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Mobile Laser Scanning: Field Methodology for Achieving the Highest Accuracy at Traffic Speed

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ABSTRACT

Mobile Laser Scanning (MLS) is a new technology that has had great success and immediate results in corridor surveys. The technology allows us to measure all features along roads and railway lines accurately and quickly. Measurements are taken at traffic speed, i.e. without any impediment to traffic flow. There is no need for surveyors to be on or near the carriageway during the course of the survey because all data is collected from the safety of the cab of the working vehicle. Traffic lanes do not need to be closed or traffic diverted. The power of MLS is evident, and as surveyors we are interested to (a) explore the boundaries of accuracy that such a system can provide by understanding the technology used (scanner, GPS, IMU) and by developing field methodologies to eliminate or mitigate these errors, (b) develop field procedures to ensure surveyors can work safely at traffic speed and do not have to access the road at any time, and (c) continue research into the potential of the technology and the impact that it may have on standard surveying procedures. This paper describes several methods and techniques that have been developed by McMullen Nolan to meet these aims and how they have been implemented on the various MLS jobs that the company has completed throughout Australia.

KEYWORDS: *Mobile laser scanning, point clouds, corridor surveys, road safety, accuracy of MLS data.*

1 INTRODUCTION

Mobile Laser Scanning (MLS) technology emerged in the survey market in 2009 as an ideal tool for high-accuracy, comprehensive corridor surveys. MLS is a Light Detection And Ranging (LiDAR) technology combining the principles of airborne LiDAR with the accuracies achievable with Terrestrial Laser Scanning (TLS). The benefits that MLS offers include the increased work safety for road or rail workers, more detailed and comprehensive measurement of all features on the corridor, high-speed data acquisition and the accuracy of the final result.

As surveyors, we are particularly interested in the accuracy that can be achieved by MLS. Each of the component parts of an MLS system – i.e. Global Navigation Satellite System (GNSS) units, laser scanners and Inertial Measurement Units (IMUs) – are subject to error budgets that contribute to the overall accuracy of the system. Apart from incorrect ambiguity resolution after a loss of lock, the largest errors affecting MLS point cloud positioning include satellite multipath, jumps due to changes in satellite configurations and the accuracy of the geoid model (relationship between GNSS heights and orthometric heights). Traditional approaches to error minimisation or mitigation are based on placing multiple control targets along the corridor. The targets enable the point cloud to be monitored for positional accuracy, corrected for any drifts and then ‘pinned down’ to the local control. This approach is supported by MLS manufacturers and is widely used throughout Europe and the USA.

Since entering the MLS market in Australia in 2009, the McMullen Nolan Group (MNG) has developed specific methodologies and processes for MLS surveys. This resulted in a system that works at traffic speed, can easily identify and eliminate any errors caused by satellite multipath, does not require multiple targets placed along the corridor, is portable and flexible, and provides the highest possible accuracy result through the averaging of redundant observations.

This paper introduces MLS survey technology and discusses some of the major sources of positioning errors that can limit absolute accuracies of the generated point cloud. The current approach to reducing and eliminating the error sources of MLS are outlined and the limitations and advantages of this approach discussed. The Multi-Pass approach developed by MNG to increase the accuracy of MLS data is then presented. This approach is compared with traditional MLS survey methods and the advantages and limitations are discussed. Finally, some of the recent developments taking place in the MLS world and their potential impact on this fast-evolving technology are outlined.

2 MOBILE LASER SCANNING

Mobile Laser Scanning (MLS) has been actively used in the survey market since 2009. MLS is the process of mounting a ‘line scanner’ on a moving platform. The line scanners in use today typically collect several 100,000 points per second. Thus, as the platform moves forward, a cloud of points is generated. This point cloud is usually so dense that it appears like a picture (Figure 1). Every feature within the line of sight of the scanner is picked up within the survey corridor. Data is later extracted from the point cloud into strings and point features that are used for a range of engineering and survey purposes. MLS has had a significant impact on corridor surveys as comprehensive data is collected quickly, safely, accurately and economically.

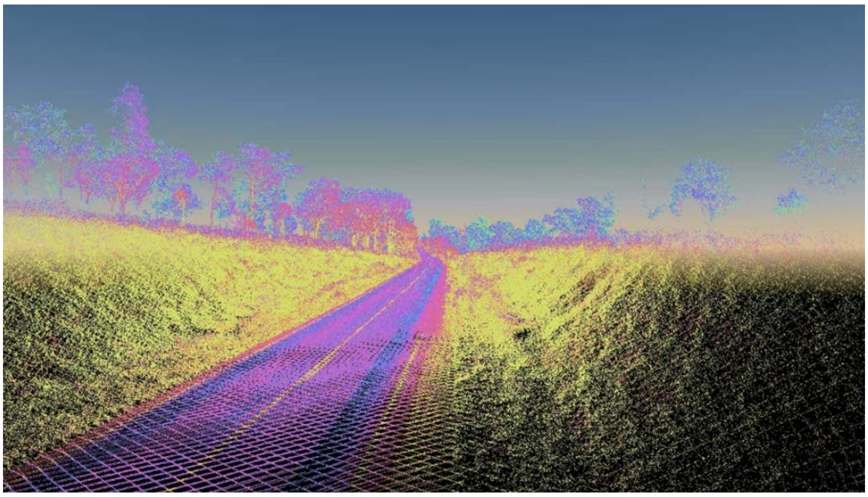

Figure 1: Point cloud of Dawson Highway, Queensland.

