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A comparison between photogrammetry and laser scanning

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Abstract

A comparison between data acquisition and processing from passive optical sensors and airborne laser scanning is presented. A short overview and the major differences between the two technologies are outlined. Advantages and disadvantages with respect to various aspects are discussed, like sensors, platforms, flight planning, data acquisition conditions, imaging, object reflectance, automation, accuracy, flexibility and maturity, production time and costs. A more detailed comparison is presented with respect to DTM and DSM generation. Strengths of laser scanning with respect to certain applications are outlined. Although airborne laser scanning competes to a certain extent with photogrammetry and will replace it in certain cases, the two technologies are fairly complementary and their integration can lead to more accurate and complete products, and open up new areas of application. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The comparison below will be restricted to airborne systems, and ranging laser systems only, i.e., excluding airborne-based probing lidar that is used mainly for environmental and other thematic applications. Different experimental systems (see Baltsavias, 1999b), developed mainly by NASA, as well as ALS systems with dual frequencies for bathymetric/hydrographic applications, will not be treated here. The first group shows some interesting technological developments and new areas of application, while the application domain of the second group can in principle not be treated by other optical sensors. In photogrammetry, both analogue and digital sensors, and analytical as well as digital photogrammetric systems will be included.

1.1. Short overview

Photogrammetry is based on processing of images, with main products: DTMs, DSMs, orthoimages, 2D and 3D reconstruction and classification of objects for mapping or thematic applications, and visualisation (maps, 3D views, animation and simulation). Processing of films is usually made by analytical plotters (in use for about 20 years), while digital data are processed by Digital Photogrammetric Systems (DPS) which are in use for about 7–9 years. The processing algorithms are being continuously developed. Photogrammetric theories can count on a long history of developments for over a century. Intensive research has been conducted for the last 20 years for the automation of information extraction from digital images, based on image analysis methods.

Laser, one of the most important technological developments of this century, was introduced in our

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community mainly through the research activities of the Institute of Photogrammetry (Prof. F. Ackermann), University of Stuttgart, in 1988. During the last 2–3 years, the interest in airborne laser scanning (ALS) has strongly increased. Currently, about five companies sell (or plan to sell shortly) ALS systems, while worldwide about 35 companies offer services, and about half of them with custom-made systems. Almost all systems make use of GPS and INS for sensor orientation. The laser frequency is in the 500–1500 nm range, with typical values of 1040–1060 nm. Airborne laser ranging systems typically use optically pumped (often with laser diodes) solid-state lasers with short pulses (ca. 10 ns) of medium to high power and a beam divergence of ca. 1 mrad. Some systems allow the recording of multiple echoes from one laser pulse, e.g., first and last, or even additional ones in regular intervals in-between. Some of the systems deliver not just range but also intensity information, whereby the latter has been used very little up to now. Many systems provide additional on-board standard video or digital cameras; these are, however, usually only loosely integrated with the ALS and GPS/INS systems. Integration with photogrammetric cameras, multispectral sensors, SAR, etc. has remained up to now on a limited level. ALS can be performed from helicopters, fixed-wing aircrafts or both. Flying heights can vary from 20 to 6000 m, while typical values are in the range of 200–1000 m. The processing of the raw data is usually done by the service firms with partly unknown algorithms and procedures, especially for the more complicated and later processing involving point filtering and classification, while there are some commercial packages that allow GPS/INS processing, geodetic transformations, visualisation, and DTM interpolation. ALS is a relatively new technology, with obvious influences on costs, system integration and processing methods maturity, number of providers, etc.

1.2. Major differences

The major differences between photogrammetry and ALS are: passive vs. active, high-power, collimated and monochromatic sensing; generally frame or linear sensors with perspective geometry vs. generally point sensors with polar geometry; full area coverage vs. pointwise sampling; indirect vs. direct acquisition or encoding of 3D coordinates; geometrically and radiometrically high quality images with multispectral capabilities vs. no imaging or monochromatic images of inferior quality; and ability for ALS to 'see' objects much smaller than the footprint (small openings below vegetation, power lines, etc.). All other differences are a consequence of the above mentioned ones. Additional differences exist with respect to technology maturity and potential for further development. From a product point of view, ALS is currently available only by service providers, while photogrammetric systems can be found on private desktops all over the world where users can generate their own data.

