Wide-area, Sub-decimetre Positioning for Airborne LiDAR Surveys Using CORSnet-NSW

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Key words: GPS, airborne LiDAR, topographic surveys, DEM, CORSnet-NSW

SUMMARY

Airborne LiDAR surveys produce high-resolution, very accurate surface elevation models which are used for many applications in surveying and civil engineering, as well as for flood prevention and mitigation, monitoring coastal erosion and land subsidence, etc. The key to producing high quality elevation products is very precise geolocation and orientation (or "georeferencing") of the LiDAR instrument at the times when the measurements are made, obtained with a combination of on-board GNSS and inertial sensors. The usual practice is to deploy reference GPS/GNSS land receivers in the area where the aircraft will be flying, and to obtain a precise trajectory by means of the short-baseline differential GNSS technique. This could mean installing and operating receivers at many sites during a flight mission if the area surveyed is a large one.

In this paper, an example of an alternative approach will be presented: using as reference receivers those of a sparse network of Continuously Operating Reference Stations (CORS) in New South Wales known as CORSnet-NSW, and a wide-area GNSS technique for obtaining the aircraft trajectory with sub-decimetre accuracy even with baseline lengths of several hundred kilometres. This may be comparable in precision and accuracy to the short-baseline method, but without the cost and logistical complications of having to deploy and operate one's own reference receivers during a mapping mission. This opens up a new level of operational capability allowing flexibility for weather conditions and priority response applications. The paper will be illustrated with the results of tests organised and conducted by the NSW Government's Land and Property Management Authority, in collaboration with the University of New South Wales, in June 2009.

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1. BACKGROUND

The use of Global Navigation Satellite Systems (GNSS), in particular the Global Positioning System (GPS), for precise positioning of fixed and moving receivers, has evolved over the last thirty years into an ubiquitous, economical and reliable tool for both precise surveying and navigation. It has been used for such different purposes as monitoring the very slow tectonic movements of the Earth's crust, the displacement of glaciers, and – mostly for remote sensing – determining the trajectories of buoys, ships, trucks, aircraft, as well as the orbits of Earth-observing satellites. In addition to the above, data from satellite-borne receivers have been used to obtain better maps of the Earth's gravity field. World-wide networks of receivers are being used to define the global reference frame, in combination with other space techniques, and to provide support for precise positioning. They are run by civil, military, civil service, academic and commercial organisations, as well as by the International GNSS Service (IGS). These entities use their networks' data to do some or all of the following: determine precise GNSS orbit and clock estimates, find, on a daily basis, the shifting coordinates of the network's sites, and refine the parameters that define the always changing orientation of the Earth relative to the stars.

Airborne Light Detection and Ranging (LiDAR) surveys are among the most advanced means of producing high-resolution, very accurate surface elevation models which are used for many applications in surveying and civil engineering, as well as for flood prevention and mitigation, monitoring coastal erosion and land subsidence, etc. (e.g. Wehr and Lohr, 1999; Brock et al., 2002; Rottensteiner, 2003; Anderson et al., 2005). The key to producing high quality elevation products is very precise geolocation and orientation (or "georeferencing") of the LiDAR instrument at the times when the measurements are made, obtained with a combination of on-board GPS and inertial sensors. The usual practice is to deploy reference GPS/GNSS land receivers in the area where the aircraft will be flying, and to obtain a precise trajectory by means of the short-baseline differential GNSS technique. This could mean installing and operating receivers at many sites during a flight mission if the area surveyed is a large one. We have tried a different approach: using as reference receivers those of a sparse network of Continuously Operating Reference Stations (CORS) in New South Wales known as CORSnet-NSW (White et al., 2009; Janssen et al., 2010), and a wide-area differential GPS technique for obtaining the aircraft trajectory with sub-decimetre accuracy even with baseline lengths of several hundred kilometres. This may be comparable in precision and accuracy to the short-baseline method, but without the cost and logistical complications of having to deploy and operate one's own reference receivers during a mapping mission. This also allows much greater flexibility for dealing with adverse weather conditions and priority response applications.

2. PRECISE WIDE-AREA POSITIONING

In GNSS positioning there are always two distinct sets of receivers: “network” receivers, at known locations, whose data are used to calculate corrections and other types of information to enable the use of the second type of receivers, and “user” receivers, fixed or mobile, at unknown or poorly known locations, where those corrections are received either via a radio or mobile internet link in real-time applications, or in data files for off-line processing. When using a hand-held receiver, and probably unknown to many users, the supporting network is that of the tracking stations of the GPS Control Segment – for example – used to obtain the satellite ephemerides and clock corrections the spacecraft broadcast in their Navigation Message.

The actual data of the network’s receivers can be sent to the users so they can correct their data, in what is known as “differential” positioning, or can be used indirectly to calculate corrections that are then transmitted to the users in what is known as “point” positioning. When those corrections are only meant to improve the GNSS satellite ephemerides and the clock corrections in the GNSS Navigation Message, this is also known as “absolute” positioning.

By “wide-area” positioning we mean here both long-baseline differential positioning, where a user’s GNSS receiver is often far from any network station (possibly hundreds of kilometres away), and absolute positioning.

In our study, we have used a technique for long-baseline differential, off-line positioning, able to deliver centimetre precision for fixed receivers and sub-decimetre precision for moving receivers. This choice of technique was dictated by three considerations:

a) The intended application was the geolocation of the data of an airborne scanning LiDAR sensor to be used in the generation of high-accuracy digital elevation models (DEM).
b) Off-line processing, where all the GNSS data collected during the flight are available for processing and (as in this case) there is no need for immediate results, is intrinsically more reliable than real-time processing, where the data are available only up to the present epoch, and accurate results must be obtained right away, with no chance for a second try.
c) Differential processing makes it possible to resolve the carrier phase ambiguities using well understood methods.

Our objective was to investigate the usefulness and advantages of the wide-area approach as a possible substitute for the more labour and resource intensive short-baseline approach commonly used in airborne LiDAR surveys. The network stations used in our study are part of the CORSnet-NSW continuously operating reference stations run by the Land and Property Management Authority of the Australian state of New South Wales. CORSnet-NSW currently (January 2010) consists of 29 stations and is being expanded to provide state-wide GNSS positioning infrastructure across NSW with a planned 70 stations in operation by 2013 (Janssen et al., 2010).