There are a range of scanners on the market that employ different observation techniques. For high-accuracy survey requirements, both phase and pulse lasers are used. Their accuracy is in the order of millimetres or centimetres depending on the type of scanner, range to targets, reflectivity of the measured surface, etc. The accuracy of each laser measurement from the scanner is specified to 10 mm accuracy (compared to true distance) and 5 mm precision (comparing measurement repeatability) (Riegl, 2012). As the scanner rotates quickly (100-200 Hz), all the points within each rotation and between subsequent rotations of the scanner head are highly correlated. This system feature results in high 'relative' accuracies of points within the point cloud. Measurement of point features collected at one location in the point cloud are accurate to millimetre level.

As surveyors, we are also concerned about the 'absolute' accuracy of the system. This is the accuracy of the point cloud relative to the local reference frame. High absolute accuracy enables surveyors to use data extracted from the point cloud for survey and engineering applications with confidence that they will tie in closely with the local survey control.

A typical MLS system for use on a vehicle is shown in Figure 2. Positioning the scanner is the role of GNSS combined with the IMU. In a MLS survey, it is common practice to employ multiple GNSS base stations along the corridor. These base stations can be either temporary local sites or permanent sites belonging to a Continuously Operating Reference Station (CORS) network such as CORSnet-NSW (Janssen et al., 2011), although the latter are generally not available at the desired density. Typically, the GNSS unit on the working vehicle collects data once per second and provides an Easting, Northing and ellipsoidal height at that epoch. The IMU collects data at a much faster rate (200 Hz) and provides the pitch, roll and yaw of the working vehicle, but also augments the GNSS-derived positions in times of satellite blockage and outage. The IMU enables all the vehicle vibrations from road corrugations etc. to be measured and taken into account.

Figure 2: MLS system components and mounting on working vehicle.

3 SOURCES OF SATELLITE POSITIONING ERROR

GNSS provides excellent absolute positioning accuracy over long distances. Positioning accuracy can be challenged, however, in urban canyons, heavily vegetated areas and under bridges and tunnels due to loss of satellite lock. The IMU assists the GNSS solution and aids in cycle slip detection and recovery when satellite lock is impaired. As GNSS is used as the major positioning tool for the MLS system, any satellite errors that affect it will translate directly into the accuracy of the point cloud position. In order to achieve high ‘absolute’ accuracy of a MLS survey, it is important to identify and eliminate these errors.

The biggest error that needs to be identified is loss of lock, which may lead to incorrect ambiguity resolution. Incorrect ambiguity resolution can lead to jumps in absolute position to the order of decimetres. By using today’s GNSS processing algorithms, and augmenting the positioning solution with IMU data, this scenario is minimised. Assuming that incorrect ambiguity resolution is eliminated, the three further contributors to the GNSS positioning error budget include multipath, changes to the satellite configuration and geoid undulation (causing variations in the orthometric height).

Multipath is the error caused by GNSS signals being reflected off nearby surfaces and arriving at the GNSS antenna from a slightly deviated path. Multipath effects change with location (different reflective surfaces) and over time (changing location of satellites). There are many publications (e.g. Leick, 2003; Lau and Cross, 2007; Schön and Dilßner, 2007) about the effects of multipath and it is generally accepted that it can introduce positioning errors of the order of 1-3 cm.

The satellite configuration is ever changing, and GNSS data is usually observed with some minimum elevation cut-off to avoid using low-elevation satellites. As satellites rise or fall in the constellation, the geometry (Dilution of Precision or DOP factor) of the satellites changes and the position solution at the rover receiver can also be affected. In essence, this simply highlights the multipath errors, which are much more pronounced for low-elevation satellites.

As GNSS positioning is based on the ellipsoid and not the geoid (the basis for AHD71 – see Roelse et al., 1971), it is important that the relationship between these two surfaces is fully understood – known as the geoid undulation. Any errors in the determination of the geoid undulation will directly affect the AHD71 values resulting from the point cloud. In Australia, the AUSGeoid09 model can be used to obtain AHD71 heights from GNSS-derived ellipsoidal heights (Brown et al., 2011).

3.1 Minimising Positioning Error in Static GNSS Surveys

For static GNSS surveys, there are a range of actions that can be taken to mitigate satellite errors. These actions include (ICSM, 2007):

- Lengthening site occupations to average the effects of multipath and changing satellite configuration.
- Multiple set-ups on network stations to average set-up errors and measure under different satellite configurations.
- Measuring a number of ‘known’ control points to monitor the difference between orthometric and ellipsoidal height.

Real Time Kinematic (RTK) surveys on static points can be tested by increasing the number of occupations at each point of interest (repeat observations) where every occupation is taken with different satellite geometry (e.g. Janssen et al., 2012). Routine practices are in place to minimise satellite errors in static surveys (or surveys occupying static points). However, what actions can be taken to minimise these errors in kinematic surveys?

4 ACCURACY OF MLS SURVEYS: GNSS KINEMATIC SURVEYS

It is difficult to monitor the effects of satellite errors on a kinematic platform, unless the exact trajectory of the GNSS antenna is known. This is possible if an independent measurement device (say a robotic total station) is available and work is performed on a fixed and known track (say a railway track), or the GNSS antenna is fixed to a ‘rotating arm’ that allows monitoring the repeatability of GNSS measurements. However, for field surveys, monitoring the accuracy of kinematic GNSS is much more difficult. The ability to identify and minimise GNSS positioning errors is a major challenge for MLS systems in order achieve high-accuracy results. This section describes the current approach to achieving high absolute accuracy MLS surveys. The following section compares this approach with the ‘multi-pass’ methodology developed by MNG.

