QUALITY IMPROVEMENT OF LASER ALTIMETRY DEM'S

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ABSTRACT:

The new Dutch national digital elevation model (AHN), acquired with laser altimetry, is almost complete. Local water boards want to use the laser data for water management tasks such as determining permitted water levels within draining areas and measuring land subsidence rates. In most parts of the Netherlands the precision of the AHN is sufficient for this purpose. However, in peat meadow areas the precision demands are higher because these areas are more susceptible to land subsidence. In these areas the mean field heights of water management entities of about 100 ha up to 700 ha have to be measured with cm-precision. Comparing traditional terrestrial methods (DGPS, tachymetry) with laser altimetry showed that the precision of the AHN does not suffice for mean field height determination in peat meadow areas. However, formerly performed block design analysis showed that adding more ground control points and extra cross strips in a 1D strip adjustment can improve the height precision of a laser altimetry elevation model. The demanded precision seemed to be achievable with those extra ground control points. In order to verify these theoretical results, a practical test was performed. The former introduced error description scheme for laser altimetry data is used to quantify the different error components and to propagate them to the precisions of mean field heights. However, the improvement of the height precision is less than expected. This is mainly caused by strip deformations due to long term positioning errors of GPS/INS. Nevertheless, the results of the pilot are useful to determine future laser altimetry block configurations taking into account the precision demands of the users. An example for weighing benefits against costs is given.

1. INTRODUCTION

1.1 The Dutch national elevation model AHN

At the end of 2003, the Netherlands, as one of the first countries, will have a national digital elevation model (DEM) at their disposal which has been acquired by laser altimetry. In 1996, this new national DEM project was initiated to meet the demand for detailed and up to date height information from water boards, provinces and "Rijkswaterstaat" (Ministry of Transport, Public Works and Water Management). The so-called AHN ("Actual" Height model of the Netherlands) has a average point density of 1 point per 16 m² or better and a height precision of about 15 cm standard deviation per point.

The AHN has been acquired by several laser altimetry companies. The task of the Dutch Survey Department (Meetkundige Dienst Rijkswaterstaat) was to co-ordinate the acquisition. This comprised the contracting of companies for the flights, the processing of the original data to get X, Y and Z terrain co-ordinates and the filtering. In addition, the quality of the delivered laser data has been checked at the Survey Department and standard products, e.g. 5m x 5m grids, are derived and distributed to the users.

The Survey Department also performs research to investigate further applications of laser altimetry for river and coastal zone management ([Brügelmann 2000]) and to improve not only the quality of the AHN ([Huising and Gomes-Pereira 1998], [Crombaghs et al. 2000]) but also the description of DEM quality ([Crombaghs et al. 2002]). This paper is about quality improvement of laser altimetry DEM's. The under-

Figure 1. Aerial photograph from a typical Dutch meadow landscape with numerous ditches.

lying demand arises from the local water boards and provinces which want to use the AHN for a specific water management task. The following section gives more information about this application.

1.2 Water level managing with the AHN

A large part of The Netherlands is lying below sea level and, as one of the consequences, draining with an extensive channel and automated pump system is necessary to keep agricultural areas dry. On the other hand, especially in peat meadow areas, the water level must not become too low because then land subsidence would proceed faster. Figure 1 gives an impression of such a watery meadow landscape in

Figure 2. Water-gauge for measuring water levels.

Holland with innumerable ditches.

One important task of the local water boards is to control and manage the water levels and determine the permitted water levels per water management area. These so-called “water level decisions” are made on principle every 10 years and at a centimetre level. The areas of these water management entities range approximately from 100 ha up to 700 ha. The water levels are measured with water-gauges. One example is shown in figure 2.

The permitted water level is related to the mean field height of the concerned water management entity. Up to now the mean field heights have been measured with terrestrial methods such as DGPS or tachymetry with a point density of 1 point per ha. These measurements are quite expensive. With the introduction of the AHN the water boards began using this new data source for determining mean field heights. In most parts of the Netherlands the precision of the AHN is sufficient for this purpose. However, in peat meadow areas the precision demands are higher because even small changes in water levels may affect the land subsidence behaviour. When water boards want to measure the land subsidence rates as height differences between mean field heights on two different points of time, a high accuracy is required too.

