ON THE MATCHING ACCURACY OF RASTERISED SCANNING LASER ALTIMETER DATA

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ABSTRACT

For certain applications irregularly distributed scanning laser altimeter data need to be rasterised - such as for use in GIS systems and for creating DEMs. Also, least squares matching on a raster grid can enable the measurement of planimetric and height shifts between overlapping strips of laser data. The shifts are a manifestation of errors in the laser altimeter, most of which are caused by the positioning elements of the system (GPS and/or INS). These translations form the input into a block adjustment to correct for relative and absolute errors. Here a discussion of the issues related to deriving a regular grid of 2.5D points from the original data is presented, with particular reference to the interpolation method, grid size, and quantisation level. An interpolation method based on a TIN of the original points with a grid size that relates as closely as possible to the point density at acquisition is found to give the best results. 8-bit quantisation is found to be sufficient for height differences of up to 100m.

1 INTRODUCTION

1.1 Scanning Laser Altimetry

Scanning laser altimeters measure 2.5D point co-ordinates using a combination of a positioning and orientation system (GPS or GPS and INS combined) and a reflectorless laser range finder. The data are acquired in strips, the width of which can vary between 70m and 800m, depending on the flying height of the platform and on the system used. The strip length is only constrained by the distance from the platform to the reference GPS receiver(s). The further the distance from the reference station the lower the accuracy at which differential GPS techniques can be used for platform positioning - for airborne positioning, 10cm accuracy is possible with distances of less than 30km (Cramer, 1999*)*. For linear features, e.g. railways, power lines, or seashores, etc., such strips of data are wide enough to measure the entire area of interest (Pottle, 1998; Hadley & Pottle, 1998; Krabill *et al.*, 2000). However, for broader areas strips must be flown parallel and overlapping until the survey site has been completely covered. The strip data are merged in a post processing stage.

Points are distributed along the length of the strip as functions of the flying speed, the flying height, and the number of points per second measured by the system. The across strip distribution of points is achieved using a fibre optic line scanner - TopoSys (Lohr & Schaller, 1999) -, or by oscillating - Optech's ALTM (Fong *et al*, 1998), Saab's TopEye, Enerquest's RAMS, Azimuth's AeroScan, and EagleScan's DATIS -, rotating - Chance's FLI-MAP (Pottle, 1998) and TerraPoint's ALTMS -, or nutating - Stuttgart University's ScaLARS (Hug & Wehr, 1997; Thiel & Wehr, 1999), NASA's AOL (Krabill *et al.*, 1996) and Geographia's SURVAIR - a single sensor by mechanical means (Baltsavias, 1999). With a single sensor the point distribution across the width of a strip is likely to be less regular than with an array system due to mechanical irregularities and wear on components over time.

1.2 Raster Laser Altimeter Data

For many users the product required is a 2.5D raster at a specific grid spacing rather than an irregular point set. An example of this is the Actueel Hoogtebestand Nederland (AHN) in The Netherlands for which data are being acquired at a density of 1 point per $16m^2$ (Huising & Gomes Pereira, 1998; Rijkswaterstaat, 2000). For linear features, that are completely measured using a single strip, only the interpolation of a regular grid is necessary. For larger areas overlapping strips must be both merged and interpolated into a regular grid. If there are no errors in the laser data, merging of strips is a simple process. However, it has been found that laser data usually contain an amount of errors (Lemmens & Fortuin, 1997; de Min *et al.*, 1999; Huising & Gomes Pereira, 1998; Gomes Pereira & Janssen, 1999; van Noort, 1999). The exact nature of the error varies with the system used, the method of derivation of the positioning

information, the integration of the system components, the distance from the GPS reference station(s), the type of terrain covered, and other factors. Some errors effect single points, others an entire strip, and others all points measured within a flight (de Min *et al.*, 1999).