4.1 Standard Approach to High Absolute Accuracy: Multiple Control Targets

The current approach to eliminating satellite errors is to establish a dense network of survey control along the corridor, from which the GNSS-derived positions of the survey vehicle can be compared. The control is used to monitor any drift in satellite-derived positions (of the order of 1-3 cm) and then to pin the point cloud down to the control marks.

Conventional MLS surveys are completed using:

- One pass of scanning.
- Two scanners angled to each other to measure a ‘3-dimensional’ point cloud.
- Measurements to multiple targets established along the corridor. Once these targets are identified in the scan, they can be used to correct any drift in the point cloud trajectory that has occurred since the last target was placed. The targets are placed from control stations that have been traversed in along the corridor.
- Levelling each of the target marks to allow determination of the relationship between geoid and ellipsoid (i.e. geoid undulation).

The advantages of this method are that, firstly, it provides a direct measurement of the orthometric (AHD71) heights over the area, which minimises the errors introduced by potential errors in the geoid model. Secondly, it leaves a trail of control along the corridor that can be used for later construction works and as a platform for picking up detail survey points that cannot be measured from the scanner.

However, adopting this approach has the following consequences and limitations:

- The requirement to place survey control and targets on the road shoulder means surveyors need to work along busy traffic corridors. Road and rail corridors are inherently dangerous places to work and therefore traffic management needs to be put in place. Lanes may need to be closed and work may have to be carried out at night.
- This approach is optimised at slower road speeds. When collecting one pass of data, it makes sense to drive the corridor at a limited speed as the point cloud is denser when travelling slowly, enabling more detail to be discerned. The approach may also require the working vehicle to slow down when passing the targets, so that they can be easily identified in the point cloud. When working on corridors at less than posted speed limits, the working vehicle will be required to have a trailing ‘traffic control’ vehicle to warn drivers of the ‘slow vehicle ahead’.
- The method provides no guarantee of eliminating all satellite-based errors for the length of the corridor. Positioning certainty can be confirmed at each control target, but there is no

way to tell whether multipath or satellite configuration changes have occurred between targets.

Figure 3 shows the variation in trajectory of a kinematic survey along 3 km of road. The chainage is shown on the horizontal axis (metres) and the variation from 'true' position is shown on the vertical axis (metres). In this example, the kinematic position oscillates around the 'true' position by up to about 3 cm due to the effects of multipath and changes in satellite configuration. If targets were placed every 250 m to pin the point cloud to the reference frames at these intervals, the drift in the point cloud between chainages 500 m and 750 m would provide a high-accuracy solution for all data between these marks. However, pinning the point cloud to the control between chainages 1,500 m and 1,750 m would not properly model the kinematic movement of the working vehicle.

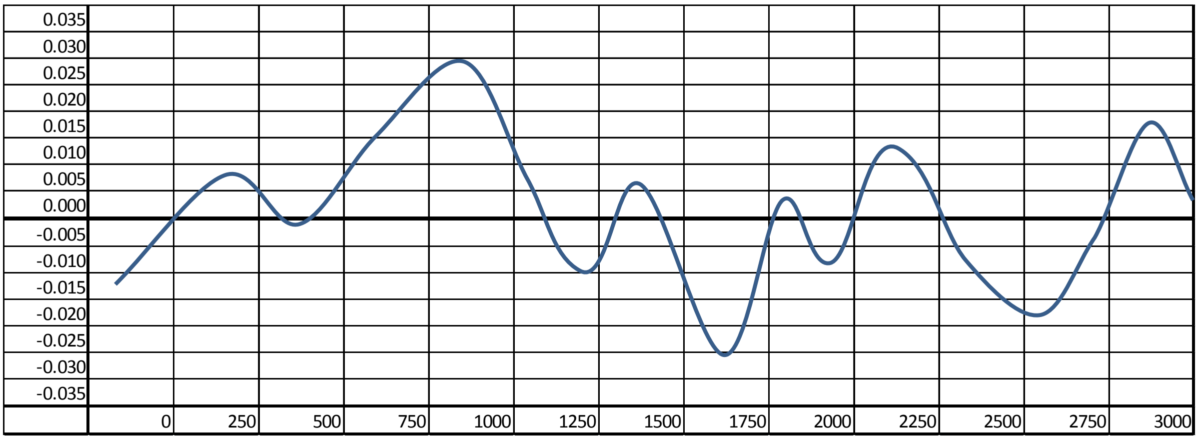

Figure 3: Multipath effects for kinematic GNSS along a 3 km stretch of road (all units in metres).

The only way to ensure high accuracies can be achieved is by placing even more control. One of the major suppliers of point cloud processing software, Terrasolid, suggests that for the highest accuracy point clouds, horizontal targets should be placed every 200 m and level points will need to be placed every 50 m (Soininen, 2012). Meeting this requirement can prove an onerous task.

5 McMULLEN NOLAN GROUP MLS: A NEW APPROACH TO SCANNING

When the McMullen Nolan Group started working on its MLS system in 2009, it was based on the following aims:

- Work the MLS at traffic speed.
- Create a system that allows the identification and correction of satellite drift issues.
- Minimal requirement to establish control along the road corridor.
- Maximise the accuracy that can be achieved by the system.
- Acquire a high-resolution, dense point cloud for identifying features.
- Create a portable system that can be mounted on a range of vehicles.

A MLS group was set up in the company, which has developed a MLS system meeting these goals and continues to work on new developments. The basis of our approach is based on repeat MLS measurements over the same corridor, as described in this section.

