ON THE ADJUSTMENT OF OVERLAPPING STRIPS OF LASERALTIMETER HEIGHT DATA

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KEY WORDS: Laser, accuracy, corrections, quality control, data processing, GPS, INS, software

ABSTRACT

From the beginning of the nineties up until now the Dutch Survey Department (Meetkundige Dienst Rijkswaterstaat) has put out to contract several airborne laser altimetry projects. In order to be able to check and to improve the quality of the delivered laser data, a strip adjustment procedure concerning the heights has been developed at the Survey Department. This enables to correct for systematic height errors occuring per strip, that is for an offset as well as an along-track and an across-track tilt of every strip. Unfortunately, this way of considering the strip as stiff and flat board turned out not always to suffice. Therefore, further correction tools have been created to eliminate possible occuring cross strip parabolic effects and to handle strip torsions or periodic effects. Apart from quality analysis of real data, some simulation computations have been done to investigate the maximal achievable theoretical precision in case of adding much more ground control points and extra cross laser strips. Averaging the heights of an area of 0.01 km^2, a precision of 1-2 cm seems to be achievable for the mean height.

1 'RIBBELS' IN LASERALTIMETER HEIGHT DATA

For a few years, a new digital elevation model for the surface of the entire Netherlands has been acquired using airborne laser scanning with a density of one point per 16 m². The new DEM is expected to be completed in 2001. For the acquisition task, the Survey Department contracted several companies. The flightplans for the acquisition of laserdata resemble those of photogrammetry. The terrain is being sampled in blocks consisting of several overlapping parallel strips. These strips can be tens of kilometres in length and several hundred metres wide. Besides, a certain number of cross strips is flown for checking purposes and some ground control 'points' per block are measured.

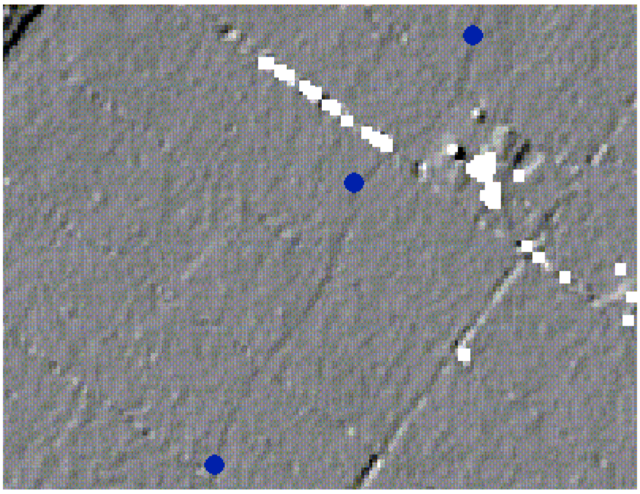

Figure 1a: 'Ribbel' in heightdata marked by dots
(the straight line is a real ditch; white pixels = no data)

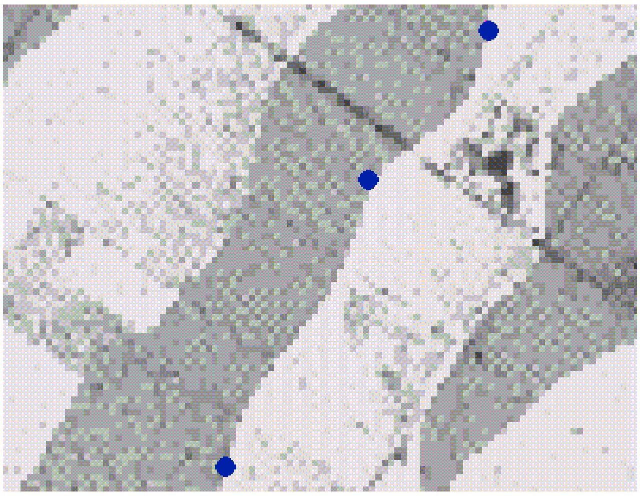

Figure 1b: Point density grid (the darker the denser)

The Survey Department has developed a quality control procedure for laser data. Part of this procedure is a visual inspection of the data. A striking property is the frequent presence of erroneous line structures in 'hillshades' created from the laser data (see figure 1a). Inspection of these so called 'ribbels' (ridges) showed that they occur in strip overlaps. Figure 1b shows the density of laser altimetry points. The density is about doubled (dark gray) in areas where two strips overlap. The ribbels are caused by height differences between laserpoints of two neighbouring strips. These height differences are caused by offsets and tilts of the strips.

