ON THE ESTIMATION OF PLANIMETRIC OFFSETS IN LASER ALTIMETRY DATA

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ABSTRACT:

Offsets between overlapping strips of laser altimetry data serve as the input for strip adjustment procedures that estimate and eliminate systematic errors in laser altimetry datasets. For a three-dimensional strip adjustment offsets are to be measured in three dimensions. Height offsets can be determined straightforward by comparing the heights of horizontal planes. Planimetric offsets are more difficult to determine. This paper shows that the usage of standard least squares matching algorithms on height data as well as on reflectance data may lead to significant biases in the estimation of planimetric offsets. For height data, a model based estimation of linear features is proposed since the number of locations in strip overlaps that are suitable for the estimation of offsets in three dimensions may not be sufficient to estimate all error parameters of a strip adjustment. To improve both the offset estimation and the offset variance estimation using reflectance data an edge response function is introduced. This function takes into account the difference in size of a laser beam's footprint and the distance between successive laser points.

1. INTRODUCTION

Laser altimetry surveys make use of measurements by GPS receivers, inertial navigation systems, and laser range finders. Due to errors in these components, the synchronisation, and calibration of the relative positions and attitudes of the instruments, systematic errors are often observed in the acquired digital elevation models (DEM) [Huising and Gomes Pereira 1998]. Strip adjustment procedures have been devised to detect and eliminate these systematic errors by making use of measurements in overlaps between strips and reference objects [Kilian et al. 1996].

Over the last few years calibration procedures improved, resulting in smaller systematic errors in the DEM's. The necessity of a strip adjustment now depends on the accuracy demands. In the case of low accuracy demands ($\sigma_Z > 0.5$ m) an adjustment may not be required, although the computation of the systematic errors, without actually correcting the data, could still be used to check whether the accuracy demands are met. For higher accuracy DEM production in the Netherlands ($\sigma_Z < 0.15$ m, systematic height error < 0.05 m), an adjustment of strip heights and tilts is incorporated in the standard procedure [Crombaghs et al. 2000]. Water boards demand average heights over large areas with even much higher accuracy ($\sigma_Z < 0.01$ - 0.02 m). For those requirements all systematic errors need to be modelled and eliminated to a high precision level.

A proper modelling of the systematic errors in the DEM should address the sources of these errors: the biases in the instruments, synchronisation errors, and calibration errors in the determination of the relative sensor orientations. These errors should be modelled explicitly [Schenk 2001]. This requires a three-dimensional strip adjustment, and not just an adjustment of the point heights. Vosselman and Maas [2001] showed that systematic planimetric errors can be several times larger than systematic height errors. The impact of such errors on the determined terrain heights, of course, depends on the terrain slopes. Crombaghs et al. [2000] also showed the need for a complete error modelling. A strip adjustment with an incomplete error model was shown to lead to a deterioration of the DEM quality.

The identification of corresponding positions in overlapping strips is an important step of the strip adjustment procedure. For a three-dimensional strip adjustment, offsets in X-, Y-, and Z-direction between overlapping strips need to be determined. This paper deals with several aspects of the determination of the planimetric offsets between strips.

Various procedures for the measurement of corresponding points have been published in the photogrammetric literature.

- Kilian et al. [1996] identified areas of interest by hand and determined the corresponding locations by a least squares matching of gridded height data. By analysis of the height data and the strip geometry, areas that were occluded in one strip are excluded from the matching.
- Burman [2000] made use of both height data and the reflectance strength of the laser pulses for the measurement of the strip offsets. Suitable areas for the simultaneous matching of height and reflectance images were determined by thresholding the response of the Sobel gradient operator. The matching equations were set up such that they directly resulted into the estimation of the heights at the DEM grid points.
- Maas [2000] formulated the matching problem on the height data in a TIN data structure, thus avoiding a loss of information due to gridding of the height data. Points near height jump edges were excluded from the matching by eliminating triangles with a steep slope. In this way areas with occlusions do not impact the matching result. In [Maas 2001] corresponding positions between strips are estimated by using the height data for the determination of the Z-

offset, and the reflectance data for the determination of the planimetric offset.

