Sparse Network

Wide-Area, Sub-Decimeter Positioning for Airborne LiDAR Surveys

The use of a precise wide-area positioning technique for airborne trajectory solutions for LiDAR surveys provides both relative and absolute accuracies similar to those derived from using a local GNSS reference station.

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Airborne light detection and ranging (LiDAR) surveys are among the most advanced means of producing high-resolution, accurate surface elevation models used for many applications in surveying and civil engineering. Precise geolocation and orientation (or georeferencing) of the LiDAR instrument with a combination of on-board GNSS and inertial sensors at the times when the measurements are made provides the key to high-quality elevation products.

The usual practice deploys reference GPS/GNSS land receivers in the area where the aircraft will be flying, to obtain a precise trajectory by short-baseline differential GNSS techniques. 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, and a wide-area differential GPS technique for obtaining the aircraft trajectory with sub-decimeter accuracy even with baseline lengths of several hundred kilometers. This may be comparable in precision and accuracy to the short-baseline method, but without the cost and logistical complications. This opens up a new level of operational capability, allowing flexibility for weather conditions and priority response applications.

The tests described here were organized and conducted by the NSW government's Land and Property Management Authority, in collaboration with the University of New South Wales, in June 2009. CORSnet-NSW consists, at this writing, of 46 stations and by 2012 will provide statewide GNSS positioning infrastructure across NSW with a planned 70 stations in operation.

Precise Wide-Area Positioning

We used a technique for long-baseline differential, off-line positioning, able to deliver centimeter precision for fixed receivers and sub-decimeter precision for moving receivers. This choice was dictated by three considerations:

- 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).
- 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.
- Differential processing makes it possible to resolve the carrier-phase ambiguities using well-understood methods.

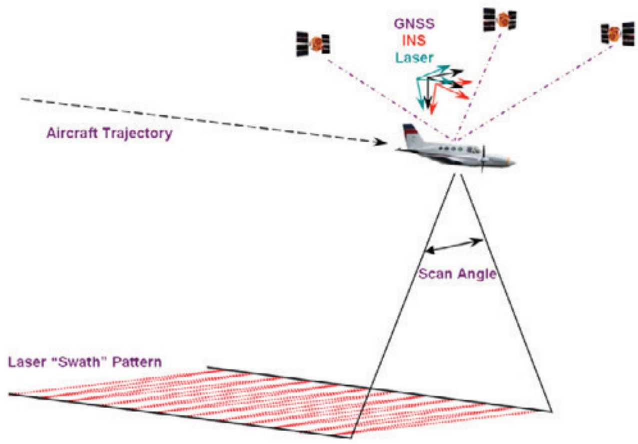
Technique. It is common practice in airborne LiDAR surveys to use GNSS both to position the instrument precisely, and to assist an inertial navigation system (INS) to obtain the orientation of the aircraft in space, as both position and orientation are needed to interpret the data properly. **FIGURE 1** illustrates the relationship between the sensors used for airborne LiDAR surveys. The aircraft uses a GNSS antenna combined with an INS to georeference its trajectory. The bore-sight calibration process aligns the individual sensor orientations and standardizes the range measurements. However, if the survey is to achieve the now-expected high level of vertical accuracy (±15 centimeters, 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 centimeters. 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.

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 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, and so on) 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, as ionospheric delay is one of the systematic effects that can be largely canceled 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. 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 seconds to a minute is possible on occasion, when the aircraft is within less than 20 kilometers from a ground receiver, or very precise corrections for the ionospheric delay are available; otherwise slower techniques, that require tens of minutes, may be used. It is also necessary to correct as well as possible such things as the neutral atmospheric delay of the GNSS radio signals, the movement of the "fixed" stations due to plate tectonics, the solid earth tide using mathematical models, and, in the case of the tropospheric delay, estimating the error in the corrections made using a standard formula 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 precisely the orbit of Earth-observing satellites, these days, after nearly 30 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.



▲**FIGURE 1** Airborne LiDAR reference frame.