One method of eliminating or, at least, minimising these errors is to perform a least squares bundle block adjustment as conventionally used in photogrammetric aerial triangulation (Forstner, 1984; Gruen, 1985). At Stuttgart University, Germany, strips of laser data were merged based on the results of a bundle block adjustment that corrected for relative and absolute discrepancies by using information from DEM matching (Kilian, 1994; Kilian *et al.*, 1996). Rijkswaterstaat in The Netherlands have developed a bundle block adjustment that corrects for the relative and absolute height variation only (de Min *et al.*, 1999) while at Delft University of Technology, again in the Netherlands, a full adjustment for height and planimetry using bundle block techniques is in development. Since the errors effecting single points are not yet fully understood no attempt will be made to correct from them in the block adjustment, at present. This will be a topic for future research. The errors per flight will be removed using an absolute correction for all points. The magnitude of the absolute corrections will be derived from the measurement of discrepancies between the laser co-ordinates and the true ground positions of control points, features, or surfaces. A relative correction will reduce or eliminate errors between overlapping strips. To derive the magnitude of the relative corrections, shifts in height and in planimetry between strips must be accurately measured. Standard least squares matching techniques on gridded data can provide this information.

1.3   Tests on Rasterised Data

The least squares matching as used in this approach works entirely with the gridded data. Therefore, it is essential that the interpolated value of each grid cell is as accurate as possible, to ensure correct estimation of the shift parameters. There are many interpolation methods available for the derivation of a regular grid from unevenly distributed points. However, the results of all techniques are not the same. We investigated two interpolation methods – nearest neighbour binning and planar interpolation on a TIN – to determine if there were significant differences in the quality of the derived data. A discussion on the results is shown in Section 3.1.3. One way of assessing the interpolation method was to analyse whether changes in grid size alter the quality of least squares matching between points. These grid size tests are detailed in Section 3.1.4 and visual checks on the data are also described.

In the initial tests the height values of the gridded data were quantised at 8-bits to be compatible with the least squares matching software. However, it could be expected that such a low level of quantisation (256 levels) would reduce the quality of matching in areas with significant height differences. In Section 3.2 terrain is simulated with significant height variation and the effect on the quality of shift estimation between strips is assessed.

2   SCANNING LASER ALTIMETER DATA USED

The data used for this assessment were provided courtesy of The Survey Department of the Ministry of Transport, Public Works and Water Management, The Netherlands and cover an area in the east of the country. The data were acquired with the FLI-MAP system (Hadley & Pottle, 1998; Pottle, 1998; Chance, 2000) – developed by John E. Chance and Associates - using a helicopter platform with GPS positioning, but no INS information. The point density is approximately 5 points per square metre, which is significantly higher than would usually be used for mapping large areas. Most of the block was flown with a strip overlap of 20% to 30% but, in the region chosen for these investigations, the overlap increased to as much as 50%, allowing larger numbers of points to be matched between strips than would usually be possible. These larger samples increase the reliability of the tests and should ensure the validity of any conclusions made. Two parallel and overlapping strips cover the area of interest that extends for 400m in X direction and 500m in Y direction. The heights recorded varied between 0m and 25m, although the area is quite flat. Most of the higher points occur on vegetation or on buildings. The FLI-MAP system works in 'first pulse' mode meaning that, in vegetated areas the laser pulse (or wave) rarely penetrates to the ground. Only height data were used here although reflectance data were also available.

3   EXPERIMENTS

For all tests, the patch size was 15x15 pixels and the minimum cross-correlation coefficient was 0.75. While an 8-parameter affine transformation is often used in least squares matching of image data to account for stretching, rotation, and differences in contrast, this is not appropriate for laser data. Laser data, as handled in matching, are in 2.5D format and, in the absence of errors, points from overlapping strips are the same, in as much as the irregular acquisition method

will allow. However, errors - particularly in the positioning of the platform – are present and cause differences between strips. These can be measured using 3-parameter least squares matching with two planimetric shifts and one height shift. The aim of each test was to measure at least 30 points. Attempts were made at using the Forstner interest operator to select points for matching but this proved to be unsuccessful. Therefore, the points were chosen manually. However, it was not possible to guarantee that the same 30 points would be "matchable" with each set of experimental conditions due to the differences between the data sets (see figures 1 to 6). Some of the variability between images is caused by gaps that are the result of a lack of laser return from certain surfaces, such as level water, which absorbs the signal, or highly specular reflectors, which deflect the laser pulse entirely away from the receiver. Also, occlusions by high buildings cause significant variation between strips, especially with wide-angle systems. Therefore, the point sets used in each of the tests are not identical (except for the final quantisation test in Section 3.2). The word 'bin' in a file name shows that the interpolation method was nearest neighbour binning. 'Plane' shows planar interpolation on a TIN was used. The grid sizes used were 50cm, 60cm, and 1m, and 't' is indicates 'translation only' (3-parameter) matching.

3.1 Interpolation Method

In this section we will describe a comparison made between data that have been interpolated using nearest neighbour binning and using planar interpolation on a TIN.

