APPLICATION NOTE

LIDAR MAPPING

LIDAR-Based Mobile Survey

VECTORNAV

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Abstract Surveying and mapping is required for a variety of applications, including agriculture, construction and GIS. Historically, surveying required usage of fixed ground stations and manual relocation of measurement targets. By utilizing techniques such as LIDAR for mobile surveying, mapping can be done quicker and more efficiently. This note goes through the advantages of LIDAR over other surveying methods, the practical implementation of using LIDAR for surveying, and the impact of GNSS/INS precision on LIDAR accuracy.

1 INTRODUCTION

Light Detection and Ranging (LIDAR) is a measurement technique that uses light emitted from a sensor to measure its range to reflective objects. LIDAR sensors typically scan an area while taking tens or hundreds of thousands of measurements per second, providing the capability to digitize an entire scene almost instantly. While this sensor technology is becoming ubiquitous through advances in automated vehicles (ie. self-driving cars), LIDAR sensors are incredible tools for surveying in applications from construction to agriculture.

By combining LIDAR with high accuracy GNSS/INS technology, range data can be coupled to pose data, creating a mobile LIDAR solution that produces georeferenced maps with dense and accurate point clouds of an environment or scene. Engineers are attracted to saving time and costs with aerial and land-based LIDAR solutions, because they can measure projects faster and more effectively than ever before while giving stakeholders vital decision-making information.

This application note highlights the advantages of using LIDAR sensors for mapping applications by comparing them to conventional measurement technologies. Later sections walk through the components and processes required to complete a LIDAR-based survey and generate actionable information, with a focus on the GNSS/INS contribution. Please contact VectorNav for a more in-depth discussion of your particular application and the impacts of various design choices.

1.1 Alternative Surveying Techniques

To better understand the advantages of mobile LIDAR solutions, its alternatives should be considered. Traditional tools for precise terrain mapping include GNSS Surveying, Laser Scanners, Photogrammetry, and Total Stations, as discussed here and diagrammed in Figure 1.

GNSS Surveying

Terrain mapping can be accomplished with a pair of GNSS receivers: (a) the base receiver mounted to a tripod and located at a known reference position, and (b) the rover receiver on a monopod that is manually relocated to the desired measurement points. This method takes a long time and produces a minimum set of data.

Static Laser Scanning

Another technique in surveying and modeling is laser scanning, where operators set up a scanning laser over a known reference position, and use additional references in the sensor's field of view to produce a referenced point cloud. This method produces dense data points, but is limited to line-of-sight and is time-consuming to reposition when scanning large areas.

Total Station Surveying

Total Stations can also be used in surveying. These systems rely on optical instruments, a theodolite placed over a known location, and a reflective prism that is transported by an operator to measure points of interest, as in GNSS Surveying. Like laser scanners, Total Stations are limited to line-of-sight.

Aerial Photogrammetry

Photogrammetry is a low cost, fast and efficient measurement technique using cameras. High definition point clouds are produced by photographing an area of interest with a single camera and stitching together the images in a post-processing step. More details can be found in Application Note AN206: Aerial Photogrammetry.