5.1 Multi-Pass

In a nut shell, Multi-Pass is the idea of removing any multipath errors through multiple measurements of the same trajectory. Each of the trajectories is processed and its position is compared with the other measurements. To increase the accuracy of the point cloud, a mean value from all the trajectories is calculated. It is interesting to note that this method takes advantage of the measurement power of MLS to enable comparisons between trajectories. A linear feature is identified (e.g. fog lines, centrelines or railheads) and extracted for each pass. The position of the features can then be compared from one run to the next (Figure 4). It is interesting that the ability to extract data from the point clouds enables us to determine the variation of each point cloud from its 'true' position. Without using MLS, it would not be possible to make this comparison.

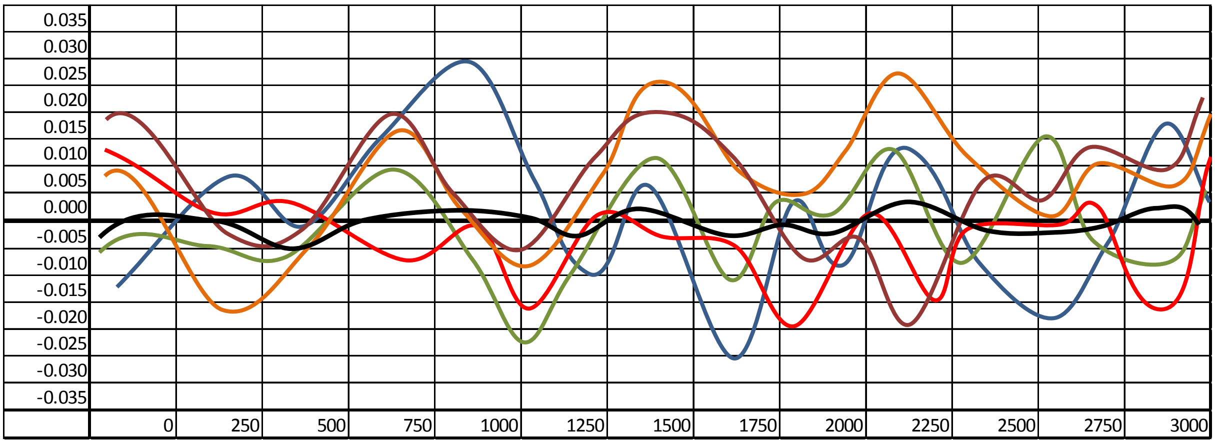

Figure 4: Multipath comparison of 5 passes of data and the mean trajectory, shown in black (all units in metres).

By comparing the individual point clouds, it is possible to:

- Identify and eliminate any suspect data (e.g. from satellite blockages).
- Increase the survey accuracy by averaging the effects of multipath and other satellite errors over repeat measurements. Inspection of the different point cloud layers provides an opportunity to analyse the data, determine the mean trajectory and the standard deviation of the trajectory. This provides a level of statistical certainty to the data.
- Increase the density of the final point cloud, as it is the result of combining all the point clouds together.
- Use one line scanner in the system. Once it is accepted that a corridor needs to be measured multiple times, one can realise that the 3D image can be measured by swinging the scanner into a different orientation once half the observations have been taken. Using only one scanner makes the equipment lighter and more portable.

The Multi-Pass approach uses the principle of repeatability of GNSS measurement to control the positional accuracy of the working vehicle, rather than pinning them to multiple targets. Adopting this approach means that control can be placed at much greater separation distances than using other methods. MNG has conducted rural surveys where the control targets are not placed every 300 m, but every 5 km or 10 km. As a sidenote to this point, it is possible in urban canyons and in heavily vegetated areas to place control more densely if required. The major advantage to this approach is that surveyors are not required to place dense control along the corridor, i.e. the requirement to close lanes, work at night and implement traffic management is minimised.

Without levelling up the entire corridor, there is no direct measurement of the geoid undulation along the corridor. Orthometric heights can be calculated using a geoid model, such as AUSGeoid09, that is constrained by spirit-levelled targets. AUSGeoid09 claims to have an absolute accuracy of 50 mm and 2 ppm relative accuracy across most of the country (Brown et al., 2011). Experience has shown that for longer corridors the accuracy of adopting AUSGeoid09 is similar to the accuracy of 3rd order levelling (Table 1).

Table 1: Comparison of vertical accuracy over distance for AUSGeoid09 (2 ppm) and 3rd order levelling (12√k).

Length (km)	**AUSGeoid09 (mm)**	**3rd Order Level 12 √ k (mm)**
0	20	37.9
20	40	53.7
30	60	65.7
40	80	75.9
50	100	84.9

In order to monitor any deviation from the AUSGeoid09 model, the targets are spirit-levelled from the control survey. Comparison of the spirit-levelled height with the height calculated from GNSS and AUSGeoid09 can be made at each target placed. If the variation is outside expected tolerances, additional level runs can be made.

5.2 Brisbane Motorway MLS survey: Description and Results

In order to demonstrate the power of the Multi-Pass approach, some data was analysed from a 30 km MLS survey that was conducted in December 2012. The survey required data to be collected for 30 km along the M1/M3 motorway in Brisbane. Survey control for the MLS was established using a spirit level traverse along the full route with control points located approximately every 200 m along both carriageways (163 control stations total). The survey specifications required us to use every second control point as a ‘target’ point (separated by 400 m), and to use the intermediate stations as control stations for QQ strings (to test the model). This dataset, however, allowed us to re-process the data in a number of ways, to demonstrate the absolute accuracies that can be achieved with the Multi-Pass approach when target separations are extended.

5.2.1 Single-Pass Data

Figure 5 shows data from one pass of MLS along the entire 30 km corridor. The ellipsoidal heights associated with the point cloud have been corrected with AUSGeoid09 to orthometric heights, and a comparison was made with 153 of the control points along the corridor. It should be noted that it was not possible to compare the heights at all 163 control points, as passing cars and other interference did not allow the targets to be identified.

