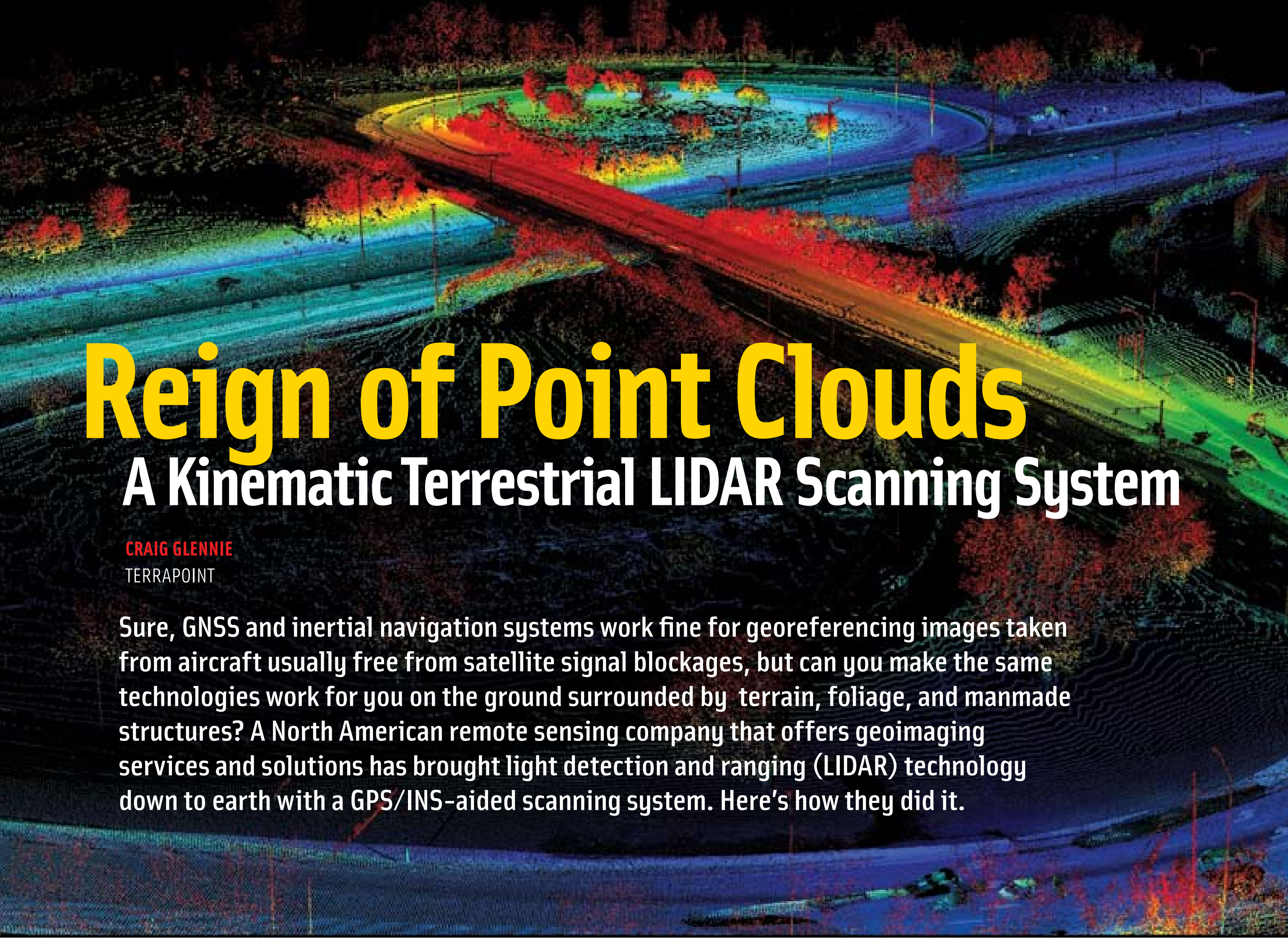

Reign of Point Clouds

A Kinematic Terrestrial LIDAR Scanning System

CRAIG GLENNIE
TERRAPOINT

Sure, GNSS and inertial navigation systems work fine for georeferencing images taken from aircraft usually free from satellite signal blockages, but can you make the same technologies work for you on the ground surrounded by terrain, foliage, and manmade structures? A North American remote sensing company that offers geoimaging services and solutions has brought light detection and ranging (LIDAR) technology down to earth with a GPS/INS-aided scanning system. Here's how they did it.

Commercially available airborne LIDAR (LIght Detection And Ranging) systems have been deployed for more than a decade, and the technology has been widely accepted as a fast and efficient means of capturing topographic information. The accuracy of a final 3D LIDAR "point cloud" is directly affected by the accuracy of the underlying positioning technology — typically a GPS/inertial navigation system — used to georeference the LIDAR measurements.

For airborne systems, obtaining the highest accuracy is primarily accomplished by paying close attention to maintaining the integrity of the GPS solution, which is collected in a fairly benign environment (that is, minimal signal shading and loss of lock, low dynamics). Consequently, a reliable GPS solution can normally be obtained by preplanning missions during good times of optimal satellite geometry, maintaining benign flight characteristics (for example, no steep banks of aircraft) and short baselines, and not flying during periods of high ionospheric activity.