Especially considering these unstable peat meadow areas, the question arose from the province South-Holland and the enclosed water boards if the standard AHN precision would be sufficient. It became evident from work undertaken by the Survey Department that the standard AHN precision could not meet the precision demands of the local water boards. Therefore, the possibilities for improving the height precision of laser altimetry DEM’s by the addition of many more ground control points and extra cross strips in the strip adjustment were investigated by means of block design analysis using simulated data.

1.3 Towards an AHN+ ?

The water boards are interested in the mean field heights of their water management entities (see figure 3). For calculating the mean field heights all laser points within an area have to be averaged excluding high vegetation, buildings and ditches. The precision of the mean heights can be derived from the laser data by error propagating of the different error components of laser data. This will be described in more detail in section 2.3 and 2.4. Note that the precision of the mean field height does not depend on the morphology of the landscape (see figure 3).

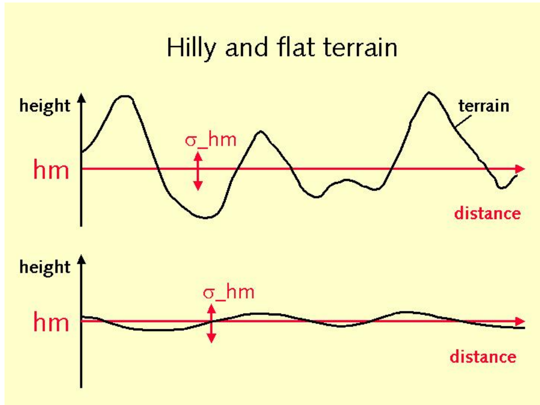


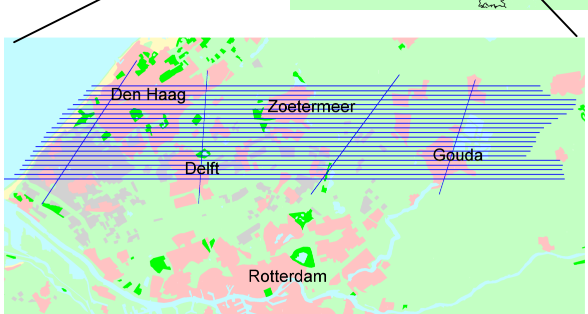
Figure 3. The precision of the mean field height (hm) is *not* dependent from the terrain type.

The block design analysis mentioned in the previous paragraph was performed three years ago. The starting point was a block with 50 strips, every strip being 30 km long and 400 m wide, with 100 m overlap between neighbouring strips. In the 1D strip adjustment three parameters were estimated per strip: a height offset, an across-track and an along-track tilt (see [Crombaghs et al. 2000]). In the block design analysis the number of ground control points, tie points and cross strips was varied as well as the position of the ground control points.

The analyses showed that a block configuration with more ground control points clearly improved the height precision of the strip offsets (and thereby the precision of mean field heights). The benefit of additional cross strips (e.g. three instead of one) was, above all, a homogenization of the final precision of the entire block.

For a standard AHN the ratio between number of strips and number of ground control points is about 2.6. The analyses yielded a ratio of 1.3 to meet the desired height precisions of

Figure 4. Test area in the Western part of the Netherlands (province boundaries in black) and flight scheme for the laser altimetry measurements.