1.3. Common aspects

Common aspects between photogrammetry and ALS include: (i) use of GPS, and with digital photogrammetric sensors, especially linear ones, GPS/INS; (ii) methods for processing of raw data, like filtering of large errors, removal of non-DTM objects like buildings, data reduction (thin-out) and compression, and detection of breaklines, are shared between ALS and image matching for DSM/DTM generation; (iii) furthermore, when laser data are regularly interpolated, they can be treated as images and various image analysis/processing techniques can be applied to them.

Thus, sensor integration and image (or digital signal) processing and analysis are two important topics that unify the two technologies.

2. Comparison

The main common application, and competition field, between photogrammetry and ALS is the 3D measurement of surfaces and single objects. The reason is that classification and identification of objects with ALS, without use of additional optical sensors, is very difficult to impossible. Before making a comparison between the two technologies, one main idea will be laid out. Measurement without interpretation is sometimes very difficult or impossible. As an example, to measure buildings among millions of other measurements on other objects, first, the measurements on buildings must be detected (this involves classification of measurements) and then the buildings must be modelled based on the detected measurements and other application domain knowledge. Since interpretation based solely on range/height data is difficult, this makes clear that images which are spatially, and for multitemporal analysis also timewise, co-registered with the laser measurements, are often a necessary supplement for interpretation, and thus measurement. An interpretation is often necessary also for surfaces/objects more general or specific than buildings, since each customer usually has concrete requirements on what has to be measured.

2.1. Available sensors

The variability of passive optical sensors (POS) is impressive. Depending on the application requirements, there are sensors of different geometry (2D, linear, multiple line ones, point detectors), different format, geometric, radiometric and spectral resolution (including number, central wavelength and width of spectral bands), geometric accuracy (metric, semi-metric, non-metric), storage medium (analogue, digital), weight, power consumption, cost, etc. ALS systems offer much less variability and flexibility. Digital sensors with panchromatic, multispectral or hyperspectral properties based on linear or area CCDs and detectors (in some hyperspectral systems) are used in a continuously increasing degree. Typical digital sensors include standard video, still video (B/W, colour, IR), custom-made ones using large area CCDs (usually only B/W), and linear CCDs (one or more for along track stereo, and spectral sensing).

The main comparison of ALS with passive optical sensors is with photogrammetric film cameras, the expected digital photogrammetric cameras (one 3-line CCD based system announced for summer 2000), and less with large format area CCD based sensors (currently, sensors with 2000^2–4000^2 pixels are used). Photogrammetric film cameras offer a large format, a typical resolution with FMC of ca. 60 lp/mm, lenses of various focal lengths and very small distortion, large storage capacity (ca. 500 images per rollfilm, corresponding to 200 GB of data for B/W film at 12 μm scan pixel size); also, they are very robust, stable and well calibrated. Furthermore, condensation and high temperature, the latter being caused by the very low efficiency of lasers and the transformation of the lost pumped energy in heat, can impair laser performance and should be controlled much tighter. Power requirements for ALS are also higher, while some systems cannot be mounted in standard aircraft holes. POS sensors, and photogrammetric cameras in particular, provide an easier, less complex and more reliable operation, and are cheaper.

A seldom discussed topic is the lifetime of the sensors. While robust aerial cameras can be used for decades (an RC 8 is still used in Switzerland), lasers have a limited lifetime, which is inversely proportionally depending on the operational temperature. For temperature regulated Nd:YAG lasers, the lifetime is ca. 10 000 h, while some systems exhibit a rapid deterioration after long use, i.e., although the same energy is pumped into the laser, the output power is drastically reduced.