In the kinematic terrestrial case, however, obtaining an accurate and reliable trajectory for the ground-based platform is a much more difficult and challenging task than that of an airborne platform. These difficulties arise primarily from increased multipath and frequent GPS signal outages caused by obstructions such as buildings, bridges, terrain, and dense vegetation.

LIDAR, whether airborne or ground-based, works by measuring the time-of-flight for a laser pulse to strike a point on terrain, structures, or other manmade objects and return. A laser scanning system generates and receives the reflected pulse.

Typically, an integrated GPS receiver determines the aircraft or vehicle position and the precise time of the pulse. An integrated inertial navigation system provides data on pitch, roll, and heading. Using the speed of light and elapsed time for the pulse return, a LIDAR system determines the distance between the laser scanner and the object reflecting the pulse. Given a precise position and attitude, the system then calculates the absolute position of the point on the scanned surface. Typical positioning accuracies of scanned objects for a terrestrial system are on the order of a few centimeters.

Down to Earth

Careful mission planning can mitigate some of the problems associated with terrestrial LIDAR applications, for instance, by traveling the optimum route and by establishing locations for zero velocity updates of the inertial measurement unit (IMU). Given the dynamic and fast-changing environment with regard to GPS positioning, a much more


difficult challenge often arises in the need to ensure the reliability and integrity of the final post-processed terrestrial trajectory.

Our company has developed a novel kinematic terrestrial-based laser scanning system, called TITAN (for Tactical Infrastructure and Terrain Acquisition Navigator), that can be deployed on a passenger vehicle or small watercraft. LIDAR, digital imagery, and digital video are collected from the survey platform while it is moving at speeds up to 100 kilometers per hour. The system is georeferenced using a high accuracy GPS/INS system. The unit's laser scanner assembly acquires 360 degrees of coverage in the LIDAR point cloud with a single vehicle pass.

To our surprise, Terrapoint's biggest initial customers have been military units. They are very interested in using data from a system like TITAN in order to collect rapid and accurate city models to employ in urban warfare. This type of data is also seen as a possible method (some day) to perform change detection, for example, on convoy routes to identify new items along the roadway that may contain IEDs (improvised explosive devices).

The other major markets for the system are for transportation engineering, although this one has proven difficult to crack because of the high accuracy requirements involved (typically less than 1 inch vertical). Urban modeling represents another prospectively large application market for LIDAR systems.

This article will discuss the design, development, implementation, and performance evaluation of the TITAN system.

A Short History of TITAN

The origins of Terrapoint's kinematic terrerstrial LIDAR system date to early 2002 when the company (formerly Mosaic Mapping Systems) was developin g a helicopter-based, low-level, high-accuracy LIDAR system.

As an aid for testing the system during the design and development stage, Terrapoint engineers developed a mounting mechanism to attach the helicopter LIDAR system to a truck. The truck mount allowed kinematic testing of the system without the high hourly cost of renting a helicopter. Once the airborne system was operational, the truck mount was not commercially developed but was used only as a testing and calibration platform.

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However, in mid-2003, a U.S. engineering firm approached Terrapoint to conduct a helicopter LIDAR survey of Highway 1 in Afghanistan between Herat and Kandahar. After much searching, a suitable helicopter for LIDAR surveying could not be found in Afghanistan. Moreover, an airborne approach had far too many safety concerns for use in a region of armed conflict.

As a result, the truck-mounted system was resurrected. Operationally, the road between Herat and Kandahar (approximately 560 kilometers in length) was an ideal place for a first kinematic terrestrial survey because of the lack of vegetation and other significant obstructions to GPS along the route.

Based on the success of the system in Afghanistan, and subsequent expressions of interest and successful demonstrations for customers in North America, Terrapoint decided to build a next-generation kinematic terrestrial LIDAR system, TITAN. The first-generation terrestrial system used in Afghanistan was essentially an airborne system, turned on its side and mounted on a vehicle. The system therefore had a number of shortcomings for terrestrial applications, namely:

- limited field of view of 60 degrees, requiring multiple passes for complete coverage
- tactical grade IMU, which was dependent upon a good GPS solution with minimum obstructions for highest accuracy
- limited digital image integration
- fixed mounting frame not easily transferable between vehicles.

A New Generation

We designed and built TITAN in order to reduce or eliminate these and other shortcomings found in the first-generation system. In contrast to the original version, TITAN incorporates an array of LIDAR sensors that provide a 360 degree field of view, a high-accuracy navigation grade IMU, and up to four integrated digital video or digital frame cameras. The laser scanning system can generate 40 points per square meter while moving at 80 kilometers per hour. A flexible mounting assembly allows the system to be deployed on a variety of mid-size trucks and boat platforms.

Figure 1 provides a block diagram of TITAN.s major hardware components. The accompanying photo shows the system mounted on a truck.