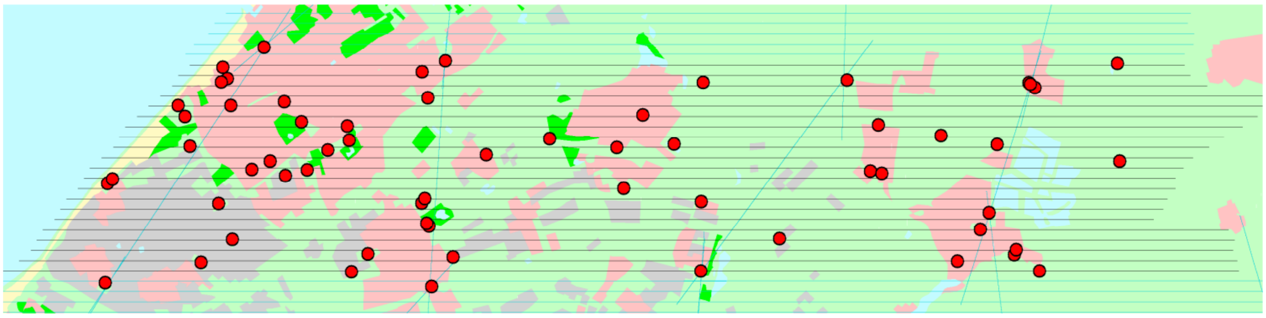


Figure 5. Locations of the 69 ground control points in the test area (rose = city area, grey = greenhouses, yellow = dunes, dark green = forest, light green = meadows, blue = water).

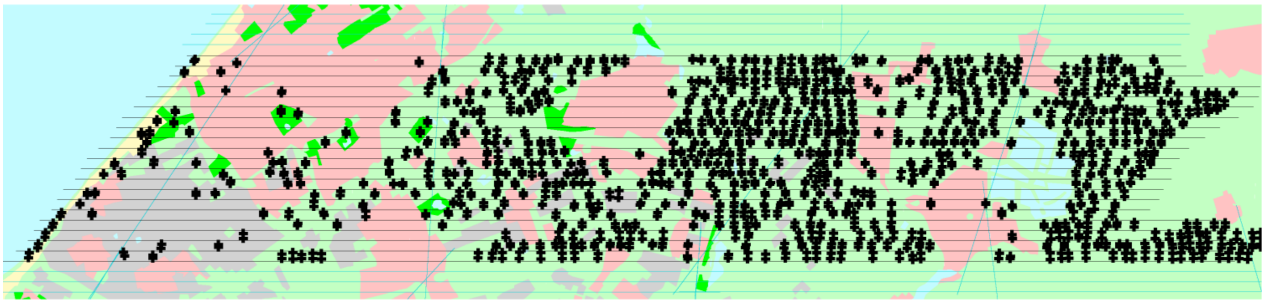


Figure 6. Locations of the 1612 tie points in the test area.

the water boards in South Holland. With such a so-called AHN+ configuration the following precisions of mean field heights should be achievable for 100 ha and 700 ha areas:

$$\sigma_{100\ \mathrm{ha}} = 1.7\ \mathrm{cm} \quad \text{and} \quad \sigma_{700\ \mathrm{ha}} = 1.0\ \mathrm{cm}.$$

Hereby, seasonal, daily and local variations are already included (see section 2.3). The possibly falsifying influence of (low) vegetation on the terrain heights is, however, not yet taken into account.

2. PRACTICAL TESTS AND RESULTS

In order to verify the theoretical results of the block design analysis, a practical test was performed. This section describes the test configuration, the strip adjustment results and the propagation of strip errors and other error components to precisions of mean heights of 100 ha and 700 ha areas.

2.1 Test area and data

For the practical test one of the final blocks of the AHN project is selected. The test area covers about 10 x 50 km^2 in the Western part of The Netherlands. Starting from the coast near The Hague this block extends to the vast peat meadows and lakes East of the city of Gouda (see figure 4). The Western part mainly consists of urban areas and greenhouses. The rest of the test area comprises some smaller cities alternating with agricultural land, mostly consisting of peat meadows.

The flight configuration was equal to the regular configuration of the AHN project, with one exception: four cross strips were flown instead of three. In East-West direction 21 strips were measured with a length of about 50 km, a width of about 500 m and an overlap of about 80 m. The cross strips approximately were measured in North-South direction (see figure 4). The East-West strips are numbered from the North to the South. The main part of the flights was carried out in the spring of 2001, the remainder in the spring of 2002. We assume that the terrain height did not change during this period.

In order to elaborate the results of the block design analysis (section 1.3) in practice, a very large number of ground control points were measured. A total of 8 ground control points would be usual for a AHN block of this size. For the practical test the number of ground control points was increased to 69 (see figure 5). Every strip contains at least two ground control points. Ground control "points" are horizontal and flat areas (mostly sport fields) of about 1 ha where the heights of 100 points are measured terrestrially. The most important limiting factors concerning the quantity of ground control points were the costs of the terrestrial measurements and the existence of suitable flat and smooth fields. Most of them are located in the urban areas. The main part of the terrestrial measurements of the ground control points was carried out in the winter of 2001-2002.