Figure 2 illustrates this effect by showing an across-track profile of a small block of laser data. The character of the height differences is strongly systematic, and can mostly be categorized as a vertical offset (z-shift) and an along-track tilt (pitch) and across-track tilt (roll) in the height values. The amplitude of the offset and tilts can be up to several decimeters. It is obvious that rms-values of the height values in overlapping areas with these height differences are much larger than in areas where data is only available from a single strip.

In this paper, the various error sources during the acquisition of laserdata will be discussed and an approach to determine and eliminate systematic height errors will be presented. These are, beside the mentioned offsets and tilts, also cross strip parabolic effects, strip torsions and periodic effects in along-track direction.

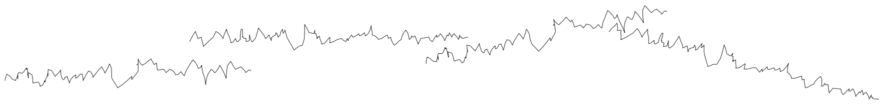

Figure 2: Across-track profile of shifted and tilted strips

2 SOURCES OF HEIGHT ERRORS

Laser altimetry is a rather new and complicated technique. The precision of the resulting height values depends on the type of laser system used and on the measuring strategy. (Huising and Gomes Pereira, 1998) have given an overview of errors in laser data measured by various systems, but a complete description of error sources is not yet available. The errors can be categorized into four components which are illustrated in figure 3.

1. Error per point. Due to the measuring uncertainty of the laser scanner each point is affected with a random error. This point noise is decreased by averaging several heights in order to compute mean height values for certain *areas*.
2. Error per GPS-observation. The GPS-observation interval usually is set to one second. Every GPS-observation is affected with a random error as well. This error, however, is constant for all laser points measured during this second. Usually, these points are lying in a strip-wide area of about 100 metres length (depending on flying speed).
3. Error per strip. GPS and INS sensors are needed to measure the position and orientation of the aircraft along the flight path. This GPS/INS-system introduces a vertical offset for every strip as well as an along- and across-track tilt. Sometimes even other systematic effects are caused by GPS/INS (see section 3.2).
4. Error per block. Terrestrial reference measurements (ground control 'points') are used to correct blocks of laser measurements. Thus, errors in these reference measurements affect whole blocks of laser altimetry data.

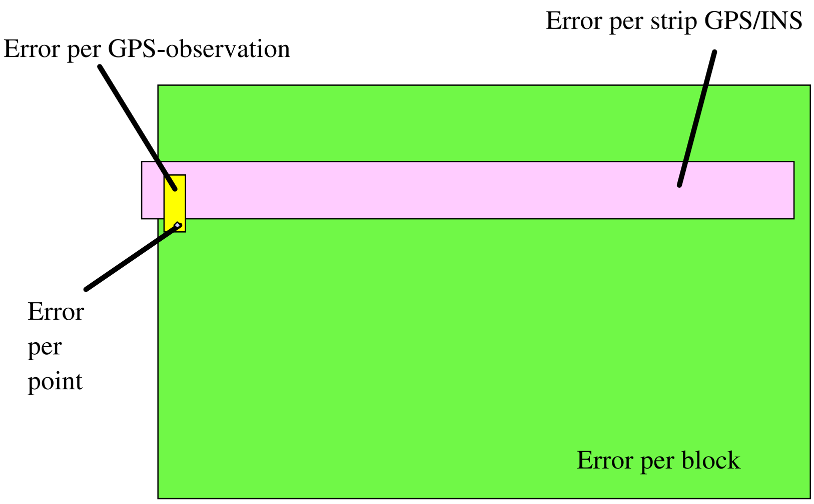

Figure 3: Error components in laserdata

It is impossible to correct for error components 1 and 2. Error component 3 is the main cause of the occurence of ribbels. Because this component is constant for large areas (in which a huge number of observations is available), it is possible to subject it to correction procedures, which are described in the next section. In these procedures also component 4 is corrected for.

