CHALLENGES AND SUCCESSES IN PHOTOGRAMMETRIC APPROACHES TO LIDAR-DERIVED PRODUCTS

Devin Kelley, Project Manager
Thomas Loecherbach, PhD., Chief Photogrammetrist
HJW GeoSpatial, Inc.
kelley@hjw.com
loecherbach@hjw.com

ABSTRACT

Airborne LiDAR is a technology that has proven its utility to supplement and sometimes substitute conventional photogrammetry. The decision to use LiDAR data is sometimes driven by its unique character and at other times by the client’s motivations to have a cost-effective, quick-turnaround alternative to conventional photogrammetric mapping. It is not straightforward to characterize the nature of a LiDAR dataset; there are many variables involved, some of which cannot be sufficiently quantified, such as the effects of localized terrain undulations and ground cover on vertical accuracy and bare-earth classification. The steps of acquiring and processing LiDAR data, performing redundant checks to increase confidence in processing, and optimal ground classification, all have existing procedures that cater appropriately to the characteristics of data and sensors. Bridging the gap between these tasks/considerations and client’s expectations is challenging, because the demands of the market often follow a legacy of product specifications and expectations that are built around conventional photogrammetry, which can be much more predictable and controlled upfront, by design. Additionally, LiDAR is sometimes marketed as the simple, quick alternative to producing accurate terrain data, but end-users must be prepared to make accommodations for data volumes and specialized software, as well as personnel training. HJW GeoSpatial, Inc. provides LiDAR-based processing and production, from calibration through to LiDAR-derived end products. Recent experiences underscore the unique role that LiDAR plays in our ever-changing industry.

BACKGROUND

LiDAR Data is the Result of a Chain of Processing Steps

A LiDAR bare-earth point dataset is the result of a chain of processing, each step a critical link to the next. Chronologically, the chain consists of project design, field operations (land surveying, data acquisition), data decoding, trajectory processing, system calibration assessment and refinements, point cloud export, point classification (usually bare-earth), and production of the LiDAR-derived end-product. Along the way, there are quality assessment steps, blunder-detection checks, and other checks that add redundancy and increase confidence in that particular “link” of the chain.
LiDAR Data has Unique Characteristics

Two major challenges of LiDAR processing have been identified as dealing with systematic errors and derivation of bald earth data (Schickler and Thorpe 2001). Absolute accuracy is a function of the errors introduced by the approaches and models used in the chain of processing, as well as limits of the technology. (ASPRS 2004) discuss the effect of terrain vegetation on the resulting bare-earth classification. There is a high probability that there will be skewing in the data in these areas due to failure of the laser to penetrate to the ground with a reasonable density.

A LiDAR dataset is characterized by number of returns, scan angle settings and rate, as well as scanner rate. These are often driven by the sensor that is used, and the project design/specifications for density. Some characteristics of a LiDAR dataset are a function of the terrain that is being modeled. Steep slopes affect vertical accuracy (Kraus, Rieger 1999), and thick canopy and vegetation affect the point density on the ground. Additionally, when point density is compromised, there is less redundant information available from which to classify bare-earth points. The reduction of density effectively lowers the confidence in the ground classification in such areas, as low vegetation may be classified as ground, or discrete changes in the terrain may not be modeled.

Regarding contour mapping, one must also take into consideration that there are no breaklines in the dense set of point data. The typical high density, inherent noise and lack of breaklines will contribute to the generation of contours that are aesthetically much different than the industry-standard photogrammetric contour mapping. Proactive steps should be taken to mitigate these issues if they are important to the end product.
Industry Standards

The geospatial industry has enthusiastically embraced the use of airborne LiDAR for a vast array of applications. Data providers and processors must be well-versed in the applicable standards. The 2004 ASPRS Guidelines for Vertical Accuracy Reporting for LiDAR Data (ASPRS 2004), NDEP Guidelines for Digital Elevation Data (Maune 2001), the FEMA Guidelines and Specifications for Flood Hazard Mapping Partners (FEMA 2003), and the ASPRS DEM User’s Manual all explicitly refer to, and strive to comply with NSSDA requirements. The applicable standards generally acknowledge and conform to the unique nature of LiDAR datasets and to the specific application (FEMA 2003). Industry standards are usually referenced by the LiDAR service provider during contract negotiations with end-users. The LiDAR service provider is at that point responsible for complying with the standards, as well as bridging the gap between the obscure processing methodologies, and the client’s needs for a useable end-product.