3.1.1 **Nearest Neighbour Binning.** In this technique a grid cell is filled with the value of the closest original laser point. If no point is found within a maximum search radius the grid cell remains empty. A 'fillgaps" routine can interpolate a value for these cells using linear interpolation from neighbouring cells distributed over at least three quadrants. The binned data at 50cm and 60cm were filled twice to reduce the number of gaps. The 1m data were only filled once. Without applying "fillgaps" it was not possible to match a significant number of points because there were too many differences between the strips.

3.1.2 **Planar Interpolation.** A TIN structure is established from the laser ground points using a Delauney Triangulation routine. A sequential search then establishes the triangle in which each grid cell is contained. Using the gradients of the selected triangle a value is interpolated for the grid cell.

3.1.3 **Interpolation Comparison.** Figures 1, 3, & 5 show areas of the left and right strips for binned data at 1m, 60cm, and 50cm grid size, respectively. These figures show, in detail, a section of the area used for matching (the images are not to scale). Figures 2, 4, & 6 show the equivalent images for planar interpolated data.
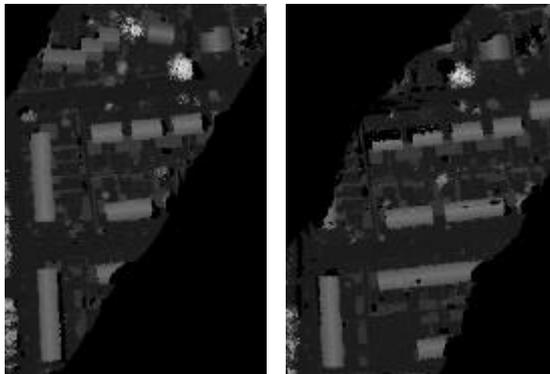

Figure 1. Left and right strips at 50cm,
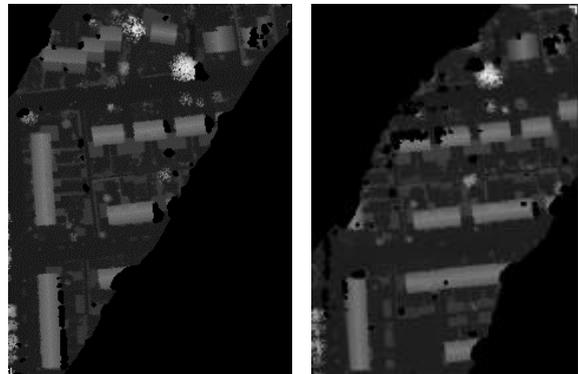nearest neighbour binning

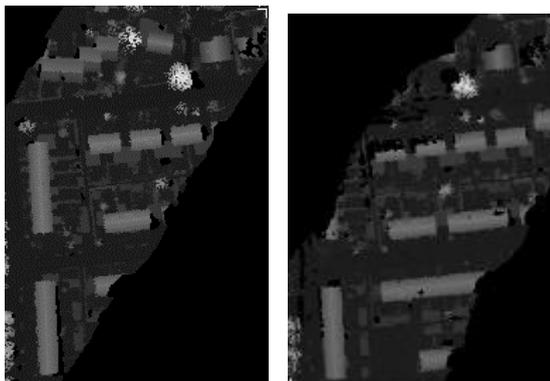Figure 2. Left and right strips at 50cm,
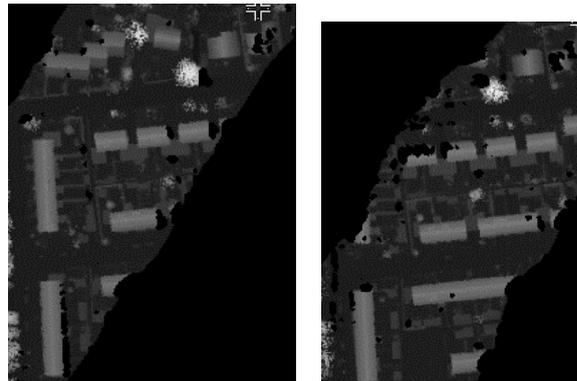planar interpolation