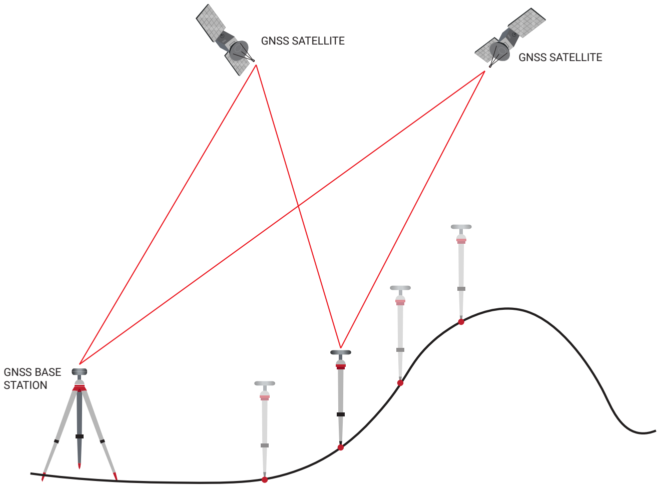
1.2 LIDAR Mapping Advantages

A significant benefit of mapping with mobile LIDAR technology is speed and efficiency: the sensor samples millions of points as it travels around the area of interest, as seen in Figure 3. Mobile LIDAR solutions can reduce a conventional GNSS mapping task from days to minutes and provide exceptional point density. These time savings in the field directly impact the amount of time it takes to make informed decisions during critical phases of a project. Since site surveys can be done quickly with mobile LIDAR versus traditional counterparts, site surveys would likely take place more often, in turn giving stakeholders more comfort and decision-making power.

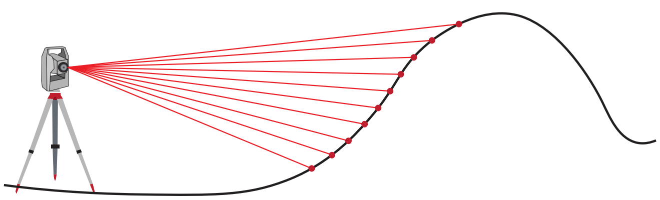
Compared to stationary laser or optical measurement techniques, a LIDAR solution with GNSS/INS produces point clouds that are referenced to the sensor's continuously varying pose; therefore, station setups are eliminated. Time savings are more apparent when an area of interest would require multiple relocations of the stationary sensors to overcome line-of-sight limitations.

Remote sensing also eliminates the need for a ground crew to travel over the terrain of interest, as is the

