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Correcting height differences in digital elevation models derived from overlapping LiDAR survey runs

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Abstract: An aerial LiDAR survey was acquired for the Tully-Murray floodplain in Tropical Queensland involving multiple runs by a light aircraft. Height differences between overlapping areas on adjacent runs of the survey were noted and, upon further investigation, appeared to manifest themselves as both offsets and as systematic tilting across the width of the run. The pattern of height variations was attributed by the supplier to slight timing, filtering and processing issues with the global positioning system (GPS) and the aircraft's internal measurement unit (IMU) data. These differences (in most instances less than 70 cm) were larger than the level of accuracy attributed to the laser scanner ranging system (less than 10 cm). So, while relatively small compared to many topographic variations, they created artifacts along the run edges in a merged digital elevation model (DEM) that were detrimental to further analysis, particularly as the DEM represented extremely flat terrain (i.e. a floodplain).

Gridded DEMs were developed separately for each run from the raw data files. Then, during merging of the runs, a technique was developed and applied to minimize the height differences between runs and thus the artifacts they may generate in a merged product. The technique firstly identified height differences along all the edges of runs and then applied a linear interpolation between these edges to allow the heights to conform more closely to the averaged values at the edges. The correction technique was successful in improving flow patterns by removing the strongest height differences and consequential artifacts from the merged DEM. However, the technique is sensitive to horizontal (X, Y) misalignment of features between runs (which occur for similar reasons to the height offsets) and thus requires careful checking and some manual interventions to avoid erroneous adjustments where there are sharp changes in height (e.g. near river banks). This paper will discuss these issues and suggest some future improvements to the technique.

Keywords: *LIDAR, DEM height correction*

1 INTRODUCTION

1.1. Background

The Tully-Murray floodplain in northern Queensland, Australia is considered to be a significant source of sediment and nutrients to the Great Barrier Reef (GBR) lagoon (e.g. Furnas, 2003). It's location in the wet tropics subjects it to frequent flooding. During the flood events, overbank flows can create semi-continuous sheets of water spanning between the two river systems and provide overbank connectivity between the numerous wetlands located on the floodplain. In the dry season the river systems and wetlands still maintain some connectivity via natural streams and man-made drains. A study, funded by Marine and Tropical Sciences Research Facility (MTSRF), is currently underway in CSIRO Land and Water to monitor and model the floodplain's transport of nutrients and sediments. Additionally the modeling will be used to explore ecological connectivity within the floodplain and its numerous wetlands. To support such modeling work, highly detailed survey data was acquired using an airborne LiDAR system. Figure 1 below shows the extent of the survey in relation to the Tully-Murray Floodplain.

As modeling was required to simulate both overbank high flow events and within-channel low flow events, LiDAR data was used to provide input data for both: i.e. a 2-D gridded DEM for modeling overbank events and, for modeling low flow events, provide detailed channel cross sections and assist in the mapping of fine scale drainage features. The cost to acquire LiDAR for the entire floodplain was prohibitively expensive. Thus a smaller area was selected (90km^2) covering the region where the two rivers interacted most closely and which included many wetlands and drains.

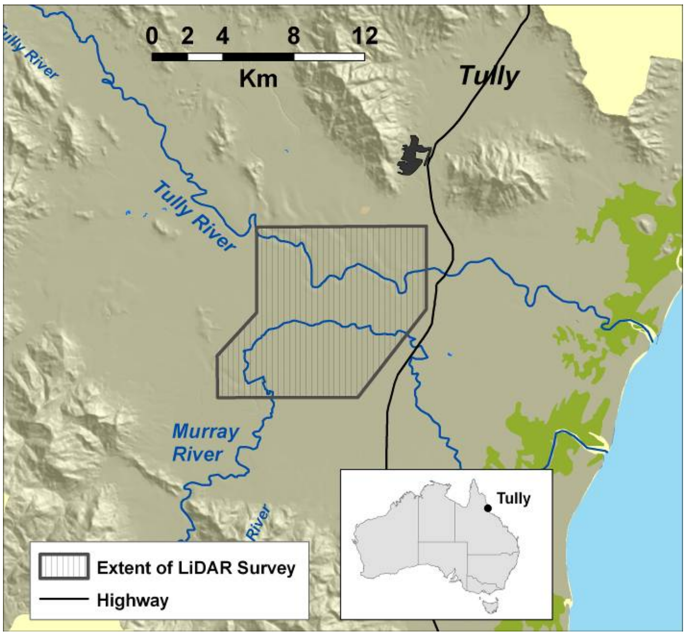


Figure 1: Location of LiDAR survey on the Tully Murray Floodplain, northern Queensland, Australia.