Regarding spectral information, although lasers exist in a much wider spectrum than the visible and near infrared (e.g., 50–30 000 nm, excluding X-ray and free electron lasers), those used in ALS are limited to the NIR region. Some lasers are tunable, i.e., their wavelength can be shifted, sometimes over large ranges of several hundred nanometers, but again this does not refer to lasers commonly used in ALS, and in addition, the frequencies cannot be used simultaneously. Recently, semiconductor lasers that have been developed at Bell Labs emit simultaneously in three wavelengths, but they are currently in the 6.6–8 μm range and their commercialisation will take years. Simultaneous emission in more frequencies is possible through generation of harmonics (multiples of the fundamental laser frequency), e.g., with Nd:YAG lasers having 1064 nm wavelength, the 1st harmonic has 532 nm wavelength (used in bathymetric lasers), the 2nd 266 nm, etc. Such systems cost more, are more complex, require more resources (e.g., storage) and sometimes the power of the higher harmonics is lower. In spite of these interesting and promising developments, ALS currently cannot compete with POS in provision of simultaneous multispectral information.

2.2. Platforms

POS have been placed on almost all possible platforms from small balloons to geostationary satellites. ALS systems have been restricted, with the exception of a few spaceborne systems, to helictopters and airplanes with flying height mainly up to 1000 m. New commercial ALS systems have been announced with flying height up to 6000 m, but very little is known up to now on their operational use and the achieved accuracies. Furthermore, the maximum flying height is restricted by the laser power, the sensitivity of the detector, and for high pulse rates by the maximum unambiguous range (Baltsavias, 1999a). The minimum flying height may also be restricted due to eye safety considerations. With ALS, flying speed may be restricted by the technical parameters of the system (e.g., scan rate), storage capacity, the requirement to have smooth turns and small interpolation errors due to the use of GPS/INS for the laser beam positioning, and the manoeuvres required in rough terrain in order to ensure overlapping strips. Some of the POS, like digital cameras, especially linear CCD based ones, also have certain restrictions with respect to flying height and speed of the platform.

2.3. Integration of GPS / INS

With ALS and non-area POS, GPS/INS systems are a necessity. With area based POS, especially photogrammetric film cameras, integration of GPS is a clear tendency. INS, which is still a very expensive component of the ALS systems, is not necessary, although it can be used, if required. In addition, for POS with 2D or 1D geometry, the frequency of GPS/INS measurements can be lower than for a point sensor.

2.4. Flight planning

With photogrammetric cameras, flight planning is simple and well established. With ALS, it is much more complicated, and there were projects where gaps between flying strips have occurred even in flat terrain. Some reasons are the relatively narrow strip width, especially with low flying platforms and possibly no use of DGPS for navigation, the small strip overlap for productivity/cost reasons, and the partly contradictory requirements, e.g., the maximum laser range is constrained by the lowest terrain points, while a sufficient overlap must take into account the highest terrain points. In difficult terrain, e.g., flying in steep valleys towards rising mountains, flight planning can become quite complicated and would require the existence of at least a rough DTM, and possibly the use of a helicopter as a platform. In addition, with POS, through sufficient overlapping in both along and across flight direction, the block geometry is more stable and a redundancy is provided which can be favourably used in the processing stage, e.g., for mapping occluded areas. With ALS, mapping of large areas requires a careful selection of number and distribution of ground reference stations. Visibility of usually 5–6 GPS satellites is also required, while in valleys with steep high mountains, GPS outage can occur. Any serious error during flight will require its repetition. With POS, almost no flight must be repeated and errors are much less, and often can be compensated by a posteriori measures (e.g., failure of GPS or INS with frame sensors can be accommodated by use of control points for sensor orientation).

2.5. Flying time and covered area

As explained under platforms above, flying speed and height are lower with ALS than with POS. In addition, the swath width with POS is generally larger. E.g., while with aerial cameras, typically a wide angle lens (75° effective FOV) is used, ALS typically have a 20–40° scan angle. Thus, for the same flying hours, a POS can cover a much larger area. Even if we assume equal flying height and speed, a POS with 75° FOV results in a 2.9 times larger covered area than a laser with 30° FOV, assuming equal sidelap.