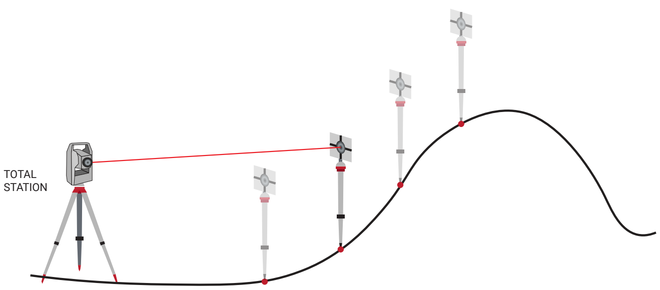
Alternate Surveying Techniques



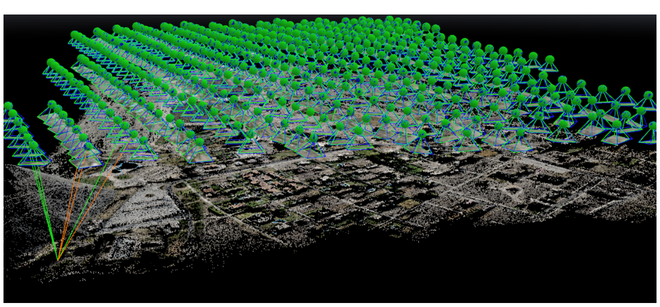
(a) GNSS Surveying



(b) Static Laser Scanning



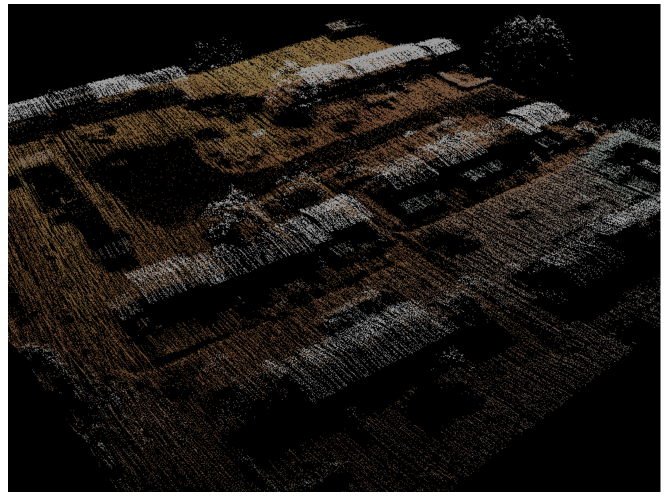
(c) Total Station Surveying



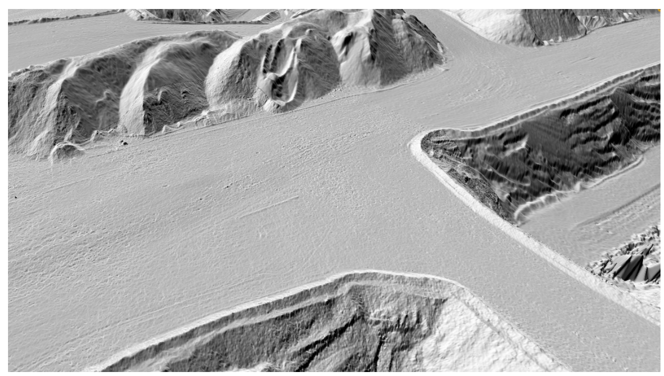
(d) Aerial Photogrammetry

FIGURE 1

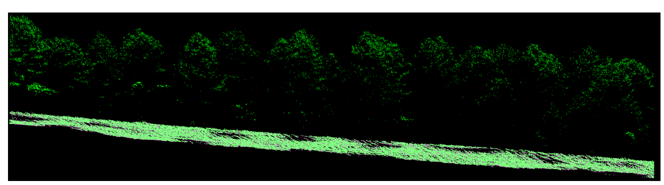
Example Applications



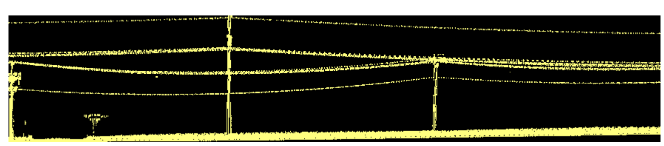
(a) Construction



(b) Surface Mining



(c) Siviculture



(d) Infrastructure Inspection

FIGURE 2

Mobile LIDAR Survey

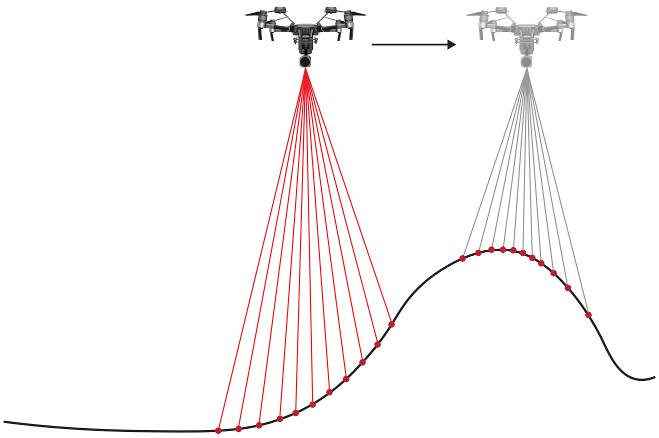


FIGURE 3

case with manual surveying techniques. Fluid environments such as earthworks frequently place operators near steep gradients and heavy machinery. As a result, operators must adhere to strict safety protocols. The remote sensing capability provided by LIDAR sensors with accurate GNSS/INS benefit operators by removing them from danger, adding to their safety and efficiency.

While photogrammetry techniques offer a fast and efficient remote sensing capability, LIDAR functions independently of lighting conditions, making the technology applicable regardless of visibility and lighting conditions. And while photogrammetry suffers in areas with vegetation, LIDAR light pulses penetrate through gaps in the foliage and provide multiple measurement returns - one of the foliage and another of the ground below. The direct measurement nature of a LIDAR system means there is no need for triangulation of sensor positions, a necessary calculation in photogrammetry, which increases reliance on post-processing software.

1.3 Example Applications

Ideal applications for LIDAR mapping involve those that require, or benefit from, a wide-area 3D survey. Some of the more common include construction, surface mining, siviculture, and infrastructure inspection, as discussed here and shown in Figure 2.