Figure 3. 60cm, nearest neighbour binning

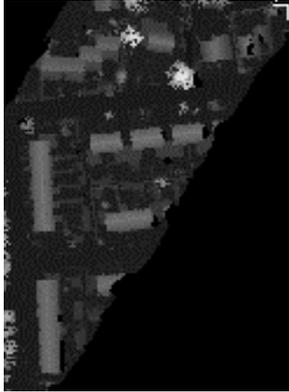
Figure 4. 60cm, planar interpolation

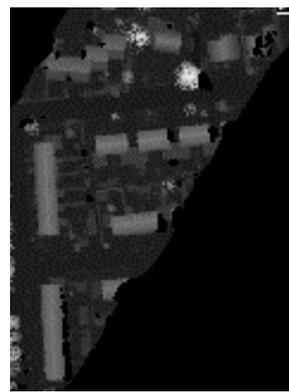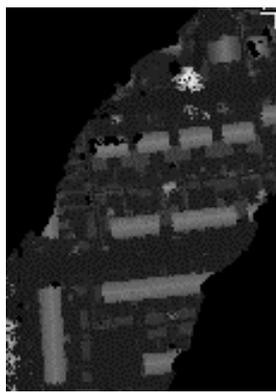Figure 5. 1m, nearest neighbour binning   Figure 6. 1m, planar interpolation

On visual comparison of the images it is clear that there are significant differences between the results of the two interpolation types at each of the grid sizes. With both rasterisation methods, particular variation is noticeable in the 4 houses in a row in the right strip. (3 of the same buildings are visible in the left strip and, while there are differences between the grid sizes and interpolation methods, these are not as apparent upon visible inspection as were the differences in the right strip.) As well as matching between overlapping strips at the same grid size, points were matched between a 50cm grid and a 60cm grid of the *same* strip rasterised using binning. The same 50cm to 60cm test was performed on interpolated images. These tests were given the file names 50_60_tbin and 50_60_tplane, respectively.

File	Number of Points	Average Standard Deviation (in cm)			Average Height Shift (cm)
		Translation Row	Translation Column	Height Shift	
50_tbin	25	4.70	5.20	5.70	-4.80
50_tplane	34	4.00	3.90	3.96	-2.15
60_tbin	30	5.76	5.82	5.94	-4.08
60_tplane	28	4.74	5.04	4.64	-2.11
1_tbin	21	9.00	9.50	8.07	-9.36
1_tplane	17	7.40	7.80	6.47	-8.20
Total Average Translation	**26**	**5.93**	**6.21**	**5.80**	**-5.12**

Table 1. Average standard deviations of translations and height shift and average height shift for matching between overlapping strips at the same grid size.

Table 1 shows the average standard deviations of the translations and the height shift in centimetres, as well as the average height shift, in centimetres, for each of the grid sizes from each of the interpolation techniques. In all cases the lowest standard deviations in planimetric and height shift are from the 50cm planar interpolated data, with the 60cm planar data next lowest (to within 0.1cm). At 1m, the standard deviations for the planar data are also lower, by an average of 1.5cm, than those for the binned data. Looking at the average height shifts, it can be seen that the results from the planar interpolation at 50cm and 60cm are the same to within 0.04cm. For the binned data the measured z-shift is 2cm more than measured on the interpolated data. Any of the following reasons, or a combination of them, could have caused the difference of 4 to 5cm between the 1m and the 60cm data. There are less points measured in the 1m data sets, therefore a single spurious point would have more influence than in the other cases. The differences between the two strips at 1m grid size are more evident than at smaller grid sizes (compare figures 1 to 6). The occlusions caused by the slant of the laser path, particularly at the edge of the scan line, make measurement of the exact shape of features difficult, and this effect is more evident at larger grid sizes. However, with all three raster grids it is clear that the quality of matching on planar interpolated data is better than on binned data.

It should also be noted that the quality of matching for the planimetric and height shifts is the same to within 0.41cm. This result is unusual because it is known that the quality of heighting from laser altimetry is approximately 5 to 10cm, while in planimetry positioning accuracy is thought to be in the decimetre range. This would suggest that the results from the x and y shift measurements are too optimistic. This could, again, be the result of occlusions caused by buildings and vegetation, or by noise in the signal, which increases the internal confidence in the least squares match.

These results may, therefore, not be entirely representative of the true quality of matching and more research is needed to see if they can be verified (see Maas (2000) for further discussion).