3. WIDE-AREA POSITIONING TECHNIQUE AND SOFTWARE

3.1 Technique

It is common practice in airborne LiDAR surveys to use GNSS both to position the instrument very precisely, and to assist an inertial navigation system (INS) to obtain the orientation of the aircraft in space, as both position and orientation are needed to interpret the data properly. Figure 1 illustrates the relationship between the sensors used for airborne LiDAR surveys. The aircraft utilises a GNSS antenna combined with an INS to "georeference" its trajectory. The bore-sight calibration process aligns the individual sensor orientations and standardises the range measurements. However, if the survey is to achieve the now expected high level of vertical accuracy (±15 cm, 1 sigma), then the position of the GNSS/INS-derived aircraft trajectory for each laser swath must be determined with a relative precision in the order of just a few centimetres. This is achieved via differential GNSS post-processing of the kinematic airborne data together with static observations collected on precisely surveyed ground reference stations. The GNSS positions are then blended with high-frequency measurements taken by the onboard INS to produce the final trajectory and reference orientations.

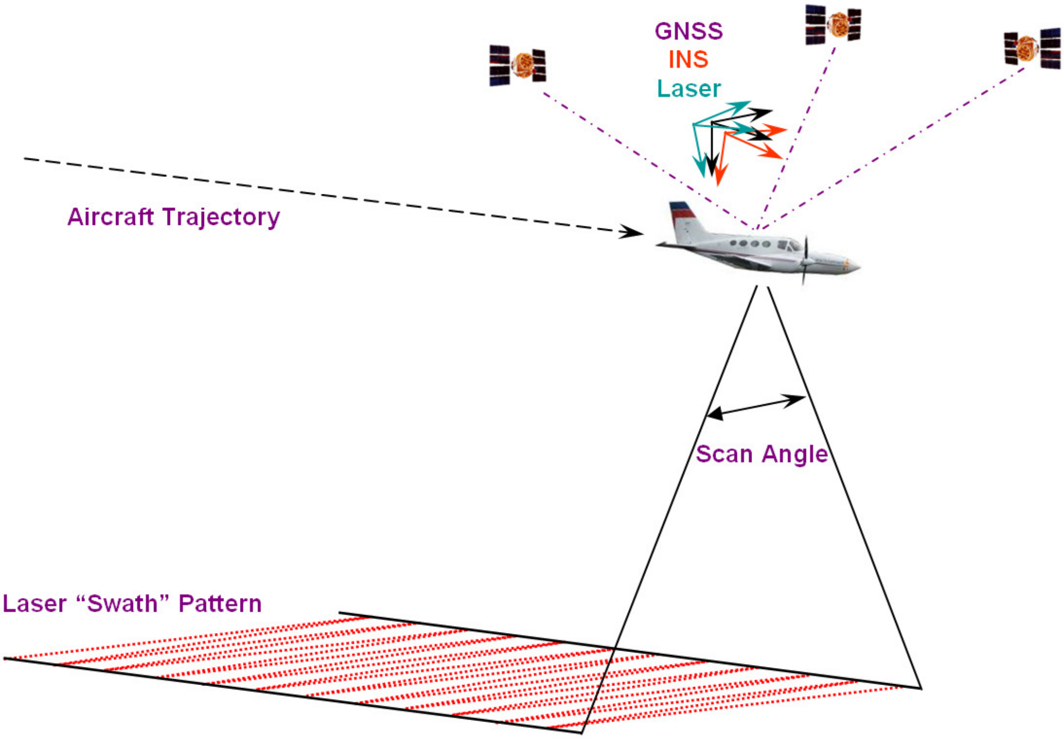

Figure 1: Airborne LiDAR "reference frame".

To such ends, the aircraft trajectory is usually determined by short-baseline differential GNSS, with ground receivers deployed near the intended flight-path of the aircraft. In this way it is possible to use GNSS data analysis techniques that are both very precise and quite straightforward to implement in software. The simplicity of these techniques is possible because, in short-baseline differential solutions, the data of the aircraft receiver and any nearby network receivers have much the same systematic errors (due to such things as satellite ephemerides errors, transmission delays, etc.) that cancel out – or nearly so – when their observations are differenced between them. This also makes it possible to resolve quickly and reliably the cycle ambiguities in the observed carrier phase, the most precise type of GNSS data, overcoming one of the main obstacles to obtaining good results. Furthermore, it is possible to get such results with single-frequency receivers, because the delay in the ionosphere is one of the systematic effects that can be largely cancelled out.

In wide-area solutions, those cancellations are not complete enough to ignore the systematic data errors, and they have to be included in the form of additional unknown parameters in the observation equations (Colombo, 1991; Colombo and Evans, 1998). Also, it is necessary to account for the ionospheric delays using dual-frequency data, which means using more expensive GNSS receivers and antennas. Resolving the carrier phase ambiguities is no longer straightforward or assured. The standard way of dealing with the ambiguities is to include them as unknowns in the observation equations and adjust them along with the other unknowns: this is often referred to as “floating the ambiguities”. Fixing (or resolving) those ambiguities to their most likely integer values in a matter of minutes is possible on occasion, when the aircraft is within less than 20 km from a ground receiver, or very precise corrections for the ionospheric delay are available (Colombo et al., 1999); otherwise slower techniques, that require tens of minutes, may be used (Colombo, 2009). It is also necessary to correct as well as possible such things as the neutral atmospheric delay of the GNSS radio signals, and the movement of the “fixed” stations due plate tectonics, the solid earth tide, etc. (e.g., see Kouba and Héroux, 2001), using mathematical models and, in the case of the tropospheric delay, estimating the error in the corrections as an additional unknown per receiver.