We designed the truck-mounted version so that all components could be operated and monitored from within the vehicle. The equipment pod (containing lasers, IMU, GPS and digital video) is installed on the end of a hydraulic lift that can raise and lower the instrument pod between two and four meters above the pavement. An umbilical cord connects the pod to the data logging computers and power module contained within the truck cab. All equipment is powered by the truck with an additional fully redundant battery back-up.

In developing TITAN we faced two major technical challenges — one we have overcome, and the other remains a continual evolutionary process. The first obstacle was the complexity of the system. In comparison to a land vehicle–mounted system, airborne LIDAR and photography is fairly easy. You normally have one GPS/INS system, one laser (usually), and one downward-looking camera.

However, in TITAN, we were dealing with multiple lasers, multiple cameras, and the possibility (although not implemented yet) of multiple GPS/INS subsystems. The biggest challenge was making sure that all of the individual components were synchronized (using the 1 pulse per second output from the GPS receiver) and "talking" to each other properly. To accomplish this, we developed some specialized hardware circuit boards to allow the capture and synchronization of multiple cameras and lasers simultaneously.

We also had to totally redesign our data storage methodology in order to accommodate the tremendous increase in the volume of data we were collecting. This also led to a redesign of our point-cloud generation software in order to "push" more data through in a shorter amount of time.


TITAN Mounted on Truck

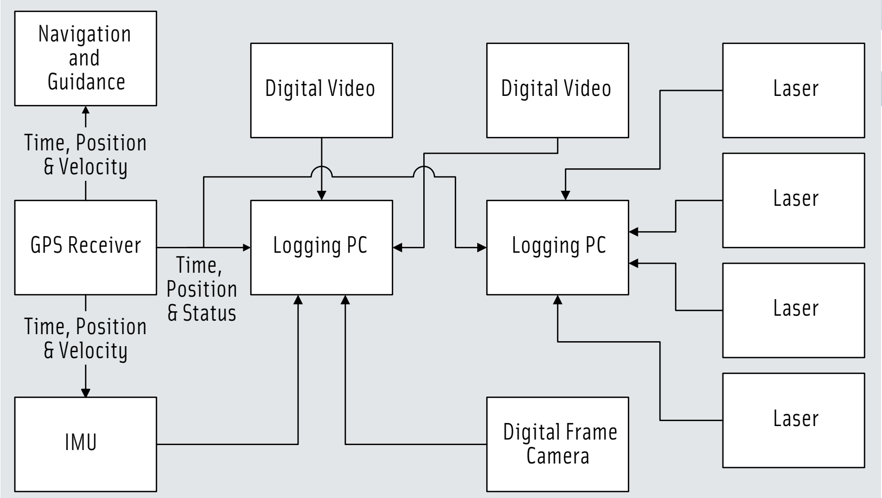


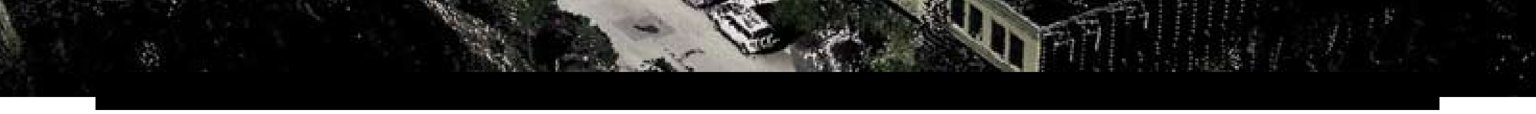
FIGURE 1 Block Diagram of TITAN System

The second problem has to do with GPS itself. Most airborne GPS/INS systems rely very heavily on the GPS component, because the conditions for GPS are benign in the air. For a ground system, however, obstructions (especially in urban areas, the application environment that draws most of the interest in TITAN data collection) can block the satellite signals and mean that we can't rely as heavily on GPS. Consequently, we have to rely more on an inertial system and other alternative aids (such as distance sensors on the vehicle).

We have worked hard on decreasing the dependence upon GPS in post-processing but have not yet arrived at a point of being able to replace it. Our future research will concentrate on ways to further decrease dependence on GPS. Because the availability of a larger number of satellite signals could help us solve the blockage problem, we also have plans to incorporate a new GNSS receiver into TITAN that will provide GLONASS capability as well.

Postprocessing Nav Data

Because TITAN collects data dynamically, the overall accuracy of the generated LIDAR point cloud is directly limited by the underlying accuracy of the GPS/INS navigation trajectory. The generation of an accurate trajectory is often a fairly difficult problem, especially in urban areas due to the unreliability



of obtaining a strong GPS positioning solution.

To provide the most reliable and robust solution for terrestrial navigation, we clearly required a tightly integrated GPS/INS Kalman filter processing strategy. Terrapoint uses its own GPS/INS software package called CAPTIN (Computation of Attitude and Position for Terrestrial Inertial Navigation) to postprocess the GPS/INS data.

Owning the software for postprocessing has allowed Terrapoint to optimize the performance of the tightly integrated GPS and INS Kalman filter for our specific terrestrial navigation needs and to tune the Kalman filter for land vehicle applications. It has also allowed us to take advantage of the extra geometric data provided by the LIDAR scanners to be able to enter some non-standard inputs into the Kalman filter. This has helped improve the accuracy and reliability of the underlying vehicle navigation solution.

