Airborne LiDAR In-flight Accuracy Estimation

A flexible quality-monitoring tool that assesses data quality in-flight avoids costly problems that are currently detected only in post-processing.

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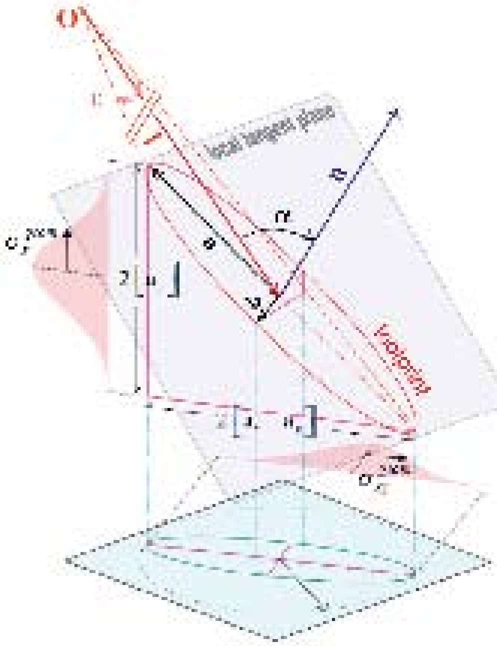


▲ **FIGURE 1** Decomposition of the 3D footprint into its vertical and horizontal error components

A key problem of today's airborne laser systems (ALS) is the lack of reliable data-quality assessment within or shortly after the airborne survey campaign. We have developed a new tool that enables complete data quality assessment directly on-the-fly. It requires real-time (RT) GPS/inertial navigation system (INS) processing and georeferencing of the laser returns, followed by the analysis of the trajectory integrity as well as the scanning precision and geometry.

A full ALS error-propagation engine forms the core of this monitoring tool, yielding the estimation of the expected point cloud accuracy in-flight. The error propagation considers the errors due to the direct georeferencing (DG), the measurement errors of the laser itself (ranging accuracy, encoder errors, and so on), and the variation of the range-finder error due to changing scanning geometry. Unlike the first two error sources, which can be assessed by propagation of the functional relations, the influence of scanning geometry is much harder to assess, as it requires prior knowledge of the local terrain and the footprint size. Here we present a methodology to estimate these parameters directly from the laser point-cloud and derive a final quality indicator reflecting the georeferencing quality and the scanning geometry. To predict the accuracy of the point cloud, the tool includes an algorithm predicting the likelihood of fixing the differential carrier-phase ambiguities in post-processing.

We discuss our strategy for data processing and communication to cope with constraints imposed by RT processing, and validate the predicted data quality and accuracy estimates by early tests.

During the last decade, ALS has become a well established and broadly used technology in the mapping industry. Performance in terms of pulse repetition rate, maximal ranging distance, and full-waveform digitizers of the commercially available ALS systems has improved at a rapid rate, hand-in-hand with reduced acquisition times and production costs. Surprisingly, the development of accompanying monitoring and processing software has not followed the same evolution. Today, it is still very difficult to avoid mission repetitions due to undetected sensor behavior and insufficient data quality, consistency, and coverage. In most cases such problems are detected only in post-processing (PP), in other words, long after the flight. Worse, some types of errors can only be quantified by independent and expensive ground-based surveys. This may cause quality control to assume an overwhelming part of the cost of the final mapping product. In addition, the need to invoke such control increases the time between data acquisition and product delivery to a client.

Conventional ALS error analysis considers the errors coming from DG, such as navigation errors and system calibration, and the measurement errors of the laser itself, such as range-finder and the encoder angle measurements. These errors can be estimated by means of error propagation via the known functional relation between all observations and the calculated coordinates. The impact of the incidence angle and the beam width is usually not considered, principally because of the difficulty in assessing the scanning geometry, which requires prior knowledge of the terrain slope and orientation. Our approach analyzes the scanning geometry quantitatively by estimating the incident angle directly

HELI-MAPPING UPDATE

This article describes new developments in an airborne mapping system described in the May 2006 issue, "**AN EYE FOR LANDSCAPES: RAPID AERIAL MAPPING WITH HANDHELD SENSORS**," by Jan Skaloud and co-authors. The portable system offers fast deployment with no recalibration and maps both vertical and horizontal features while maintaining optimal flight parameters. The geo-referenced image and 3D point-cloud data can be processed into digital terrain models, digital surface models, and automatically derived 3D city models. See *www.gpsworld.com/helimap.*

from the laser point-cloud, by approximating the local terrain normal trough eigenvalue decomposition of the covariance matrix obtained from neighboring points. This information provides the missing link to the subsequent computation of the 3D laser footprint. Thus, for every laser point, a final quality indicator can be computed that reflects not only the quality of georeferencing but also the scanning geometry.