2.2 Strip adjustment

The total error budget of laser altimetry data can be divided into four components with different amplitudes and with different spatial resolution (see [Crombaghs et al. 2002]). These errors, which are illustrated in figure 7, are:

1. *error per point*: laser scanner point noise
2. *error per GPS observation(strip section)*: short term positioning error of the airplane

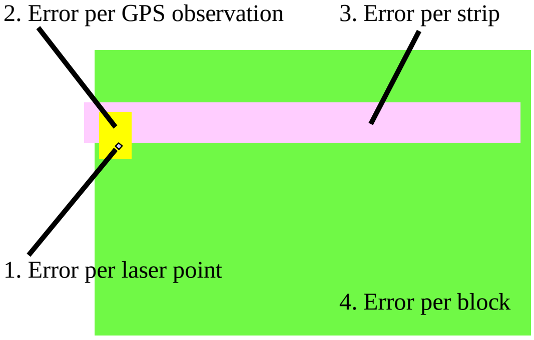


Figure 7. Error components of laser altimetry and their spatial resolution.

3. *error per strip*: long term positioning error due to GPS/INS
4. *error per block*: error in the connection to the national height system (NAP).

The first three error types are on the input side of the strip adjustment, the fourth is part of the result of the adjustment.

In a 1D least squares strip adjustment, overlapping strips are connected to each other by tie points in strip overlaps (see figure 8). At the same time, the strips are connected to the national height system by ground control points. Observations are the height differences at tie points and at ground control points. The quality of these observations is a function of the first three error types mentioned above. The stochastic model of the observations has been simplified and turned into a diagonal matrix, see [Crombaghs et al. 2002]. The unknowns are the height offsets per strip. We chose not to estimate the across-track and along-track tilts per strip in order to avoid introducing even more errors, e.g. deformation of the whole block due to possible cross strip parabolic deformations, see [Crombaghs et al. 2000]. The quality of the height offsets is described in the covariance matrix of the unknowns. This matrix depends on the precision of the observations and the block configuration. The block configuration includes the number and location of:

- tie points,
- cross strips and
- ground control points.

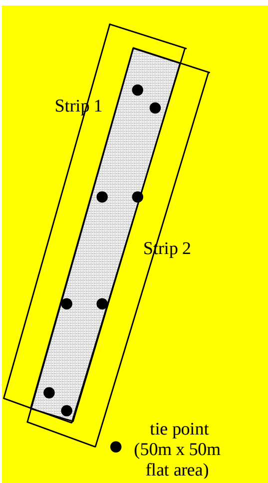


Figure 8: Tie points in strip overlaps.

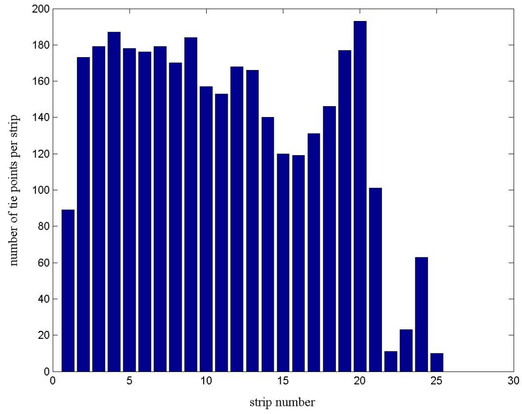


Figure 9. Number of tie points per strip.

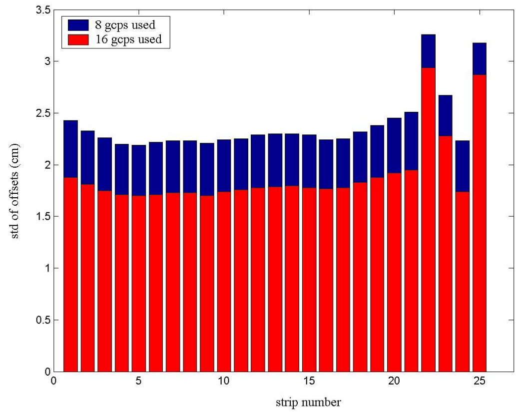


Figure 10. Standard deviations of strip offsets from strip adjustment with 8 (blue) and 16 (red) ground control points.