This paper concentrates on the 2D gridded DEM development, where we needed to obtain a seamless DEM suitable for analysing 2-D flow patterns across the floodplain during overbank flood events. However, the height corrections developed were found to also be necessary to ensure a consistent height datum between runs when extracting channel cross sections from the raw LiDAR data for 1-D low flow event modeling.

2 THE LIDAR SURVEY

The LiDAR survey was flown during two days in October, 2007 (dry season) by Airborne Research Australia (ARA) based in Adelaide. The survey was acquired using a Riegl560 laser scanner mounted underwing aboard an Eco-Dimona aircraft. At 400m flying height, scan widths covered approximately 300m with a point density approximating one raw return every 0.3 m along-scan and 0.5m between scans. The laser scanner's ranging system was theoretically capable of providing accuracy of 10 cm at such a flying height. Differential GPS was then used in combination with the aircraft's internal navigation system (INS) to georeference all points to GDA94 Geoidal heights. A scan width of 300m for each run meant that numerous parallel runs were required to provide coverage (with overlaps for redundancy and multiple look angles) of the 90 km^2 area (see Figure 2).

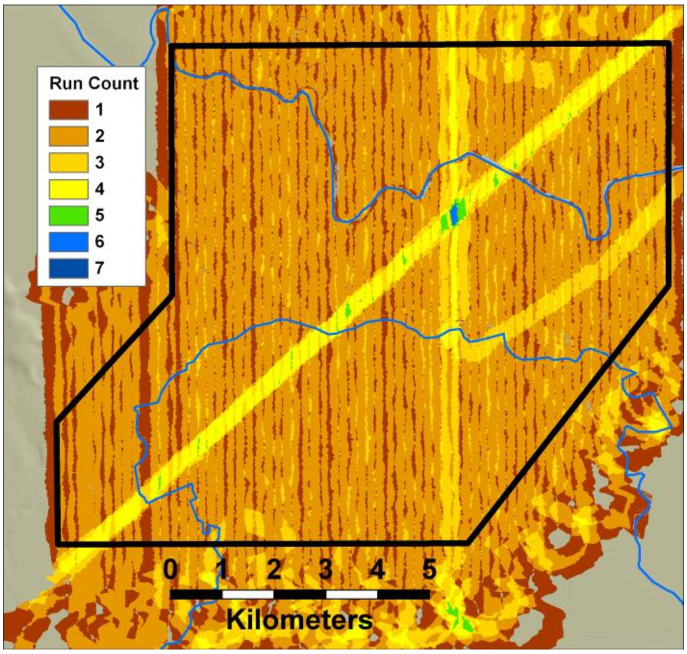


Figure 2: Flight run geometry showing extent of overlap in LiDAR survey data.

3 DEFINITION OF PROBLEM

Raw returns were provided by the LiDAR by Airborne Research Australia already classified into bare ground and vegetation. Bare ground returns were then extracted and used to generate a 3m rectangular DEM grid for each run. Once DEMs were generated, they needed to be combined in order to provide a continuous surface on which to base the 2-D flow modeling work. Initially the DEMS were combined using a simple grid cell averaging technique. However, it was noted that there were significant "steps" of up to 0.5 (well above the quoted accuracy of 10 cm for the scanner) in the resulting merged DEM. These steps coincided with the edges of runs. Upon investigation, it was discovered that there were height differences between overlapping DEMs commonly up to 70 cm (see Figure 3).