Nav Solution Validation

LIDAR has proven to be a very useful tool for validating and correcting errors in the GPS/INS navigation trajectory. Integrated LIDAR measurements act as a very long lever arm that has the effect of magnifying any errors or inconsistencies in the navigation solution. Moreover, the LIDAR measurements give a system operator the ability to directly relate the vehicle trajectory to fixed features on the ground.

In turn, tying a series of positions to real-world features allows a comparison of the navigation solution at different time epochs when the trajectories overlap. It also provides the opportunity to compare the navigation solution to known ground control of higher accuracy and thus enables an independent external check of the navigation solution.

The TITAN system uses the LIDAR data extensively to validate the final integrated GPS/INS solution. To illustrate that, let's look at a couple of examples in which laser data helped isolate GPS errors that had not been detected and removed by the CAPTIN postprocessing software.

In the first case, a poor satellite observation was identified by looking at the overlap between two TITAN lasers. In the second case, we used overlapping multiple passes across the same section of roadway to isolate the source of a constant bias in one of the passes.

The current configuration of TITAN has two forward-looking and two rear-looking lasers. The mounting of these lasers is such that a slight area of overlap exists between the forward-pointing and rear-pointing laser swaths. As a result, the forward and rear LIDAR pairs will both observe objects in this area of overlap, but with a slight time difference. Therefore, any short term deviations in the navigation trajectory (i.e due to

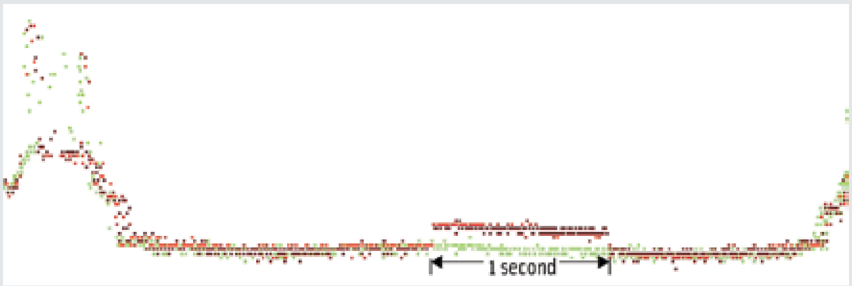


FIGURE 2 Short-duration difference in overlapping lasers (profile view: green – forward look; red – rear look), 10x vertical exaggeration

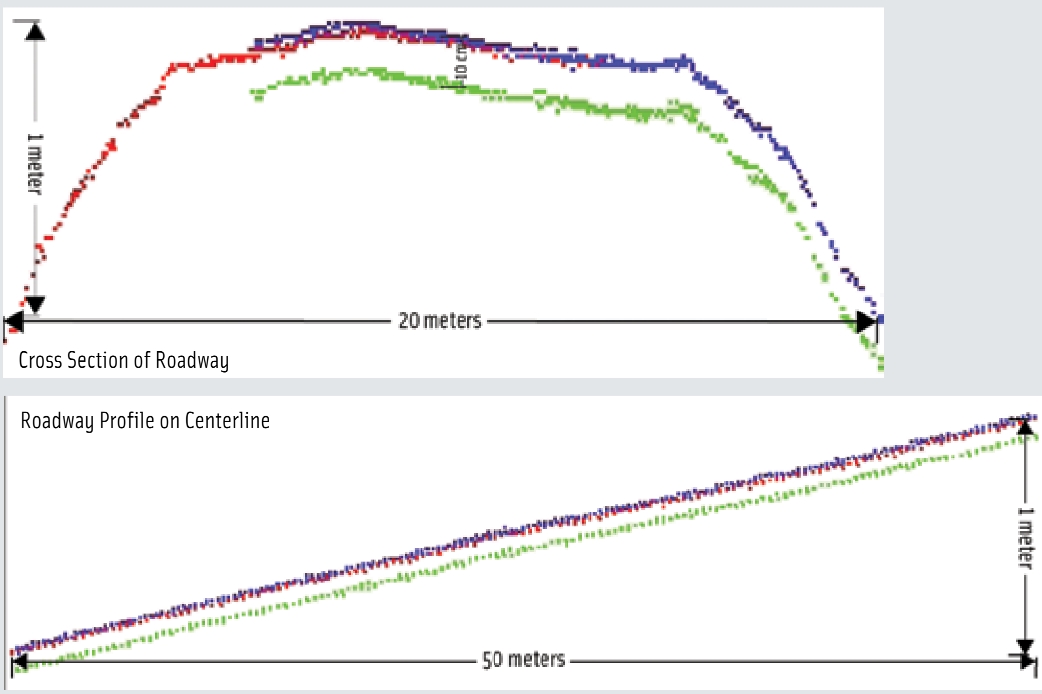


FIGURE 3 Observed vertical bias between three separate passes (red, green, blue) of TITAN on roadway, 10x vertical exaggeration

cycle slips or bad observations) may be observed as differences between the forward and rear laser point clouds.

