Filling in the Gaps with Complementary Technologies

by Ron Roth

The use of airborne laser profiling has increased in a variety of surveying and mapping applications. Concurrently with this increase in usage, the performance of airborne laser profiling systems has increased dramatically over the past several years. Nonetheless, users of these systems have recognized that there are still applications in which airborne surveys provide inadequate results (compared to ground-based systems) despite current high performance levels. In this article we will review the history and convergence of airborne- and ground-based lidar technologies. We will also demonstrate how the two technologies can be employed either 1) separately or 2) jointly in a complementary fashion.

Market Perspective and System Design

Airborne lidar systems have existed commercially for approximately 10 years. There are now roughly 120 airborne lidar systems worldwide and virtually all of them are still in service. The pioneering systems integrated primarily by institutional organizations (i.e., government agencies, military and universities) have given way to a mature merchant-supplied market.

Similarly, the installed base of ground-based lidar systems has grown, from initial systems delivered in 1998 to a current installed base of nearly systems world-wide700, including 400 High-Definition Surveying (HDS) systems. This market is supplied by at least 5 manufacturers, including Leica, Riegl, Optech, Mensi, MDL and others.

Both airborne and ground-based lidar are served by products aligned along an array of applications, as summarized in Figure 1 below: Airborne lidar systems generally fall into two categories:

- flexible, generally-purpose mapping systems and
- low-altitude systems designed for corridor mapping applications.

General-purpose mapping systems mounted in fixed-wing aircraft form the bulk of the airborne lidar fleet. General-purpose mapping requires systems that can cover vast amounts of terrain from high altitudes, while retaining the ability to deliver tight post spacing (<1 m) even from fixed-wing aircraft, all with accuracy of better than 10-15 cm RMSE. Maximum flying height for these systems is typically 3000m AGL or higher, though the bulk of general-purpose mapping is performed at somewhat less strenuous altitudes.

Low-altitude systems, typically flown on helicopter platforms, are part of a growing specialty market segment. These systems can economize in the mission planning area by flying low enough for the pilot to navigate by merely looking down through the bottom of his/her polycarbonate cocoon to confirm that the intended target (power line, pipeline, roadway, etc.) is at nadir. Systems serving this market segment commonly fly as little as 50 m above ground, resulting in impressive accuracy and post spacing, while entering the market at prices significantly lower than that of general-purpose airborne lidar.

To clarify, most general-purpose airborne lidar systems are well capable of providing data as accurate and as dense as specialized corridor-mapping systems when used at similar altitudes and aircraft speeds. The increased flexibility of general-purpose systems does, of course, result in higher prices for these systems. The data production process is virtually identical for both general-purpose and corridor-mapping lidar systems.

Ground-based lidar systems tend to fall into three major categories:

- systems for engineering applications requiring fine (2-3 cm) post spacing and high (~6 mm) accuracy
- systems for stand-off (100-1000 m range) data capture where medium (2-3 cm) accuracy is needed
- systems with ultra high measurement rates for very high point density at very short (typically <20 m) distances.

	Airborne Lidar	Ground-based Lidar
Year introduced	1995	1998
Number in service (all manufacturers)	~120	~700
No. of manufacturers	3	5
Subtypes	• Flexible, general-purpose mapping systems • Low-altitude corridor mapping systems	• Engineering systems • Stand-off systems • Ultra-high measurement rate close-in systems
Primary subtypes	Flexible, general-purpose mapping systems	Engineering systems

Figure 1. Market composition, airborne and ground-based lidar.

The vast majority of ground-based lidar applications fall into the first category. Although impressive productivity is achieved by phase-based systems from the third category, the maximum range inherent in phase rangefinding technology limits the number of applications for this hardware. Similarly, the maximum range achieved by stand-

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off sensors from the second category is offset by slightly lower accuracies. The resulting stand-off systems are more than adequate for specialty applications such as production monitoring in the extractives industry, but are not generally sufficient for tackling engineering work.

From the market perspective, the majority of applications come from the engineering-related segment. In this market, the level of documentation generated demands post spacing of approximately 2-3 cm, with an associated accuracy of better than 1 cm. As we develop the discussion of airborne and ground-based systems in this article, we have placed the focus on the types of systems used for general purpose airborne mapping and engineering-related ground-based data acquisition.