Step phenomena have been observed in many LiDAR surveys (Maas, 2001, 2002, 2003; Latypov, 2002, and 2005) and a number of papers have discussed attempts to deal with the problem, although all studies found (Crombaghs *et al.*, 2000; Pfeifer, 2005; Willers *et al.*, 2008) focused on adjustments to the original LiDAR point cloud. Point cloud adjustment methods were complex and beyond the scope of this study or the in-built capabilities of the GIS software. So the view was taken that, since the point clouds generated for each run appeared to be internally consistent, it should be possible to generate a gridded surface of reasonable integrity for each run, albeit in error relative to adjacent or overlapping runs. It was then possible to adjust the DEMs generated for individual runs using tools within the existing ArcGIS software.

Maas (2003) observed that "Both height ...(in the order of 10-15 cm)... and planimetry precision are affected by significant systematic effects, which are often larger than the stochastic errors." Indeed, there were many patterns in the observed height differences which suggested systematic causes (see Figure 3). Some areas also show a regular gradient in height differences across the run and some showed an almost constant offset across the full width of the overlap. Superimposed on this, where a run edge deviated substantially from a straight line, for example where the aircraft suddenly tilted, the height differences across the run shifted up or down relative to the other run. In Figure 3 this phenomena can be seen as a striped texture, strongest where a run edge suddenly shifts (eg striping associated with the pointy run edge feature marked with an arrow in Figure 3). While not included within the DEM area, more extreme versions of these error patterns were observed where the aircraft was banking.

ARA have recently identified the cause of striping patterns in the error as slight timing/filtering inconsistencies between the Global positioning system (GPS) and the aircraft's internal measurement unit (IMU), which they were not able to correct during the post-processing of The Tully-Murray survey. The more generic height differences were related to differential GPS processing. These causes are consistent with those noted by others such as Maas, 2003.

Detectable horizontal offsets of features in the DEMs (approaching 1 pixel (3 m) in some of the worst) confirm that there was also some difficulty getting an accurate horizontal fix for almost certainly the same reasons already mentioned.

ARA has addressed these issues through consultation with the manufacturer regarding post processing corrections for timing/filtering issues and through optimization of the differential GPS processing for generic height difference errors. Thus the magnitude of errors is much smaller for more recent surveys.

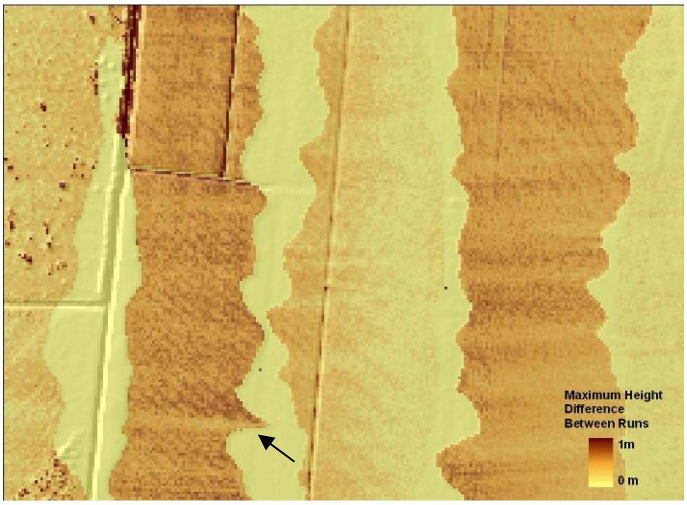


Figure 3 The maximum height differences observed between runs. Unshaded pale yellow areas were covered by only one run.

4 METHODS

The height differences noted in the previous section, while variable in magnitude and form, show a common tendency to trend smoothly across the width of a run. This trend was exploited in developing a height correction routine by extrapolating adjustments from the run edges while ignoring more localized adjustments internal to the runs. Such an approach also allowed areas with only one DEM height value to be extrapolated to new heights, taking into account adjacent run data. In a merged DEM, edges of areas covered by only a single run tended to be the locations that showed the largest step-ups or step-downs. So being able to apply a correction to a single DEM, by taking into account adjacent DEM heights, was critical to improving the resultant merged DEM.

The correction routine avoided including adjustments near sharply varying features, in recognition that erroneously large height differences could occur over such features as a result of the horizontal offsets in the DEMs. Furthermore, to minimize effects of horizontal offsets on calculation of localized adjustment values, all height adjustments were based on the average of a neighborhood of pixels rather than on a single pixel.