Software. We used the Interferometric Translocation (IT) wide-area positioning software developed by one of us for the long-baseline aircraft trajectory solutions and also to re-position in the IGS05 international reference frame 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). For both purposes we used the precise final GPS orbits computed and distributed by the IGS.

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. We also used commercial 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).

Airborne Tests

This study has used data from two airborne LiDAR surveys conducted by the NSW Land and Property Management Authority (LPMA) in June 2009. The first took place near the township of Glen Innes, and the second was a bore-sight calibration flight near the city of Bathurst. 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.

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 2** shows the distribution of the reference stations and the flight runs.

Bathurst Test. Bathurst Airport is LPMA's LiDAR calibra-

The "IT" Software

- Runs under Windows, Unix, Linux, and FreeBSD.
- Source code compatible with most Fortran compilers.
- 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 and static.
- Stop-and-go for rapid mobile surveys with pre-surveyed way-points.
- Differential, precise point positioning, mixed mode (precise differential + point positioning).

Data corrected for: Earth tide, neutral atmosphere radio signal delays, carrier phase windup, and so on.

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 (allows precise differential near-real time solutions).
- Integer ambiguity resolution available in differential mode, with short baselines up to 20 kilometers (in minutes), and baselines of unlimited length (in tens of minutes — or just minutes, with a precise ionosphere correction).

tion site and has various arrays of accurate ground checkpoints. AIR2, near the runway of the Bathurst airport, 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 3** shows reference-station distribution and a schematic of the flight runs.

Effect on LiDAR Data

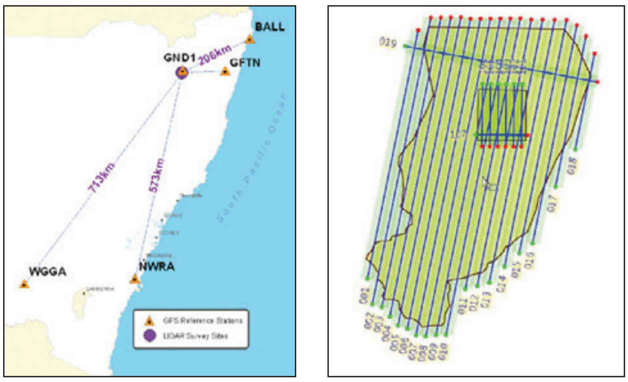
Rather than simply comparing aircraft trajectories, this study aimed to determine what effect the use of wide-area GNSS positioning has on the actual LiDAR point data and associated elevation surfaces. In terms of the horizontal accuracy required for LiDAR surveys, initial tests showed that the differences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

To quantify differences between LiDAR data generated from trajectories using various combinations of distant GNSS reference sites, we applied four types of analysis:

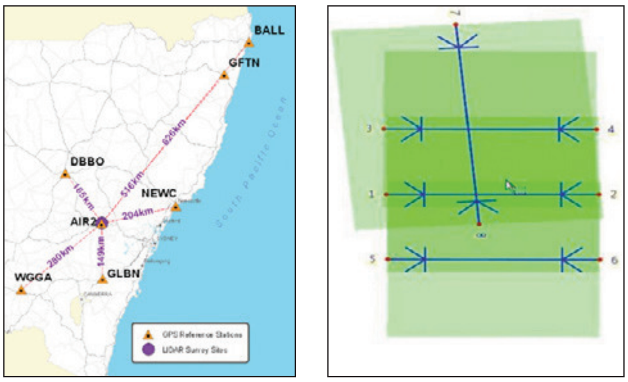
- Comparison of trajectories — directly compare the locally computed trajectory (assumed to be truth) with each wide-area derived trajectory.
- Relative LiDAR point comparison — compare the positions for a sample of LiDAR ground points derived from the locally computed trajectory with those derived from each wide-area derived trajectory.
- DEM comparison — difference the raster surfaces derived from the locally computed trajectory and a wide-area derived trajectory to find the effect over a LiDAR run.
- Absolute LiDAR ground control comparison — 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.

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 used (**TABLE 1**).