To correctly predict the accuracy of the resulting point-cloud, some knowledge about the achievable carrier-phase differential GPS (CP-DGPS) positioning accuracy is crucial. **FIGURE 1** [illegible]vs that accuracy of the laser point-cloud gathered by ALS is largely related to the accuracy of the post-processed GPS solution.

Particularly in close-range surveys (range < 400 meters), the GPS error contributes more than half of the overall error budget. The GPS position used for georeferencing the point cloud is computed in PP. This implies that GPS epochs causing problems for correct ambiguity resolution are detected long after the flight. Our GPS data quality monitoring tool uses several indicators such as GPS constellation assessment, signal-to-noise ratio, cycle slip detection, or the phase tracking-loop performance. It focuses on the prediction of the likelihood to correctly resolve the ambiguities during CP-DGPS processing. The information can identify most problematic epochs within the flight and provides early warning to the mission operator about possible quality degradation.

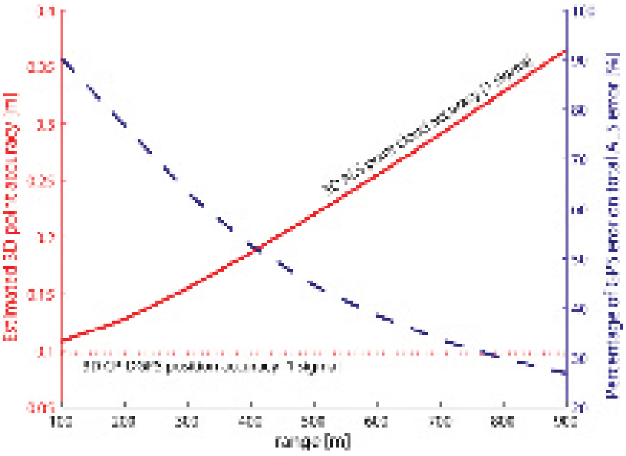
Point-Cloud Error Estimation

The calculation of ground coordinates *[x y z]*m [illegible]n ALS observations in classical error propagation is well documented. Coordinates on the ground can be calculated by combining information from the scanner, GPS/INS measurements, and calibration parameters.

Many factors unique to every ALS system can affect the accuracy of target coordinates. For the purpose of the RT error analysis, we assume that the system is calibrated and we restrict the internal ALS error sources to random errors in distance and encoder angles. Additionally, to achieve fast computations, our error model is simplified to 14 error states:

- 6 navigation errors: errors in the absolute positioning (σ_X, σ_Y, σ_Z) and orientation (σ_r, σ_p, σ_y). These errors can rapidly change over time due to changing GPS constellation and/or variable flight dynamics.
- 6 system calibration errors: remaining uncertainties in the boresight angles (σ_{ex}, σ_{ey}, σ_{ez}) and in the lever arm (σ_{ax}, σ_{ay}, σ_{az}). These components should change only with a change in system installation.
- 2 internal laser errors: range-finder error (σ_ρ + ppm) and the error of the encoder angle (σ_θ). These errors are supposed to be intrinsic to every ALS system and of constant magnitude.

Scanning Geometry Impact. To compute the incident angle and the footprint, we need prior knowledge of the terrain normal. Eigenvalue analysis of the covariance matrix of a local neighborhood is a very efficient method to estimate local surface properties such as the local terrain normal.



▲ **FIGURE 2** Estimated contribution of the CP-DGPS position error to the overall point cloud accuracy for a representative ALS system

Knowing the terrain normal *n* and the laser direction *l*, the incident angle α can be computed by

$$\alpha = \mathrm{acos}\left(\frac{\mathbf{l}\cdot\mathbf{n}}{|\mathbf{l}||\mathbf{n}|}\right)$$

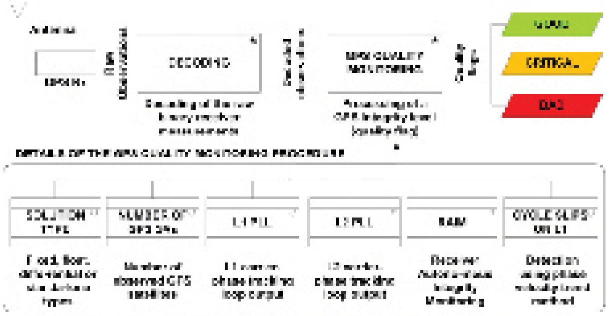
The footprint of a laser beam can be modeled as an ellipse formed by the intersection between a cone formed by origin *O*, laser direction *l* and beam divergence ε, and the local tangent plane with normal *n* (see **FIGURE 1**). From the footprint size and shape, we established the covariance degradation in range measurement. We validated this model empirically for the Scan2map system.