Development History of Airborne Lidar

As mentioned earlier, both airborne and ground-based systems are approaching the 10-year mark in terms of time-in-market. Over that time period, performance, by most technical metrics, has increased steadily.

Figure 2. Typical airborne lidar system (Leica Geosystems ALS50).

In the case of airborne systems, the maximum pulse rate of airborne lidar systems has increased twenty-fold. To put this in perspective, "Moore's Law" suggests that the number of transistors on an integrated circuit would double each year. The computer industry generally subscribes to this same theory as a rule-of-thumb regarding the increase in computer performance though, in fact, computer speed doubled initially every 2 years. Since the development of the 80486 processor, the doubling time has increased to roughly 2.5 years. By contrast, the maximum pulse rate of airborne lidar systems has doubled every 2.1 years, beating the current progress of the computer industry processor technology. This increase means greater productivity during raw data collection. It also paves the way for increased point density or, conversely tighter post spacing from the airborne system.

In parallel with the increases in maximum pulse rate, airborne lidar systems have shown an increase in maximum flying height. First-generation systems with maximum flying heights of only 1000 or so meters AGL, have been suceeded by systems regularly operating at up to 4000 m AGL. Specialized versions have flown at up to 10 km AGL, providing slant range data for terrain up to 15 km from the scanner. Though not as radical as the growth in pulse rate, the growth in maximum altitude has provided increased flexibility to the user, allowing for single-altitude flight plans even over areas of great vertical relief.

Finally, airborne systems have steadily increased in accuracy, particularly when operating at lower altitudes where GPS errors are minimized. Early systems provided data with accuracies on the order of 20+ cm, even at their lowest flying heights. Today's systems take advantage of more developed rangefinder and DGPS technology to allow accuracy as fine as 5 cm when used at low altitudes with short GPS baselines and optimal GPS planning.

For the users of airborne lidar systems, the above has meant a steady increase in both productivity and the accuracy of the delivered data product, allowing airborne systems to be used in applications that may have demanded field surveys only a few years ago.

Development History of Ground-based Lidar

Ground-based lidar systems, like their airborne counterparts, have also experienced a steady level of performance improvement, though their history is somewhat shorter. Like airborne systems, one metric of performance is measurement rate. Early systems featured pulse rates of around 1000 Hz while attaining engineering-level performance. Recently, systems with pulse rates of 1500 Hz have become available.

The other performance metric that has seen greater improvement is the maximum range at which the needed 6 mm resolution can be obtained. This has increased two-fold since 1998, from maximum useable ranges of 50 meters initially to approximately 100 meters today. There are engineering reasons why maximum range has not been expanded beyond that point, but there is also an operational reason. While it is possible to obtain range data at larger and larger distances, there comes a point when the system operator cannot get any farther away from the target. Trees, vehicles, or even other buildings tend to obscure the target at some distance. As a result, there has not been much time invested in improving the maximum range capability in the high-precision portion of the ground-based lidar market.

One aspect of ground-based lidar performance that has improved substantially is field-of-regard. Initial systems managed a 40 x 40 degree field-of-regard. Very quickly, the industry began to introduce systems capable of greater coverage. Some of today's systems may offer coverage areas in excess of one hemisphere. Therefore, although increases in pulse rate have provided only modest increases in data collection productivity, the ability to "set-and-forget" (setting up the system and then letting the system autonomously collect data over a large coverage area) allows operators to perform other duties while the system continues to collect data. A by-product

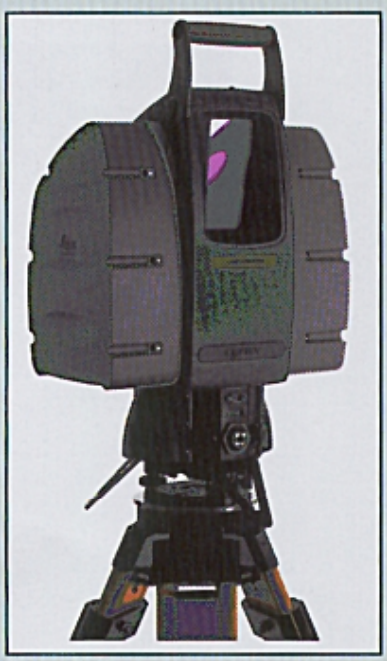

Figure 3. Typical ground-based lidar system (Leica Geosystems HDS 3000).

of this "set-and-forget" feature is that the operator need not spend lots of time planning the data acquisition effort. Instead of having to carefully plan the locations of numerous reflectors that had to be installed and targeted for high-resolution scans, the operator can perform the field survey with a minimal number of non-critical setups.