Over the years, all these difficulties have been gradually dealt with more effectively, more efficiently, more reliably and, from the user’s point of view, less painfully. Originally developed for the repeated determination of station positions to measure the slow tectonic deformations of the Earth’s crust, and to calculate very precisely the orbit of Earth-observing satellites, these days, after nearly thirty years of steady progress, GNSS wide-area techniques and the corresponding software find many applications in science, engineering, and navigation, and are becoming widely used in remote sensing.

3.2 Software

We used the wide-area positioning software “IT” (“Interferometric Translocation”) developed by one of us (Colombo – see for example Colombo et al. (1995) for a description of its use in one of the first wide-area, high-accuracy kinematic experiments conducted in Australia), for the long-baseline aircraft trajectory solutions and also to re-position in the IGS05 international reference frame (Ferland, 2006) some CORSnet-NSW stations, so their data could be used consistently in the differential wide-area solutions. These stations were originally given in the Geocentric Datum of Australia (GDA94) (ICSM, 2002). For both purposes we used the precise final GPS orbits computed and distributed by the IGS.

In order to validate the aircraft trajectories calculated with the wide-area method, we relied mainly on the quality of the LiDAR DEM results obtained with those trajectories. But we also used NovAtel's WayPoint GrafNav software to generate short-baseline differential solutions with receivers deployed near the intended aircraft flight-path, as is common practice in this type of survey, and compared them with the wide-area solutions (they turned out to be quite similar to short-baseline solutions obtained with the wide-area software).

3.2.1 The ”IT” software

General Characteristics:

- Runs under Windows, Unix, Linux, and FreeBSD.
- Source code compatible with most Fortran compilers, including G77.
- Refined through its use in a variety of projects requiring precise navigation and/or static positioning.
- Follows the IERS 2003 conventions.
- Available mainly for collaborative research purposes, with a Free Software Foundation General Public License.

Type of Solutions:

- Recursive, post-processing (Kalman filter + smoothing).
- Kinematic, e.g. for vehicles such as aircraft, and Static, e.g. for CORS network sites and local field stations.
- Stop-and-Go for rapid mobile surveys with pre-surveyed waypoints.
- Differential, Precise Point Positioning, Mixed Mode (precise differential + point positioning).

Data Corrected for:

- Earth tide, neutral atmosphere radio signal delays, carrier phase windup, etc.

Estimated Parameters:

- Receiver position in the IGS05 reference frame, with the WGS84 reference ellipsoid, earth spin-rate, light speed, GM constant.
- Biases in ionosphere-free carrier phase linear combination (“floated” ambiguities).
- Neutral zenith delay correction error.
- Broadcast orbit errors (enables the making of precise differential near-real time solutions).
- Integer Ambiguity Resolution available in differential mode, with:
  a) short baselines up to 20 km (in minutes), and
  b) baselines of unlimited length (in tens of minutes –or just minutes, with a precise ionosphere correction).

4. AIRBORNE TESTS: STUDY AREAS AND OBSERVATIONS

This study has utilised data from two airborne LiDAR surveys conducted by the NSW Land and Property Management Authority (LPMA) in June 2009. The first took place in the northeast of the state of New South Wales near the township of Glen Innes, and the second was a bore-sight calibration flight near the city of Bathurst (Figure 2). These surveys were undertaken as part of LPMA's LiDAR test and development program.

For both LiDAR surveys, the following data were acquired:
- Aircraft trajectory, raw dual-frequency GPS (1 Hz) and IMU data (200 Hz).
- LiDAR (raw return data for each laser pulse).
- GPS reference station data from local receivers and multiple CORSnet-NSW sites.

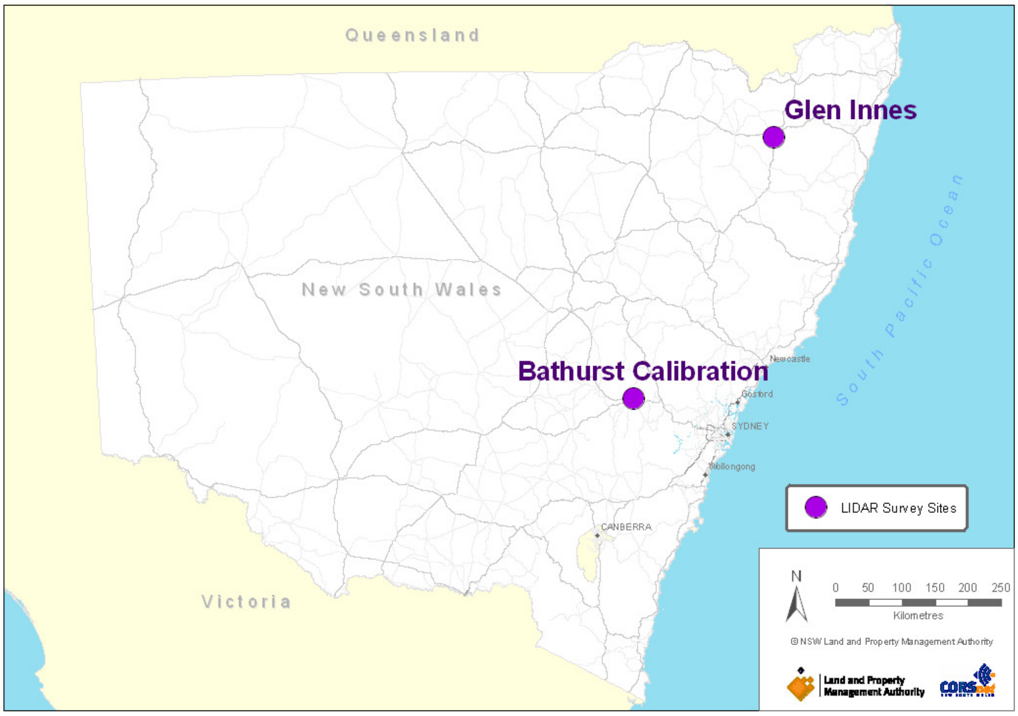

Figure 2: Location of the LiDAR survey sites used in this study.

4.1 Glen Innes Test

This operational LiDAR survey established GND1 as the local reference station within the survey area. CORSnet-NSW data were collected for the test from GNSS receivers in Ballina (BALL), Grafton (GFTN), Nowra (NWRA) and Wagga Wagga (WGGA). Figure 3 shows the distribution of the reference stations and a schematic of the flight runs.