Global Quality Indicator. Once all components contributing to the ALS error budget are assessed, they can be regrouped into one unique quality attribute.

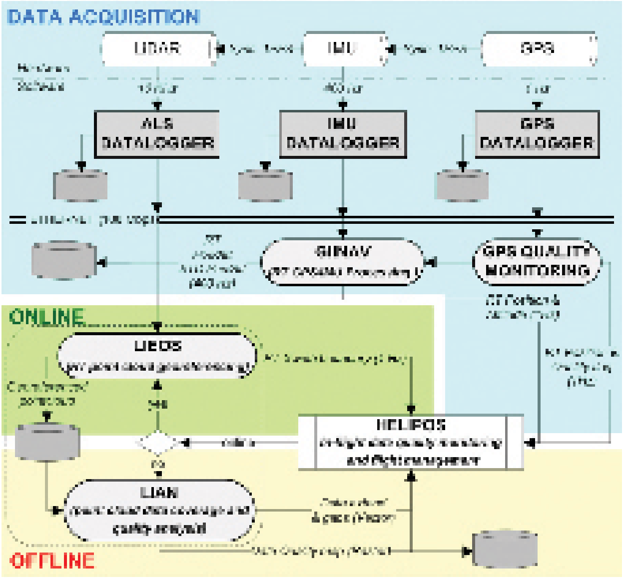
Obviously, the correct scanning geometry depends entirely on accurate estimation of the local terrain normal. Using the covariance method, this estimation is only reliable when a point neighborhood approximately forms a planar surface. Laser points lying for example on vegetation have no clear geometric structure, hence the derived normal is geometrically not interpretable. Thus we need to filter out such points, in this case by means of an automated ground-classification algorithm.

In the complete data workflow for the computation of a quality indicator map, the error propagation is carried out using the navigation data an their accuracy estimates. After the RT point cloud generation, we build up a *k-d* tree for spatial indexing.

Subsequently, the points not belonging to the terrain are removed. We then analyze the scanning geometry, using the estimated local terrain normal, the laser direction, and the beam divergence to compute the laser footprint in 3D. Finally we combine these data streams to one unique quality indicator and build a strip-wise quality indicator map by projecting the *q*-indicator for the single laser points to a 2D raster map.



▲ **FIGURE 3** Overview of RT GPS quality monitoring tool



▲ **FIGURE 4** Overview of the multi-modal architecture interfacing the scan2map-system with the online quality monitoring tool HELIPOS

Quality Prediction

As previously mentioned, the GPS positioning quality is of uppermost importance for the accuracy of the final point-cloud. The in-flight GPS quality assessment represents therefore a crucial step in the whole processing chain. Poor GPS quality can originate from very different problems, spanning poor GPS constellation, cycle slips, and poor signal-to-noise ratios (interferences jamming, and so on). The monitoring tool uses a set of indicators (**FIGURE 3**) for quality evaluation:

- Solution type: if a communication line between the rover and a reference station gets established and real-time kinematics (RTK) is enabled, the ambiguities can be solved on-the-fly, yielding the best possible estimate for achievable CP-DGPS quality.
- Analysis of the GPS constellation (DOP values, number of visible satellites, and so on)
- L1/L2 carrier phase tracking loop output monitoring: In general, L2 is more affected by cycle slips than L1. Therefore monitoring the availability of the L2 signal is important for detecting quality degradations.
- Receiver autonomous integrity monitoring (RAIM): Most current GPS receivers used in kinematics are RAIM-equipped. RAIM enables analyzing the GPS integrity and consistency based on code measurements only.
- Cycle slip detection on L1: Using a velocity trend method, the ambiguity time difference can be computed as the temporal difference between the phase and the integrated Doppler observations.