Both height and reflectance data can be used for the determination of the strip offsets, but both have there advantages and disadvantages. These will be analysed in the following paragraphs. Furthermore, new procedures will be suggested to improve the accuracy of the matching and to make matching possible in a larger number of areas in order to increase the number of offset measurements between the strips.

2. MATCHING HEIGHT DATA

For stereo matching it is well-known that texture is required in order to obtain a good precision of the estimated disparities. Similarly, when matching height data, height variations are required in order to be able to estimate planimetric offsets. However, there are restrictions to the kind of height variations that can be used for matching height data.

- As already pointed out by Kilian et al. [1996] and Maas [2000], areas that are occluded in one of the strips should not be used for matching. The usage of heights that are derived from interpolation over an occluded area results into systematic errors in the determination of the offsets. In laser altimetry data sets, such occlusions are mostly caused by buildings.
- Due to the characteristics of the laser sensor, one should, however, also avoid the usage of height jump edges in areas that are *not* occluded. When taking an image with a CCD-camera of a checkerboard, pixels that cover a part of a white field and a part of a black field will obtain grey values that are somewhere in between white and black. Such mixed pixels do not occur in height images acquired by laser altimetry sensors. If a laser beam at the edge of a building roof hits both a part of the roof and the ground, the recorded height will be either the roof height or the ground height, depending on whether one selects first or last pulse data. Hence, the characteristics of a roof edge in a height image are comparable with the characteristics of an edge in a binary image. The location precision of such edges, and thus the precision of matching height images using these edges, depends on the length of the edges and the orientation of the edges with respect to the grid [Förstner 1986]. For laser altimetry data, the orientation of the grid corresponds to the orientation of the scan lines of the laser scanner. In the worst case (edges parallel or perpendicular to the scan lines) biases of up to 0.5 times the distance between the laser points may occur in both strips. Hence, matching such edges in data sets with a point distance of e.g. 2 meters, may result into an error of 2 meters.

Although the maximum bias that may occur varies with the orientation of the edges and may average out over a large number of edges, the quality of the offset estimation is hard to predict. Whenever possible, one would like to avoid the usage of height jump edges for the estimation of planimetric offsets, even if these edges do not cause occlusions. This is in sharp contrast to matching grey value images where strong step edges give the best matching results.

In order to estimate the planimetric offsets from the height data, height variations are, however, required. These height differences then need to be provided by smooth surfaces with surface normals pointing in three independent directions. At least two of these surfaces need to be slanted. Parts of sloped terrain or slanted roof faces can provide suitable information. Unfortunately, the number of locations in strip overlaps with such surfaces will usually be small, in particular in rural areas with relatively flat terrain. Under these circumstances it will not be possible to find sufficient locations where offsets between strips can be measured in three dimensions. Therefore, tie points should be completed with other tie features such as ridges or planes that only supply information on the offset in two or one dimension respectively. These dimensions, of course, do not need to be parallel to one of the axes of the coordinate system. By combining the different tie features in a strip overlap, sufficient information should be acquired to make the strip adjustment possible.

In flat terrain usually provisions are made to drain water. Figure 1 shows an example of such a terrain with many ditches in meadows and along roadsides. Such linear structures can be used to determine the offsets between strips in height and in the direction perpendicular to the ditch orientation.

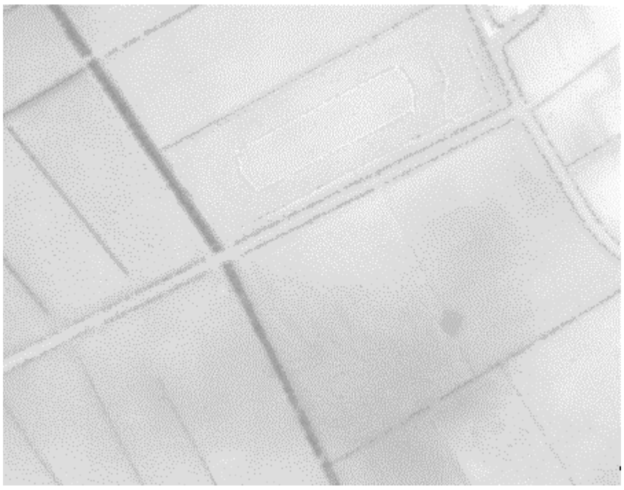

Figure 1: Height image with ditches.