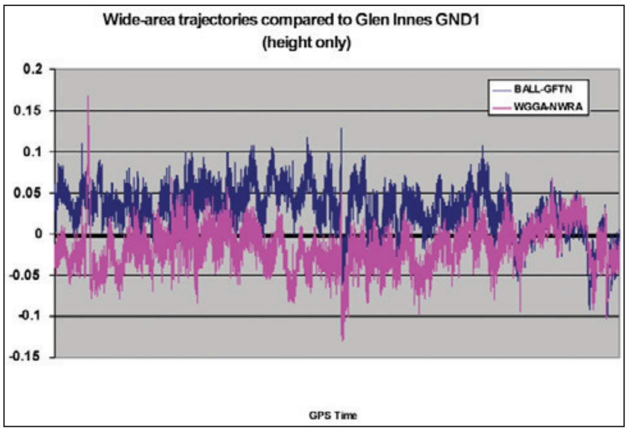
▲ **FIGURE 2** Glen Innes survey of June 9, 2009, showing the distribution of reference stations with baseline lengths and the survey area with (numbered) flight runs.



▲ **FIGURE 3** Bathurst test of June 16, 2009, showing the distribution of reference stations with baseline lengths and the survey area with (numbered) flight runs.

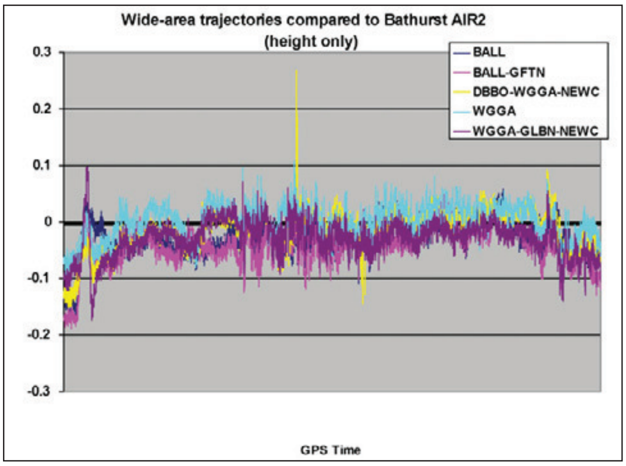
Glen Innes	Bathurst Calibration
GND1 (the local solution)	AIR2 (the local solution)
BALL/GFTN	BALL
WGGA/NWRA	BALL/GFTN
	DBBO/WGGA/NEWC
	WGGA
	WGGA/GLBN/NEWC

▲**TABLE 1** GNSS reference station combinations used in each test area.



▲**FIGURE 4** Trajectory elevation differences for entire Glen Innes flight.

Glen Innes Test. FIGURE 4 shows the vertical comparison of two wide-area derived trajectories (using BALL and GFTN, and WGGA and 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 centimeters of the locally derived solution.



▲**FIGURE 5** Trajectory elevation differences for entire Bathurst calibration flight

Bathurst Test. The Bathurst test differs from the Glen Innes test in that both the duration of the flight and the length of each run are significantly shorter. FIGURE 5 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

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**

▲**TABLE 2** Displacement vectors for each combination relative to the local solution for Glen Innes run 002 (values in meters).

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**

▲**TABLE 3** Displacement vectors for each combination relative to the local solution for Bathurst Calibration run 7 (values in meters).

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 collected at those instances; therefore, the effect on ground data could not be fully assessed.

Relative Comparison

Regardless of the trajectory and orientation 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 large number (many millions) of points in a LiDAR dataset, we used a representative sample of evenly spaced 10 × 10 meter areas each containing 50–100 points (on level ground) for statistical analysis. We calculated displacement vectors between points computed from the locally derived trajectory and those using wide-area trajectories. Results from flight run 002 at Glen Innes (see Figure 2) and run 7 at the Bathurst Calibration test site (see Figure 3) are presented here.

Glen Innes Test Run 002. The displacement vectors from 46 sample areas (4,620 points) are summarized in **TABLE 2**, being points computed using the two wide-area solutions compared with the locally derived solution using reference station GND1. Note the high accuracy achieved in the all important vertical component.