In figure 6 the location of tie-points is shown. In the test area a total number of 1612 tie-points have been measured semi-automatically. As tie-points have to be flat and smooth and cover at least 50 by 50 meters (about 150 laser points), most of them are lying in rural areas. In every along track overlap the number of tie points lies between 50 and 100. In two cross strips it was difficult to find suitable flat tie points because the strips covered cities, greenhouse and water areas. The number of tie points varies between 10 in urban and water areas and up to 50 in rural areas. In figure 9 the number of tie points is shown for every strip (most of the strips have two overlaps). Strip numbers 22-25 denote the cross strips.

The main focus of the practical test was to assess the accuracy improvement when adding more ground control points in strip adjustment. In theory, each strip-offset will be determined more precisely, when using more ground control points in a strip adjustment. In a normal AHN configuration a total number of 8 ground control points would be used and 16 in a so-called AHN+ configuration. Actually, it is the ratio between the number of strips and the number of ground control points that matters. As the number of strips is constant in this pilot, the focus is on the influence of the number of ground control points.

Figure 10 shows the standard deviation per strip as result of the strip adjustment for the AHN and the AHN+ case. Doubling the amount of ground control points yields a precision improvement of about 0,5 cm for every strip offset.

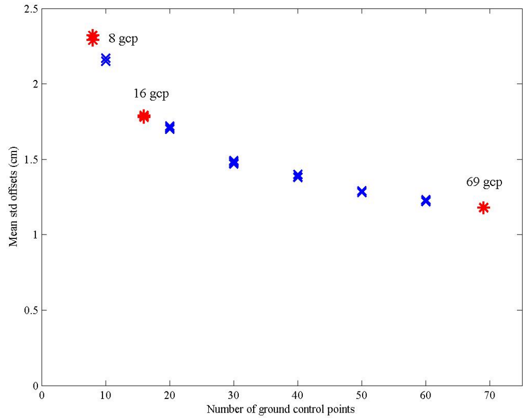


Figure 11. Mean standard deviations of all strips (except cross strips) for different numbers of ground control points.

With 16 ground control points in 21 strips the standard deviation of the strip offsets is about 1,8 cm. Furthermore, it is apparent that using less than 25 tie points per strip overlap has a negative influence on the accuracy (see precision of cross strips in fig. 10). Because of the bad connection of the cross strips to the other strips due to a lack of tie points, experiments with varying numbers of cross strips in strip adjustment could not be performed.

To further analyse the accuracy improvement, the relation between number of ground control points and mean standard deviations of strip offsets of the whole block (excluding the cross strips) was investigated. In figure 11 the relation between the number of ground control points and the mean standard deviation is visualized. More than one cross for the same number of ground control points indicates that different sets of ground control points are used. Adding ground control points obviously improves the accuracy. However, with increasing numbers of ground control points the improvement proceeds less fast. From a certain number of ground control points, say 30, the accuracy improves scarcely.

2.3 Precision of the mean height of an area

In section 2.2 the attention is focused on the precision of the height of a strip, or more specifically on the precision of the strip offset in regard to the national height system (error type 4). This section shows how this error type can be used together with other error types to compute the precision of the mean height of an area. In addition to the four error components mentioned in section 2.2, three other error components are taken into account:

A. *Seasonal variation* is added as an error component, dealing with seasonal shrink and swell processes in the soil caused by seasonal fluctuations of the groundwater level.

B. *Daily variation* is added as an additional error caused by refraction of light in the atmosphere. This error, which mainly depends on the daily variations in temperature is known from tachymetry and probably also plays some role in laser altimetry.

C. *Local variation* is added as an error component denoting the difference between the height of a DEM-grid-cell and the mean height of the real terrain for the same grid-cell.

Seasonal and local variation have nothing to do with the precision of the laser altimetry technique. Instead these error components are characteristic of the terrain type that is measured. However, for the computation of the precision of the mean height of an area, as used for water management purposes, these two error components may not be neglected.