Figure 2 illustrates this point by displaying a profile view of a one-second period when the forward and rear LIDAR point clouds do not agree. (Note that the vertical component of the graph is exaggerated to highlight the offset.) The jump in the red (rear looking) laser for this time period is approximately eight centimeters.

Analysis of the GPS data identified a satellite that was visible for only one epoch or position fix that was corrupting the position solution. The satellite signal produced inaccurate range and phase measurements and therefore "biased" the GPS position solution for the epoch it was visible. Rejection of the satellite for this epoch removed the sudden step in the data.

The standard operating procedure when performing a highway survey is for the TITAN operators to drive roadways of interest multiple times, often in different lanes and different directions. The multiple passes with the system in all travel lanes ensures that data coverage for the entire roadway is uniform.

A side benefit of this procedure arises from the redundancy in the passes that provides an opportunity to look at the repeatability of the data and examine areas of disagreement between passes to isolate and fix any problems with the navigation solution. **Figure 3** shows an example of a roadway that was driven three times.

Examination of Figure 3 clearly shows that the data in the green pass along the roadway is offset from the other two passes by almost 10 centimeters. Because the red and blue passes have very good agreement (less than two-centimeter RMS difference), the likelihood of a bias in the green pass seems fairly evident.

For this particular mission, each transit along the project roadway was followed by a route under several overpasses and through heavily vegetated areas. In the latter areas, fewer than four satellites were available during periods of almost two minutes, with several epochs having no GPS data at all. On the green run, after the urban canyon, the integer ambiguities were incorrectly resolved, and producing an erroneous position solution. A simple extension of the ambiguity search time window for the green run removed the bias in the navigation solution and resulted in the green pass agreeing with the other two passes at the two-centimeter level.

Expected TITAN Performance

The accuracy requirements for a kinematic terrestrial LIDAR system are quite stringent because in a majority of applications the system will be competing against traditional survey techniques (GPS, total station) and/or static tripod mounting scanners. Therefore, before final assembly of the system, a detailed error analysis was undertaken in order to characterize the system error budget, along with the contributions of individual system components to this overall error budget.

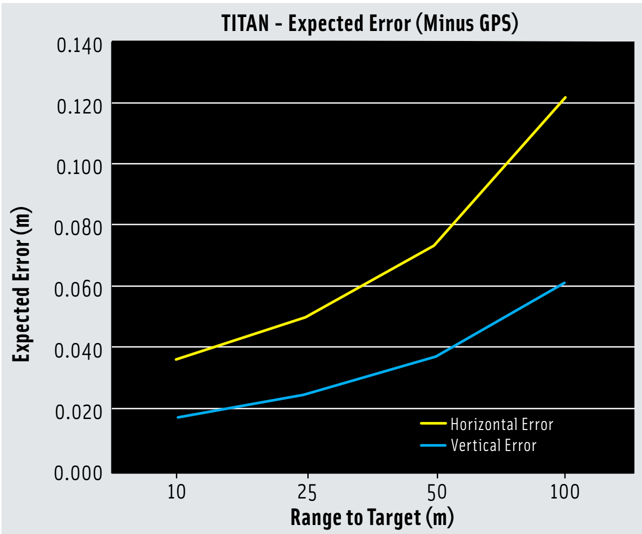


FIGURE 4 TITAN, Expected Accuracy

Details of this error analysis for TITAN, and airborne LIDAR systems can be found in the author's paper in the *Journal of Applied Geodesy* cited in the Additional Resources section at the end of this article. As discussed in greater details in the papers by C. Glennie and K. W. Morin cited in the Additional Resource section, the basic formula for calculating this error is:

$$\begin{bmatrix}\delta X\\ \delta Y\\ \delta Z\end{bmatrix}_G^l = \begin{bmatrix}\delta X\\ \delta Y\\ \delta Z\end{bmatrix}_{GPS}^l + J\begin{bmatrix}\delta\omega\\ \delta\varphi\\ \delta\kappa\end{bmatrix} + K\begin{bmatrix}\delta d\omega\\ \delta d\varphi\\ \delta d\kappa\end{bmatrix} + B\begin{bmatrix}\delta\alpha\\ \delta d\end{bmatrix} + C\begin{bmatrix}\delta l_x\\ \delta l_y\\ \delta l_z\end{bmatrix}$$

The matrices, J, K, B, and C are the so-called Jacobians of the transformation, and are defined as:

$$J = \begin{bmatrix}\frac{\delta p_G^l}{\delta\omega} & \frac{\delta p_G^l}{\delta\varphi} & \frac{\delta p_G^l}{\delta\kappa}\end{bmatrix}, K = \begin{bmatrix}\frac{\delta p_G^l}{\delta d\omega} & \frac{\delta p_G^l}{\delta d\varphi} & \frac{\delta p_G^l}{\delta d\kappa}\end{bmatrix}, B = \begin{bmatrix}\frac{\delta p_G^l}{\delta\alpha} & \frac{\delta p_G^l}{\delta d}\end{bmatrix},$$

$$C = \begin{bmatrix}\frac{\delta p_G^l}{\delta l_x} & \frac{\delta p_G^l}{\delta l_y} & \frac{\delta p_G^l}{\delta l_z}\end{bmatrix}$$

The results of the analysis are displayed graphically in Figures 4 and 5. **Figure 4** shows expected horizontal and vertical accuracy of TITAN as a function of range to target. **Figure 5** details the contribution to TITAN's overall error budget from each individual system component or unknown parameter set.