2.6. Flying date and time, dependence on weather

Laser, being an active sensor, can theoretically be used 24 h a day. Actually, the less the background irradiance, especially from sunlight, the better its maximum range performance. For the same reason, ALS does not lead to 'illumination' shadows cast by objects (actually they exist, but they correspond to the occluded areas of POS). Since ALS is mainly used for ranging and does not depend on presence of texture for accurate measurements, the land cover conditions are less important. For DTM generation, as with POS, data acquisition is better when trees have no leaves, whereby flights can take place even in winter with a thin snow layer (depending on the laser wavelength, this can even lead to a stronger laser pulse reflection and better results). Dependence on weather conditions (clouds, fog, smog, smoke, dust, precipitation) is in principle as with the POS. Flying with light rain may be possible but not advisable. Strong wind is more of a problem with ALS, due to the narrow swath width and the higher accuracy navigation requirements. Summarising, with ALS much more flying hours are possible, which can be an important advantage, if results are needed fast.

2.7. Object reflection

Laser is a monochromatic light with a very narrow spectral width (called also linewidth). Although there are lasers that emit in more than one frequency, and some can have a large spectral width (e.g., 100 nm), the typical width is about 2–5 nm (the often used Nd:YAG has typically 0.1–0.5 nm width, while there are lasers with a linewidth of < 1 pm). POS on the other hand, although they can have a narrow spectral width of a few nanometers, as with some hyperspectral sensors, typically they either cover the whole visible spectrum or have a few broad spectral bands. Thus, with ALS, objects that have narrow spectral characteristics in the laser wavelength region will exhibit a higher response (contrast) than with the POS. On the other hand, other objects will reflect very little (close to zero) the laser wavelength. Thus, with ALS, the signal from some objects will be very low and may thus not be detected (e.g., newly tarred roads), while the dynamic range (range of recorded reflectance) is much higher than with POS, and more difficult to be accommodated by the detector, leading often to saturation. With POS, all objects are 'visible', while saturation is a much smaller problem. Light reflections, e.g., on water bodies, and hot spots can occur with POS, while specular reflections are a problem also with laser and a bigger one than the light reflections with POS.

2.8. Imaging

The laser footprint is approximately circular and varies with the scan angle and the topography. The point spacing along and across track differ and the latter varies also along the scan line with the scan angle (often along the track spacing too, depending on the scan pattern). Thus, it is impossible to image the whole area, homogeneously and without gaps and overlaps; plus, the further visualisation, processing, etc. of the image requires the interpolation of a regular grid. These problems are mainly due to the active nature of laser, i.e., the image is formed on the ground, and not in the sensor focal plane as with POS. The 'lasels' have a much larger footprint, i.e., worse geometric resolution, than the pixels from the same flying height (a typical laser beam divergence of 1 mrad results in a 1 m footprint for 1000 m flying height, while a 15 μm pixel with 15 cm camera constant corresponds to just 10 cm). In addition, the radiometric quality is inferior to that of the POS (with ALS the signal can be very low especially for high flying heights and low reflectivity targets, see range equation in (Baltsavias, 1999a)), and even artifacts (interference patterns) that completely distort the image have been observed in some cases. Additional problems have been mentioned in Section 2.7. With pulse lasers the recorded intensity is in most cases not the integration of the returned echo but just its maximum. The topic of the spectral information has been treated above. One minor advantage of ALS images is that, being produced by active systems, they are insensitive to illumination shadows. Furthermore, laser images are already geocoded, i.e., no orthoimage generation is necessary. Concluding, laser images cannot compete and substitute high quality optical imagery. However, they can provide useful additional cues, which, together with the 3D object description, can help the detection and classification of objects (see Hug and Wehr, 1997).

The high quality, large-coverage images provided by aerial cameras are a very important advantage of photogrammetry. They are needed for generation of orthoimages, 3D visualisations, simulations and animations (products that gain in importance), and facilitate detection, classification, identification and measurement of objects. Furthermore, they are a valuable archive, allowing arbitrary revisiting, control and updating of the derived data, extraction of additional information, multitemporal analysis, etc.