For a clear explanation of the method we start with the computation of the height precision of a *single laser point*:

$$\sigma_{laserpoint} = \sqrt{\sigma_{seas}{}^2 + \sigma_{day}{}^2 + \sigma_{loc}{}^2 + \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4{}^2} \quad (1)$$

with:
σ_{seas} = std. of seasonal variation
σ_{day} = std. of daily variation
σ_{loc} = std. of local variation
σ_1 = std. of laser scanner (point noise)
σ_2 = std. of GPS (short term positioning error)
σ_3 = std. of GPS/INS (long term positioning error)
σ_4 = std. of strip offset (in regard to the national height system)

All error components are present in a single laser point to full extent. The standard deviation of the *mean height of an area* is computed in a similar way, with the difference that some of the error components are reduced by averaging:

$$\sigma_{area} = \sqrt{\sigma_{seas}^2 + \sigma_{day}^2 + \frac{\sigma_{loc}^2}{n1} + \frac{\sigma_1^2}{n1} + \frac{\sigma_2^2}{n2} + \frac{\sigma_3^2}{n3} + (\alpha \cdot \sigma_4)^2} \quad (2)$$

with:
n1 = number of points in the area
n2 = number of strip-sections (length about 100 m) in the area
n3 = number of strips covering the area
α = scale factor

To get the standard deviation of the offset for a larger area covered by several strips, the standard deviation for a single strip (σ_4) is reduced by a scale factor α ranging from 0 to 1. The value of α depends on the number of strips in the area and the correlation between the (standard deviations of the) offsets of these strips.

For a single strip α = 1 is valid. For many strips α seems to be approaching a certain minimum value (see figure 12). The exact value of α can be inferred from the covariance matrix resulting from the strip adjustment. For practical use α can be approximated by the following rule of thumb, which is deduced from empirical tests based on AHN data:

$$\alpha = a + (1-a)e^{-b(n3-1)} \quad (3)$$

with : *a* = minimum value of the function (fig. 12)
b = slope coefficient of the function (fig. 12)
n3 = number of strips

The values of a and b in this equation depend on the ratio between the number of ground control points and the number of cross strips. With a larger number of cross strips the correlation between strip offsets is stronger. A larger number of ground control points has the opposite effect. For practical use three cases for the values of *a* and *b* have been adopted (table 1 and figure 12).

case	*a*	*b*	condition
1	0.83	0.02	$n_{gcp}/n_{cross} < 2$
2	0.70	0.10	$2 < n_{gcp}/n_{cross} < 5$
3	0.58	0.18	$n_{gcp}/n_{cross} > 5$

Table 1. Adopted cases for the values of a and b depending on the number of grond control points (n_{gcp}) and the number of cross strips (n_{cross}).

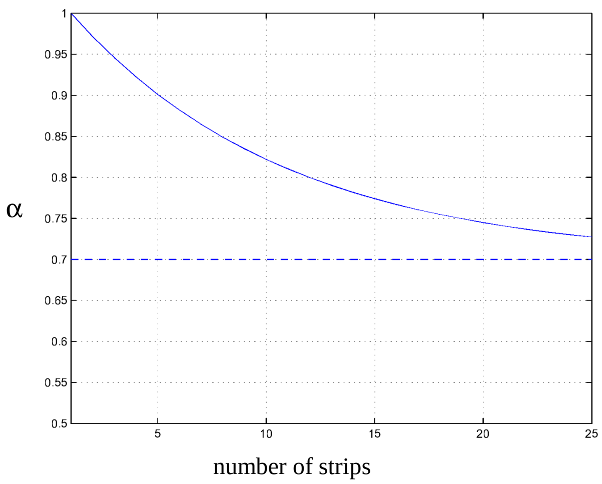


Figure 12: Scale-factor α depending on the number of strips for case 2 ($2 < n_{gcp}/n_{cross} < 5$)

variance	error source		amplitude
σ^2_{seas}	seasonal variation		0.25^2 cm^2
σ^2_{day}	daily variation		0.35^2 cm^2
σ^2_{loc}	local variation		5^2 cm^2
σ_1^2	laser point noise		7^2 cm^2
σ_2^2	short term positioning error		4.47^2 cm^2
σ_3^2	long term positioning error		3.6^2 cm^2
σ_4^2	variation of strip offset with regard to the national height system NAP	with 69 gcp's	1.3^2 cm^2
		with 16 gcp's	2.0^2 cm^2
		with 8 gcp's	2.6^2 cm^2

Table 2. Variance values of error components.