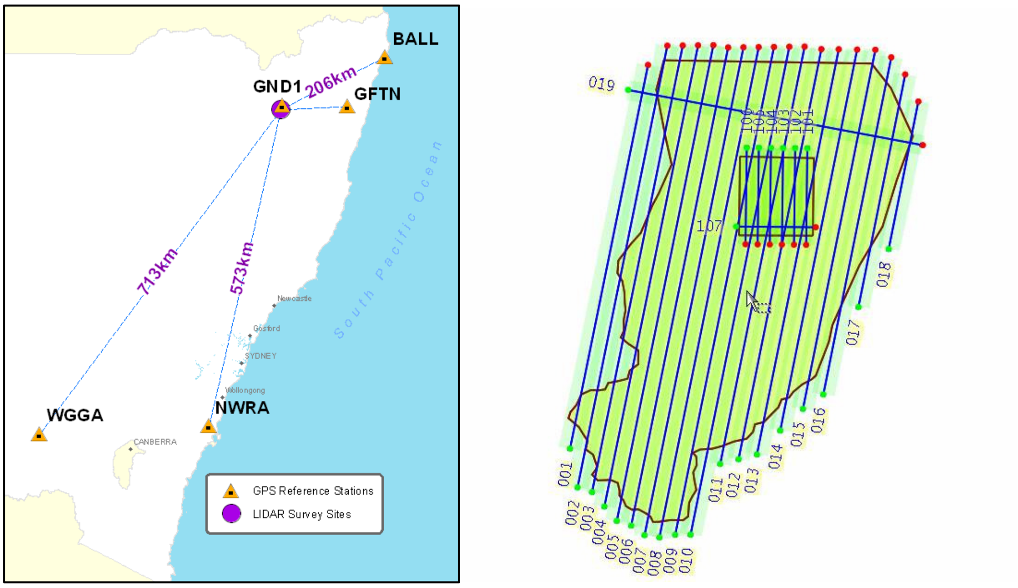

Figure 3: Glen Innes survey of 9 June 2009 showing the distribution of reference stations with baseline lengths and the survey area with (numbered) flight runs.

4.2 Bathurst Test

Bathurst Airport is LPMA's LiDAR calibration site and has various arrays of accurate ground check points. AIR2 is the locally established GNSS reference station. CORSnet-NSW data were collected for the test from receivers in Ballina (BALL), Dubbo (DBBO), Grafton (GFTN), Newcastle (NEWC), Nowra (NWRA) and Wagga Wagga (WGGA). Figure 4 shows the distribution of the reference stations utilised and a schematic of the flight runs.

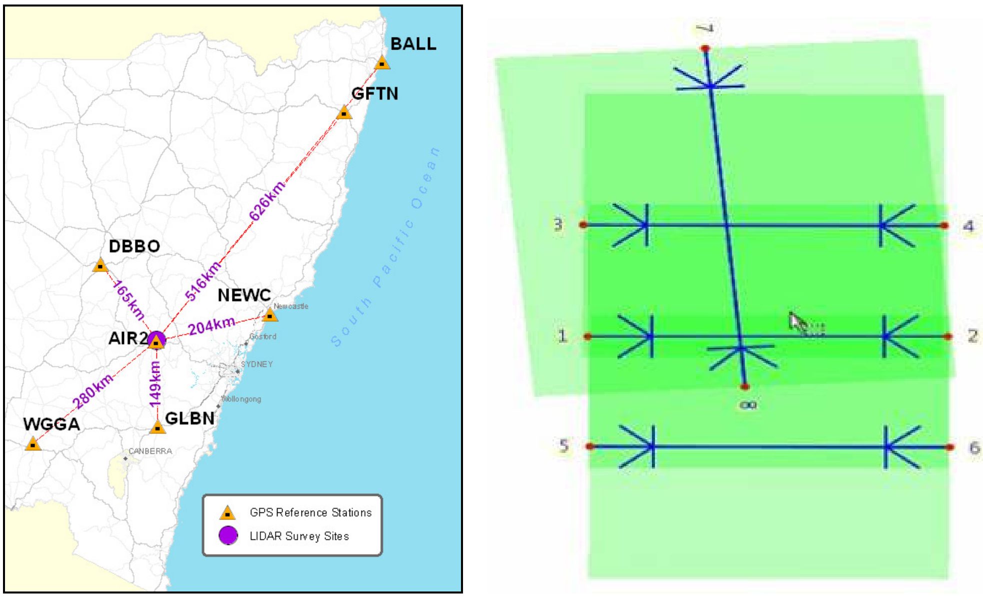

Figure 4: Bathurst test of 16 June 2009 showing the distribution of reference stations with baseline lengths and the survey area with (numbered) flight runs.

5. AIRBORNE TESTS: TEST METHODOLOGY AND RESULTS

Rather than simply comparing aircraft trajectories, this study aimed to determine what effect the use of wide-area GNSS positioning has on the actual LiDAR point data and associated elevation surfaces. In terms of the horizontal accuracy required for LiDAR surveys, initial tests showed that the differences between the horizontal positions of various trajectories was negligible, therefore only the vertical component was considered in this analysis.

In order to quantify the differences between LiDAR data generated from trajectories using various combinations of distant GNSS reference sites, the following four types of analysis were applied:

1. Comparison of trajectories, i.e. directly compare the locally-computed trajectory (assumed to be "truth") with each wide-area derived trajectory.
2. Relative LiDAR point comparison, i.e. compare the positions for a sample of LiDAR ground points derived from the locally-computed trajectory with those derived from each wide-area derived trajectory.
3. DEM comparison, i.e. difference the raster surfaces derived from the locally-computed trajectory and a wide-area derived trajectory to find the effect over a LiDAR run.
4. Absolute LiDAR ground control comparison, i.e. compare the LiDAR derived surface from various trajectories to the surveyed ground control (Bathurst Calibration test site only). This also involves vertically shifting the resulting surface so that its offset relative to the one used as control is zero, thus removing the effect of using different reference frames for the GNSS trajectories and the control surface.