2.9. Degree of automation

ALS can provide under ideal conditions fully automatically raw X, Y, Z data. This data still needs manual editing for error correction and fill-in of gaps. Filtering-out of vegetation and buildings can be automated to a high degree. Photogrammetric processes, especially when involving film, need more manual intervention. Interior orientation can be fully automated, but this is not offered by all commercial systems. Sensor orientation (aerial triangulation) is very difficult to fully automate, and image matching with most commercial programmes typically exhibits more and/or larger errors than those observed in raw laser data, thus requiring more manual editing. This situation can drastically change with the introduction of a digital photogrammetric camera, use of GPS/INS and the development of sophisticated processing algorithms. Then, the only difference to ALS with respect to automation will be the more extensive manual editing for matching and reduction of the DSM to a DTM. This longer manual editing will be largely compensated, however, by the fact that stereo images can be directly used for manual interpretation and 3D editing, while for laser data they must be provided somehow, and by the existence of more developed editing tools in some digital photogrammetric stations.

Although, as mentioned above, ALS can theoretically provide automatically raw X, Y, Z data, this is not always the case in practise. Unmodelled errors lead to shifts (planimetric and vertical) and tilts between overlapping strips (see Huising and Gomes Pereira, 1998). These errors are better visible when the laser points are denser and when the errors are clearly above the noise level of the system (thus, the errors will be more visible in more accurate systems!). In this case, the strips have to be corrected relatively to each other and the whole block should be tied to the local coordinate system (Kilian et al., 1996). This requires a procedure similar to the photogrammetric strip adjustment, i.e., well defined tie points between the strips, and control points at the block borders are needed (possibly with the inclusion of across strips at the block ends). Tie points are more difficult to get than in images, since they must be well-defined 3D structures, e.g., building corners. Furthermore, the laser measurements usually have gaps between them, so these 3D structures might not be well-defined (e.g., building corner missing); plus, their appearance in different strips can vary (since laser points from neighbouring strips will almost never be identical). Matching these tie 'points' is more complicated since the data are not in a regular grid and the transformation of one point to the other should be a 3D one. Acquisition of control points is equally difficult. Height control points can be measured by GPS in flat areas, but these areas must be quite extended so that an identification error of the GCPs in the laser data does not introduce a height error. Full 3D GCPs can only be visible, well-defined and large 3D structures, like building corners, but these are not always available and cannot be easily measured by GPS.

Summarising, ALS has a higher degree of automation, which is one of the reasons why data delivery can be also faster. One reason for the increased automation is that ALS raw data include implicitly different functions which with photogrammetry must still be performed, like optionally film scanning, interior orientation and aerial triangulation (latter generally needed also for ALS), and matching. The 'rawest' possible ALS data are the X, Y, Z coordinates in WGS84 which are very close to the end product, while in photogrammetry, the first processing steps are just a necessary evil and never the aimed product themselves. Thus, ALS shortens considerably the road from data to useful information.

2.10. Maturity of the technology, availability of systems

Photogrammetry relies on mature, sophisticated algorithms developed and tested over decades. There are several commercial systems available, from complete ones, to smaller ones for orthoimage and DTM generation. Some of this functionality is also integrated in remote sensing and GIS packages. Thus, users cannot just make use of services, they can also produce custom-made products themselves. Thereby, they can make use of abundant, variable, affordable, and generally available data. ALS has up to now remained a provided service. There are very few owners that use ALS for internal production, and primarily for power line surveying. There is no single system for processing of laser data. A number of separate and often not interoperable packages need to be used, while proprietary processing algorithms of service providers are kept in darkness. Large data amounts also prohibit the use of several packages. There are no standards or commonly accepted guidelines on how to perform critical operations like calibration, strip adjustment, number and distribution of control points, etc., but these are badly needed for quality assurance and control. Thus, customers cannot be sure about the quality and reliability of the provided data. A positive development in this direction, although with a limited scope and some weaknesses in the content, are the 'Guidelines and Specifications for use of LIDAR Technology' for use in the National Flood Plain Insurance Program in USA, which are under preparation by FEMA (ourworld.compuserve.com/homepages/martinflood/ALMDownloads.html). Also regarding the number of providers, in photogrammetry the choice is much larger. Furthermore, with ALS, due to the current market uncertainty and the high initial investment costs, the probability that some firms will not survive increase, thus posing an uncertainty for customers.