The step by step method for creating an adjusted DEM grid is shown in Figure 4 and described below:

1) An average DEM height grid was calculated by the mean height from all the runs for any one grid cell location. For some locations there was only one height value while for others there was up to 5. The shaded relief in Figure 4(a) illustrates the resultant stepping artifacts along run edges from such an averaged DEM.
2) All grid cells located at the edges of runs were identified by applying a high pass filter to a grid of run count. Erroneous edges, formed by voids (e.g. from waterbodies) within a run were removed.
3) A grid of final heights (to which all DEMs were to be adjusted) was generated by
    a. smoothing the averaged height grid from step 1 using a 9x9 (27m by 27m) averaging filter then keeping only the grid cell values identified as edges in step 2.
    b. determining the maximum height difference in a 9x9 (27m by 27m) area from the average height grid in step 1 and keeping only those grid cells from step “a” where the height difference was less than 1m. Thus areas of sharp height change (eg. near river embankments or drains) were excluded.
4) A similar grid of original run heights was generated for each run using the same method as step 3, but applied to the individual run DEMs. As many of the adjustment points occurred along the edges of runs, the default option for averaging filters (i.e. don’t calculate the value if a null value is encountered) would have resulted in NULL values for all grid cells. Thus the 9x9 averaging filter used the option to ignore the existence of null cells and calculate the average with whatever pixels could be used.
5) A grid of adjustments for each run was created by subtracting the individual DEM grid values from step 4 from the averaged DEM grid values from step 3.
6) All run adjustment grids from step 5 were converted into points from which a triangulated irregular network (TIN) lattice adjustment surface was then constructed (see Figure 4(b)). The TIN was converted to a grid to represent an interpolated adjustment surface for each DEM.
7) The interpolated adjustment surface was then used to adjust each run DEM by simply adding the two grids together.
8) All adjusted DEMs from step 7 were then combined by using the same technique as for the averaged grid in step 1. This created a continuous DEM surface (see Figure 4(c)).