Summary of Technology Advancements

Let's take a moment now to summarize the changes in airborne and ground-based lidar performance. Notice that both airborne and ground-based lidar systems have advanced in their abilities to acquire data faster and over a longer range. A summary is presented in Figure 4 below:

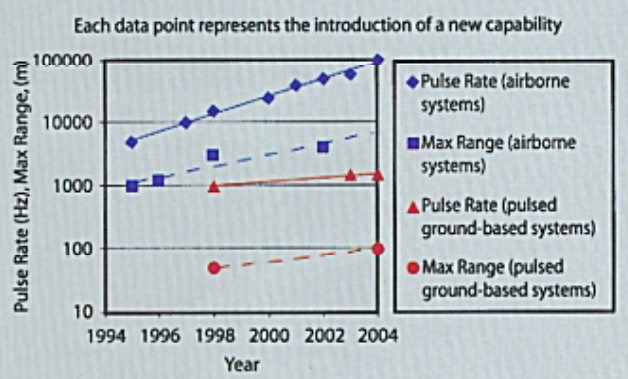

Figure 4. Summary of lidar technology advancements.

Figure 4 also shows that airborne systems are advancing at a more rapid rate than ground-based systems. Extrapolating trends must be done cautiously, but past trends indicate that airborne lidar systems will continue to provide higher and higher pulse rates. Economics is the driver for this trend. At operating costs of about $1,000 per hour for plane, pilot and operator, doubling the pulse rate would cut the hourly costs of airborne raw data acquisition to $500. A typical airborne lidar operator flying 300 hours per year would save $150,000 per year. This is not an insignificant sum, particularly for the smaller firms investing in the technology today.

In the case of ground-based lidar, the next jump in raw data acquisition productivity would come when the operators could scan an entire wide field of view (FOV) scene rapidly enough to warrant standing beside the system while it scans. One might describe this as a migration from "set-and-forget" to "stand-and-scan." This transition will require a "quantum leap" in pulse rates. As suggested earlier, maximum range is not likely to grow significantly, since current systems already offer enough range for most practical purposes. Finally, the accuracy provided by current high-precision ground-based lidar systems is adequate for the engineering applications most frequently seen. Therefore, there are not likely to be huge gains in this area. As an instrument most often employed by surveyors, ground-based lidar will develop more along the lines of other surveying instruments, where portability, low power consumption and ease of use are watchwords.

Point of Convergence

This discussion leads us to two questions. What are the obvious points of convergence for these technologies? Is it possible that airborne data acquisition could replace ground-based lidar?

The two most obvious points of convergence involve technical performance:

- Data density, particularly from low-altitude platforms (i.e., will airborne systems be able to deliver engineering-level post spacings of 2-3 cm?)
- Accuracy (i.e., will the accuracy of airborne systems ever be adequate for engineering work?)

In terms of data density, let's look for a moment at one parameter in airborne lidar systems that is directly affected by pulse rate, namely post spacing. In terms of data density, it is important to discuss post spacing, since it is one parameter in airborne lidar directly affected by pulse rate. As high-performance airborne lidar systems acquire data at faster and faster rates, the potential exists to decrease post spacing. This is especially true if the aircraft is allowed to fly at low altitude (or otherwise cover a narrower swath). This is further enhanced if the system is mounted in a platform with a very slow forward speed, such as a helicopter. In an effort to provide a legitimate comparison, the average post spacing of various airborne lidar systems over time has been calculated assuming a 40-degree swath (similar to initial ground-based systems) and system mounting in a helicopter with 30 knot forward speed. The results are compared to the typical post spacing of ground-based lidar systems (i.e., 2-3 cm posting). The results are summarized in Figure 5 below:

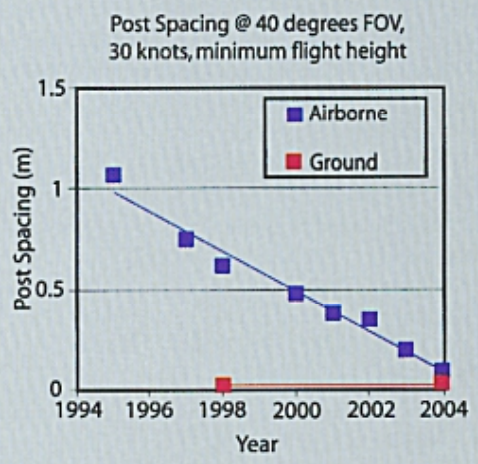

Figure 5. Post spacing of airborne and ground-based lidar systems.