Construction

Many new construction projects begin in a software application, often with a 3D CAD modeling tool. Georeferenced LIDAR data comes into play at a design's planning phase, when a base map or surface is required to begin drawing and budgeting the work ahead. As earthwork or construction progresses into the execution phase, LIDAR solutions continually provide engineers with updates of the project, which can be used to anticipate problems and make design changes. This type of data, used in Building Information Management (BIM), is critical to maintaining schedules, speeding up time to completion, and ensuring a low deviation from design.

Surface Mining

Surface mining operations require constant terrain measurements, earthmovers are regularly changing the landscape, and engineers need a closed feedback loop to understand how work is progressing. During extraction, stockpile volumes, gradients, and fill volumes need to be known for inventory, safety, and business decisions. During reclamation, engineers need to return the land to its original condition, requiring measurements to verify the work done. The efficiency of a LIDAR solution brings obvious value to this vast area, high measurement rate application.

Siviculture

The fast and safe characteristics of LIDAR solutions mapping apply to silviculture, where controlling the establishment, growth, and health of forests is the ultimate goal. The ability for LIDAR signals to penetrate gaps in foliage enables the detection of competing vegetation and provides location data of each canopy and the terrain. Terrain and canopy data can be used to learn stocking levels (trees per acre), and stand volumes so stockholders can make necessary business and treatment decisions. Traditional measurement techniques often rely on sample measurements that are extrapolated to include an entire forest, a less-informed and riskier approach.

Infrastructure Inspection

A mobile georeferenced LIDAR solution enables engineers to maintain a project after completion. Utility lines, for example, require constant monitoring over large areas to anticipate failures and keep the right of way clear, and cannot be reliably tracked via photogrammetry or other survey techniques. Using LIDAR to monitor similar sites also provides historical snapshots that can be used to analyze changes over time and paint a clear picture of future needs.

2 GEOREFERENCING A POINT CLOUD

In order to create a point cloud, individual points from multiple scans taken at different locations and orientations have to be referenced to the same reference frame. Utilizing combined GNSS/INS allows for the points in the point cloud to be georeferenced to a fixed global reference frame. Once each point is georeferenced, a point cloud can easily be created. The basis of georeferencing an individual point lies in the georeferencing equation (Eq. 1), which can be used to solve for the absolute position on ground ($\boldsymbol{p}_g$) of the point.

$$\boldsymbol{p}_g = \boldsymbol{p}_a + [C]\boldsymbol{\rho} \tag{1}$$

Where $\boldsymbol{p}_a$ is the estimated position vector of the LIDAR sensor, $[C]$ is the estimated direction cosine matrix mapping from the LIDAR to an inertial coordinate frame and ρ is the LIDAR measurement vector.

The estimated LIDAR position vector ($\boldsymbol{p}_a$) comes directly from the GNSS/INS system and is subject to both GNSS position errors and timing errors between systems. The coordinate frame transform between the LIDAR reference frame and an inertial coordinate frame (eg. NED) comes from the attitude measured by the GNSS/INS. Errors in $[C]$ come primarily from sensor attitude misalignments, GNSS/INS attitude uncertainty, and timing errors between sensors.

The LIDAR feature vector (ρ) is defined in Eq. 2, where the (x, y) come from the attitude of the point in relation to the LIDAR and z comes from the LIDAR range measurement. Errors in ρ are created directly by errors in the LIDAR sensor.

$$\boldsymbol{\rho} = [x \quad y \quad z]^{\intercal} \tag{2}$$

2.1 Position Errors

Position errors come from the uncertainty in position of the GNSS/INS sensor. This position uncertainty is represented in an inertial North, East, Down (NED) coordinate frame. The position uncertainty of a GNSS/INS is mostly determined by the accuracy of the GNSS solution alone, and due to the nature of GNSS, typically has double the uncertainty vertically as horizontally.

Standard, single-frequency GNSS can provide a position estimate with around 2 m horizontal uncertainties, which does not offer the precision needed for LIDAR surveying. However, errors can be reduced substantially by using real-time kinematic (RTK) or post-processed kinematic (PPK) techniques on a multi-frequency GNSS receiver, which yields uncertainties in the centimeter range. These require real-time corrections transmitted from an independent base station or time to post-process such corrections after logging considerable raw data from the GNSS, respectively. These two techniques are discussed in more detail in the next section.