The rough saw-tooth appearance in Figure 5 can be largely attributed to the effect of multipath on the GNSS signal as the vehicle traverses along the highway. There is also a noticeable jump approximately three quarters along the route. This may be due to a change in satellite constellation (i.e. a satellite rising or setting) causing an abrupt change in the error signature. These drifts and errors can be minimised by pinning the point cloud at key control points along the road.

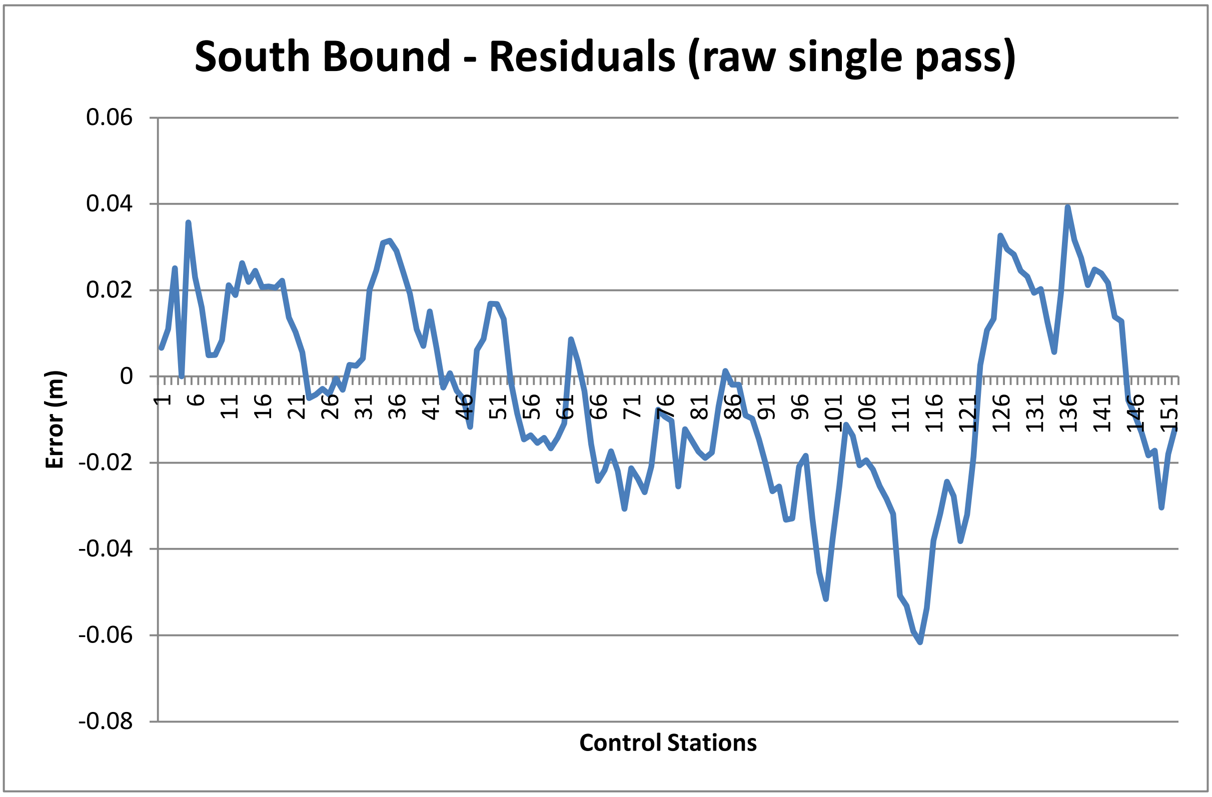

Figure 5: Monitoring the height deviation of GNSS with ground truth over 30 km motorway.

Figure 6 shows the deviation to ground truth when a single pass of MLS data is pinned to control points every 400 m along the corridor. The resulting heights are compared to the 'ground truth' provided by the QQ strings from the alternate control marks in-between (i.e. 200 m from the pinned control). It can clearly be seen that in most cases this provides suitable accuracy when the GNSS data is good. The standard deviation for the data is 6.0 mm.