2.4 Test results for 100 ha and 700 ha areas

Equation (2) is used to compute the precision of the mean height for areas of 100 ha and 700 ha in the previously described test area. The results for different numbers of ground control points are compared with the expected precisions based on the block design analysis. The variance values of the error components used are listed in table 2.

The standard deviations of the error components of the laser altimetry measurements are estimated from the laser data of the test project. The standard deviations of the seasonal and daily variation have been adopted from [Grondmechanica Delft 1995]. Field experiments have shown that even larger seasonal variations may occur in certain parts of the Netherlands (Schothorst, 1977, Beuving & van den Akker, 1996). The standard deviation of the local variation is estimated using AHN data yielding 5 cm for the AHN point density of 1 point per 4 x 4 m^2.

The use of equation (2) is illustrated with an example of our test area. The precision of the mean height is computed for an area of 700 ha, comprising 437500 laser-points, 182 strip-sections and 7 strips (part of the test area). The number of ground control points is 16. The value of α is 0.895.

$$\sigma_{700ha} = \sqrt{0.25^2 + 0.35^2 + \frac{5^2}{437500} + \frac{7^2}{437500} + \frac{20}{182} + \frac{13}{7} + (0.895 \cdot 2.01)^2}$$

$= 2.3$ cm.

	block design analysis	practical test		
n_{gcp}	16	8	16	69
$\sigma_{100\ ha}$ [cm]	1.7	3.4	3.0	2.6
$\sigma_{700\ ha}$ [cm]	1.0	2.8	2.3	1.8

Table 3. Precision of mean field heights for different sized areas (n_{gcp} = number of ground control points).

The results for different numbers of ground control points are compared with the expected precision based on the block design analysis. Table 3 shows that the expected precision is not achieved. Even with all available ground control points, which is an extremely huge and unrealistic number, the precision demands of the water boards could not be met.

The main cause of these disappointing results is the long term positioning error, which was not yet known at the time of the block design analysis. The results show that this error component has a large impact on the precision of the mean height of an area. First it leads to distortions within strips. Second, the results of the strip adjustment are affected by a lower precision of the strip offsets. With the available software it is not yet possible to remove or reduce the effect of these long term positioning errors. A complete 3D strip adjustment, such as proposed in Burman [2000], Burman [2002] or Vosselman and Maas [2001] could probably increase the height precision of laser altimetry DEMs due to a better modeling of the occurring errors.

3. BENEFITS AND COSTS

The results of the performed test nevertheless enable us to find answers to the following questions: What is the price for quality improvement of laser data? What are the different options for flight configurations and their consequences with regard to costs, point density, precision and reliability? In order to answer these questions, three options for quality improvement are pointed out in this paragraph. Furthermore, the improvement of precision is quantified for some cases and shown in relation to the costs.

The following three possibilities for precision improvement of laser altimetry DEM's will be discussed:

- higher point density,
- more ground control points,
- flying the same area twice.

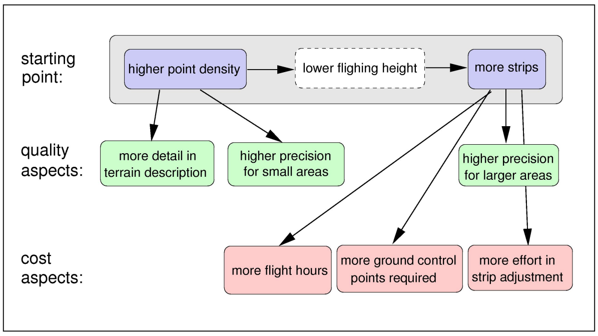


Figure 13. Consequences of higher point density.