We should note that both Figures 4 and 5 do not attempt to quantify the total absolute positioning error of the system. Specifically, that portion contributed by GPS has been disregarded. This is deliberate, as positioning errors are normally specific to a survey site and depend upon multiple factors that can degrade the GPS solution, such as baseline length, atmospheric activity,

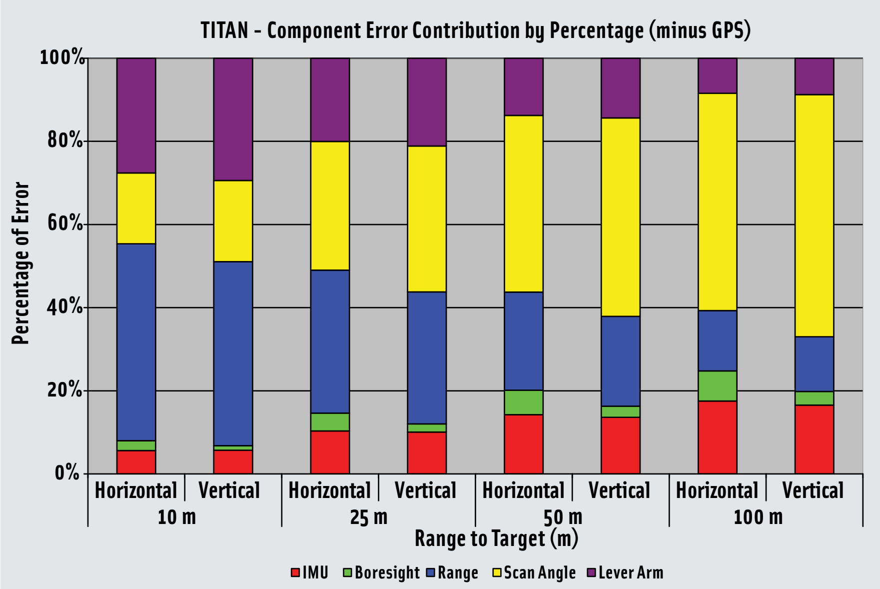


FIGURE 5 TITAN Component Error Contribution by Percentage of Total (from paper by C. Glennie cited in Additional Resources)

line of sight obstructions (e.g., vegetation and buildings), multipath, and satellite geometry.

As a result of such extrinsic variables, positioning errors for the system are difficult to quantify and do not lend themselves easily to estimation using a generic error model. However, at best, relative kinematic DGPS/INS positioning reaches the level of 2cm + 1ppm; so, this figure could be used to predict optimum system performance at particular project locations.

In practice, when system performance for a specific mission is independently determined (for example, by comparing the LIDAR to dense GPS/total station ground control), we can compare it to expected system accuracy by using the postprocessed estimate of position accuracy that is available from TITAN's GPS/INS Kalman filter. As a side benefit, the GPS/INS Kalman filter can also be tuned by matching expected mission accuracy with the actual accuracy results obtained by comparison of the LIDAR data to existing ground control.

The results illustrated in Figure 5 suggest that, with an optimum GPS/INS solution (that is, 2cm + 1ppm), vertical accuracy produced by the system should be at the 3- to 4-centimeter level; horizontal accuracy should be less than 6 centimeters for the shorter ranges (< 25 meters) to target typically observed in TITAN surveys.

By examining Figure 5, we can clearly see that the majority (>50 percent, not including absolute positioning error) of the current system error results from ranging and pointing errors from the laser scanner assembly itself. Therefore, improvements in system performance can most easily be realized by upgrading the laser scanner sub-assembly.

Observed System Performance

In order to validate the expected system accuracy model outlined previously and to provide an independent assessment of TITAN's achievable accuracy, the following section examines observed performance in three different ways: by analyzing repeatability of results between data collections, by examining residuals from a system boresight adjustment, and by comparisons of TITAN data with dense GPS/total station ground control. We will then compare the results from these analyses with expected system performance to further validate the expected accuracy model and to provide a firm basis for expectations about actual system performance.

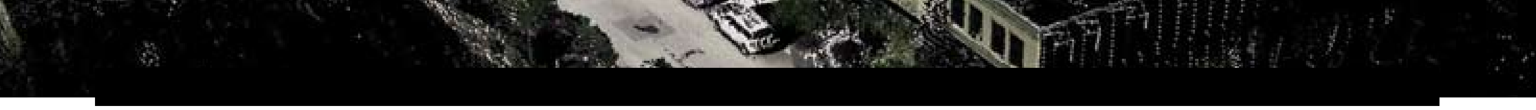
To evaluate measurement repeatability, we examined two separate TITAN missions along different sections of roadway. For each mission, the road was driven multiple times (in the same and opposing directions), which allows multiple comparisons between different passes. Roadway profiles at a common location were generated from the point cloud for each separate pass to produce an estimate of repeatability.