3.1.4 **Effect of Grid Size on the Interpolation Technique.** Sensitivity to grid size can give an indication of the quality of the interpolation technique. The data in table 1 show that there is an improvement in the quality of matching as the grid size gets smaller with both planar interpolation and nearest neighbour binning. For both interpolation types the difference between the average quality of matching at 50cm and 60cm is close to 1cm. However, the reduction in quality between 60cm and 1m with binned data is about 3.5cm and only 2.5cm with the planar data. For the average height shifts there is much closer agreement between the measurements made on planar data and those made on binned data, with the exception of the 1m data which give very different results.

In table 2 there are comparisons between the matching of a 50cm data set and a 60cm data set of a single strip rasterised using nearest neighbour binning and a 50cm to 60cm match on planar interpolated data. The average standard deviations of the shifts are better in the planar data by 0.6cm, 0.9cm, and 1.73cm for x, y, and z, respectively. This agrees with the tests on data at the same grid size and also indicates that the use of planar interpolated data is somewhat more independent of grid size than is nearest neighbour binning. However, the average height shifts indicate that some of the matching was not correct as 20cm and 17cm are much larger differences than would be expected when matching the *same* data from one strip. The 50cm data delivers the highest quality matching results but these conclusions are a function of the density of point acquisition and are specific to this particular data set. However, it is clearly very important to choose a grid size that is equivalent (in as much as this is possible) to the original point density in order to minimise the effect of the interpolation method. It is also possible that the use of a linear interpolation routine to fill the gaps in the binned data significantly improved the quality of these data such that differences between the nearest neighbour binned results and those from planar interpolation on a TIN were reduced.

File	Number of Points	Average Standard Deviation (in cm)			Average Height Shift (cm)
		Translation Row	Translation Column	Height Shift	
50_60_tbin	32	4.895	4.950	7.35	-20.41
50_60_tplane	46	4.290	4.070	5.62	-17.65

Table 2. Average standard deviations of translations and height shift and average height shift for matching between data at different grid sizes.

3.2 Quantisation

Quantisation is the act of subdividing into small but measurable increments (Webster, 2000). When obtaining rasterised data from irregular point sets it is important to know the effect(s), if any, of quantisation on the derivation of the dependent quantity (height or reflectance, in the case of laser scanning). The least squares matching technique used here worked on data quantised to 256 levels (8-bit). Following on the results of the tests previously described, the least squares matching used 3 parameters, the grid size was chosen as 50cm, and the raster was derived using planar interpolation.

Height per Quantisation Level	Number of Points Measured	Average Standard Deviation (cm)			Average Height Shift (cm)
		Translation		Height Shift	
		Row	Column		
10cm	34	3.95	3.80	3.83	-2.15
20cm	33	4.10	4.10	4.02	-0.82
40cm	34	4.00	4.10	4.04	-3.08
1.60m	34	4.65	4.60	5.12	-3.68
6.40m	12	4.55	5.00	8.32	1.92

Table 3. Average standard deviations of translations and height shift and average height shift for differently quantised data.

The values in the first column of table 3 show the height range that is mapped to each level of the 256 available when using 8-bit quantisation. The reason that there are so few points measured in the data at 6.4m is that there are almost no recognisable features. This very small sample means that no reliable information could be derived from the test and that what seem like 'high quality' matches cannot be trusted.

The average standard deviations for the 10cm, 20cm, and 40cm data are all very similar with a notable decrease in the quality of matching at the 1.6m data level. The average height difference for the 20cm data is much lower than derived from the other data sets but this could be accounted for by the choice of points. To gain a better indication of the influence of quantisation on the measurement of z-shifts, 10 identical points were measured in data quantised at 10cm, 20cm, 40cm, and 1.60m (the larger 6.40m set used above could not be used because the points could not be identified.) Figure 7 shows the location of these points and table 4 shows the z-shifts as measured for each of the points at each quantisation level. Since points 1 and 5 have extremely large offsets it is presumed that identification errors occurred and these points are excluded from further discussion.

