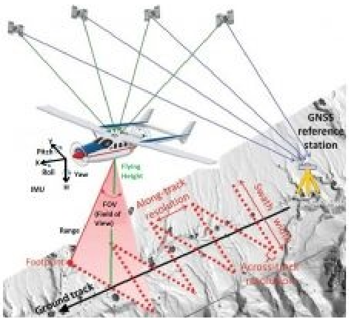
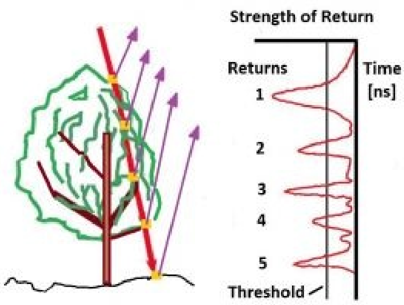
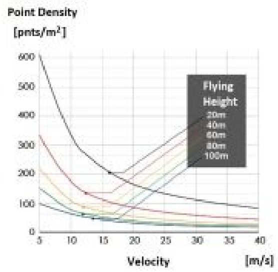
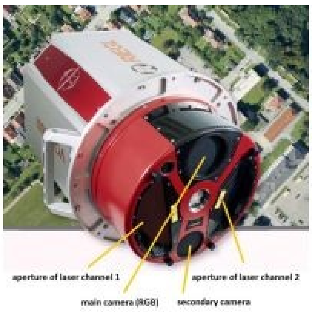
A VIEW ON STATUS, DEVELOPMENTS AND TRENDS

The Fierce Rise of Airborne Lidar









Today, automatic matching of overlapping aerial imagery and airborne Lidar are the main geodata technologies for capturing dense point clouds of the Earth's surface. The sampled points are used for the generation of bare ground representations which are often augmented with buildings and trees. Airborne Lidar is flourishing as a prevalent geodata acquisition technology and continues to show a fierce rise in terms of advancements and applications. Read on for an article that discusses the main technological advances of today's operational systems and surveys the state of the art, developments and trends.

Having trained as a geodesist and photogrammetrist, I first started conducting research into laser scanning and more specifically airborne Lidar in early 1997. Ever since I have regularly reported on and discussed the state of the art and developments – often in the form of product surveys – in the pages of *GIM International*. Over the past 20 years, airborne Lidar has made admirable progress and has gone mainstream, joining aerial photogrammetry as an important geodata acquisition technology for creating digital elevation models (DEMs), digital surface models (DSMs), orthophotos and derived products, 3D models of cities and 3D digital landscape models. Indeed, airborne Lidar has evolved into a most successful geodata acquisition technology used for multiple applications, including forest stand monitoring, urban planning and monitoring, heritage mapping, natural resource management, disaster management, corridor mapping, hydrological modelling and forest carbon monitoring.

From Points to Returns

Over the course of time, design and engineering of airborne Lidar systems have mainly been concentrated on improving the resolution, i.e. point density, and the amount of attributes recorded per individual ground point. Initially the main end product was considered a DEM or

DSM. Therefore, the emphasis was on calculating X,Y and H coordinates of the individual points in a preferred local or regional geodetic reference system using GNSS and an inertial measurement unit (IMU). Figure 1 sketches the basics of the computation of X,Y,H coordinates of Lidar points. An additional attribute recorded was the strength of the return. In many applications this strength was used for checking and quality assurance purposes only and was discarded once the DSM or DEM had been created and approved. Filtering, i.e. the removal of unwanted points such as multipath outliers, points on cars, cows or other cattle, was done by checking whether a point fitted within a neighbourhood of points using geometric constraints. When the aim was to create a DEM, i.e. a bare ground representation, points which reflected on buildings and vegetation had also to be removed. A lot of academic research has been devoted to the automatic detection of unwanted points.

Full Waveform Digitisation

The more attributes that are recorded per point, the better the assignment of classes will perform. The desire to collect more and more attributes resulted in two major advances. The first of these occurring on the market was full waveform digitisation (FWD), in which not only the first and last return are recorded but rather the entire return is sampled in regular intervals. This capacity to sample the entire return has now been available from all major manufacturers for nearly a decade.