2.2 Attitude Errors

Any angular uncertainty (σ_a) projects to a positional error ($\bar{\sigma}_a$) based on the distance from the point to the LIDAR sensor (d). This distance can come straight from LIDAR range measurement.

$$\bar{\sigma}_a = d\frac{\sigma_a \pi}{180}[m] \tag{3}$$

A system designer typically must decide between two different INS performance grades that will impact the attitude uncertainty error contribution: industrial grade and tactical grade. When evaluating the grade of sensor needed it is important to not only consider the final precision needed, but also the distance between the sensor and the target. Representative performance values for each can be found in Table 1.

INS Attitude Error Values

ERROR SOURCE	INDUSTRIAL	TACTICAL
Yaw (σ_ψ)	0.3°	0.1°
Pitch (σ_θ)	0.1°	0.03°
Roll (σ_ϕ)	0.1°	0.03°

TABLE 1

Since a LIDAR solution would be in motion, consider the vehicle dynamics to determine if a dual antenna or single antenna GNSS/INS would suffice for heading determination. Typically ground-based vehicles do not have sufficient motion that is required to sustain dynamic alignment in a single-antenna GNSS/INS. In contrast aerial vehicles can often provide the dynamics for a single antenna configuration.

2.3 Aligning LIDAR to GNSS/INS

When assembling the critical components of a LIDAR solution, a clear understanding of the physical locations of each part - the LIDAR sensor's reference point with respect to the GNSS antenna and the INS - is a must. This information is critical in referencing each range measurement from the LIDAR sensor, and is typically derived from mechanical drawings and specifications provided by the sensor manufacturers.

Angular misalignments are introduced through manufacturing tolerances at the level of the INS, the LIDAR, and the interface between the two. When performance matters, they are typically calibrated on a part-by-part basis after gimbal assembly. Without calibration, these errors are often similar in magnitude to the attitude errors from a GNSS/INS. Contact VectorNav for tools and techniques to perform this calibration.

A mapping LIDAR design must incorporate a mechanism to synchronize each range measurement to the GNSS/INS provided pose data. To simplify this task, most LIDAR manufacturers design sensors with the capability to receive a time synchronization pulse from the GNSS/INS, along with GNSS time data via standard NMEA messaging.

3 PRECISE POSITIONING

As mentioned earlier, achieving centimeter-level positioning typically relies on one of two techniques: (a) Post-Processed Kinematic (PPK) GNSS positioning (offline), or (b) Real-Time Kinematic (RTK) GNSS positioning (online).

3.1 Post-Processed Kinematic (PPK)

Since a real-time point cloud is not critical in most mapping and monitoring applications, a typical LIDAR solution is configured to produce an accurate point cloud offline using PPK techniques. The offline approach simplifies the operation of the sensor, as seen in Figure 4, and improves the accuracy of the measurements.

Without the requirement to have a real-time link with the sensor, the operator is not constrained to communication limits between a GNSS base station and the LIDAR solution. The LIDAR's position can be determined in post-process using stored data from remote or local base stations.

Remote base stations like Continuously Operating Reference Stations (CORS) and virtual reference stations (VRS), facilitate the operator's workflow. CORS are permanently set up at known locations and monitored for accuracy and function, since their data is typically available for download, a user does not have to concern himself with the base station set up during his mission.

The highest positioning accuracy can be reached when post-processing GNSS and INS data by using precise satellite ephemeris data, which is not available in real-time. Forward and backward smoothing techniques can also be applied to improve the solution. Furthermore, without onboard computations to georeference a point cloud online, compact and low power hardware can be selected to record LIDAR sensor and GNSS/INS data. The post-processed approach reduces the size, weight, and power of the overall solution, which is especially critical in airborne applications.