3 APPROACH FOR CORRECTION OF HEIGHT ERRORS

The Survey Department has developed strip based adjustment methods to determine the above described systematic height errors and to correct for them (de Min et. al. 1999). The strip adjustment only comprises the *height* (z-co-ordinate) in opposition to approaches of (Kilian et.al., 1996) and (Fritsch and Kilian, 1994). It turned out that focussing on only the heights already results in so many different error aspects that the feasibility of the three dimensional adjustment is doubted. Besides, it was necessary to quickly get a tool to improve and check the delivered laser data. Height control points were much more easier to generate than planimetric control points.

In a first step, a height strip adjustment is performed, assuming strips to be stiff and flat boards. Since this did not always suffice, further correction tools have been created to correct for possible cross strip parabolic effects and to handle strip torsions or other periodic effects. In the following sections, these methods will be described.

3.1 Strip adjustment (hammering boards together)

Height differences in overlapping areas of neighbouring strips (tie 'points') and height differences of laserdata and reference measurements (ground control 'points') are used for the determination and correction of offsets and tilts. This method can be imagined as hammering boards together like a carpenter. Every individual strip gets corrections for offset (*a*) and for along-track (*b*) and across-track (*c*) tilts. This means that to all heights the correction-function (1) is applied:

$$\Delta H(U,V) = a + bU + cV \tag{1}$$

In this formula U en V are coordinates in a local strip-system, as indicated in figure 4a. RD is the Dutch national grid. Strip adjustment can only be carried out when the laser altimetry data is available per individual strip.

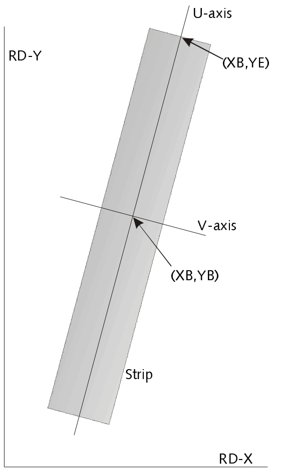

Figure 4a: Local strip system

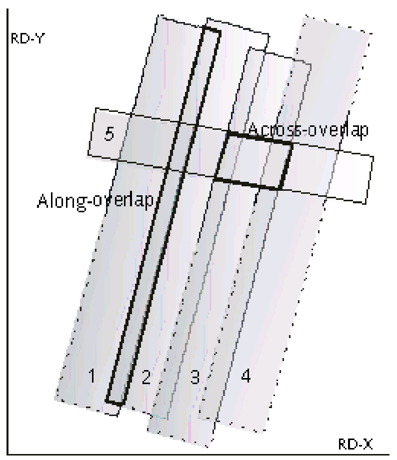

Figure 4b: Along-overlap and across-overlap

The principle of strip adjustment can be described in five steps:

1. Create height differences between two laser altimetry strips in overlapping areas (height differences in tie 'points'). A number of conditions have to be fulfilled in order to ensure a correct adjustment:

   a) The tie points must not lie on a straight line in order to avoid singularities
   b) The differences must not be computed for *individual* points because of the point noise of about 10-15 cm. Therefore, differences are computed as mean differences for groups of minimal 100 points in areas of 50x50 m^2. In this case, a point noise of 12 cm results in (12*√2)/√100=1,7 cm for the averaged height differences. This way, an offset of for example 6 cm can be found in spite of the original point noise of 12 cm.
   c) The tie 'point' areas of 50x50 m^2 have to be flat and smooth. Otherwise small planimetric errors might have a large impact on the mean difference for this area. The smoothness is checked by cross validation computations. Interpolation errors are taken into account in the adjustment.

2. Create height differences between laser altimetry data and reference data (ground control 'points'). Conditions a, b en c of step 1 also apply to this step. The number of height differences from step 1 and step 2 together has to exceed three times the number of strips (per strip three parameters are estimated), to ensure redundancy.

3. Execute an integral least squares adjustment in which correction parameters are estimated from the height differences which were determined in step 1 and 2. In this adjustment also height differences with the prescribed cross-strips (figure 4b) are taken into account.