5.1 Trajectory Comparison

The comparison between the locally determined and each wide-area derived trajectory was made along the entire trajectory for each flight. The importance of this step lies in the assumption that all LiDAR data are directly positioned from the trajectory and so any systematic effect in the trajectory should be reflected on the ground. For each test site the locally derived solution is assumed to be "truth" with the vertical difference computed against wide-area solutions for each combination of reference stations utilised (Table 1).

Table 1: GNSS reference station combinations used in each test area.

Glen Innes	Bathurst Calibration
GND1 (the local solution)	AIR2 (the local solution)
BALL/GFTN	BALL
WGGA/NWRA	BALL/GFTN
	DBBO/WGGA/NEWC
	WGGA
	WGGA/GLBN/NEWC

5.1.1 Glen Innes test

Figure 5 shows the vertical comparison of two wide-area derived trajectories (using BALL & GFTN and WGGA & NWRA, respectively) against the locally derived trajectory (using GND1). It can be seen that once the aircraft attained its stable operating altitude, the wide-area derived trajectories are generally within 5 cm of the locally derived solution.

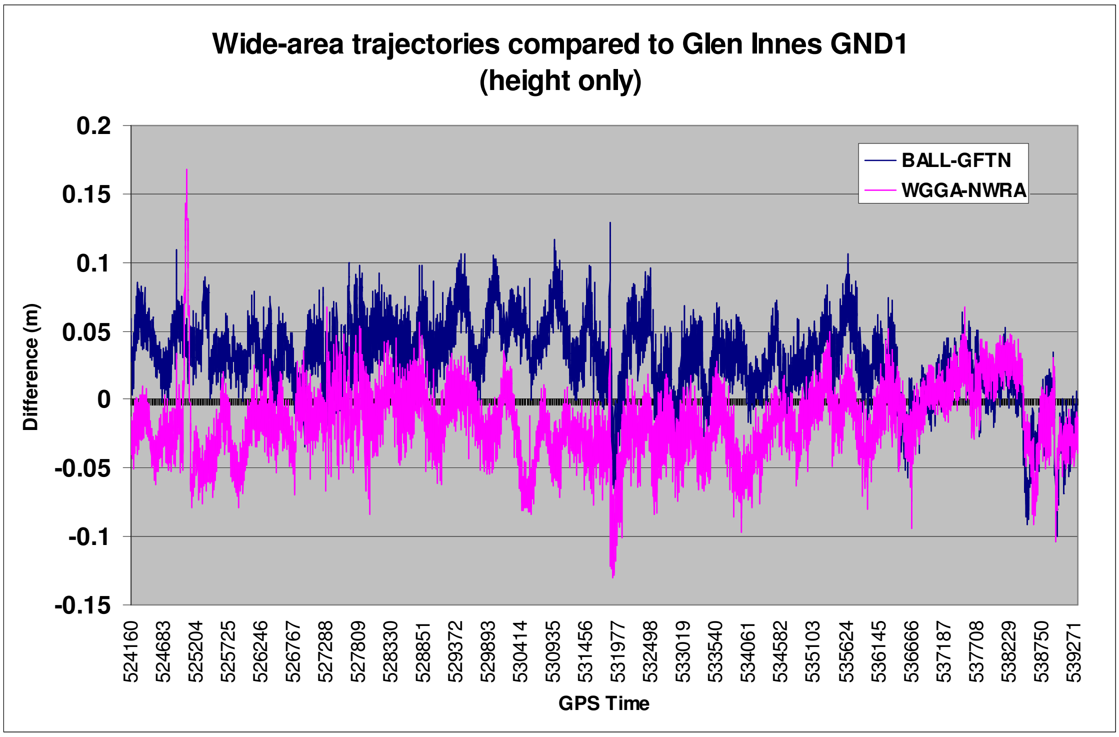

Figure 5: Trajectory elevation differences for entire Glen Innes flight.

5.1.2 Bathurst test

The Bathurst test differs to the Glen Innes test in that both the duration of the flight and the length of each run are significantly shorter. Figure 6 shows the vertical component of five wide-area derived trajectories, using several combinations of CORSnet-NSW reference stations, compared against the locally derived trajectory (using AIR2). The results once again show a remarkably consistent comparison with the locally derived solution. Data spikes showing up in the DBBO/WGGA/NEWC (yellow) solution were attributed to small data glitches at the DBBO CORSnet-NSW site. Unfortunately, LiDAR data were not being collected at those instances, therefore the effect on ground data could not be fully assessed.