The results provide an intriguing picture. Does this mean that the two technologies are converging? Perhaps they are in some way. If so, what is the time horizon for convergence? Today's airborne lidar systems could perhaps achieve 0.090 m average posting versus 0.025 for ground-based systems in a full-scene scan. This is a factor of 3.6 in post spacing, so the two technologies are not as close together as they look in the graph. Furthermore, reducing post spacing in both the X and Y directions captured by the airborne system would require a factor of $3.6^2 = 13$ higher pulse rate. Even if the rapid pace of advancement in airborne lidar is kept up (refer back to the estimate of a doubling in this spec every 2.1 years), we would not expect to see this level of performance until the year 2011.

As for data accuracy, low-altitude lidar systems (say, to a maximum of 50 – 150 m AGL) are being advertised at levels as precise as 5 cm in XYZ. This is clearly not acceptable for typical engineering applications, where 6 mm accuracy is needed. Is there any chance

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that airborne systems can achieve this 6 mm accuracy level? This is unlikely, given the fact that airborne lidar has both GPS and IMU errors in its error budget. This is something that ground-based systems are unconcerned with. Even survey-grade kinematic DGPS can only deliver accuracy in the area of 2 cm, so it would seem that this alone could be a limiting factor. In addition, the IMU used to determine the orientation of the airborne lidar with respect to the earth below introduces error in determining the location of a point in the scene. Though it is a small error at low altitudes, it is present nonetheless.

Complementary Versus Competing

Examining the merits of ground- and airborne-lidar systems naturally leads to the question, "Which technology is better?" The answer literally depends on your point of view. Without scoffing national aviation regulations and employing a staff composed of former crop-dusting pilots, there are certain applications that will forever remain the domain of ground-based lidar systems. Even current ground-based systems are capable of delivering point densities higher than that regularly achieved by high-resolution aerial photography, much less that of airborne lidar. Furthermore, obtaining spatial data under overhangs remains a virtual impossibility for airborne lidar. There are also several factors that will drive manufacturers down different development paths for these two technologies:

- Accuracy – Georeferencing airborne data is inherently more challenging than providing accurate data from a stationary platform.
- Mobility – Airborne lidar will allow the user to "drop in" on remote or inaccessible survey areas
- Maximum Range – Airborne lidar is not generally constrained to human-portable, battery-pack operation. This allows the use of more powerful laser devices and larger collecting apertures.
- Eye Safety – Ground-based systems must essentially be limited in terms of maximum laser output to energy levels not unlike that of a typical laser pointer, thus maximizing safety for persons in the immediate vicinity of the system while, airborne systems need only be eye safe for a person on the ground when the aircraft flies overhead.

From the foregoing, it therefore seems that the two technologies only *appear* to converge. If we look for a moment at some typical applications for airborne and ground-based lidar we will see some trends.

Airborne Lidar	Ground-based Lidar
Small scale (large area) mapping	Large scale (engineering) mapping
Tops of buildings	Facades of buildings
Archaeology (lost cities)	Architecture (details)
Flood plains maps	Flood damage
River beds	Curbs and gutters
Pipelines	Refineries
Power lines	Power plants
Highway	Bridges

Figure 6. Trends in airborne and ground-based lidar use.