   There are two types of observation equations, that are the basis for the adjustment. For the height differences i between two laser altimetry strips j and k the equation reads (cf. equation (1)):

$$H_{ki}^{laser} - H_{ji}^{laser} = a_j + b_j U_{ji} + c_j V_{ji} - a_k - b_k U_{ki} - c_k V_{ki} \tag{1a}$$

   For the height differences i between laser altimetry data in strip j and reference data k (NAP heights, the national height system), the observation equation reads:

$$H_{ki}^{NAP} - H_{ji}^{laser} = a_j + b_j U_{ji} + c_j V_{ji} \tag{1b}$$

4. Analyse the results by investigating the residuals (see below).

5. Apply the corrections. Strips are fit together in the best possible way by shifting and rotating.

Figure 5: Is he doing a strip adjustment?

The inspection of the results (step 4) is done in various ways. One of them is analyzing the spatial distribution of the height residuals after adjustment. Figure 6 shows the locations of the 50x50 m^2 areas (tie points). These areas are grouped in pairs, so that two profiles of height differences in the along overlap can be created: one for the right and one for the left part of the overlap. Analyzing these profiles of residuals before and after adjustment facilitates the interpretation of the achieved improvement and occuring errors.

An example is given in figure 7 ('real' data). The outer black lines are the height differences for the two profiles before the adjustment. Apparently, the strips cross each other in the overlap at a line which is approximately parallel to the flightline, because one profile reads positive values, and the other negative values. The inner (colored) lines yield the residual height differences after the adjustment. In this example relevant corrections were determined.

The pattern shows random effects that are within the expected noise from error sources 1 and 2 (see section 2). Furthermore, the empirical covariance function (ECF) in the lower part of figure 7 indicates, that almost no systematic behaviour remains after adjustment for the two profiles. An ECF shows the spatial correlation of the height residuals after adjustment. If correlation (systematic effects) between points up to distance *s* apart from each other exists, the function will not go to zero before distance *s* at the horizontal axis. The value at distance zero reads the quadratic standard deviation of the residuals.

The standard deviation of the residuals after adjustment is small (2-3 cm). The effectiveness of the strip adjustment can also be examined by analyzing histograms of residuals before and after adjustment for whole laser blocks. In figure 8 an example is given. The figure relates to a large block of strips in the southern part of the Netherlands (more than 300 strips). The residuals are significantly smaller after the strip adjustment, leading to the conclusion that strip adjustment increased the quality of the dataset considerably. GPS-errors (component 2) can be blamed for the remaining residuals.

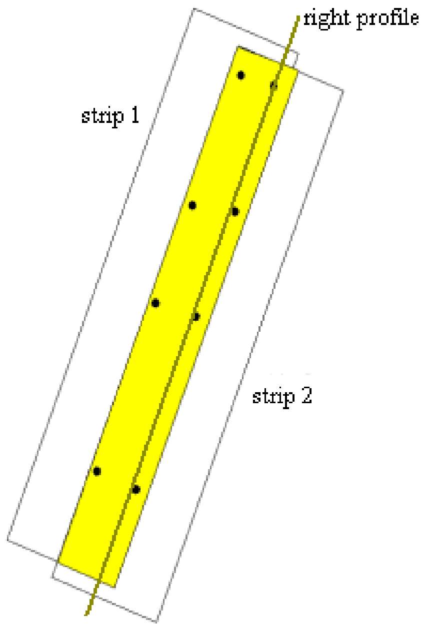

Figure 6: Pairs of tie points in overlap

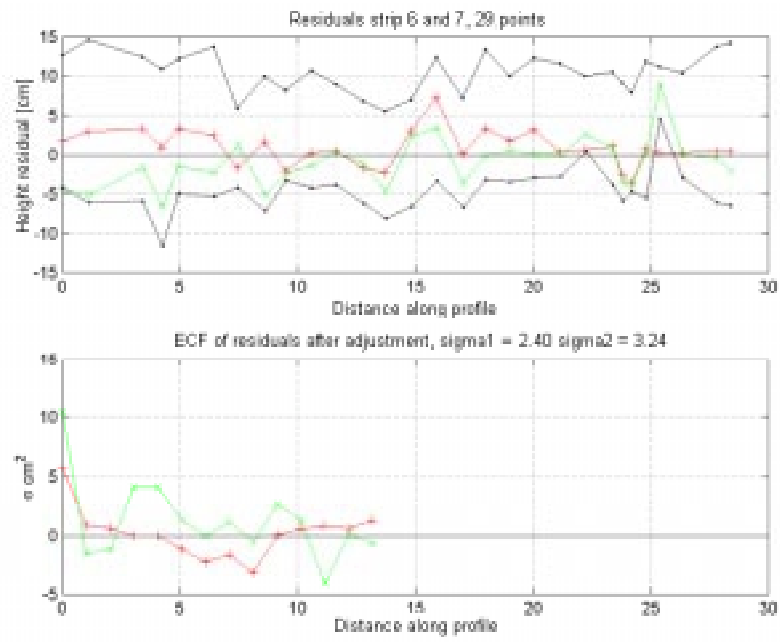

Figure 7: Residuals before and after strip adjustment (above) and empirical covariance function (below)