The height data of such structure can, however, not be matched with a standard image matching tool. Because of the relatively small width of the ditches with respect to the distance between the laser points, not every ditch part is represented well by the laser points. When computing a DEM from the triangulated laser points, interpolation between points on either side of the ditch produces incorrect height values (figure 2). Such errors would effect the performance of a standard image matching algorithm.

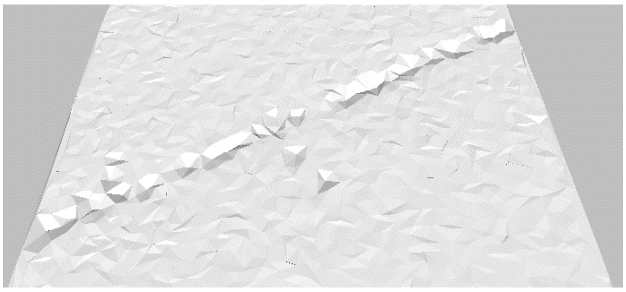

Figure 2: Perspective view of a DEM part with a ditch.

Viewing the point cloud in the direction of the ditch confirms that the ditch of figure 2 is uninterrupted. An estimation of the offset of such a ditch between two strips can be made if the algorithm requires no interpolation between the laser points. This can be achieved by fitting an analytical model of the ditch height profile to the laser points in both strips (figure 3). In this way the height gradients that are required for the fitting can be taken from the analytical model instead of from the laser data.

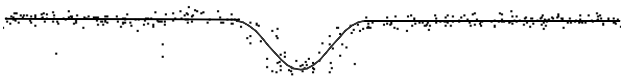

Figure 3: Point cloud of the same ditch as in figure 2 viewed longitudinally and fitted to an analytical profile.

Because of the relatively low point density, the detection of such linear features can not be done by a standard edge detection in a height image. As can be understood from figure 2, this would result in very fragmented edges. Clustering-like techniques seem to be more suitable for this task.

Combining the information of several linear structures and planar faces results into the same information on the offsets between strips as would otherwise by gathered by the estimation of corresponding locations. Still, it may be questionable whether the height data alone can always provide sufficient information for a three-dimensional strip adjustment.

3. MATCHING REFLECTANCE DATA

Most laser sensors nowadays have the possibility of recording the intensity of the reflected laser pulse. Several authors suggested methods to make use of this data for the estimation of planimetric offsets between strips [Burman 2000, Maas 2001].

Indeed, reflectance data often contains much more detail that can be used to determine offsets (figure 4). The usage of reflectance data, however, also has some inherent problems. In the next paragraph several aspects of the noise characteristics of reflectance images are discussed. We then present a more detailed look on how edges are represented in reflectance images and how this affects the edge location. Finally a procedure is suggested to partially overcome the noticed problems.

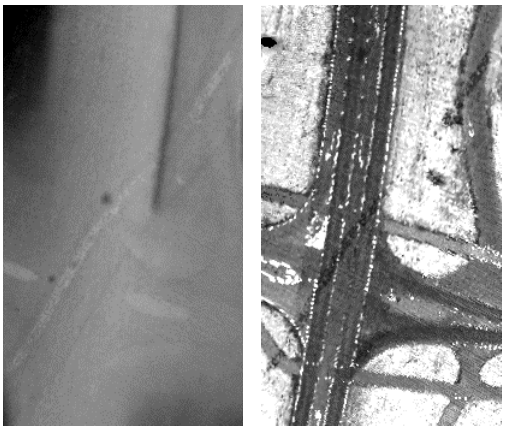

Figure 4: Height and reflectance data of a road crossing.