PPK Diagram

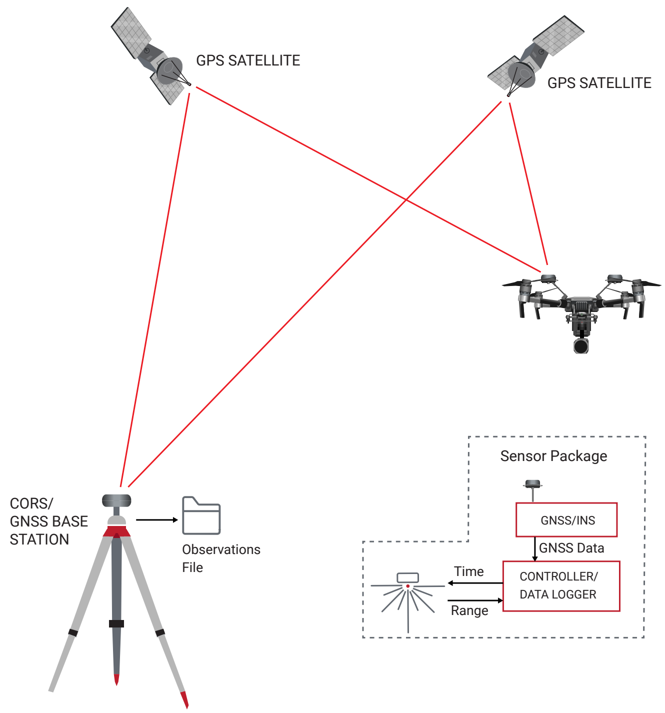


FIGURE 4

3.2 Real-Time Kinematic (RTK)

It may be necessary to produce a point cloud in real-time, for example, to immediately ensure that the device is capturing the required data or to make immediate decisions based on current observations.

Configurations that require results without delay or minimal post-processing need to use RTK GNSS technology. Contrasting with the PPK solution, an RTK solution needs a robust link between a GNSS base station and the mobile GNSS/INS in addition to the computational capability to reference each measurement from GNSS/INS data, as seen in Figure 5. The operator must have access to a correctly set GNSS base station with a radio link to the mobile GNSS/INS. However, the post-processing workflow is simplified as the point cloud is generated in real-time.

RTK Diagram

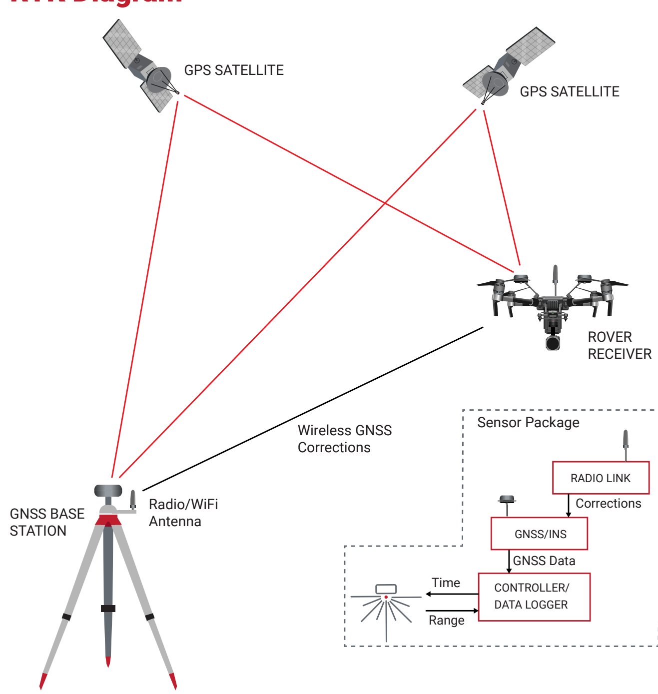


FIGURE 5

4 PROCESSING POINT CLOUDS

Regardless of whether an online or offline approach is selected, the raw LIDAR data must be processed to produce a meaningful georeferenced point cloud. The post-processing step takes a sequence of timestamped ranges produced by LIDAR and correlates each point with timestamped pose data obtained from the GNSS/INS. Mapping the LIDAR measurements to a global reference frame yields the desired point cloud. This process is shown in Figure 6.

While 3D point clouds are the end products of a LIDAR solution, this data is typically the starting point for generating actionable insights. LIDAR point clouds are typically imported into CAD packages to provide surface or model data. Engineers can then use their digital toolsets to measure volumes or distances and find differences in the measured environment.