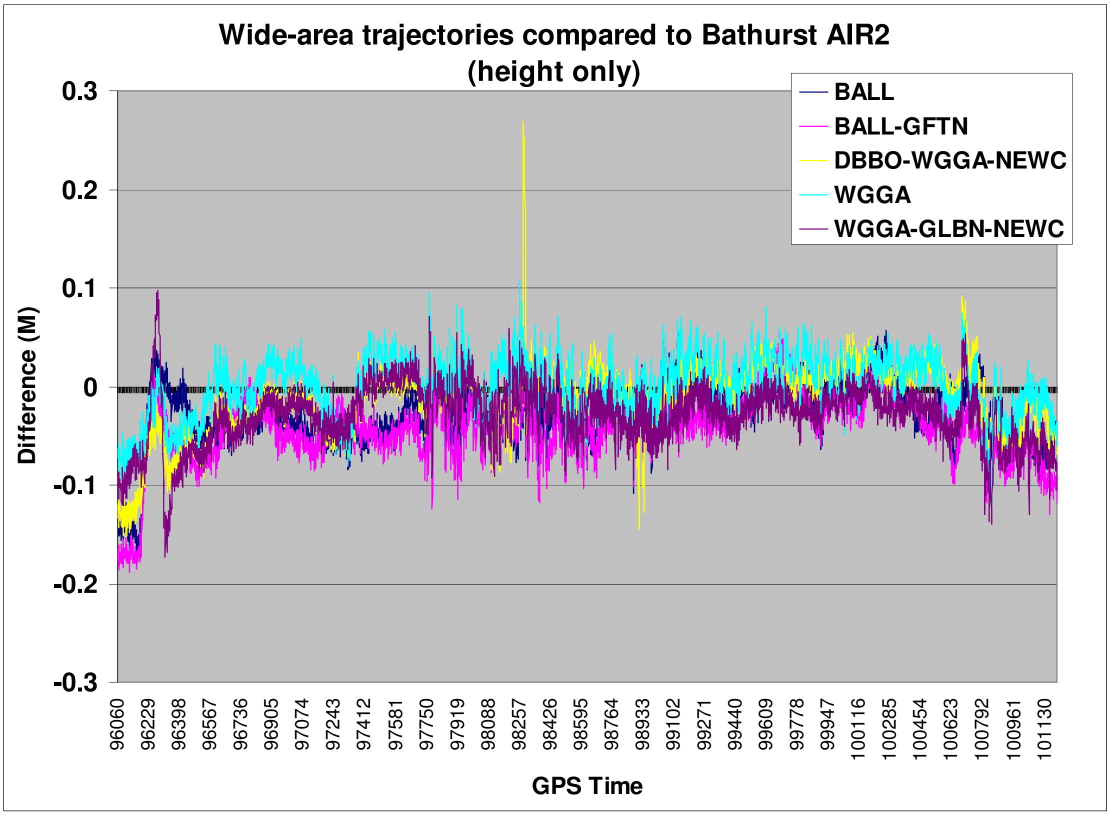

Figure 6: Trajectory elevation differences for entire Bathurst Calibration flight.

5.2 Relative LiDAR Point Comparison

Regardless of the trajectory and orientation that is used to georeference LiDAR data, the same number of points will be created. It is therefore possible to create a LiDAR dataset using the same raw LiDAR data but different GNSS trajectories and compare the results to determine the relative positioning differences "on the ground".

Given the very large number of points in a LiDAR dataset (many millions), a representative sample consisting of evenly spaced 10 m by 10 m areas each containing around 50-100 points (on level ground) was used for statistical analysis. Displacement vectors were calculated between points computed from the locally derived trajectory and those using wide-area trajectories. The results from flight run 002 at Glen Innes (see Figure 3) and run 7 at the Bathurst Calibration test site (see Figure 4) are presented here.

5.2.1 Glen Innes test run 002

The displacement vectors from 46 sample areas (4620 points) are summarised in Table 2, being points computed using the two wide-area solutions compared with the locally derived solution utilising reference station GND1. Note the high accuracy achieved in the all important vertical component.

Table 2: Displacement vectors for each combination relative to the local solution for Glen Innes run 002 (all values in metres).

GNSS Reference Station		Min.	Max.	Average	Std. Dev.
BALL/GFTN (average 200 km baseline)	East	-0.008	0.029	0.011	0.008
	North	-0.027	0.018	-0.004	0.011
	Vertical	**0.004**	**0.045**	**0.025**	**0.009**
WGGA/NWRA (average 600 km baseline)	East	-0.050	0.024	-0.017	0.021
	North	-0.106	0.083	-0.018	0.057
	Vertical	**-0.050**	**0.001**	**-0.024**	**0.014**

5.2.2 Bathurst test run 7

The displacement vectors from 25 sample areas (1700 points) are summarised in Table 3, being points computed using the five wide-area solutions compared with the locally derived solution utilising reference station AIR2. Once again the results clearly show that the height values agree to within a few centimetres, even over baselines of more than 600 km in length.

Table 3: Displacement vectors for each combination relative to the local solution for Bathurst Calibration run 7 (all values in metres).

GNSS Reference Station		Min.	Max.	Average	Std. Dev.
BALL (626 km baseline)	East	-0.013	-0.005	-0.009	0.002
	North	-0.034	0.012	-0.012	0.013
	Vertical	**-0.031**	**-0.003**	**-0.020**	**0.008**
BALL/GFTN (average 570 km baseline)	East	-0.009	0.002	-0.004	0.002
	North	-0.036	0.007	-0.015	0.011
	Vertical	**-0.048**	**-0.014**	**-0.037**	**0.008**
DBBO/WGGA/NEWC (average 220 km baseline)	East	-0.035	-0.026	-0.031	0.002
	North	-0.031	-0.002	-0.016	0.008
	Vertical	**-0.020**	**0.017**	**-0.008**	**0.009**
WGGA (280 km baseline)	East	-0.024	-0.009	-0.018	0.004
	North	-0.028	0.000	-0.014	0.006
	Vertical	**-0.027**	**0.015**	**-0.016**	**0.010**
WGGA/GLBN/NEWC (average 210 km baseline)	East	-0.006	0.004	-0.002	0.002
	North	-0.029	0.003	-0.015	0.009
	Vertical	**-0.020**	**0.017**	**-0.009**	**0.009**

5.3 DEM Comparison

In order to investigate how the LiDAR surfaces derived from each trajectory compare across the entire data swath, raster surfaces were created from the LiDAR point data. Each surface was then subtracted from the local solution to create a difference surface. Visual inspection and interpretation was then used to discern any patterns or effects.

The result shown in Figure 7 (Bathurst Calibration flight run 7) was typical of the cyclical effect evident for all solutions. The magnitude of the difference was in the order of 2-3 cm and is in the direction of flight (north to south).

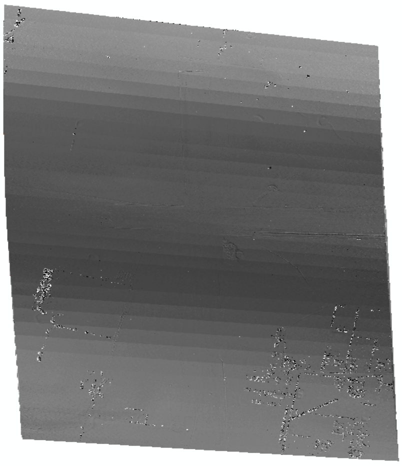

Figure 7: Subtraction surface for Bathurst Calibration run 7 (AIR2 vs. BALL).

If this cyclical variation is compared with the trajectory comparison for just the 33-second duration of flight run 7, a clear (expected) correlation with the variation in height is evident (Figure 8).