These profiles were each 300 meters in length. Given that the truck carrying the TITAN system was traveling at approximately 75 km/h during data collection, the analysis compares approximately 15 seconds of data collection from each pass and highlights the differences among the multiple roadway profiles. This process was repeated 7 times for each mission in order to generate 14 separate comparisons. **Table 1** presents the results of each vertical comparison.

Note that, for both missions discussed here, significant periods of time occurred during which the number of available satellites was less than four due to obstructions such as overpasses and vegetation. However, despite the significant degradation of GPS, the results displayed in Table 1 are very encouraging and, in fact, better than the a priori expected system performance.

Even more encouraging is that, in most cases, the largest portion of the RMS difference in Table 1 results from a small bias in the navigation solution between passes, which probably represents the noise level of the GPS/INS system. The actual standard deviation of the differences is nearer to one centimeter. This would suggest that the additional information obtained from overlapping passes could be used to eliminate the bias and reduce the overall RMSE of the TITAN point clouds.

Our second method for assessing the system's actual performance involves a process known as boresighting, which calculates the differences between reference frames of a LIDAR sensor. The laser scanners and IMU of a LIDAR sensor are always mounted on a plate that rigidly fixes their relative locations with respect to each other. However, initially, the position and orientation differences between the IMU frame and laser scanner frames are unknown (or known only



approximately), and their precise values must be derived.

The process of determining the values of these differences is called boresighting, which is normally performed using a least squares adjustment that generates residual misclosure values. Various formulations for the boresighting adjustment are possible, and readers are referred to the articles by K. W. Morin and J. Skaloud and D. Lichti listed in Additional Resources for a detailed discussion of the subject.

Essentially, the boresighting of TITAN is done in a similar manner as the airborne case, with the added complexity that the boresight values for four lasers (instead of one in the airborne system) must be solved for simultaneously. After adjustment, if we assume that all systematic errors sources have been accounted for in the measurement processing and modeling, the measurement residuals should give a good indication of the overall system accuracy.

Figure 6 represents a histogram of the measurement residuals for a typical boresight adjustment of TITAN. The data for this adjustment was collected in two sessions on two different days and involved passes of the system along a series of intersecting roads in opposing directions.

GPS coverage for the boresight tests was good (nominally observables from six space vehicles or SVs are available for position solutions, and only short outages of less than 10 seconds when fewer than four SVs were available). Consequently,the estimated positional accuracy of the GPS/INS solution was at the 3- to 4-centimeter level (all three components) for the majority of both missions. Ranges to target in the observations were from 3 to 35 meters.

The residuals in Figure 6 are centered on zero (i.e., unbiased) and have an approximately normal distribution. This is a good indication that no significant parameters were missing from the measurement modeling or boresight adjustment. Therefore, the residuals should offer a good indication of the expected

Profile #	RMS	Mean	σ
1	0.013	0.007	0.011
2	0.015	0.012	0.009
3	0.015	0.005	0.014
4	0.020	0.019	0.008
5	0.012	0.008	0.008
6	0.009	-0.003	0.009
7	0.038	-0.037	0.008
8	0.020	-0.018	0.008
9	0.015	-0.013	0.008
10	0.046	-0.045	0.008
11	0.009	-0.004	0.008
12	0.008	0.002	0.008
13	0.019	-0.007	0.017
14	0.012	0.010	0.008
Overall	0.018	-0.005	0.009

TABLE 1. Vertical repeatability: comparison of profiles between two TITAN passes (all values in meters)

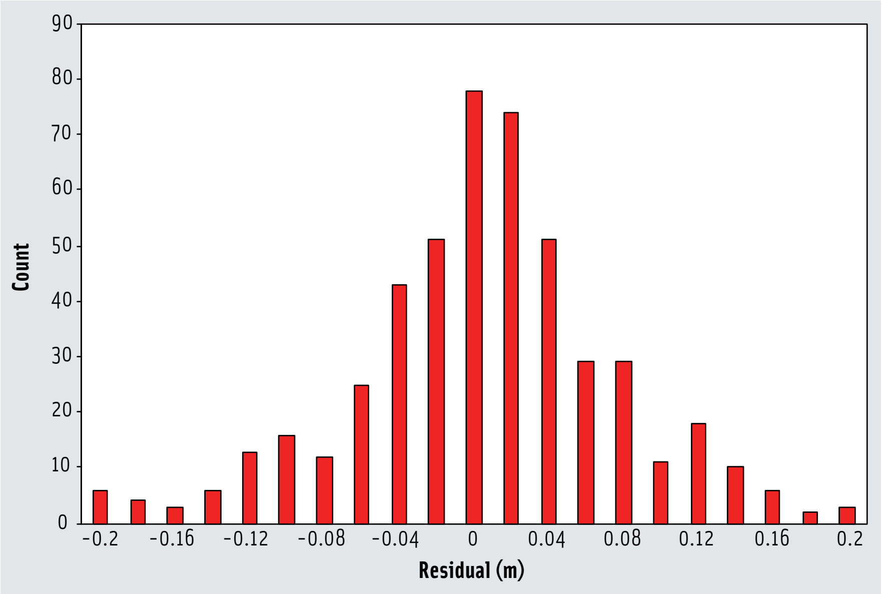


FIGURE 6 Least Squares Boresight of TITAN, Residuals

system noise level. **Table 2** presents the statistics on the adjustment residuals.