Finally, the status of the individual indicators is combined into one final quality flag that can be immediately presented to the system operator. The quality flag has three levels:

- Good: the ambiguities should be fixed in forward and backward processing. The expected 3D position accuracy should be less than 0.1 meters.
- Critical: the ambiguities can be resolved only partially or with low reliability. The GPS position accuracy is expected to fall between 0.1 and 0.5 meters.
- Bad: no ambiguity fix possible, the expected accuracy equals the float ambiguities or carrier-smoothed code solution (accuracy > 0.5 meters).

Using these flags, the covariance of the GPS point-positioning (used as input to the RT GPS/INS integration) can be adopted accordingly. This yields more realistic position accuracy estimates (outputted from the RT GPS/INS integration), which are subsequently used as input values for the RT error propagation.

Tool Architecture

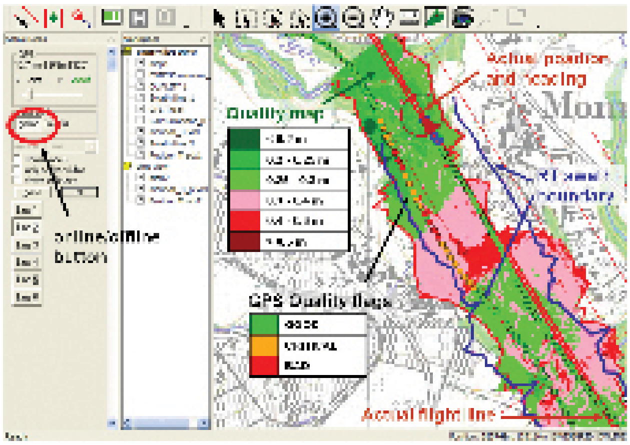
The Scan2map airborne mapping system, whose development was led by EPFL-TOPO, combines a GPS receiver, an inertial measurement unit (IMU), a light detection and ranging (LiDAR) unit, and a digital camera in one solid mount. The system is designed for helicopter-based surveys, with the sensor head suspended on its side. The architecture is based on hardware and software modules and fast communication across components (**FIGURE 4**). The software modules can run on different processors if needed. The main data-processing modules are:

- GIINAV: RT strapdown inertial navigation and GPS/INS integration engine;
- LIEOS: RT laser point-cloud georeferencing engine;
- HELIPOS: Flight monitoring and management module.

Embedded in LIEOS runs the LiDAR analysis module (LIAN), which computes the spatial distribution of the laser data, derives the data extent (outer bound of all strips within one flight zone) and estimates data gaps (zones within the extent that were not scanned completely or have not reached the minimal required point density). Currently, LIAN functionality has been enhanced by the capacity of performing full error-propagation and computing quality-indicator maps, all within the flight.

Data handling and processing consists of three phases:

- Data acquisition: As soon as the system is started, raw measurements are stored and the actual position (including the GPS quality flag) is transmitted to HELIPOS. GIINAV merges the GPS and IMU data streams and computes RT attitude and



▲ **FIGURE 5** Example for display of RT quality data (swath, GPS quality flag, q-indicator map) in the HELIPOS GUI

position estimates.

- Online: LIEOS generates the point-cloud by merging the trajectory with the laser measurements. All information needed for the error propagation (range, encoder angle, sensor exterior orientation and its accuracies) is saved to a file. RT swath boundaries are sent to HELIPOS and displayed (**FIGURE 5**).
- Offline: LIEOS stops the georeferencing, and the computed point-cloud of the previous flight line is loaded to LIAN. The strip is analyzed as one block and the outcome sent to HELIPOS for display in form of vector and raster data.

One reason for separating the two main tasks, RT georeferencing and data analysis, in time is to keep CPU requirements at reasonable level. Performing both tasks in parallel would significantly reduce the computational speed and threaten the RT monitoring capacity. Additionally, by pressing the on/offline button in the HELIPOS application, the operator ensures that the computationally demanding analyses (such as the error propagation) are carried out only over the areas of interest.

Quality Assessment

By enabling a full quality assessment for airborne LiDAR data directly during data acquisition in-flight, the operator is immediately informed if a part of the mission does not correspond to the requirements. From our experience, such information is necessary in complex flight missions using helicopters and/or oblique orientation of the LiDAR sensor.

A test has demonstrated the capacities of the GPS quality monitoring algorithm to identify parts of a flight that might be problematic in CP-DGPS. The produced quality map, computed by full error propagation within the flight, was able to indicate the point cloud quality deterioration caused by poor GPS data.