For some data sets, it may be necessary to apply software tools that classify or filter point cloud data. For the most demanding applications, it may be necessary to apply software tools that improve the accuracy and quality of the point cloud. These tools are designed to calculate correction values for misalignment angles as well as location errors. Intermediate software packages can also be applied to simplify point clouds into line or surface drawings for compatibility with traditional CAD software. Figure 7 shows an example of a surface mesh generated from a LIDAR point cloud.

LIDAR Workflow

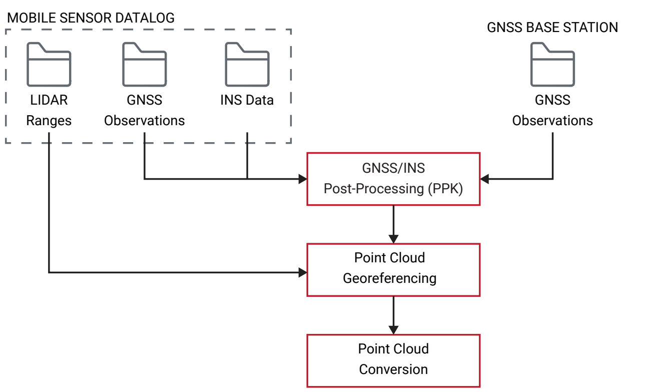


FIGURE 6

5 CONCLUSION

Traditional surveying techniques simply cannot match the efficiency and resolution of mobile LIDAR mapping. As comfort with the technology grows, engineers across a wide range of disciplines increasingly rely on the detailed 3D models that a LIDAR-based survey can produce.

LIDAR mapping solutions rely on accurate range measurements from a LIDAR sensor coupled with accurate pose information from a GNSS/INS. Depending on the measurement range, either an industrial-grade or tactical-grade INS may be used to provide attitude, while positioning requires RTK or PPK GNSS solutions. Integrators must carefully design the pairing of the two sensors to minimize misalignments in position, orientation, and timing.

Surface Model of Valley

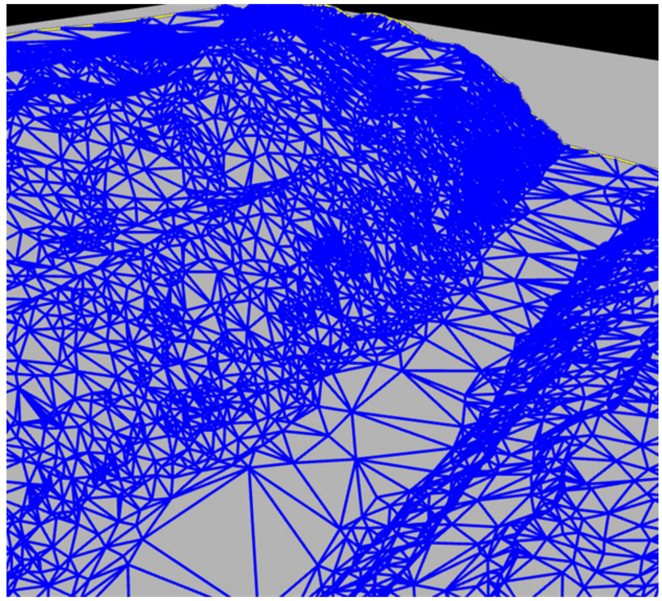


FIGURE 7

To turn the raw data into actionable information, post-processing involves (a) performing PPK techniques on the GNSS data, followed by (b) georeferencing the LIDAR measurements using time-aligned pose data, and then (c) performing smoothing operations on the resulting point cloud to generate a high-fidelity model that can be used by other software packages.

When carefully integrated, LIDAR sensors and high accuracy GNSS/INS sensors combine to perform a powerful mapping tool that beats traditional techniques in speed, safety, and accuracy. Please contact VectorNav for a more in-depth discussion of your particular application and recommendations on how to achieve your desired results.

VectorNav Technologies, LLC
10501 Markison Rd
Dallas, TX 75238, USA

Tel: +1.512.772.3615
Email: sales@vectornav.com
Web: vectornav.com

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