LiDAR Processing Tools

Systems and software for processing LiDAR data are often proprietary and undocumented. Many photogrammetric software vendors have extended their DEM packages for LiDAR processing (Zhang 2006). Some of the packages, while having excellent editing and filtering tools, cannot easily handle the high volume of data that a LiDAR sensor delivers. They are often organized under the paradigm of “stereo models” and the user is left alone when it comes to organizing and administering data sets, especially when dealing with a production environment where data is edited simultaneously by a group of technicians.

A widely used DEM package which has been designed to handle high volumes of data is SCOP, developed jointly by Inpho and Technical University of Vienna (e.g. Kraus, Otepka 2005). Perhaps the most widely used package developed specifically for LiDAR is the Terrasolid Suite by Terrasolid (www.terrasolid.fi). While SCOP is based on a robust estimation to derive the terrain surface from the LiDAR points, Terrascan as part of the Terrasolid suite employs TIN-based filtering methods. GeoCue by GeoCue Corp. (Graham 2006) is a workflow management tool which, among others, aims at organizing the LiDAR workflow. One of its features is the generation of stereo imagery from LiDAR intensity data to support the LiDAR editing. This can be a considerable help for collecting breaklines or identifying power lines (Flood 2006) and (Tack, Graham 2006). LiDAR Analyst (Roth 2006) is a system that focuses on deriving vector outlines of geographic features from LiDAR points. In this paper we describe data processing with Terrascan and GeoCue among others.

EXPERIENCES

Technical/Professional Judgment as Part of LiDAR Ground Classification

Ground Classification in Difficult Areas. Bare-earth ground classification is the task of separating points on vegetation or buildings from the points on the ground. The first step is mainly logical, which is to designate “only” and “last” returns as candidates for bare-earth. This reduces the computational search space. Then, outlying points are removed from the dataset. Next, geometric classification (in our work, TIN-based) is applied, using low-elevation points as “seeds”. From these seed points, the ground is classified by using user-defined angle and distance thresholds, along with an iteration strategy. Experience and manual guidance is useful in arriving at a strategy that yields an optimal solution. The LiDAR technician uses his judgment to determine what constitutes an optimal solution. There are quite a few approaches to addressing QA/QC of this process, and many times the approach is based on the resources (money, time) allocated to a given project as well as the available data (stereo imagery, orthophotography) and tools (software).

In 2005, HJW GeoSpatial, Inc., working under contract with the County of San Mateo, California, produced a LiDAR DEM and orthophotography for the entire County. Under contract to HJW, Airborne 1 Corporation, of El Segundo, California, collected roughly 100 lines of LiDAR data. The LiDAR data was collected with an Optech sensor, with specifications for one meter point spacing, and two returns. The LiDAR data was subsequently processed by HJW to create a single dataset of bare-earth points, which would serve as a foundation for a DTM. HJW also flew county-wide photography to product orthophotos at 6” and 3” pixel sizes.

San Mateo County has exceptional geographic features- the Santa Cruz Mountains, coastal cliffs, hilly, thick forests and high-density urban developments built into hills, and marshes with levees along the San Francisco Bay. Additionally, there are complex structures such as freeway interchanges, raised railway systems, and the San Francisco International Airport. All of these characteristics combine to make the bare-earth ground classification and accuracy
assessment a non-trivial matter.

San Mateo County encompasses a variety of habitats including estuarine, marine, oak woodland, redwood forest, coastal scrub and oak savannah. Roughly 50% of the 443 square mile county consists of thick forests, hills and mountains. Figure 2 shows an orthophoto tile (2000’ X 3000’) of a hilly, forested area. There are roughly 150 square miles of similar terrain in San Mateo County. Filtering the bare-earth points from the LiDAR point cloud in these areas requires technical judgment.

![Figure 2. Orthophoto tile showing thick canopy. Original photo scale is 1:15,000.](image)

For the 138 acre area shown in Figure 2, roughly one million LiDAR returns were measured (two returns). Of these returns, 500,000 were “last returns”, which become candidates for bare-earth points. Automated geometric classification assigned 28,000 points as bare-earth. The resulting density is roughly 350 points/acre. The results are shown in Figure 3. There is however one large gap: 100’ X 200’ (0.45 acre) in the data, which warrants further inspection. Such results are typical for these types of areas.
The gap is either the result of failure to penetrate the canopy, or the inability of the geometric classification to grow the bare-earth points through that area. Assessing some profiles (5’ in width) reveals that there are not many obvious ground points available that relate to the nearby bare-earth points (see Figure 4). In an attempt to increase the density of the bare-earth points in this area, we manually classified a few points from vegetation to ground, and re-ran the automated geometric classification, using those manually-classified points as “seed points”. Selecting seed points requires an adequate amount of redundant information provided by candidate points, as well as assumptions about terrain smoothness. Figure 5 illustrates that the area now has less of a point gap. The technician must make the determination as to whether or not this is the optimal ground classification.