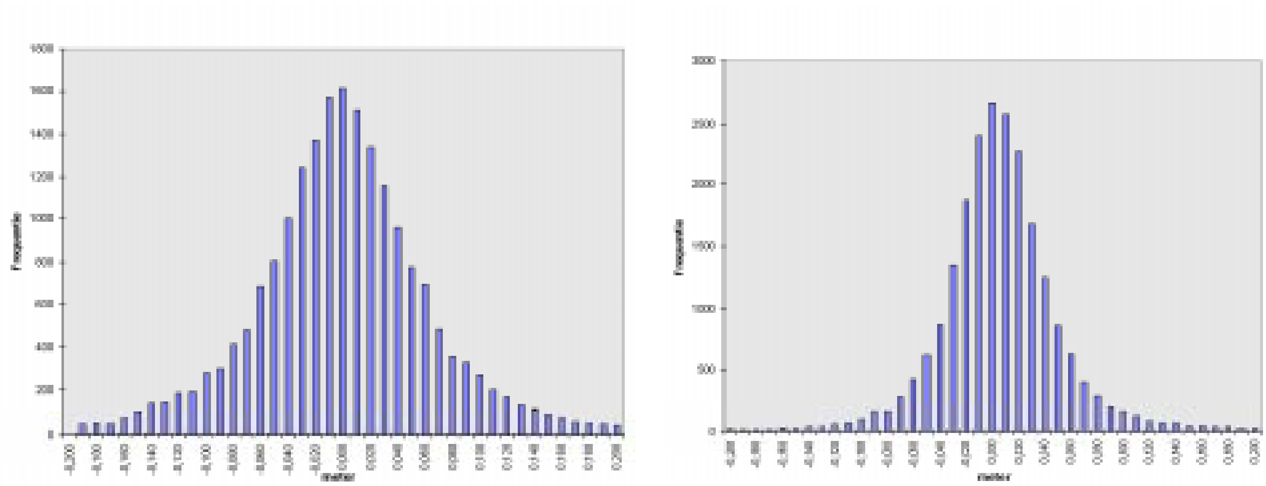

Figure 8: Histogram of residuals before (left, σ = 7.1 cm) and after (right, σ = 4.6 cm) strip adjustment

The computed corrections tell someting about the errors in the strips before the adjustment. Figure 9a shows that most offsets are positive, which means that the computed heights from the laser measurement are in general higher than the groundtruth. Figure 9b does not show a normal distribution, however correction up to 4 cm/km occur frequently. For a striplength of 30 km this corresponds to 1 meter height difference between the two ends of the strip. Figure 9c shows the across-track tilts which are more or less randomly distributed, with a standard deviation of 33 cm/km.