Point Number	10cm Height Difference	20cm Height Difference	40cm Height Difference	1.60m Height Difference	Maximum Range	Maximum Range (excl. 1.6m)	Average Height Difference	Average Height Difference (excl. 1.6m)
1	61.96	79.56	57.40	20.96	58.60	22.16	54.97	66.31
2	-0.97	-1.56	0.36	-5.28	5.64	1.92	-1.86	-0.72
3	3.89	2.94	1.08	2.08	2.81	2.81	2.50	2.64
4	-3.10	-3.56	-4.60	-5.76	2.66	1.50	-4.26	-3.75
5	16.63	16.94	15.60	16.32	1.34	1.34	16.37	16.39
6	4.73	7.32	9.80	7.52	5.07	5.07	7.34	7.28
7	-8.77	-8.34	-10.88	-11.20	2.86	2.54	-9.80	-9.33
8	-7.49	-6.80	-8.68	-13.44	6.64	1.88	-9.10	-7.66
9	-5.85	-7.70	-7.80	-11.68	5.83	1.95	-8.26	-7.12
10	-10.50	-9.96	-9.92	-11.04	1.12	0.58	-10.36	-10.13
Average (excl. 1 & 5)					4.78	2.28	-4.23	-3.60

Table 6. Height differences (cm) for 10 identical points measured at different quantisations

The same z-shift between strips would be calculated for each point in each test if there was no negative effect on interpolation and matching by the level of quantisation. However, variations of between 0.5cm and 2.9cm, with an average of 2.28cm, can be seen for the 8 points at quantisation levels 10cm, 20cm, and 40cm. When the 1.6m quantisation level is included the ranges increase to between 1.12cm and 6.64cm, with an average range of 4.78cm.
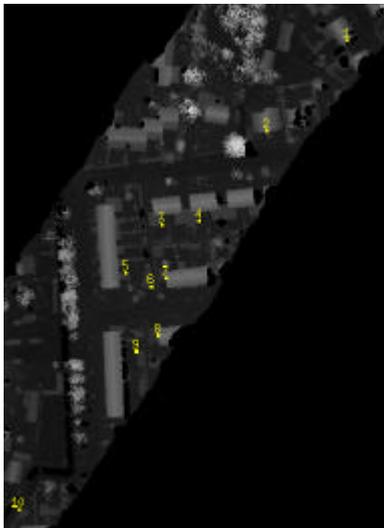

Figure 7. Locations of 10 points for quantisation tests

Ignoring points 3 and 6, the average height differences show a pattern of increasing differences (from –0.72 to –10.13) and this could be the result of a tilt of one of the strips as shown by the point locations in figure 7. Since the area in which all the points are included covers only 500m in the along strip direction it is difficult to assess whether this possible tilt is a local effect or is present in the whole strip. Also the presence of a number of outliers reduces the reliability of the results. In research carried out on least squares matching on the original laser TIN similar effects have been noted with significantly higher reliability (Maas, 2000).

Similar to the average standard deviation measurements shown in tables 1 and 2, some of the height difference measurements are possibly too optimistic. The presence of occlusions could again be an important factor in these results. Also, for all but two of the points, 3 and 6, the height difference measured in the 1.6m data is significantly different from the measurements in the other quantised data sets. This indicates that 8 bit quantisation seems to be sufficient for the measurement of height differences of up to 100m but that a higher level of quantisation (16-bit or more) would be necessary for accurate matching on raster data with larger height differences.

4 CONCLUSIONS

The tests described above have shown that matching on rasterised scanning laser altimeter data is affected by a number of factors:
- the interpolation method,
- the grid size, and
- the level of quantisation.

It is clear that a 3-parameter (x, y, and z shifts) least squares match will provide the most reliable results from rasterised data. The grid size must be very similar to the original density of the data or bias effects will become evident. These effects are significantly reduced by using planar interpolation based on a TIN of the original laser points as compared to using nearest neighbour binning. In areas with only minor height differences (up to 100m) quantisation to 8-bit does not have a significant negative effect on the quality of matching. This would usually be the case in relatively flat countries such as the Netherlands. However, in mountainous regions, or in urban areas with high-rise developments, the effects could be very significant. This would suggest that the dependant variable should be interpolated and stored at a higher level of quantisation than 8-bit, to ensure that important information is not lost and that the quality of shift estimation is as high as possible with rasterised data.

5 FUTURE WORK

It is clear that extreme care must be taken with the use of rasterised data for matching and the derivation of discrepancies between strips of laser data, particularly in terms of grid size, interpolation method, and quantisation level. However, Maas (2000) has shown that a significant improvement in the quality of matching results is possible using least squares matching directly on a TIN of laser points. The shifts thus derived will form the input into a least squares bundle block adjustment for scanning laser altimeter data. The relative discrepancies between strips and the absolute discrepancies between the laser data and the true ground data will be measured and used as observations in the adjustment that is in development. Further research is also needed into the nature and magnitude of individual point errors and this inventory will allow for their proper handling in the block adjustment.

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