3.1 Noise characteristics of reflectance images

Reflectance images are known to be relatively noisy. Several reasons can be identified for this property:

- The way most laser scanners measure the intensity of the reflected pulse is by quantising the intensity at some point of time, instead of integrating the intensity over a small period around that point.
- Compared to the distance between the laser points the amount of detail may be very high. Images of urban scenes generally look noisier than images of rural areas (figure 5).
- If a laser beam hits multiple objects at different heights, only the energy that is reflected by one of these objects is used for the determination of the intensity of that pulse.
- Finally, the footprint of a laser scanner is usually much smaller than the distance between two laser points. Hence, the intensities only represent the reflectance properties of a small part of the terrain. The difference between the footprint size and the distance between two laser points can be quite large. E.g. a typical scanner has a footprint size of 0.3 m at a flight height of 1000 m. Scanning with an opening angle of ± 20º and a pulse rate of 25 kHz, the average point distance recorded with this scanner at a flight height of 1000 m and an aircraft speed of 60 m/s would be 1.3 m. In such a configuration, the footprints only cover about 4% of the surveyed area. This amplifies the noisy appearance of reflectance imagery.

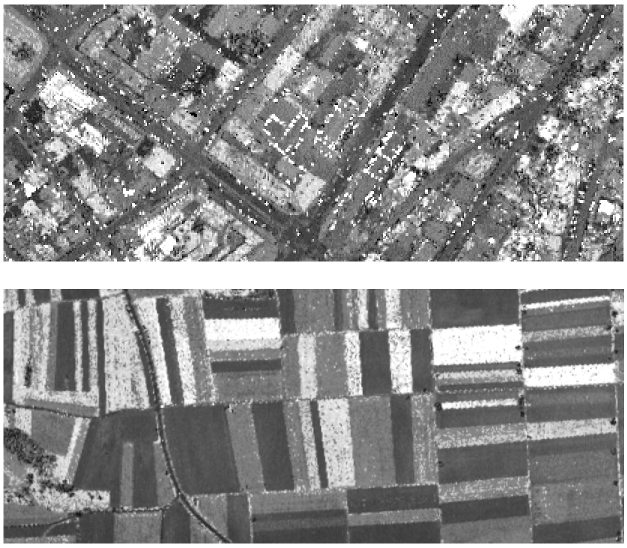

Figure 5: Reflectance images of an urban and an agricultural scene.

3.2 Edges in reflectance images

In the ideal imaging case the grey value of a pixel represents the average grey value of the area that is covered by that pixel. When generating a reflectance image the grey value of a pixel is based on the reflectance properties of only a small fraction of the pixel area.

This characteristic has an impact on the location accuracy of edges in reflectance imagery. In the extreme case of an infinitely small footprint the measured reflectance intensity will be representative for the surface properties at only one side of the edge. As in the case of height jump edges in height imagery, an edge in such a reflectance image should be considered as an edge in a binary image with the edge location properties as described in [Förstner 1986]. Both the bias and the standard deviation of edge location depend on the orientation and length of the edge.

The behaviour of edges in real reflectance imagery is somewhere in between the ideal case and the case of the infinitely small footprint. The different ways in which a reflectance image may be generated from the reflectance strengths of the laser beams is visualised in figure 6. The left picture shows a grey value edge and different locations of three successive footprints in scan lines perpendicular to the edge. In the top scan line the second and third footprint are at the same distance from the grey value edge. The reflectance strengths in the footprints are used to derive the grey values of the rectangular areas that are represented by the footprint. The resulting grey values are depicted in the right picture. In the top scan line the grey value edge exactly coincides with the edge between the second and third pixel of the reflectance profile. In the following scan lines the footprints are gradually shifted to the right. Although the pixel of the second footprint in the second scan line is partly in the bright area, the footprint is still completely in the dark area. Therefore, the pixel is assigned a low reflectance value. In the reflectance image in the right picture, this leads to a reconstructed edge position that has a bias to the right. This bias increases in the following scan lines until the footprint is tangent to the grey value edge. In the next few scan lines the footprint captures intensity information from both sides of the edge and the pixels in the reflectance image obtain mixed grey values. An unbiased estimate of the edge location is again obtained in the scan line where the centre of the footprint is located on the edge. Shifting the scan lines further to the right a pattern symmetric with the upper half of the pictures appears.