Next, we focus on using RTK to improve positioning accuracy. Solving ambiguities directly in-flight gives more reliable control of the integrity of the GPS code and/or phase measurements. As all necessary processing for a final geo-product can be done in-flight, this enables immediate delivery of the final mapping product after landing, with accuracy comparable to post-processed data sets.

RTK and ALS

If the quality of CP-DGPS is insufficient for periods longer than 10 to 30 seconds, there is a high probability that the quality of the GPS/INS integrated trajectory will also be insufficient during this interval. In (rare) cases, the resulting positioning error has constant influence during the flight-line. Then, its effect could be mitigated by the strip adjustment supposing there is a good overlap between the adjunct strips. In most cases, however, there is some fluctuation in the phase data observation, or in the satellite constellation, the reasons for which the above condition does not hold. The same is true in corridor-mapping, where the internal point-cloud accuracy cannot be judged from inter-strip discrepancies. In such cases, the remaining alternative for improving data quality is re-flying the mission, or at least part of it. This alternative is not only costly, but also not viable under some circumstances such as monitoring applications supporting decision making, short-data delivery, and so on.

Therefore, the ultimate control for checking the eminence of the phase observations is performing CP-DGPS positioning in real-time. This RTK concept is certainly challenging for airborne rovers when relying on publicly available mobile communications that are restricted in coverage (such as radio power or mobile-phone infrastructure) or continuity (dynamic allocation of service in radio-packed transmission as GPRS). Nonetheless, the RTK approach is feasible for helicopter-based ALS missions, at least in the European milieu.

Communication

Communication links are required for the real-time transmission of GPS measurements or its corrections. The transmission possibilities of this information range from (geostationary) satellites to terrestrial wireless data transmission techniques. The satellite-based (SBAS) concept is limited to code-corrections, accuracy of which is not sufficient. The reasons related to bandwidth, interference, coverage, or cost further limit the relatively wide possibilities to two choices: radio- and cell-phone-related technologies. The transmission by radio is used in the traditional survey RTK applications.

The second generation of the Global System for Mobile communications (GSM) is limited by its data rate of only 9.6 kbps. On the other hand, the General Packet Radio Service (GPRS) available on practically all GSM networks does not suffer such setback and has four times larger bandwidth (four voice channels). This approach is therefore less suitable for RTK positioning than GPRS. Although the cell-network coverage decreases in rural regions, the coverage in European countries is good and constantly spreading.

Results

FIGURE 6 shows distribution of the downsampled laser point-cloud coordinate differences between PP-RTK ALS solutions. The 3D RMS is at 0.1 meter level. In other flights these distributions are very similar or better and confirm that this approach provides a final point cloud with sufficient quality for a range of applications, and opens new opportunities for monitoring missions with short reaction time.

Acknowledgment

This article combines portions of two papers by the authors, “In-flight Accuracy Estimation for Airborne Lidar Data,” to be presented at ION-GNSS 2009, Savannah, Georgia, and “Real-time Registration of Airborne Laser Data with Sub-decimeter Accuracy,” submitted to the *ISPRS Journal of photogrammetry and Remote Sensing*. These papers show test results validating the concepts presented here. 🌐

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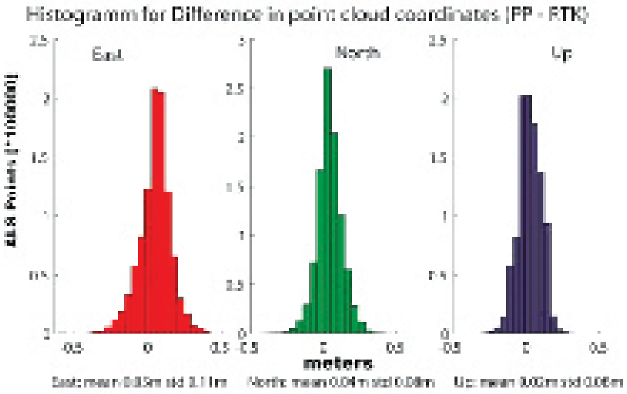
Manufacturers

Scan2map combines a **JAVAD GNSS** *Alfa T2G* GPS receiver, a **Litton** *LN200* IMU, a **Riegl** *LMS-Q240i* LiDAR unit, and a **Hasselblad** *H2* digital camera.



▲ **FIGURE 6** Difference in point-cloud coordinates computed in real time and in post processing (RTK by NTRIP/GPRS, 1-million point sample)