Generalizing, we observe that airborne systems are good a mapping infrastructure in between nodes in the infrastructure system (e.g., pipelines/power lines) while ground-based systems are good at mapping the nodes themselves (e.g., refineries/power plants). These two technologies are then, for the most part, complementary. An example is shown in Figure 7 below:

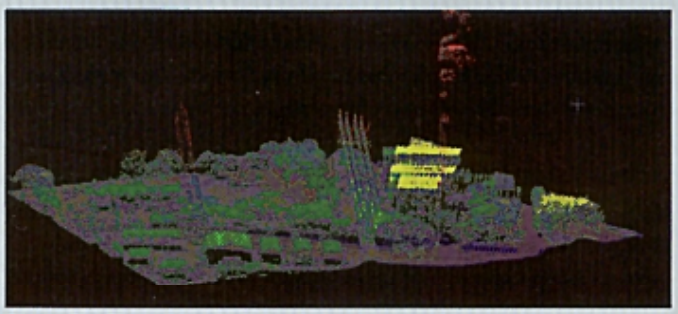

Figure 7a. Typical level of detail for airborne lidar systems.

Figure 7b. Typical level of detail for ground-based lidar systems.

Parting Thoughts: Predictions for the Future

It appears that airborne and ground-based systems both have a healthy future. They will continue to fill the important mapping/surveying niches they presently fill. As the performance of airborne systems increases, there may be some small overlap with some demands currently met using ground-based techniques, but it is even more likely that we will see both types of data acquired at the same location for differing purposes. Consider also these possibilities and parting thoughts, and what they might mean to lidar users in the future:

- At some point, we may see GPS and possibly IMU/compass functions embedded with ground-based lidar.
- Pulse rates of both airborne and ground-based lidar will continue to increase, as this is the primary measure of system productivity in the marketplace.
- Airborne lidar will continue to take advantage of the best that GPS technology can offer, and that this will push airborne lidar accuracies closer to that of today's ground-based lidar systems, though likely never quite getting there. GPS is simply one error source that ground-based lidar systems do not have to contend with.

- Airborne and ground-based lidar data will see increased use in fused data sets (see Figures 8 and 9 below). To facilitate this, the lidar industry must increase the speed with which
  - Ground-based data can be georeferenced,
  - Large data sets from airborne systems can be ingested, and
  - Ground-based and airborne-acquired data can be displayed and handled, especially in conjunction with auxiliary sensors.
- Planning and processing software will continue to be enhanced for both airborne and ground-based systems. Processing takes a large portion of the overall job budget and is the most obvious "point of pain" for practitioners

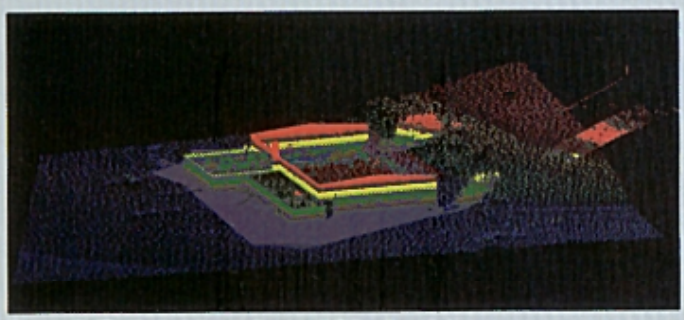

Figure 8. Typical airborne/ground lidar fused data set.

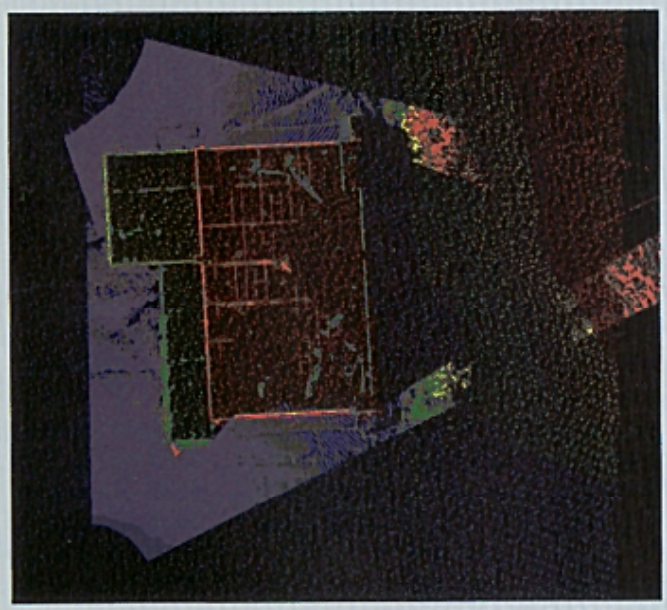

Figure 9. Overhead view of fused data set, highlighting the higher density of ground-acquired data.

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