Bathurst Test Run 7. The displacement vectors from 25 sample areas (1,700 points) are summarized in **TABLE 3**, being points computed using the five wide-area solutions compared with the locally derived solution using reference station AIR2. Once again the results clearly show that the height values agree to within a few centimeters, even over baselines of more than 600 kilometers in length.

DEM Comparison

To investigate how the LiDAR surfaces derived from each trajectory compare across the entire data swath, we created raster surfaces 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 6** (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 centimeters and is in the direction of flight (north to south). 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 7**).

No DEM comparison results are presented for the Glen Innes data because of significant variation in terrain and vegetation, making interpolation difficult and unreliable.

Absolute LiDAR Comparison

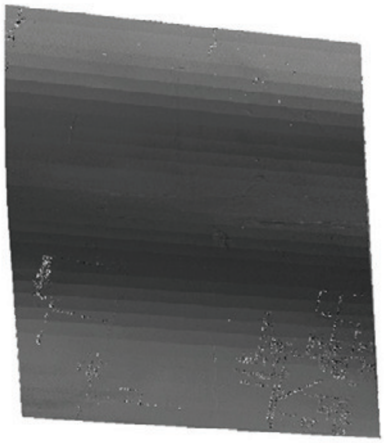
Ground control points serve two purposes in a LiDAR survey:

- The calculation of statistics to describe vertical accuracy, that is, quantifying the match of the surface to the local height datum.
- The calculation of a surface adjustment to enable transformation of the LiDAR points to fit the local height datum.

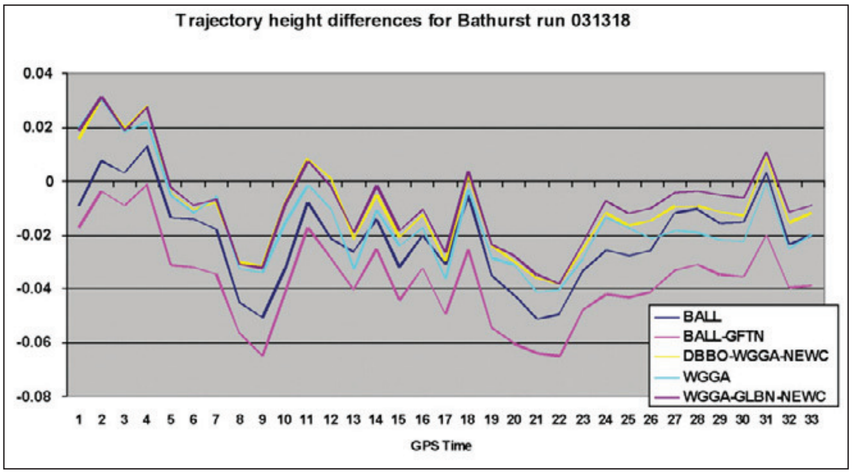
Additionally, ground control points with accurate heights are used to calibrate the sensor before use in active LiDAR surveys to account for internal electrical delays in the ranging and measurement system. LPMA maintains a calibration site at Bathurst Airport for this purpose, and regularly surveys 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.

Surveyed Ground Control. The airport runway centerline vertical profile for the Bathurst Calibration site (**FIGURE 8**) was re-computed in terms of the same IGS05 reference frame determined for the LiDAR trajectories, thereby allowing an independent comparison with ground truth.

Point Comparison. Data from Bathurst run 7 were used to compare LiDAR results with the established ground control using a basic triangulated irregular network (TIN) surface



▲**FIGURE 6** Subtraction surface for Bathurst Calibration run 7 (AIR2 vs. BALL).



▲**FIGURE 7** Trajectory comparison for Bathurst Calibration run 7 (031318).

▲**FIGURE 8** Runway vertical profile at the Bathurst Airport calibration site.

comparison (**FIGURE 9** and **TABLE 4**). In Figure 9, the TIN surface is indicated by the white line, while the ground control points are shown with yellow buffers.