Initially, most airborne Lidar systems detected the first return reflected from objects on the Earth's surface hit by the laser pulse. In forestry, which was an important application area in the early days, foresters discovered that it would be beneficial if not only the reflection on the canopy (first return) but also the ground underneath the trees could be captured to generate a bare ground elevation model (DEM). In response, manufacturers introduced facilities to capture the last return in addition to the first return. The approach was based on the observation that the foliage cover is usually not completely impermeable but rather semi-porous; a part of the pulse may reflect on leaves but gaps between the leaves allow the pulse to reach the ground and to be scattered back to the Lidar receiver. In other words, the first return reflects off the foliage and the last return off the ground, i.e. indicating the bare ground and thus suited for DEM generation. The difference between the last and first returns provides a measure of the height of the tree and ultimately the forest stand as a whole.

The recording of the backscatter of each emitted pulse did not stay limited to two returns for long. To allow more information to be derived from the data, returns also started to be recorded between the first and last return (see Figure 2) finally resulting in full waveform digitisation. FWD samples the entire return signal from its leading edge to its trailing edge at regular intervals, e.g. 1ns. Depending on the sample interval and the height of the object, either 64, 128 or 256 samples are taken. FWD requires huge data storage capacities, of course, but benefits from the fact that it generates more attribute data about ground features, resulting in more reliable classification of objects and a refined classification scheme.

Multispectral Lidar

Multispectral Lidar can also increase the number of attributes per ground point. In December 2014 Teledyne Optech introduced the world's first multispectral airborne Lidar, called Titan. Three independent pulses – wavelengths 532nm, 1,064nm and 1,550nm – are emitted, each with a 300kHz effective sampling rate for a combined ground sampling rate of 900kHz. When the point density is high the system produces, after gridding, an image-like picture (Figure 3). Uses include topographic surveying, 3D land cover classification, environmental modelling, vegetation mapping and shallow water bathymetry.

Multiple Pulses in Air

Point density depends on a number of system parameters including pulse frequency, rotating speed of the scanning mirror, field of view, the speed of the aircraft and the flying height. Figure 4 shows the relationship between point density, flying height and aircraft speed for a particular Lidar system. One of the limitations of the early Lidar systems to increase point density was that the return of the previous pulse had to be captured by the sensor before the next pulse could be emitted. This was necessary to avoid confusion between returns of subsequent pulses. At a flying height of 1km and given that the speed of light is approximately 300,000km/sec, the pulse frequency, also called laser pulse repetition rate, could thus not exceed 150kHz. However, using smart solutions embedded in the system, the phenomenon of multiple pulses in air was introduced, largely eliminating the limitation discussed above.

Increased point density can not only be achieved through multiple pulses in air or higher pulse frequencies but also by combining several Lidar heads into one system. In March 2014 Swedish firm Airborne Hydrography AB (AHAB), which has been part of Leica Geosystems since October 2013, launched the Dual Head consisting of two scanners each emitting up to 500,000 pulses per second, totalling a pulse frequency of 1MHz. When flying at a height of 1km, the point density is 16 points per square metre. Leica has not only combined two oblique laser sensors into one system to increase pulse frequency, but has also added two digital cameras: one for high-resolution imagery and one for quality control. The system has been specifically designed for surveying urban environments with many high-rise buildings and other objects that complicate 3D mapping as well as utility corridors with obscured objects.

In order to increase point density, RIEGL introduced a dual-channel system which was released at Intergeo 2016: the VQ-1560i (Figure 5). This waveform processing system has a pulse frequency of up to 2MHz, resulting in 1.3 million measurements per second on the ground. The operation altitude is up to 5km, making the system suitable for multiple tasks including ultra-wide area mapping, mapping of complex urban environments, city modelling, corridor mapping, agriculture and forestry.

Compact

Unmanned airborne systems (UASs) have garnered the earnest interest of a broad group of geomatics professionals. UASs have proven to be a reliable technology for capturing 3D geodata of small areas, individual buildings or complexes of man-made structures using cameras. Up until recently the use of airborne Lidar was largely confined to manned flights, mainly due to the fact that Lidar sensors used to be heavy – in the order of tens of kilograms – and consume a lot of power which constrains their use on small, unmanned aircraft. As a result, until recently UAS Lidar surveys were unfeasible for all but the very largest UASs. Overcoming this barrier requires small dimensions as well as low weights and modest power consumption. Such lightweight, compact and low-energy-consuming Lidar devices have recently become commercially available. I consider a few of them below, ranked according to weight.