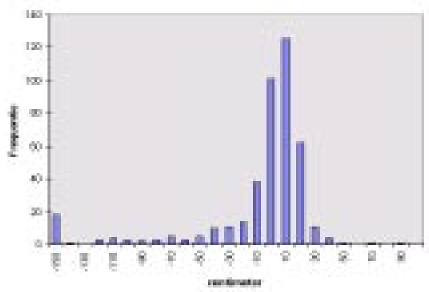

Figure 9a: Offset-corrections
σ = 11 cm

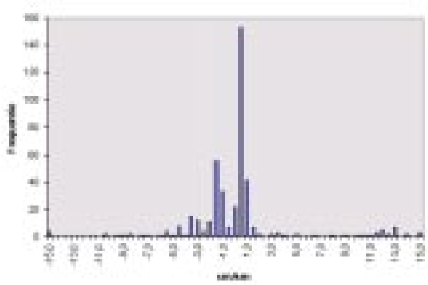

Figure 9b: Along-track tilts

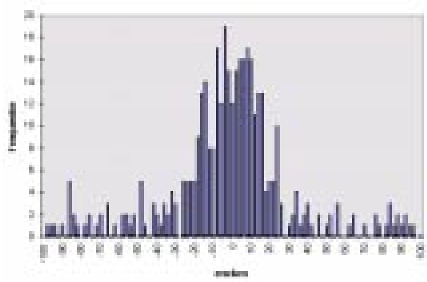

Figure 9c: Across-track tilts
σ = 33 cm/km

3.2 Correction for strip deformations (bending deformed boards into flat ones)

The above described strip adjustment does not always yield satisfying results. An example is given in figure 10. The residual profiles illustrate that a systematic effect with a wavelength of about 15 km obviously remains in the residuals after strip adjustment. This can be explained by a deformation of the strips. Thus, they cannot be treated like stiff boards. The various deformations that appeared in the laser altimetry projects of the Survey Department can be described by a cross strip parabolic deformation, a periodic effect in along-track direction and even torsions of the whole strips. These deformations can differ for every individual strip. The error sources are mainly unknown.

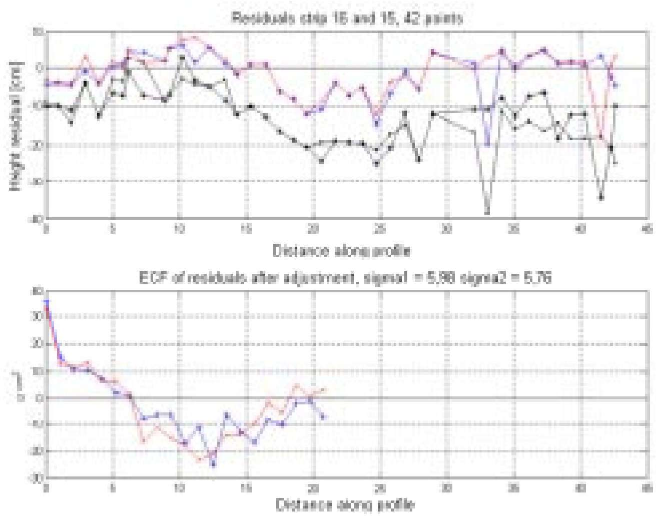

Figure 10: Residuals showing a systematic effect after strip adjustment

In (Boon, 1999) it is demonstrated that strip deformations are responsible for disturbances in the results of strip adjustment. Figure 11a illustrates, for example, the undesired effects of cross strips parabolic deformations on the resulting strip adjusted block. In figure 11b the roll and offset parameters that are computed from the corresponding strip adjustment are depicted. They are up to several metres. The offset values cross the zero axis at strips where reference measurements are available. The results improve dramatically when cross strips are added. Hence, whenever adding cross strips yields large changes in the estimated strip adjustment parameters *a*, *b* and *c*, strip deformations are probable. This way, cross strips are used as indicators for possible occuring deformations. They are not primarily used to correct the data.

From the height differences of tie ‘points’ in the overlapping areas, it is not possible to say whether the additional systematic errors originate from the left or right strip, or even from both strips. Therefore, a different approach is chosen, which does not make use of strip overlaps. Instead, the heights of the complete strip are compared with reference heights of ‘TOPhoogteMD’. This is the former height dataset, covering the Netherlands with an average density of 1 point per hectare. Although the point noise of this dataset is about 50 cm, it can be assumed that systematic errors are absent over several kilometers. It is therefore supposed that systematic effects in the differences between ‘TOPhoogteMD’ data and altimetry data are caused by the latter.

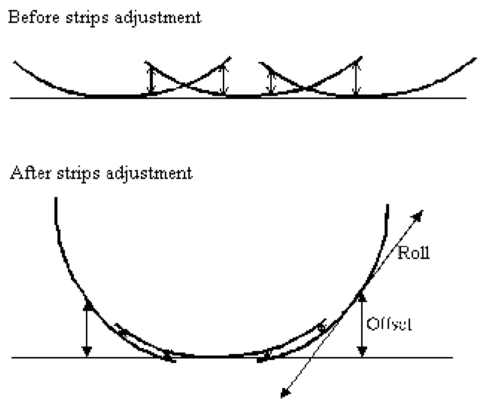

Figure 11a: Influence of across-track parabolic deformation on the results of strip adjustment

