 | 0.142 | 0.165 |
| Sigma [m] | 0.029 | 0.022 | 0.030 | 0.046 | - | 0.062 |
| Block B | | | | | | |
| # of strips | 9 | 24 | 16 | 21 | - | 70 |
| Min [m] | 0.016 | 0.101 | 0.142 | 0.051 | - | 0.016 |
| Max [m] | 0.126 | 0.202 | 0.258 | 0.217 | - | 0.258 |
| Range [m] | 0.110 | 0.101 | 0.116 | 0.166 | - | 0.242 |
| Mean [m] | 0.066 | 0.144 | 0.184 | 0.129 | - | 0.139 |
| Sigma [m] | 0.035 | 0.028 | 0.029 | 0.038 | - | 0.047 |

Table 3: Statistics of the estimated height corrections

3.3.2 Verification of the DTM accuracy

After applying the estimated height corrections, the laser points were tile-wise classified and a regular DTM with 1 m grid spacing was produced from the ground-points using the software package TerraScan [Terrasolid, 2002].

To verify the final DTM accuracy altogether 174 independent check points were measured by field survey in 13 areas of different vegetation types. Six areas are distributed within

check-site #1 and seven areas within check-site #2 (see Figure 1). The laser data of check-site #2 has been collected in March, the data of check-site #1 in July with the vegetation more developed.

In Table 4 the empirical accuracy of the DTM is indicated for different vegetation types. N denotes the number of measured check points in that area, $Diff.$ the mean difference between the measured heights and the final DTM and σ the respective standard deviation. The height of the cereal plants in the test areas 13 and 26 has not been measured at the time of flight, but it is estimated to be approximately 1 m.

The values demonstrate, that there are no significant deviations between the DTM and the measured check points. All differences are less than 30 cm and fulfill the accuracy requirements. In test areas 14 and 15, which show the highest differences, only a few laser shots reached the ground due to the dense foliage of the poplar and plane trees. Therefore the DTM is less accurate in these parts. For the other check-sites the empirical accuracy remains below 10 cm.

| Area | Vegetation | | N | Diff. | σ |
|----------|---------------|------------|-----|-------|----------|
| | Type | Height [m] | | [m] | [m] |
| 11 | Asphalt | 0.0 | 10 | 0.07 | 0.05 |
| 12 | Soil | 0.0 | 12 | 0.01 | 0.05 |
| 13 | Cereal plants | 1.0 (?) | 12 | 0.06 | 0.05 |
| 14 | Poplars | 8.0 | 12 | 0.10 | 0.10 |
| 15 | Plane (trees) | 8.5 | 12 | 0.14 | 0.36 |
| 16 | Mixed forest | 10.3 | 20 | 0.00 | 0.08 |
| Σ | Site #1 | | 88 | 0.08 | 0.14 |
| 21 | Asphalt | 0.0 | 10 | -0.04 | 0.03 |
| 22 | Soil | 0.0 | 12 | -0.05 | 0.03 |
| 23 | Shrubbery | 1.1 | 20 | 0.00 | 0.06 |
| 24 | Shrubbery | 1.3 | 10 | 0.05 | 0.05 |
| 25 | Hazel-bush | 5.2 | 20 | 0.01 | 0.04 |
| 26 | Cereal plants | 1.0 (?) | 12 | 0.02 | 0.04 |
| 27 | Poplars | 14.3 | 12 | 0.07 | 0.07 |
| Σ | Site #2 | | 96 | 0.01 | 0.06 |
| Σ | Sites #1+#2 | | 174 | 0.04 | 0.11 |

Table 4: Mean differences between independent check points and the final DTM for different vegetation types

4. CONCLUSION

It is demonstrated, that the presented approach is suitable to generate high quality digital terrain models with accuracy in the decimeter level of wide areas in an almost fully automatic way. It is based on a block adjustment of crossing laser data strips and the estimation of height correction values for each strip.

In a future version we would like to take into account a linear drift along the strip. Its effect could be important in long strips but we will require more transversal strips. We also would like to introduce global offsets for roll, pitch, heading and scale factor that would improve the calibration parameters but this requires measuring horizontal offsets what is much more complex.

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