Lightweight Systems

RIEGL's VUX-1, introduced in 2016, weighs around 3.5kg and is compact enough to be mounted on a variety of small fixed-wing and rotary unmanned aircraft (Figure 6). The system captures up to 200 parallel scan lines per second while up to 500,000 measurements per second can be recorded. The manufacturer claims an accuracy of 10mm. The flying height is over 300m and the field of view is up to 330°. Next in line is the Alpha AL3-32, manufactured by Phoenix Lidar Systems based in Los Angeles, California, USA. This Lidar device weighs 3.2kg, the maximum flying height is 100m, the pulse frequency is 700kHz, the field of view is 360° and two returns per pulse can be recorded. Smaller than the AL3-32 is the Alpha AL3-16. This system fits in a box measuring less than 25cm square and weighs 2.2 kg. The maximum flying height is 100m, the pulse frequency is 300kHz, the field of view is 360° and two returns per pulse can be recorded. For both the AL3-32 and the Alpha AL3-16 the manufacturer claims an absolute accuracy of 25/35mm at a flying height of 50m. As the systems operate fully autonomously, they can be mounted not only on a UAS but also on cars, boats or backpacks. At 2.1kg the YellowScan Mapper, introduced in 2014, weighs a little bit less than the Alpha AL3-16 (Figure 7). The maximum flying height of the Mapper is 100m, the pulse frequency is 40kHz, the field of view is up to 100° and three returns per pulse can be recorded. According to the manufacturer, its main applications are archaeology, construction, forestry and corridor mapping. In 2016 YellowScan, based in France, introduced a system called the Surveyor with an even lower weight: just 1.5kg. The maximum flying height is 50m, the pulse frequency is 300kHz, the field of view is up to 360° and a maximum of two returns per pulse can be recorded. The applications are focused on mining, civil engineering and corridor mapping. When it comes to lightweight systems, to date the Velodyne Puck appears to be the champion – it fits into the palm of a human hand and weighs 830 grams (Figure 8). The maximum flying height is 100m, the pulse frequency is 300kHz and the field of view is 360°.

The maximum distance a Lidar pulse can bridge from sensor to ground and back depends on the power used, the pulse frequency and the reflectivity of the part of the object hit by the pulse. For example, when the reflectivity is 20% assuming flat terrain and the pulse frequency is 50kHz, the maximum operational flying height of RIEGL's VUX-1 is 350m. This figure reduces to 55m when the pulse frequency is increased to 550kHz and the pulses are emitted with reduced power.

Ease of Operation

The design of an airborne Lidar system depends not only on the needs of a specialised group of geomatics professionals who are used to capturing (ultra-)wide areas. Other professionals with modestly sized projects appreciate simplicity and ease of operation. For these types of users Teledyne Optech introduced the Eclipse in 2016 (Figure 9). This airborne Lidar system weighs 36.6kg and focuses on data collection of small areas using low-cost platforms. The system operates largely autonomously; one pilot is needed on board for navigation but no operator.

Concluding Remarks

Today, data collected from sensors mounted on aircraft can compete with data captured on the ground in terms of efficiency, accuracy and level of detail. Just 20 years ago surveyors would have expressed disbelief at the thought of such a silly idea. Lidar technology is still making strong progress which makes me curious about what the next couple of years will bring us. One interesting development is single photon Lidar (SPL). The few systems in operation to date enable a hundredfold increase in the point density. The principle is based on splitting a single emitted pulse into tens to hundreds of sub-pulses. One pulse thus results in an array of returns which enables an increase in the point measurement rate to 100 million points per second or more.

Author

Mathias Lemmens gained a PhD degree from Delft University of Technology, The Netherlands. He acts as an international consultant and is the author of the book *Geo-information – Technologies, Applications and the Environment* published by Springer in 2011. He is currently working on a book on point clouds.

Email: mlemmens@geotexs.nl

Figure Captions

Figure 1, *GNSS and IMU enable automatic calculation of the X,Y,H coordinates of ground points from range and scan angle; across-track scanning is performed using a nutating mirror.*

Figure 2, *Digitisation of multiple returns in a forest area: first, last and three returns in between (Courtesy: M. Lemmens).*

Figure 3, *Multispectral images created from a Titan airborne Lidar system manufactured by Teledyne Optech.*

Figure 4, *Relationship between point density, aircraft speed and flying height of the Phoenix Alpha AL3-32 Lidar system, weighing 3.2kg.*

Figure 5, *RIEGL VQ-1560i, consisting of two laser scanners and two cameras.*

Figure 6, *The RIEGL VUX-1 Lidar system is small enough to be carried by a UAS.*

Figure 7, *The YellowScan Mapper lightweight Lidar system in operation.*

Figure 8, *A demonstration of the miniaturisation of Lidar sensors; shown is the Velodyne Lidar Puck VLP-16.*

Figure 9, *The Eclipse has been developed for use by project engineers who prefer ease of operation.*