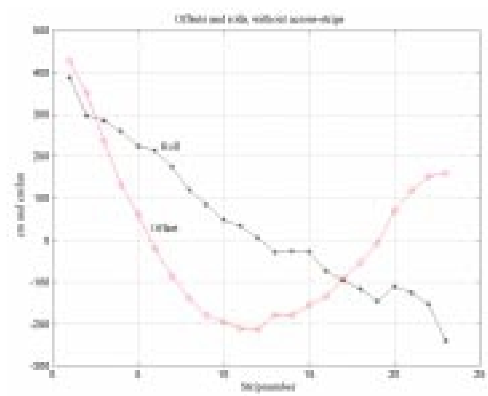

Figure 11b: Estimated roll and offset parameters in the strip adjustment for a block of 23 strips

The corrections can be described by equation (2) (cf. equation (1)):

$$\Delta H(U,V) = a + b_1 U + c_1 V + \sum_{i=2}^{n} b_i U^i + \sum_{j=2}^{m} c_j V^j + \sum_{k=1}^{l} d_k U^k V \qquad (2)$$

Let’s look at an example. Strip 15 from figure 10 is now compared with TOPhoogteMD. At every location of a point in TOPhoogteMD a laser altimetry value is interpolated. The height differences that can be created this way are shown in figure 12a. A wave effect in along-track direction is clearly visible in this picture. To assess the significance of all possible corrections from (2), several consecutive steps are performed. First the strip adjustment parameters offset, along-track tilt and across-track tilt are estimated and applied. Thereafter a parabola in across-track direction is estimated (figure 12b) and corrected for. Finally, a periodic function in length direction is fitted to te height values (figure 12c). Note that the data beyond -1 and +1 comes from zero-differences, that were added to stabilize the polynomial fit at the borders of the strips avoiding undesired effects.