Once again, considering the Kalman filter estimated positional accuracy of four centimeters, the results in Table 2 appear to be slightly better than the expected system performance.

Finally, as an independent means of determining TITAN accuracy, a dense network of ground survey points were collected and postprocessed using differential GPS, dual-frequency GPS receivers, and a total station with integrated GPS. After adjustment, the observed survey points were shown to have an estimated accuracy (horizontally and vertically) of approximately five millimeters, which is much better than the expected

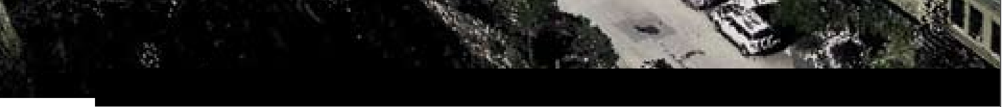
	Horizontal	Vertical
# of Obs	85	101
RMSE	4.1cm	2.8cm

TABLE 3. Comparison of LIDAR system and GPS/total station ground survey

TITAN performance and thus should provide the basis for a good independent basis for accuracy determination.

Ground survey features, such as paint markings, curb lines, guardrails and traffic signs, were then chosen that could be easily identifiable in the LIDAR point cloud. An operator digitized each individual survey feature in the point cloud, and the digitized location was then compared to the actual ground survey location. The results are displayed in **Table 3**.

Overall, the comparison results are quite encouraging, and yet again are slightly better than the a priori expected system accuracy. We should note that the TITAN data collection over the ground survey point location had a very solid GPS/INS solution (always more than six SVs), with a Kalman filter estimated position accuracy of two centimeters for most of the mission. In



(meters)	Easting	Northing	Horizontal	Elevation
Mean	0.004	0.003	0.005	0.005
RMSE	0.049	0.051	0.071	0.036

TABLE 2. Residual statistics from TITAN boresight adjustment

addition, the range to target for all point cloud features was less than 10 meters. So, the results in Table 3 should reflect the expected performance of TITAN under ideal observational conditions.

Conclusions & Future Work

Our discussion of Terrapoint's TITAN system has sought to demonstrate the robust benefit of using LIDAR observations to validate navigation trajectories. Overall, the observed system performance to date has been better than expected. This may indicate that our modeling of the laser scanner for the expected system accuracy derivation was overly pessimistic, resulting in a conservative estimate of achievable system accuracy. We need to investigate and validate this possibility further.

Currently, the analysis of the LIDAR data to validate the GPS/INS trajectory is mostly a manual process. Future work will focus on automating the improvement of the navigation trajectory by using the geometric information obtained in overlapping LIDAR point clouds.

Acknowledgments

The author would like to thank Roger Shreenan for collecting the ground-truth data and Alan Dodson for digitizing the ground survey points from the LIDAR point cloud. This article is based in large part on a paper presented at the ION GNSS 2007 conference. I thank Kresimir Kusevic and Stephen Griffiths for reading and providing constructive criticism of an earlier version of this paper.

Manufacturers

The TITAN system incorporates an IMAR Navigation GPS/INS system, **IMAR Navigation**, St. Ingbert, Germany. The IMAR system uses the OEM-4 receiver from **NovAtel, Inc.**, Calgary, Alberta, Canada, as its GPS engine. Terrapoint has plans to incorporate the new Novatel OEM5 into the unit to provide GLONASS capability as well. Terrapoint's original terrestrial LIDAR system used NovAtel's Black Diamond System from Novatel and an HG1700 tactical grade IMU from **Honeywell Space & Defense Electronic Systems**, Clearwater, Florida USA. TITAN has been designed to incorporate multiple types of laser scanners, but the data collected and discussed in this article and shown in examples was collected using **Riegl Laser Scanners**, Orlando, Florida, USA. The network of ground survey points used in the performance analysis of TITAN were collected using GSR2600 receiver from **Sokkia Corporation**, Olathe, Kansas, USA, and a SmartStation from **Leica GeoSystems**, Heerbrugg, Switzerland.

Additional Resources

[1] Glennie, C., *Rigorous 3D Error Analysis of Kinematic Scanning LIDAR Systems*, Journal of Applied Geodesy, Vol. 1, 2007, pp. 147-157

[2] Glennie, C., Kusevic, K., and P. Mrstik, *Performance Analysis of a Kinematic Terrestrial Lidar Scanning System*, MAPPS/ASPRS Fall Conference, November 6-10, 2006, San Antonio, Texas

[3] Morin, K.W., *Calibration of Airborne Laser Scanners*, Masters Thesis, The University of Calgary, UCGE Report #20179 (Available at <http://www.geomatics.ucalgary.ca/research/publications/GradTheses.html>.

[4] Newby, S., and P. Mrstik, *Lidar on the Level in Afghanistan*, GPS World, Vol. 16 Number 7, 2005, pp. 16-22

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