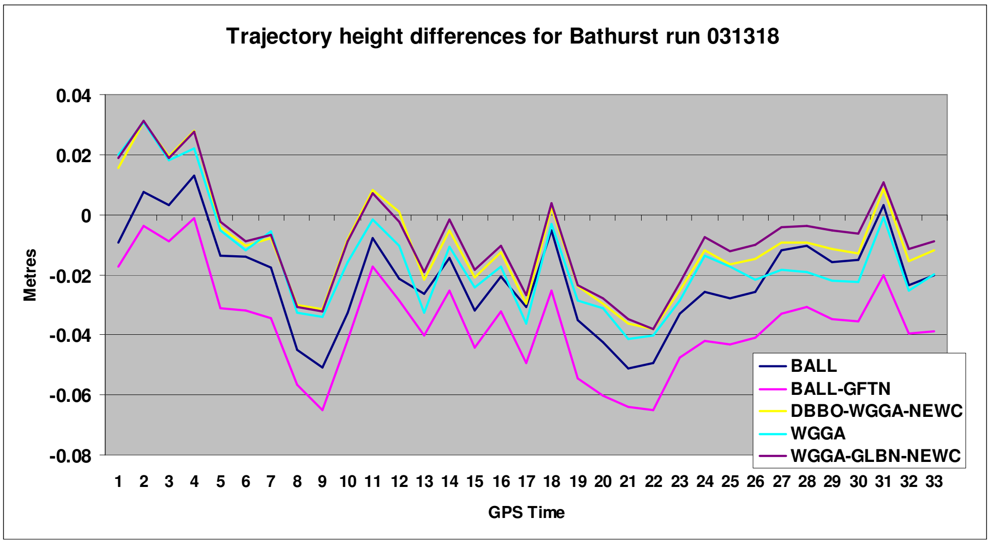

Figure 8: Trajectory comparison for Bathurst Calibration run 7 (031318).

No DEM comparison results are presented for the Glen Innes data due to the significant variation in terrain and vegetation cover, making interpolation extremely difficult and unreliable.

5.4 Absolute LiDAR Ground Control Point Comparison

Ground control points serve two purposes in a LiDAR survey:

1. The calculation of statistics to describe vertical accuracy, i.e. quantifying the match of the surface to the local height datum.
2. The calculation of an adjustment surface to enable transformation of the LiDAR points to fit the local height datum.

Additionally, ground control points with very accurate heights are used to calibrate the sensor before use in active LiDAR surveys in order to account for internal electrical delays in the ranging and measurement system. LPMA maintains a calibration site at Bathurst Airport for this purpose and regularly surveys the area to ensure the sensor is operating at maximum accuracy. It should be noted that the sensor was calibrated using Bathurst Airport ground control data prior to this study.

5.4.1 Surveyed ground control

The airport runway centreline vertical profile for the Bathurst Calibration site (Figure 9) was re-computed in terms of the same IGS05 reference frame determined for the LiDAR trajectories, thereby allowing an independent comparison with “ground truth”.

Figure 9: Runway vertical profile at the Bathurst Airport calibration site.

5.4.2 Ground control point comparison

Data from Bathurst Calibration run 7 were then used to compare the LiDAR results with the established ground control using a basic TIN (Triangulated Irregular Network) (e.g. Abdelguerfi et al., 1998) surface comparison (Figure 10 and Table 4). In Figure 10, the TIN surface is indicated by the white line, while the ground control points are shown with yellow buffers.

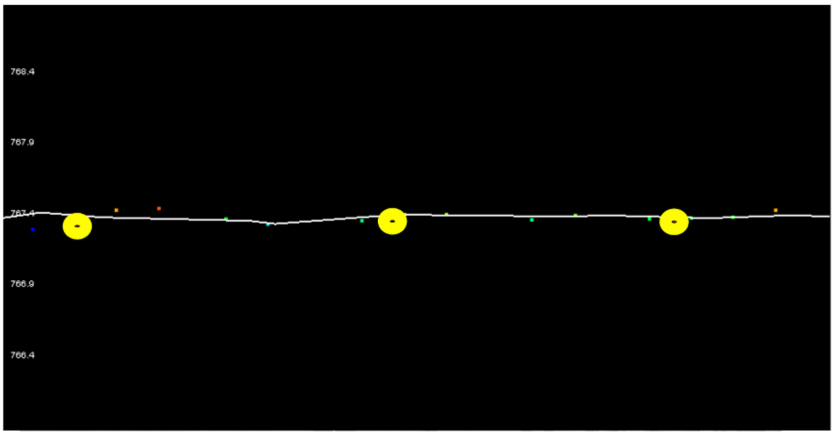

Figure 10: Comparison of LiDAR surface and ground control points.

Table 4: Comparison of LiDAR surface against ground control points (all values in metres).

Trajectory	Mean	Min.	Max.	RMSE
AIR2 (GrafNav)	0.008	-0.074	0.097	0.034
AIR2	-0.102	-0.177	-0.002	0.106
BALL	-0.102	-0.177	-0.002	0.106
BALL/GFTN	-0.117	-0.191	-0.015	0.122
DBBO/WGGA/NEWC	-0.089	-0.161	0.009	0.094
WGGA	-0.098	-0.170	0.000	0.103
WGGA/GLBN/NEWC	-0.090	-0.164	0.008	0.096

The first trajectory listed in Table 4 is the original calibration comparison using the proprietary software package “GrafNav” and orthometric height data. All wide-area solutions display a similar vertical offset which is due to variations in the test processing methodology such as antenna corrections and atmospheric modelling. At first inspection, the significant differences to the GrafNav trajectory cause the result to not satisfy the accuracy specifications for LiDAR. However, had the wide-area solutions been used for the sensor calibration, then the figures would have been much closer to the ground truth.

5.4.3 Block-shifted data comparison

In an operational environment, due to systematic errors and anomalies between geoid models and the local height datum, this mean vertical offset is a common occurrence with comparisons against ground control similar to those shown in Figure 11. Again, the TIN surface is indicated by the white line, and the ground control points are shown with yellow buffers.