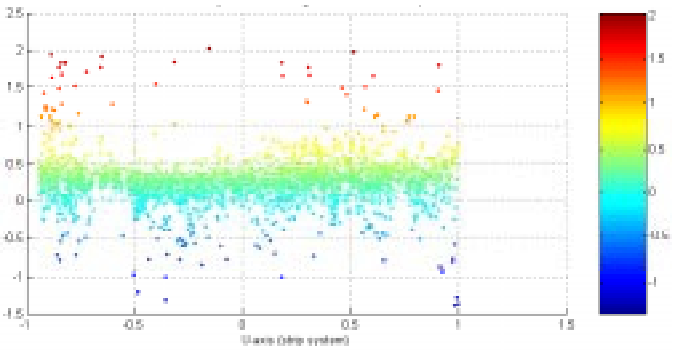

Figure 12a: Laser vs TOPhoogteMD: sideview of strip 15

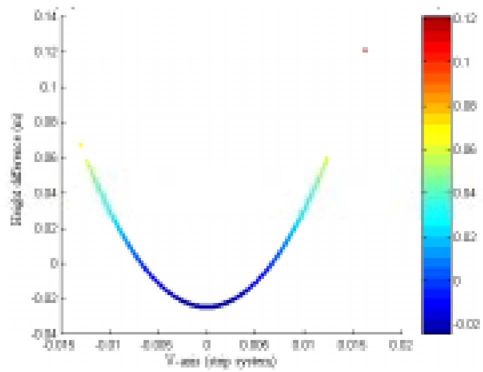

Figure 12b: Estimated parabola in across-track direction

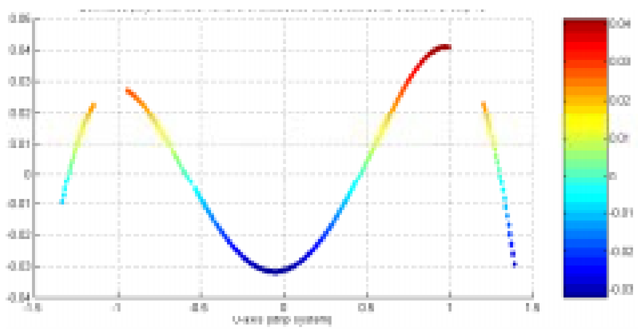

Figure 12c: Estimated wave in along-track direction

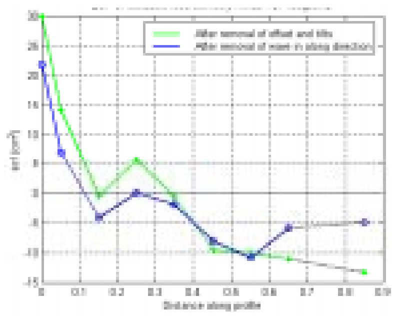

Figure 12d: Empirical covariance functions of residuals

4 ACHIEVABLE HEIGHT PRECISION WITH EXTRA EFFORT

Beside the analysis of real laserdata, some simulation computations were done in order to investigate the maximal achievable theoretical precision of mean heights in case of adding much more ground control points and extra cross laser strips. With ‘mean heights’ the over a certain area averaged heights are denoted. In the experience of the Survey Department, height precision achieved by airborne laserscanning must be considered and analyzed for different sized *regions* (e.g. 0.01 km^2 or 1 km^2) and not per single height value to describe the quality of a resulting DEM in a sensible manner.

From the parameters *a*, *b* and *c* (estimated for every strip, see section 3.1), the precision of the mean height of the entire strip and, furthermore, of regions extending over more than one strip were determined by means of error propagation. The standard deviation of a regions mean height depends - beside the error influences as GPS/INS-error and noise - on the size of the region, its position within the entire block and the configuration of the block. For the simulation computations starting point was a standard block configuration with 50 strips and one cross strip, every strip being 30 km long and 400 m wide, with an overlap between neighbouring strips of 100 m. A tie ‘point’ error of 0.8 cm is assumed, GPS-noise of 2.5 cm and an error of 1 cm of the ground control ‘points’. For the test computations, the control points always lay at the begin and at the end of every strip.

Table 1 shows the mean height precisions for different sized regions depending on the amount of control points. With an immense effort, that is control points in every strip, height precision of 1 cm seems to be achievable for 0.01 km^2 or 1 km^2 large regions. However, keep in mind that these simulation calculations only refer to the error per strip (offset and two tilts; parameters *a*, *b* and *c*) and that the possible falsifying influence of vegetation on the terrain heights is not yet taken into account. Concerning the benefit of additional cross strips, we stated that they, above all, cause a homogenisation of the final precision of the entire block.

region size	con.pt. every strip	con.pt. every 2. strip	con.pt. every 3. strip	con.pt. every 4. strip	con.pt. every 5. Strip	con.pt. every 6. strip	con.pt.e very 7. strip	con.pt. every 11. strip	con.pt. every 13. strip	con.pt. every 24. strip	con.pt. every 49. strip
25-10000 m²	1	1,6	2	2,5	2,7	3	3,5	4,3	4,5	6,5	9,5
1 km^2	1	1	1,5	1,8	2,3	2,6	2,8	3,4	3,8	5	7
5 km^2	0,6	0,6	0,9	1	1,5	1,6	1,9	2,8	3	4	5,5
10 km^2	0,5	0,5	0,7	0,8	1,4	1,5	1,5	2,4	2,5	3,5	4,5

Table 1: Mean height precisions in cm for different numbers of ground control points and different region sizes

5 CONCLUSIONS

In most cases, height strip adjustment allows a significant improvement of the quality of height data. In general, the height differences of the 50x50 m² areas (tie 'points') had 6-10 cm rms-values before, and 3-5 cm rms after strip adjustment. The decrease of rms is mainly caused by removing systematic strip errors, such as offset and tilts. In some cases, however, a more sophisticated approach is required. This applies for the occurence of strip deformations, such as cross strip parabolic deformation, along-track periodic effects and strip torsions.
Apart from the improvement of the precision of the height-data, the strip adjustment including the analysis of along-track residual profiles and provides the possibility to get a thorough insight in the quality of the delivered laser altimetry data. The quality of every individual strip can be examined, an important feature for the acceptance procedure concerning delivered data. In the meantime, the Survey Department has obliged laser data suppliers to perform strip adjustment to guarantee the quality of delivered data. Considering the various error aspects we found in laserdata, further reserach has to be done to further analyse the error sources in order to possibly avoid the occurrence of these errors in the future.

ACKNOWLEDGMENTS

N.A. Kinneging, R. van Heerd, J.G. van der Kraan, J.S. van Noort, R.J. van 't Zand (Meetkundige Dienst, Rijkswaterstaat), co-authors of the report 'Strookvereffening van laserdata'.

Arnhemse Fijnhouthandel for the photograph.

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