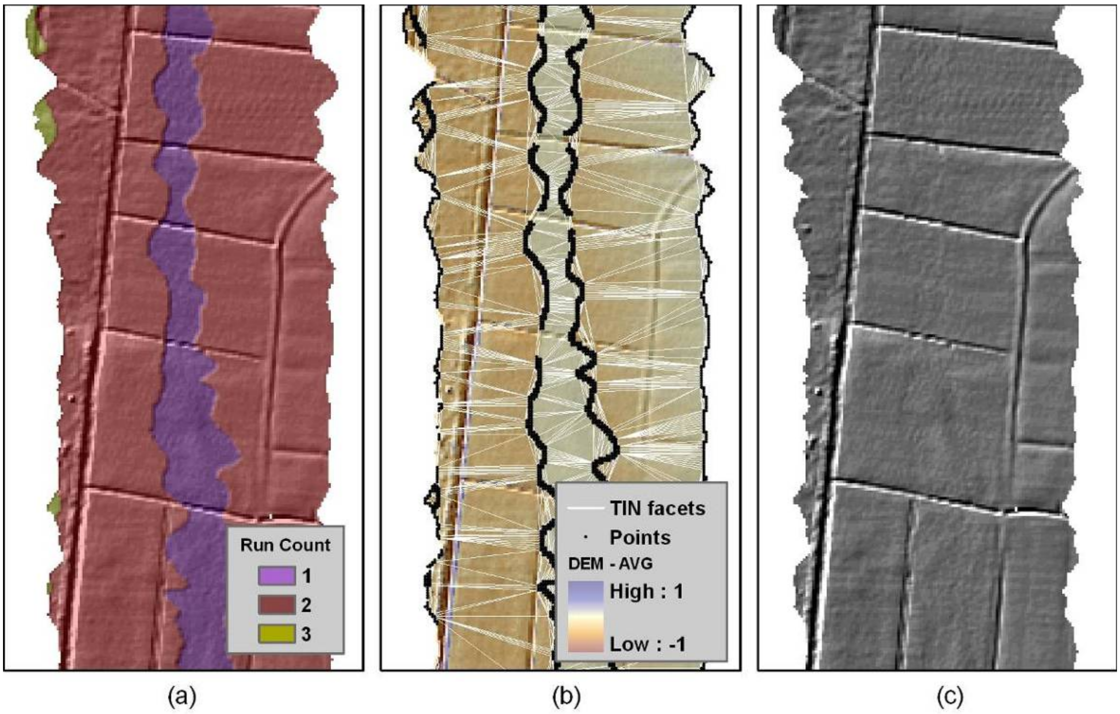
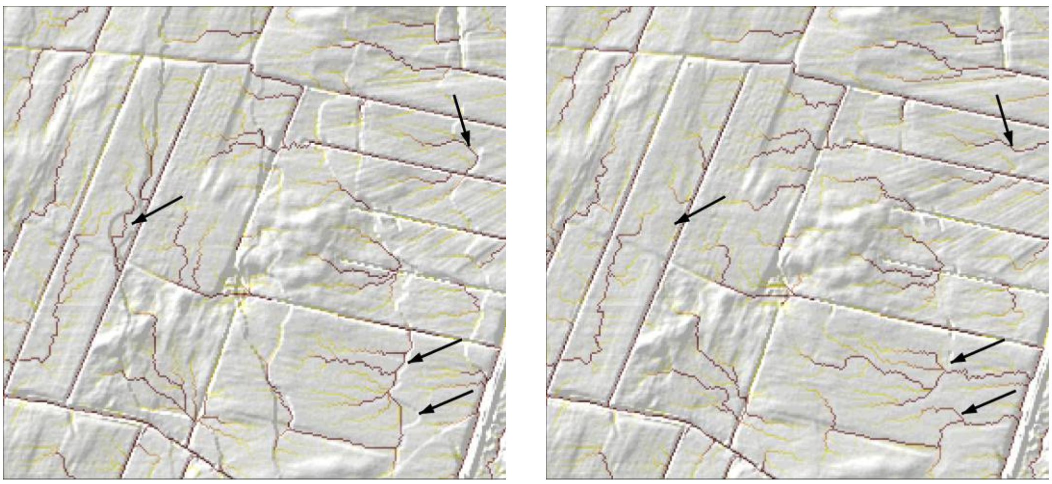


Figure 4: Height corrections steps for a single run: (a) Determine edges using run count information and determine spatially averaged heights at each edge (b) Generate adjustment points along all edges (black dots) and remove those that occur near sharp landscape features then construct a TIN lattice (white lines) to interpolate between points. (c) Use the TIN structure to determine adjustments for DEM and apply.

5 RESULTS AND DISCUSSION

An inspection of the shaded relief image of the adjusted DEM (e.g. Figure 4(c)) confirms that the method has been successful in visibly reducing run edge stepping. Even the larger steps of up to 50 cm were reduced to levels comparable to the relative height accuracy levels expected from the laser scanner ranging (i.e. better than 10cm). Improvement can also be seen to the derived flow patterns in very flat areas. Previously flow had been artificially constrained by the run edge stepping in the merged DEM (see arrows in Figure 5(a)). The adjusted DEM has removed many of these artificial flow features (Figure 5(b)) and thus should provide an improved tool for modeling flow across the floodplain.



(a) (b)

Figure 5: An example of improvement to flow patterns resulting from DEM height adjustments (a) flow patterns in merged grid of unadjusted DEMs (b) flow patterns in merged grid of adjusted DEMs. Arrows indicate flow lines that were artificially constrained by edge stepping in the original DEM.

The choice of a TIN as the interpolation method might require more consideration. It was chosen on the basis that it was capable of interpolating across large distances (eg across a complete run width) while theoretically also being able to capture some of the fine-scale texture which occurred along the runs (the striping textures shown in Figure 3). While it succeeded in creating the correct level of broad-scale adjustment required across a run (evidenced by removal of the steps), it was less successful in removing the fine-scale striped texture. The reason for the residual striping was determined to be the arrangement of the adjustment points: firstly the irregular shape of the run edges and secondly the data gaps created by removal of points near sharp topographic features. Both these arrangements tended to cause the TIN to generate wide triangles instead of thin sub-parallel triangles (see Figure 4(b)). The striped texture represented the least significant of the DEM height differences so, while there is still some hint of this texture preserved in some areas of the final DEM (e.g. visible in the top right hand corner of the shaded relief image in Figure 5(b)), it is almost undetectable and appears to have only minor consequence on overall flow patterns.