The forested areas underwent manual assessment and point classification after the automated bare-earth points were computed. The manual adjustments were done by analyzing profiles of the data, along with dynamic (interactive) contours displayed in plan view (see Figure 6). As we reclassified bare-earth points to vegetation, the contours were updated and re-displayed. In this way, sudden discrete changes in the contour appearance could be inspected to determine whether or not they were being caused by low-vegetation point(s) incorrectly classified as bare-earth. Contour wrapping around artifacts or drastic jumps in elevation indicated areas where vegetation was likely to be incorrectly classified as bare-earth. The technician generally uses the available point density, along with consideration for the number of points causing the discrepancy, to guide that decision. One assumption is always that the terrain is changing in a smooth manner.
Figure 4. Profile (5’ in width) illustrating bare-earth points (orange) and non-bare-earth points (green).

Figure 5. Profile showing the results of adding manual seed points and re-running automatic geometric bare-earth classification. The point density has increased slightly.
In order to identify blunders, contours were generated and extreme changes were examined and manually edited using cross sections. Generally, four foot contours were good for visualization in hilly areas, although 10’ contours are shown here for presentation.

HJW also has been involved with LiDAR bare-earth classification for Edwards Air Force Base, in Rosamond, California. Located in the High Desert of California, this 518 square mile area consists mostly of dunes and low brush (generally about 3’ in height). Such a scenario of rolling dunes and low brush proved to be a challenge for automated geometric bare-earth classification. It was determined that running a project-wide ground classification was not appropriate, as there was a trade-off between modeling the sand dunes (accommodating their slopes) and extracting the vegetation. Figure 7 shows the results of the bare-earth processing of one area, using the standard approach. In the 1000’ X 1000’ tile example, there were 18,764 points designated as vegetation and 179,314 points designated as bare-earth.

Because of the inclusion of the low brush into the ground model, manual tuning had to be done on a tile-by-tile basis to guide the ground classification. It was found that by using tight restriction on the threshold angles, the ground class could be built up more optimally, while manually classified “seed points” were used to guide this classification in areas where sand dune slopes would otherwise be problematic. Figure 8 illustrates the result of the manually-guided bare-earth classification. The results were 41,793 points designated as vegetation, and 156,285 points as bare-earth. There are about 23,000 less points in the bare-earth class compared to the fully automated approach. The bumps that remain seem to be inconclusive—there is not enough variation or redundancy to designate more vegetation with any degree of confidence.
Figure 7. The bumpy appearance of the shaded surface model in the right indicates that the low brush is not being adequately removed from the bare-earth dataset. A profile (5’ in width) on the bottom shows the points colored as orange for ground, and green for vegetation.

Figure 8. Manual guidance of the classification resulted in a bare-earth class that generates a much less “bumpy” appearance in the shaded surface model.
Photogrammetry and LiDAR Working Together. For San Mateo County, HJW GeoSpatial acquired aerial photography as part of the project. This enabled both stereoscopic analysis of the LiDAR data, as well as superimposition of orthophotography in the LiDAR processing environment. First, HJW ran a global classification of the LiDAR data in order to extract a project-wide rough bare-earth point class. This data was then exported as a DEM and used to generate “scratch” orthophotos that would be used to aid interpretation of the LiDAR data. The “scratch” orthos were generated using Leica LPS/IMAGINE, and utilized its functionality for automated “drop-together” mosaicking, and tiling into the project’s tiling scheme. To speed up the process, a reduced resolution was used for these intermediate orthophotos. Figures 9 and 10 illustrate the utility of having orthophotos as part of the LiDAR processing environment. The intermediate orthophotos facilitate a more rigorous approach to LiDAR bare-earth point classification and QA/QC.

**Figure 9.** Bare-earth points (orange) are superimposed on the orthophoto, while a shaded surface model is synchronized in an adjacent window. Artifacts in the shaded surface model can help identify areas that would be subject to classification scrutiny. In this example, we see an obvious artifact in the surface model.