Figure 13 gives an overview of the consequences of the first option: a higher point density. The higher precision in small areas is caused by the averaging process for the individual point noise. The higher precision in larger areas is a result of the averaging of (short and long term) positioning errors caused by GPS/INS errors within strips. The main reason for the increasing effort in strip adjustment with more strips is that many more tie points are required. Due to the semi-automatic measurement procedure of tie points this is a time consuming task.

Table 4 shows the costs and benefits with respect to an example area of 700 km^2 for the following four different flight configurations:

case 1: area is flown once at low point density,
case 2: area is flown twice at low point density,
case 3: area is flown once at high point density,
case 4: area is flown once at high point density and with a large number of ground control points.

Case 1 corresponds approximately with the standard AHN configuration. The three other cases illustrate possibilities for precision improvement. The number of €-symbols in table 4 gives an approximate price indication of each flight configuration. This way the price proportion among the different cases can be visualized without revealing the real prices which we have to treat as confidential information.

	case 1	case 2	case 3	case 4
# flights	1	2	1	1
point density	1 point per 4 x 4 m^2	2 x 1 point per 4 x 4 m^2	1 point per 2 x 2 m^2	1 point per 2 x 2 m^2
# gcp's	14	2 x 14 = 28	14	49
# strips	42	2 x 42 = 84	148	148
costs	€€	2 x €€ = €€€€	€€€	€€€€
reliability	-	+	-	-
$\sigma_{5m\,x\,5m}$	14 cm	14/√2 = 10 cm	12 cm	9 cm
$\sigma_{100\,ha}$	6.2 cm	6.2/√2 = 4 cm	9.2 cm	5.4 cm

Table 4. Precision improvement in relation to the costs for a 700 km^2 area.

When the number of strips is increased (as a consequence of a higher point density), one should also use more ground control points. Otherwise, the precision of the strip offsets with regard to the national height system will get worse. The results of case 3 in table 4 show clearly that a higher point density can even lead to a lower height precision of larger areas, if the number of ground control points is not increased at the same time. In section 2.2 it was already described that the precision of the strip offsets is a function of the ratio between the number of strips and the number of ground control points. Nevertheless, a higher point density yields a more detailed terrain description.

An alternative way to improve the precision of laser data is, even though sounding somewhat unusual, flying the same area twice (case 2 in table 4). In this case, the error budget of the laser altimetry measurements is reduced by a factor √2. This factor is based on the assumption that the main part of the errors is not correlated between two different flights. Temporal and local variations are not taken into account and it is assumed that a new independent set of ground control points is measured. An additional advantage of the flying twice option is the improvement of the reliability of the results.

As already mentioned, case 3 is not optimal because the precision of larger areas decreases. Comparing case 2 and case 4 which equal each other with respect to the costs, we would slightly prefer the flying twice option because of the precision benefit concerning larger areas. On the other hand, the terrain description is less detailed in case 2. We can conclude that many different parameters are involved in this cost versus benefit consideration. Thus, the user requirements must play a significant role in determining the right flight configuration.

4. CONCLUSIONS

The height precision of laser altimetry DEM's can be improved by using more ground control points in a 1D strip adjustment. However, the extent of improvement does not answer the expectations which were fed by former block design analysis. The main reason is the occurrence of strip deformations due to long term positioning errors caused by GPS/INS. This effect has been neglected in the block design analysis. A further improvement can be expected by a 3D strip adjustment where these strip errors will be modelled.

Although the practical test has been performed with a single laser block, the results are valid more in general because former analyses of data from different companies and scanners showed that the amplitudes of the different error types are comparable with those from our test ([Crombaghs et al. 2002]).

In spite of the somewhat disappointing results of the test, they are, in combination with our new error description model of laser data ([Crombaghs et al. 2002]), very useful for weighing benefits against costs. Future laser flight configurations can be determined taking into account the precision demands of users.

It was shown that the *ratio* of number of strips and number of ground control points is significant concerning the achievable height precision. Thus, increasing the laser point density (and therefore the number of strips) alone has not much improving effect on the height precision of small areas. On the other hand, the height precision of large areas (e.g. 100 ha) becomes even worse if no additional ground control points are included. But, of course, a higher point density yields a more detailed terrain description. Considering the costs of laser data acquisition with high point density and a large amount of ground control fields, even the possibility of flying the same area twice becomes imaginable.

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