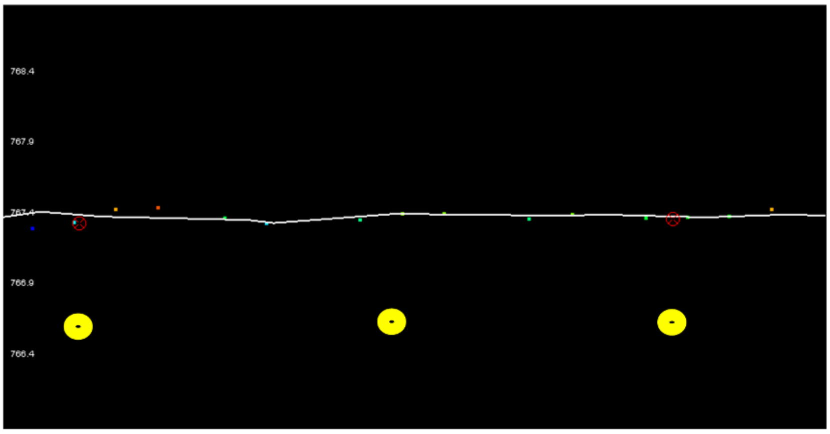

Figure 11: Usual operational comparison of LiDAR surface and ground control points.

In standard day-to-day LiDAR operations, the area mean vertical offset between the initial results and the ground control is used to "block-shift" the data in order to match the ground control, i.e. producing a zero mean offset. Following this procedure in this case results in the variation in the comparison of LiDAR data with ground truth now being well within the required limits of ±15 cm (Table 5). The values clearly show that once a block shift is applied, the trajectory solutions are virtually identical with a root mean square error (RMSE) of 32 mm. This shows that local GNSS reference stations can be replaced by distant CORS sites without loss of accuracy.

Table 5: Comparison of block-shifted LiDAR surface against ground control points (all values in metres).

Trajectory	Mean	Min.	Max.	RMSE
AIR2 (GrafNav)	0.000	-0.082	0.089	0.033
AIR2	0.000	-0.075	0.100	0.032
BALL	0.000	-0.075	0.100	0.032
BALL/GFTN	0.000	-0.074	0.102	0.032
DBBO/WGGA/NEWC	0.000	-0.072	0.098	0.032
WGGA	0.000	-0.072	0.098	0.032
WGGA/GLBN/NEWC	0.000	-0.074	0.098	0.032

6. CONCLUSIONS

From the results of all the tests described in this paper, we conclude that the use of a precise wide-area positioning technique for airborne trajectory solutions provides both relative and absolute accuracies similar to those derived from using a local GNSS reference station. In particular, it has been demonstrated that irrespective of which reference sites are used and once calibration and antenna modelling issues are addressed, the absolute comparison with ground control is well within the required accuracies.

It is clear that with the configuration of a GNSS network such as CORSnet-NSW (where, when complete, at least one of the sites is always going to be within 150 km of any point within New South Wales), an airborne LiDAR survey in the area serviced by this network is capable of providing data for the computation of an accurate sensor trajectory. This potentially negates the need to place and maintain ground reference stations close to the survey area – an exercise which not only requires significant resources but also reduces the operational flexibility of the aircraft.

The challenge for the use of this technique in an operational environment is to define and maintain a precise reference frame for all CORSnet-NSW sites and observations, including the use of a stable ellipsoidal height datum with compatible geoid modelling in order to provide local orthometric elevation data. Also, the knowledge base required for the computation of wide-area GNSS solutions is significant and requires an understanding of geodesy, GNSS positioning, absolute antenna modelling, application of precise ephemerides and derivation of the other parameters inherent to successful ambiguity resolution over such long distances.

Regardless of the GNSS processing methods, a LiDAR survey will always require independent ground surveys for the collection of vertical check points. The check points provide quality control and ensure the accuracy meets the specifications. These check points also provide the means to define any transformations necessary to fit LiDAR data with the local height datum.

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BIOGRAPHICAL NOTES

Oscar L. Colombo received a degree in Electrical Engineering from the National University of la Plata, Argentina, and a PhD in Electrical Engineering from the University of New South Wales, Australia. He has worked on different aspects of both physical and space geodesy, including satellite orbit determination, gravity field mapping, preliminary studies of space missions for Earth science, the realisation of the terrestrial reference frame, and the development of precise positioning techniques using the Global Positioning System. Currently he works as an independent consultant, with close links to NASA, the U.S. Navy, and university and government research groups in both the USA and abroad. He is a Member of the ION, and a Fellow of the IAG.

Shane Brunker is an airborne LiDAR and imaging specialist who has recently begun working in a consulting capacity for specialised LiDAR survey company Network Mapping (United Kingdom). He holds a Bachelor of Science (GIS & Remote Sensing) from Charles

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Volker Janssen is a GNSS Surveyor (CORS Network) in the Survey Infrastructure and Geodesy branch at the NSW Land and Property Management Authority in Bathurst, Australia. He holds a Dipl.-Ing. (MSc) in Surveying from the University of Bonn, Germany, and a PhD in GPS for volcano deformation monitoring from the University of New South Wales (UNSW). He worked as an assistant lecturer at UNSW and as graduate surveyor in Sydney before being a Lecturer in Surveying and Spatial Sciences at the University of Tasmania between 2004 and 2009. Volker's research interests are in the fields of geodesy and geodynamics, with an emphasis on GPS/GNSS studies and CORS networks.

Chris Rizos is the Head of the School of Surveying & Spatial Information Systems at the University of New South Wales (UNSW), in Australia. Chris has been researching the technology and high precision applications of GPS since 1985, and has published over 400 journal and conference papers. Chris established the Satellite Navigation and Positioning Lab at UNSW in the early 1990s, today Australia's premier academic GPS and wireless positioning R&D group. He is a Fellow of the Australian Institute of Navigation, a Fellow of the International Association of Geodesy (IAG), and is the Vice President of the IAG. He is a member of the International GNSS Service (IGS) Governing Board and currently the Chair of the joint IAG/IHO Advisory Board on the Law of the Sea (ABLOS).

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