**Figure 10.** In addition to overlaying points, contours generated on-the-fly are useful in assessing the appropriateness of ground classification, especially when superimposed on an orthophoto.
Finally, this aerial photography was used in difficult areas to set up stereo-models in a softcopy environment and load in the LiDAR points to verify whether or not points had been correctly classified. The photogrammetric stereo-models also allowed for easy identification and digitization of overhead structures, which allowed for re-classification of points. The stereo-compiled data of overhead structures were also incorporated into the production of the final orthophotos.

The San Mateo County and Edwards Air Force Base examples stand to illustrate the necessity of manual inspection and technical guidance of the automated processes that are relied on for LiDAR point classification. These steps are necessary in order to generate the optimum acceptable product for the end-user. The technician has to make certain assumptions that are sometimes limited by point density and terrain characteristics. Also, a clear understanding of where responsible data processing meets the point of diminishing returns is critical. The notion of statistically and subjectively filtering out “bad” points is a concept that is vastly different from the conventional way of compiling terrain data from photogrammetric stereo-compilation. Additionally, using photogrammetric operations to supplement LiDAR processing has proven to be valuable.

Assessing the Results

The absolute accuracy of a LiDAR data set is affected by random and systematic errors introduced in most steps of the processing chain, but the foundation lies in the airborne GPS/IMU trajectory solution. The GPS solution is normally determined by way of several ground base stations that are tied into a national control network. Static GPS baseline processing is used to verify and troubleshoot any discrepancies in datum epoch or blunders in data settings. The adjusted coordinates of the base station positions are generally computed by a Professional Land Surveyor and used as the foundation for the airborne GPS processing. GPS/IMU processing affords statistical output that can be analyzed to gauge the expected accuracy of the trajectory solution. This accuracy is never constant throughout the flight mission, and there may be localized areas that suffer from a loss of lock or PDOP issues. The notion of a LiDAR dataset that has localized areas with degraded accuracy is not necessarily addressed by the quantitative accuracy assessment of the resulting bare-earth TIN. Nonetheless, the end-user’s expectation is that the LiDAR data provider will follow all responsible steps “behind the scenes” to ensure that the end-product will be of uniform quality, if not otherwise noted.

For HJW’s San Mateo County project, ground checkpoints were used throughout the County, mostly in open areas. The checkpoints came from varying sources: a GPS-car (665 points), control surveyed for HJW’s prior projects in the County (233 points), and also HJW’s field surveys under a subject area under thick canopy (188 points). The points were distributed throughout the County, as illustrated in Figure 11. Figures 12 and 13 summarize the results.
Figure 11. Ground checkpoint distribution for San Mateo County project.

Figure 12. Histogram showing the ground checkpoint residuals of the LiDAR TIN.
Statistics (ft)
Number of points: 898
Average vertical error -0.002
Min vertical error -0.936
Max vertical error 1.009
Average magnitude 0.256
Standard deviation 0.332
RMS 0.332
Accuracy (95%): 0.651

Figure 13. Statistics of the San Mateo ground control checkpoints.

Of special interest is the accuracy assessment of areas that lie under thick canopy. Recently, HJW GeoSpatial had performed photogrammetric mapping in Hillsborough, a city within San Mateo County. When comparing the 2’ contours that resulted from conventional photogrammetric stereo-compilation with the contours derived from LiDAR, it became apparent that the LiDAR was not only penetrating the canopy better than could be modeled with photogrammetry, but it was also able to model a drainage that was missed in the photogrammetric mapping. Figure 14 illustrates the area.

Additionally, HJW’s field survey crew went to this site and ran a cross-section survey, collecting 188 points. These surveyed points, when compared to the LiDAR data show a skew value of 1.6. This indicates that there is asymmetry in the dataset (low vegetation points are likely affecting the LiDAR TIN z-values). Using the 95th-percentile approach to accuracy assessment, the resulting value is 1.3’. The 95th percentile indicates that 95% of the errors in the dataset will have absolute values of equal or lesser value and 5% of the errors will be of larger value. With this method, Accuracy(z) is directly equated to the 95th percentile, where 95 percent of the errors have absolute values that are equal to or smaller than the specified amount (ASPRS Vertical Accuracy Requirements). These points were then used as input for contouring, and compared with the LiDAR data. The results are shown in Figure 15. These results illustrate the utility of LiDAR data, particularly in areas with thick canopy.

Experiences with Contour Mapping

Comparisons to Conventional Photogrammetry. LiDAR, as a source for terrain data, is very similar in utility to terrain data compiled from photogrammetric methods. There are some major differences, however, which are worth mentioning.