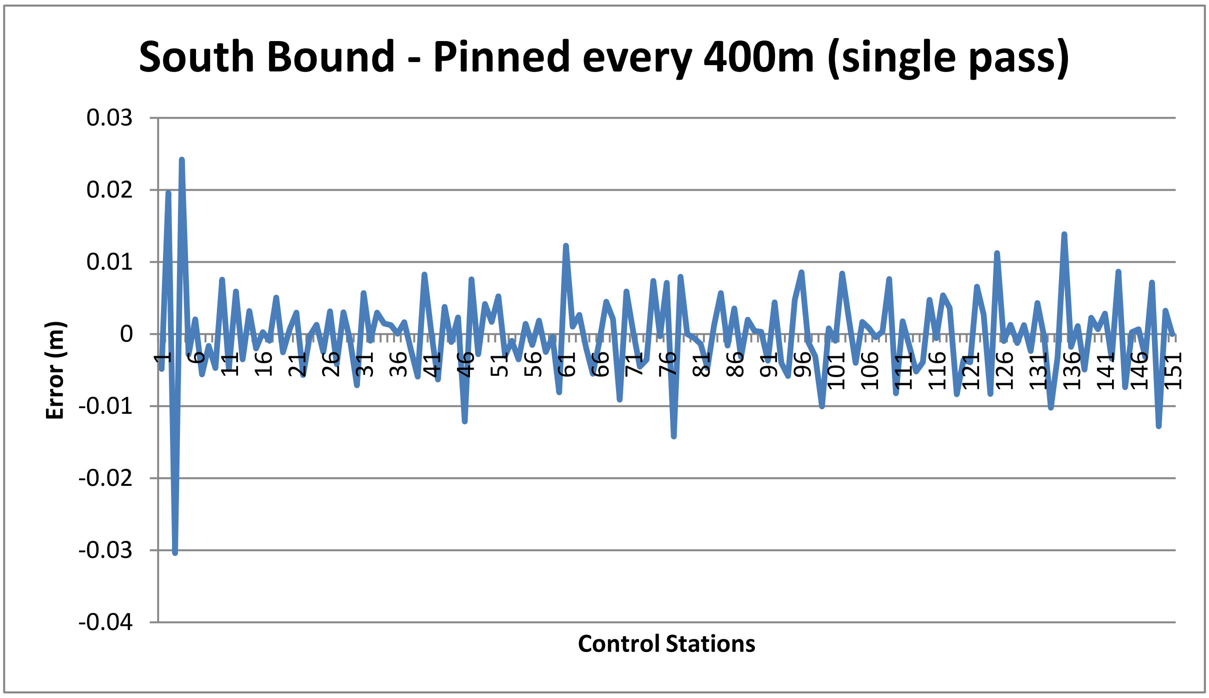

Figure 6: Comparing MLS height with ground truth (single pass) – 400 m control station separation.

The processing can be repeated using control stations that are more widely separated. Figure 7 compares the residuals when the MLS data is pinned to control every 800 m and every 1,600 m. As expected, the standard deviation of the residuals increases with wider control separation. This process can be repeated for a range of control point separations, and a graph of the one sigma errors plotted (Figure 8).

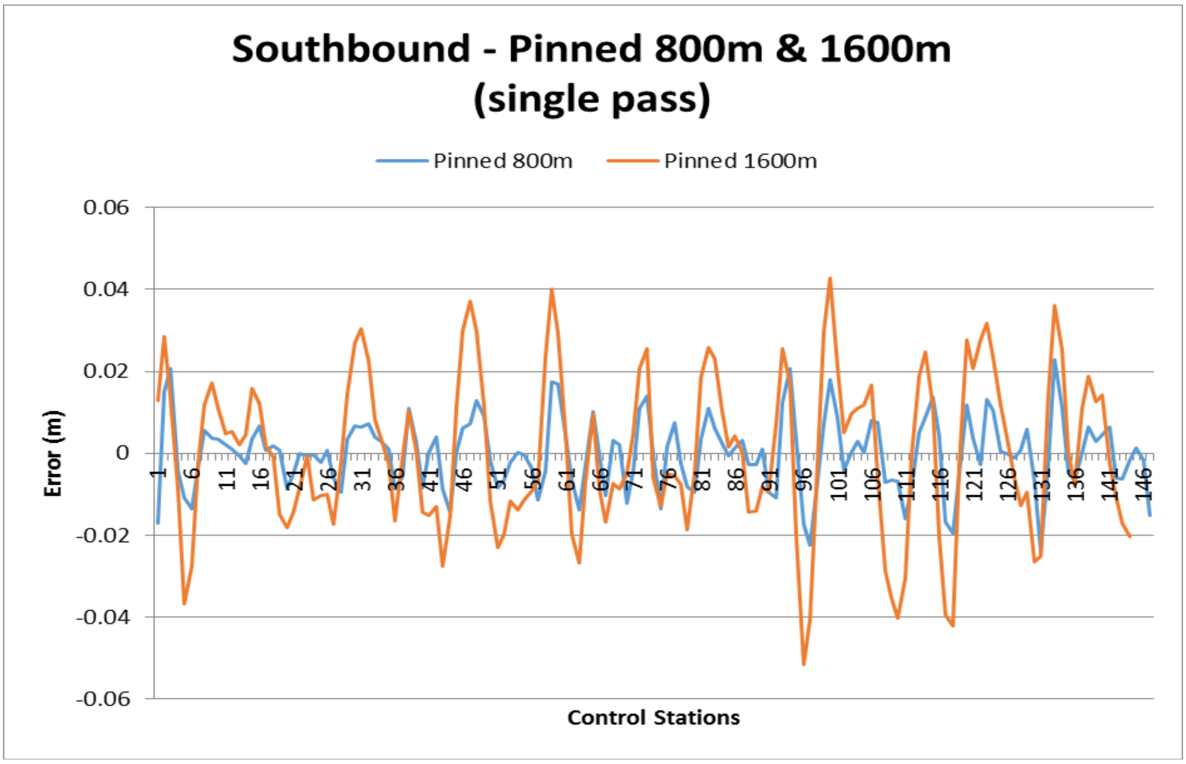

Figure 7: Comparing MLS height with ground truth (single pass) – 800 m and 1,600 m control station separation.