The first trajectory in Table 4 is the original calibration comparison using commercial software and orthometric height data. All wide-area solutions display a similar vertical offset, because of the use of different reference frames for the GrafNav and wide-area solutions (IGS05 vs. GDA94), and differences in the implementation in software of, for example, antenna corrections and atmospheric modeling. At first glance, the significant differences to the GrafNav trajectory caused the wide-area result to not satisfy the accuracy specifications for LiDAR. However, had the wide-area solutions been used for the sensor calibration, the figures would have been much closer to the ground truth.

Block-Shifted Data Comparison. In an operational environment, because of systematic errors in the resulting DEM relative to the local height datum, this mean vertical offset is a common occurrence with comparisons against ground control similar to those shown in **FIGURE 10**. Again, the TIN surface is indicated by the white line, and the ground control points are shown with yellow buffers.

In standard LiDAR operations, the mean vertical offset between the initial results and the ground control, at the control points, produces 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 centimeters (**TABLE 5**). The values show that after a block shift, trajectory solutions are virtually identical with a root mean square error of 32 millimeters. Thus, local GNSS reference stations can be replaced by distant CORS sites without loss of accuracy.

Conclusions

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. Irrespective of which reference sites are used and once calibration and antenna modeling issues are addressed, the absolute comparison with ground control is well within the required accuracies. With the configuration of a GNSS network such as CORSnet-NSW (when complete, at least one site will always be within 150 kilometers of any point within New South Wales), an airborne LiDAR survey in the network's service area can provide data for 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 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 modeling in order to provide local orthometric elevation data. The knowledge base required for computation of wide-area GNSS solutions is significant and requires understanding of geodesy, GNSS positioning, absolute antenna modeling, application of precise ephemerides, and derivation of the other parameters inherent to successful ambiguity resolution over long distances.

Regardless of processing method, a LiDAR survey will always require independent ground surveys for collection of vertical checkpoints, which provide quality control to ensure the accuracy meets specifications, and the means to define any transformations necessary to fit LiDAR data with local height datum.

Manufacturer

NovAtel's WayPoint GrafNav software *(www.novatel.com)* was used for comparison purposes.

OSCAR L. COLOMBO received a degree in electrical engineering from the National University of la Plata, Argentina, and a Ph.D. in electrical engineering from the University of New South Wales, Australia. He is an independent consultant.

Trajectory	Mean	Min.	Max.	RMSE
AIR2 (commercial software)	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

▲**TABLE 4** Comparison of LiDAR surface against ground control points (all values in meters).

Trajectory	Mean	Min.	Max.	RMSE
AIR2 (commercial software)	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

▲**TABLE 5** Comparison of block-shifted LiDAR surface against ground control points (all values in meters).

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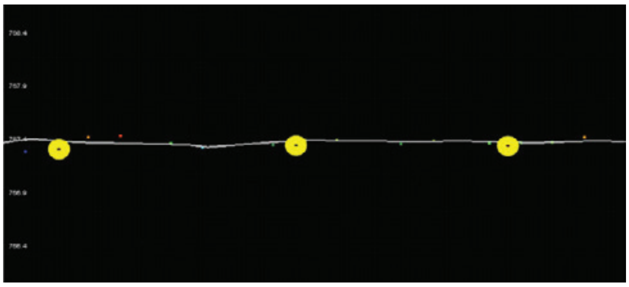
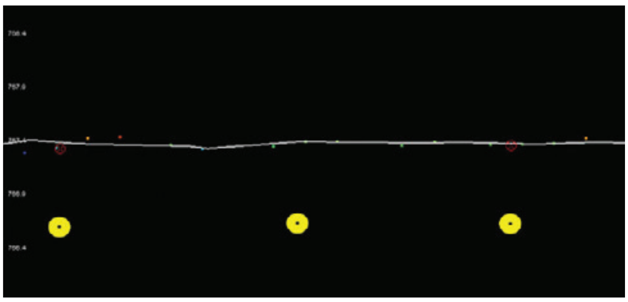


▲**FIGURE 9** Comparison of LiDAR surface and ground control points.



▲**FIGURE 10** Usual operational comparison of LiDAR surface and ground control points.