Photogrammetric stereo-compilation is the traditional way of generating a digital terrain model. Breaklines are measured along characteristic features of the terrain, and mass points are measured throughout the project site. The breaklines and mass points are then used as input for contour generation. This approach has been used for decades to produce topographic maps that support the GIS and engineering communities. The benefits of this approach are that there is a wealth of experience in the procedures, there are well-established conventions used to generate these products, and there is manual scrutiny every step of the way. Additionally, the contouring process is often iterative, as stereo-compilers may generate an intermediate set of contours to make sure that characteristic features are being adequately represented. Cultural features such as drainages and road edges are often explicitly modeled with breaklines. Each stage of measurement is subject to operator interpretation supported by automation, where applicable. Absolute accuracy is easily assessed from statistical analysis of aerial triangulation (or absolute orientation) data, and with a high degree of confidence, when following best practices for this mature technology.
Figure 14. Contours derived from photogrammetric DTM compilation (purple) were not able to model the drainage that is apparent when looking at the LiDAR-derived contours (yellow). Visibility through the thick canopy limits the effectiveness of stereo-compilation in this area.
With LiDAR, no feature is explicitly measured—instead, the entire project area and all features are measured. The echo-based and geometric classification steps are used to extract the bare-earth points. This is a stark difference from the conventional photogrammetric method of strategically selecting and measuring each terrain point, while at the same time, having a good understanding of the vertical accuracy of that point. In the case of LiDAR data, a misclassified bare-earth point can contain vertical errors, and never be caught or quantified.

There are no breaklines inherent in the bare-earth point dataset. When generating contours from LiDAR data, the photogrammetrist is typically challenged to do so in such a way that the end-product approaches the usefulness of photogrammetric topographic mapping of a similar accuracy (1' or 2' contours). The uses of contour mapping often rely on the aesthetics that breaklines introduce. A challenge with LiDAR data is that breaklines cannot be properly compiled unless the terrain is being visualized in a stereoscopic environment. Acquiring photography (and ground control) to aid in breakline collection can easily cancel out the cost-effectiveness of the LiDAR approach, which sometimes is the main factor driving a client’s decision to use LiDAR in the first place.

High-altitude photography used for breakline placement. In 2005, HJW GeoSpatial performed a LiDAR mapping contract of the San Pablo Bay, in Sonoma County, California. In this project, we were required to generate 2’ contours for roughly six square miles, based on LiDAR data. In order to incorporate breaklines, stereo-photography of the project area was flown at a high altitude. Conventional photogrammetry at that scale would not allow for breakline measurement to meet the vertical accuracy required of the project, but instead it allowed for stereo-interpretation for breakline placement. During measurement, the breaklines were snapped to the dense set of LiDAR points, in order to retain the high vertical accuracy of the LiDAR in the breaklines. The inclusion of breaklines allowed subsequent contouring to meet our requirements of terrain modeling.

LiDAR Stereo-Imagery as a Tool for Breakline Measurement. Currently, HJW is providing QA/QC oversight to a LiDAR project for the County of Santa Clara, California. The County is roughly 1280 square miles and has mountainous terrain as well as dense urban development in Silicon Valley. Among other things, HJW is responsible
for the quality of the LiDAR-derived DTM, which involves the use of breaklines measured from LiDAR intensity stereo-mates. HJW is using GeoCue’s (patent-pending) software functionality to generate LiDAR intensity stereo-images and perform quality control analysis stereoscopically, in SocetSet. Currently, HJW is devoting research efforts to assessing the logic and accuracy of measuring breaklines under such a scenario. Nonetheless, we are hopeful that the use of breaklines measured directly from LiDAR data will serve to function as a low-cost alternative to photo acquisition. HJW is currently developing new criteria for breakline measurement for these types of datasets.

CONCLUSION

Digital terrain modeling is often derived from LiDAR, photogrammetric compilation, field survey, or a combination. The characteristics of LiDAR data make it stand out dramatically from other sources, in that its accuracy, and the ability to model certain terrain/ground cover types is often difficult to quantify before acquisition and processing. Photogrammetrically-derived terrain products are typically held as the “gold standard”, and clients, as well as data providers, have to look at LiDAR-derived terrain data as uniquely different. The procedures of processing LiDAR data and generating derived products are enhanced by innovative production approaches that involve photogrammetry, and facilitate added redundancy in QA/QC. Such techniques allow the full potential of LiDAR-derived products to be recognized in highly-accurate and high-quality deliverables to the end-user.

REFERENCES