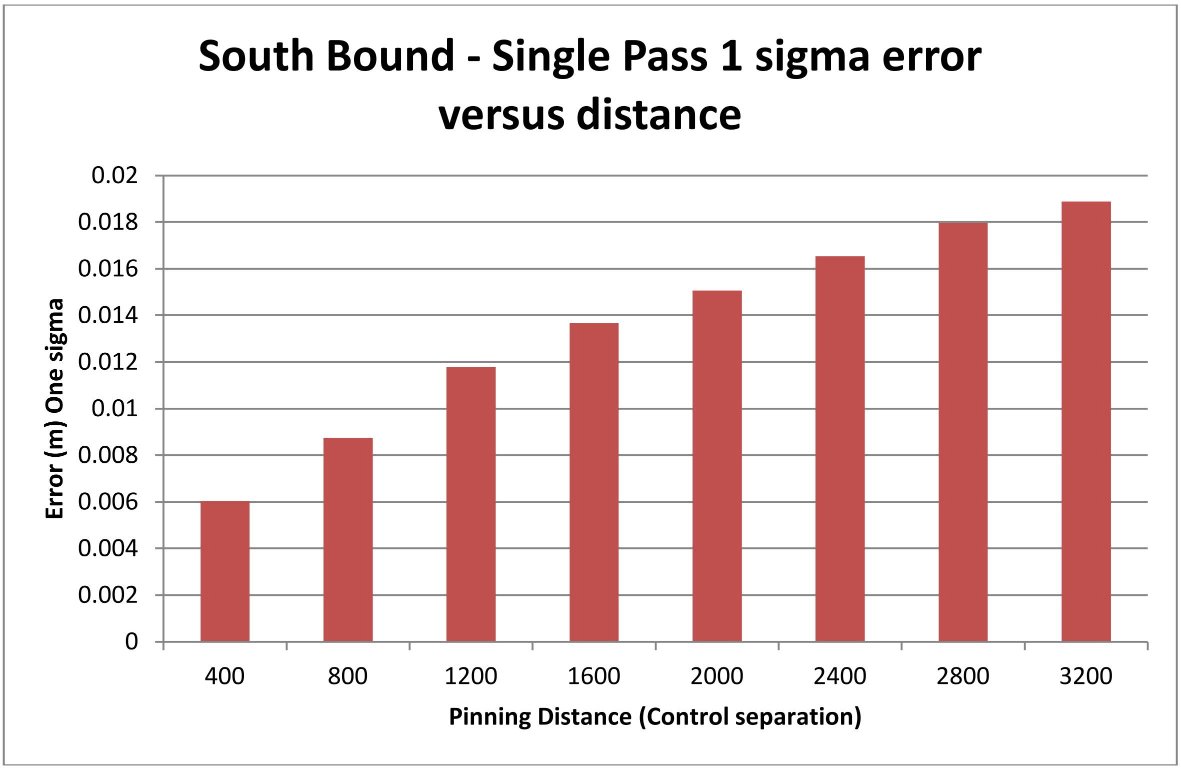

Figure 8: Standard deviation of the height error using differing control station separation spacing.

5.2.2 Multi-Pass Data

Multi-Pass data combines 6 independent passes of MLS data along the same road section. Each pass is considered ‘independent’ if more than 15 minutes different in time from the original pass. This allows satellite configurations and the multipath signature to change between each run. Figure 9 shows the results of pinning every 400 m with 6-pass data. This provides a 1-sigma standard deviation of approximately 3 mm.

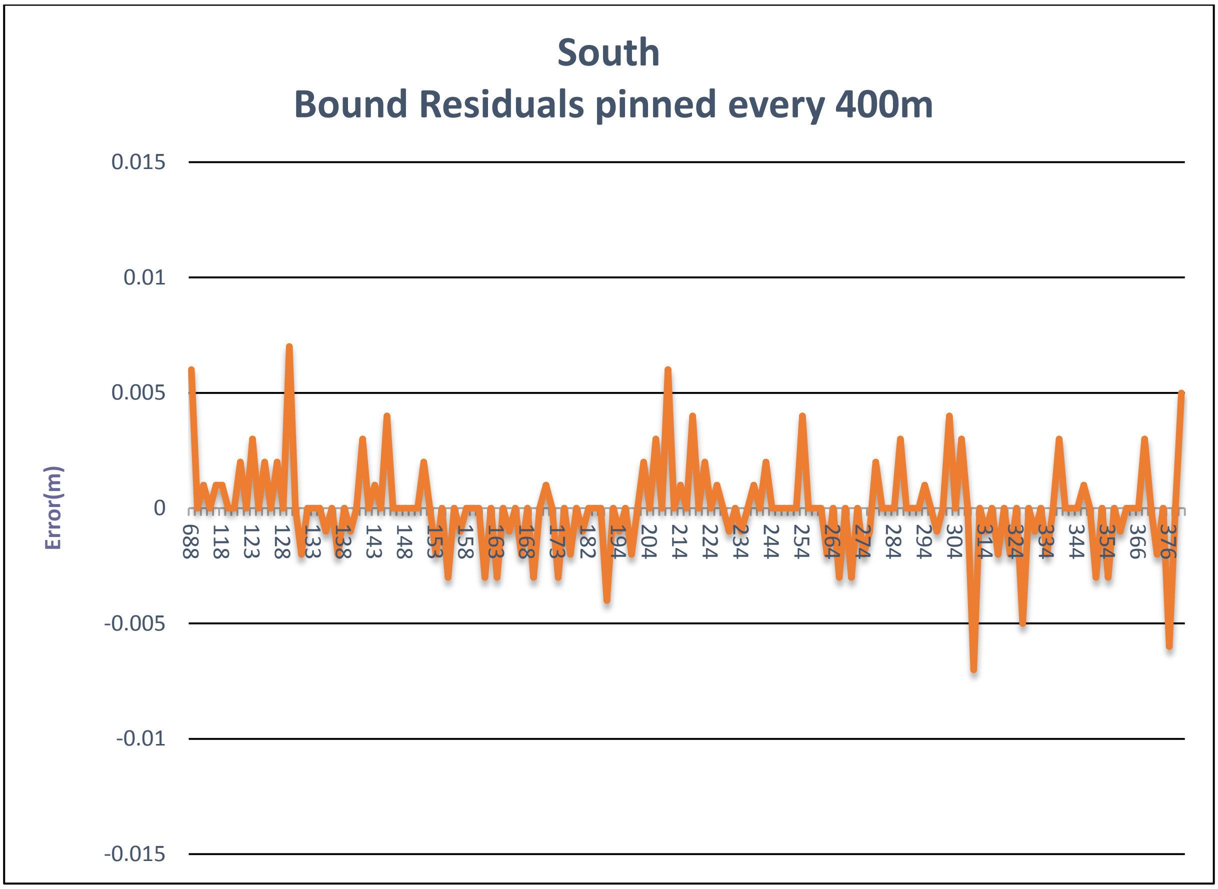

Figure 9: Comparing MLS height with ground truth (6 passes) – 400 m control station separation.