The horizontal offsets inherent between the individual run DEMs is possibly the most problematic aspect in terms of making further improvements to the adjustment method. In the first instance, it made inclusion of adjustment points near sharp topographic features impossible. In the case of the Tully River and its adjacent embankments and levee banks, where there were often sharp changes in relief, adjustment points were spaced up to 200m apart. This resulted in huge unconstrained TIN facets which, if left in the adjustment surface, generated erroneous height corrections in the embankments. In several cases these artificially low or high embankments adversely affected the modeling by allowing water from the river the flow out into the surrounding floodplain prematurely. Artificial adjustment points had to be introduced to constrain the adjustment surface in these areas – a very time-consuming process. In the second instance, the horizontal offsets resulted in blurring of features in the merged DEM. The shaded relief image underlying Figure 4(b) shows a north-south drainage feature just to the left of the legend. In the shaded relief images in Figure 4(a) and Figure 4(c), the merged DEM data shows how this feature has been blurred, suggesting a horizontal offset of almost the full width of a DEM pixel (3m) between the individual run DEMs.

6 CONCLUSIONS AND RECOMMENDATIONS

Ideally, all runs should have high accuracy 3-dimensional survey data collected at regular intervals along the areas of run overlap to tie the data directly back to ground locations (eg. differential GPS for horizontal locations supplemented with total station readings for accurate heights) thus avoiding the need for any adjustments using the methods discussed in this paper. However, such a massive survey is generally not a realistic option, as it is very time consuming and requires extensive access to areas on the ground. Figure 2 illustrates just how massive a survey this would be. So, it is important to bear in mind then that the technique discussed in this paper is at best an internal calibration. Also, with improvements to post-processing of raw signals and GPS locational systems, these errors should also be substantially smaller in more recent surveys, reducing the need for such adjustments. ARA has suggested it is possible now to correct some of the errors in the Tully-Murray Lidar data by compensating for the known sources of error (see section 3), although this has not yet been done.

In the absence of detailed survey data, or post-processing adjustments required to deal with historical datasets suffering from these types of errors, a better result would be achieved with the grid-based correction technique discussed here if horizontal offset corrections could be applied prior to height adjustments. Such corrections would require the use of sub-pixel adjustment techniques such as outlined in Van Niel (2008). Such corrections would then allow the inclusion of all edge points, thus avoiding some of the interpolation problems due to exclusion of points near sharp features (e.g. along the Tully River). Horizontal adjustments were not applied as the procedure was not available at the time.

If horizontal adjustments are not applied, other aspects of the method should still be reconsidered in light of this work. These include:

1) *The choice of interpolation methods (in this case a TIN)*. Other interpolation methods may be able to reproduce the finer scale patterns of the height errors more faithfully.

2) *whether or not it is best to average all DEMs into one merged surface or choose a single adjusted DEM to represent the surface over particular areas*. Choice of a single DEM might avoid the blurred features, but would introduce offsets to drains and other features. Both options have potentially adverse (albeit subtle) effect on flow modeling.

3) *Whether or not the edges of each run should be simplified into more regular linear or semi-linear shapes and, in doing so, whether the run overlaps should be removed altogether in favour of single*

edge joins. Averaged heights would still be used to generate the adjusted height values along these joins. Such a geometry would be easier to interpolate across and avoid using data close to the edges of the run, where there is potential for larger errors.

In summary, despite the relative accuracy possible from laser scanner ranging measurements, the georeferenced data for each run fails to meet the accuracy requirements of the scanner data. Thus each individual run DEM was required to be adjusted before merging into a continuous surface suitable for modeling work. The height adjustment technique described in this paper was successful in that it improved flow patterns by removing the largest height differences and consequential artifacts from the final merged DEM. However, implementation was limited by the irregular shape of run lines and by the additional offsets of features in the horizontal direction.

7 ACKNOWLEDGMENTS

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