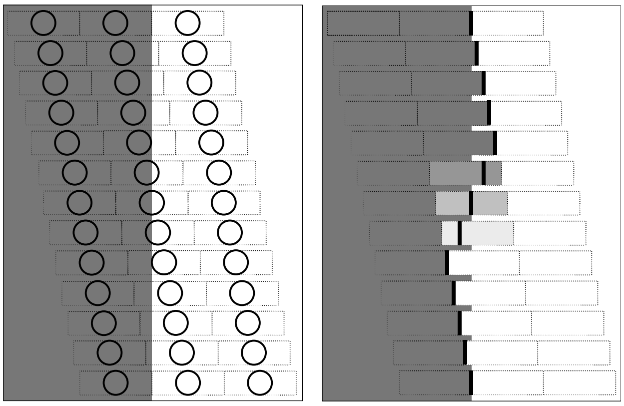

Figure 6: Left: footprints on scan lines across a grey value edge. Right: resulting pixel grey values and reconstructed edge locations. See text.

As can be derived from figure 6, the maximum bias in the location of the edge in the reflectance image equals half the point spacing minus half the size of the footprint. For the above example of a laser scanner with a point distance of 1.3 m and a footprint size of 0.3 m, an edge location bias of up to 0.5 m can occur. For DEM data acquisition with a point distance of 4.0 m and a footprint size of 0.6 m, the bias may be even 1.7 m.

3.3 Matching edges in reflectance data

When matching reflectance images the matching bias may even be twice as large since the edge location bias may be in opposite direction in the overlapping strips. In order to minimise the bias one should try to select long edges as the bias tends to decrease with the edge length, although this does not hold for all edge orientations. For edges parallel to the scan lines, the edge length does not influence the bias in the edge location [Förstner 1986].

The derivation of gradients from the grey values in the reflectance images nearly always will lead to errors in the edge location as illustrated in figure 6. In order to obtain a better estimate of the edge location a model is required for the reflectance of a laser beam on a grey value edge.

Let the position of an edge be described by

$$X\cos\alpha + Y\sin\alpha = d$$

with α as the edge orientation and *d* as the distance of the edge to the origin of the coordinate system. The signed distance *u* of a point (*X*,*Y*) to the edge is then given by

$$u = X\cos\alpha + Y\sin\alpha - d$$

Let the edge orientation be chosen such that *u* is negative for points on the dark side of the edge. If the footprint radius equals *R*, the footprints of all points with $u < -R$ are completely located on the dark side of the edge and the footprints of all points with $u > R$ are completely located on the bright side. For footprints in between, the footprint is intersecting the edge (figure 7a). The fraction of the footprint on the bright side can be defined as a function *f(u)* of the unsigned distance *u* (and the footprint radius *R*) (figures 7a and 7b).

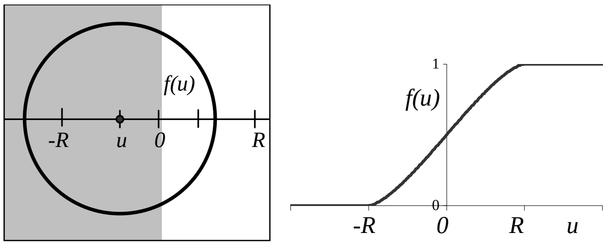

Figure 7: (a) Footprint located at unsigned distance *u* from a grey value edge. (b) Fraction of footprint on bright side of the edge.

Mathematically, *f(u)* is defined by

$$f(u) = \begin{cases} 0 & u \le -R \\ 1 - \frac{1}{\pi}\left(\arccos\left(\frac{u}{R}\right) - \frac{u}{R}\sqrt{1-\left(\frac{u}{R}\right)^2}\right) & -R < u < R \\ 1 & u \ge R \end{cases}$$

This function can now be used to model the expected reflectance strength of a laser beam near an edge. Let r_0 and r_1 denote the reflectance strength in the dark and bright area respectively. The expectation of the reflectance strength $r(X,Y)$ within a footprint on the location (*X,Y*) is then given by

$$\mathrm{E}\{r(X,Y)\} = r_0 + f(u)(r_1 - r_0)$$

This equation can be regarded as the non-linear observation equation. Linearising around the approximate values r_0^0 and r_1^0 of the unknown reflectance values on either side of the edge and the approximate edge location parameters α^0 and d^0 yields the linear observation equation for the estimation of the edge location

$$E\{r(X,Y)-r_0^0-f(u^0)(r_1^0-r_0^0)\}=(1-f(u^0))\Delta r_0+f(u^0)\Delta r_1+\frac{\partial f}{\partial u}\left[\frac{\partial u}{\partial \alpha}\Delta\alpha+\frac{\partial u}{\partial d}\Delta d\right]$$

with

$$u^0=X\cos\alpha^0+Y\sin\alpha^0-d^0$$

as the approximate signed distance of a point to the edge. This equation can be formulated for all laser points near an edge. The gradients of the reflectance strength are derived from the analytical edge response function $r_0+f(u)(r_1-r_0)$. This approach has several advantages over the standard least squares image matching:

- As the partial derivative $\partial f/\partial u$ equals zero for points at a distance of larger than R from the edge location, these points will not directly effect the estimation of the edge location, but only contribute to the estimation of the reflectance values on either side of the edge. The edge location is primarily determined by the points with footprints that actually cross the edge. The gradients at those positions are properly modelled by the edge response function and thus do not cause a bias in the estimation of the edge location.
- Since the gradients are derived analytically, they are not affected by the (high amount of) noise in the reflectance data. Maas [2000] noted that the low signal-to-noise ratio in the coefficients of equations for matching height data caused an overestimation of the matching precision. The usage of an analytical edge model will allow a more realistic estimation.
- The observation equations can be formulated for the original laser points and do not require computations on an additional data structure, like a TIN.

In order to obtain accurate results, one should, however, select long edges for the matching. This is required because of the high noise level in reflectance data, but also since only few points may fall within a distance of R from the edge. The amount of these points depends on the ratio between the point distance and the footprint size and on the orientation of the edge with respect to the scan lines. In bad configurations only very few or even no points may contribute to the edge location estimation. This should, however, then result in a very high value of the estimated edge location precision. By checking the propagated reflectance variances those edges can be selected that have a good location accuracy.

The edge location equations above were formulated such that an edge is located in a single laser data set. If the assumption can be made that the systematic errors in the laser data do not cause a rotation of an edge, the edge fitting can also be done simultaneously in two or more point sets, using the same edge orientation α for all point sets in which the edge is visible. This may further improve the offset estimation between strips.

Initial values are required for all four edge parameters r_0, r_1, α, and d. They can easily be obtained by low level image processing of the gridded reflectance data. Figure 8 shows detected long edges that were obtained in the lower image of figure 5 by a straight line growing algorithm on a median filtered image. Statistical tests on the fit of the reflectance data to the edge model should be used to eliminate those edges that can not be modelled properly by this model. This can be the case if the edge is slightly curved or if other objects near the edge violate the assumption that the reflectance strength is homogeneous on both sides of the edge.

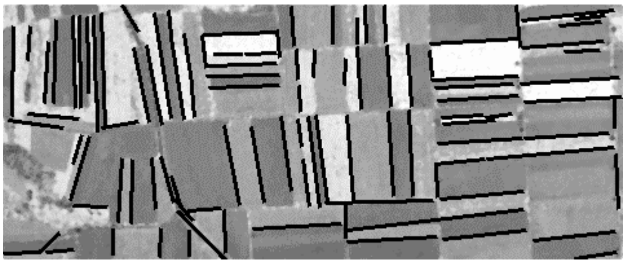

Figure 8: Extracted lines on a median filtered reflectance image.

As for matching height data, one should avoid reflectance edges near occlusions or height jumps. By examining the height data, this can be verified easily.

4. CONCLUSIONS

In this paper it was shown that the determination of offsets between laser altimetry datasets can not be solved reliably by standard least squares image matching algorithms. This holds for height data as well as for reflectance data. Height jump edges in laser altimetry data show the same behaviour as edges in binary imagery. Their location may show a bias which depends on the edge length and the orientation of the edge with respect to the scan line direction.

For matching height data it was advocated to also use linear and planar features besides points for which offsets can be determined in three dimensions. Because of the limited width of linear features a model based fitting may often be required.

Reflectance data may be suitable for the estimation of planimetric offsets, even though its noise level is often fairly high. In order to avoid biases in the estimation of edge locations, the response of a laser beam to a grey value edge needs to be modelled. The usage of such an edge response function also enables the computation of noise free gradients, which results into a better convergence behaviour and a more realistic estimate of the edge location precision.

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