If the same datasets are processed using Multi-Pass data, a similar relationship to single-pass data can be seen. The relationship between pinning distance and error follows a similar curve; however, the magnitude of the error is reduced. Empirically, the error is reduced by the square root of the number of independent passes. Hence, when 6 independent passes are combined, the accuracy is increased by √6 (= 2.4) or some 60%. The empirical data supports this theory.

The issue of accuracy can be viewed another way. If a MLS survey is specified to provide a 2-sigma accuracy of 12 mm, the results can be obtained by using one pass and pinning every 400 m or using 6 passes and pinning every 2.0 km (Figure 10).

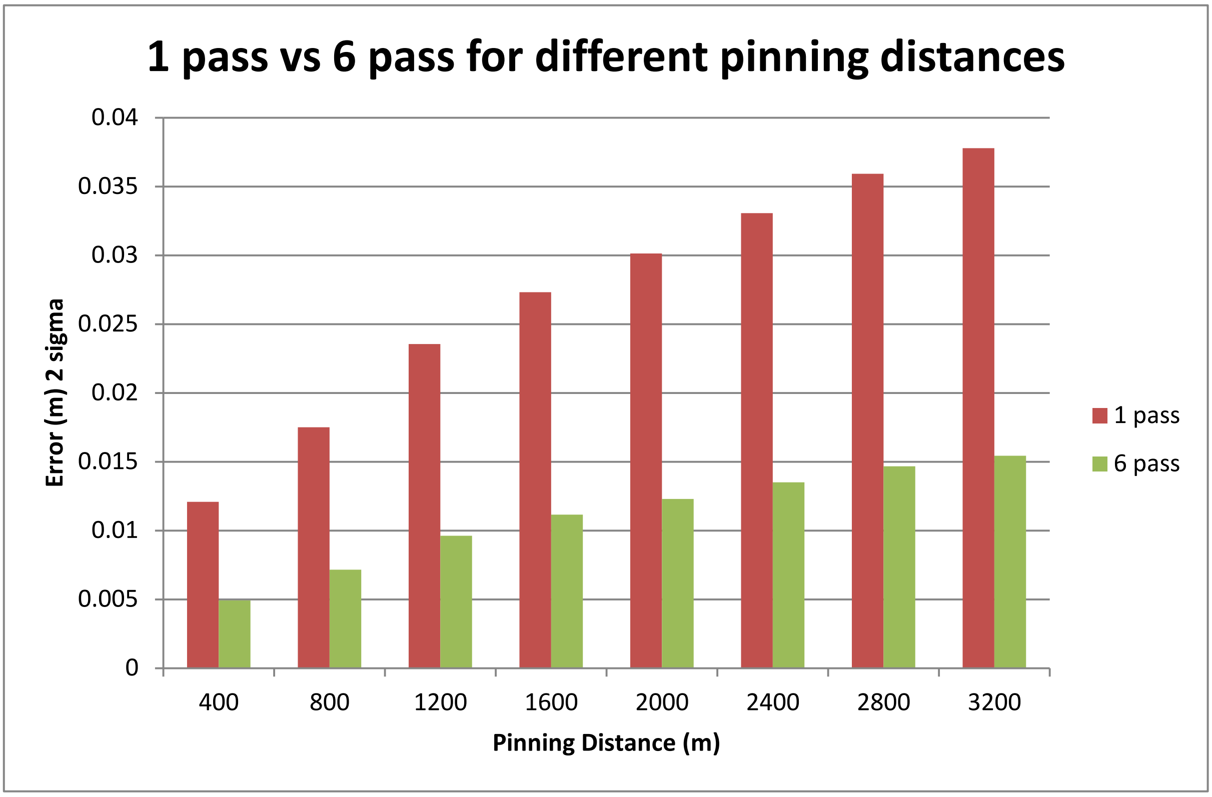

Figure 10: Standard deviation of height error (single-pass and multi-pass) using differing control station separation spacing.

6 CONCLUDING REMARKS

The Multi-Pass approach provides the solution MNG sought for Mobile Laser Scanning. Using the Multi-Pass approach, it is possible to:

- Work at traffic speed – there is no need to slow the working vehicle.
- Identify and correct for satellite drift and multipath.
- Minimise the amount of control required along the road corridor.
- Acquire a high-resolution, dense point cloud for identifying features – overcoming traffic blockages of targets.
- Build a portable system that can be mounted on a range of vehicles.

But most importantly:

- Maximise the accuracy that can be achieved by the system.

MLS is a ‘young’ technology that is improving with leaps and bounds. There are many exciting developments taking place all around the world that exploit the potential of the technology. MNG understands the importance of MLS and has a dedicated team working with MLS to stay up-to-date with hardware developments, further develop field methodologies, improve processing algorithms and create customised software solutions for our customers. The Multi-Pass approach is a fundamental building block upon which all of these developments take place.

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