Photogrammetry, however, also has some weak points. When using film, specialised, expensive hardware is required like image scanners or analytical plotters. The algorithmic developments in aerial photogrammetry have been rather slow the last period. Research is mainly focusing on automation of feature extraction, which will not soon bring results of the quality needed in daily production. Further advancements in DTM generation and digital aerial triangulation, although possible and partly necessary, are lacking or are very slow. The functionality and quality of the implemented algorithms of commercial systems are partly insufficient.

3. Comparison aspects for DTM / DSM generation

Here, DTM and DSM will be distinguished (latter including all visible object top surfaces).

3.1. Measurement of a DTM and / or DSM and reduction of a DSM to a DTM

With manual measurements in analogue or digital images, both DTM and DSM can be measured. Matching methods using digital images measure a DSM. Some commercial matching programmes offer the possibility to filter out non-DTM 3D objects like buildings and trees based solely on geometrical criteria, e.g., 3D blobs in the DSM that have a certain area and height (or slope) are excluded. This procedure, however, works well only with isolated buildings and trees (or if they are the minority within the filtering window) and in relatively flat terrain. In rough topography, terrain features like tips of hills are often also eliminated, while when the ground points are the minority, like with small openings in forests or narrow streets in densely built areas, the ground points instead of the 3D objects are filtered out. Other cues, indicating the presence of such objects, could be used in addition to the geometry in order to lead to a more complete and accurate elimination of non-DTM objects. Such cues include multispectral information, radiometric edge information (contrast, straightness, length and orientation), texture, support from existing databases, shadows which indicate 3D objects and context. Their exploitation by ALS is currently more difficult or impossible (e.g., multispectral information, shadows). These superior interpretation capabilities based on POS data have an importance not just for this limited task, but in general for automating the extraction and classification of objects. The process of non-DTM object detection is very difficult to automate fully, since the definition of 'terrain' or DTM varies from country to country (e.g., bridges are sometimes included in the DTM, sometimes not). With ALS, we should distinguish between closed surfaces (like building roofs) and surfaces with openings, like a tree canopy. In the second case, a certain penetration of the canopy can be achieved, and this permits in general the detection of both ground and tree tops. In the first case, the laser measures the DSM and similar algorithms as with image matching results can be used, i.e., detection of 3D blobs in the DSM and deletion based on geometric criteria. With respect to these criteria, ALS offers certain advantages, since measurements are in practise denser and/or more accurate than those of matching, and surface discontinuities like building walls are better modelled. This better modelling also allows the use of additional geometric criteria (Haala and Brenner, 1997; Hug and Wehr, 1997; Brunn and Weidner, 1998) for the detection of regular surfaces, e.g., detection of planar faces on building roofs.

3.2. Density and distribution of raw measurements

This is a decisive factor with respect to DTM/DSM fidelity and quality. With manual and matching photogrammetric measurements, one could measure theoretically as dense as possible. However, due to high correlation of neighbouring dense measurements, this does not make sense, even if the terrain were so rough. Here, we assume that the densest measurements are 100 μm or 5 pixels in image space (latter is based on the assumption that patches in image matching are 10×10 pixels and that the overlap between neighbouring patches should not exceed 50%; assuming a scan pixel size of 20 μm we get again a value of 100 μm). Assuming a 15 cm camera constant, this results in a grid spacing of $h/1500$ m, with h the flying height over ground. Some matching programmes, like Match-T, rely heavily on multiple raw measurements within each grid mesh. In this case, it is recommended that each grid mesh corresponds to 10^2–15^2 pixels. Thus, the minimum grid spacing increases to $h/3000$–$h/4500$ m. For ALS, assuming that the smallest reasonable grid spacing is half the laser footprint (again the overlap is not larger than 50%), the minimum grid spacing is $h\gamma/2000$ m, with γ the laser beam divergence in milliradians (for a typical $\gamma = 1$ mrad, the minimum grid spacing is $h/2000$ m). Thus, the two technologies are theoretically more or less equivalent. In practise, manual photogrammetric measurements never need to be that dense, while matching usually delivers less dense results than those of ALS.

3.3. Measuring modi and flexibility

All automatic procedures measure blindly a spatially homogeneous field of generally highly redundant points (with the only exception of feature based matching, which in low texture areas can have few points). Manual photogrammetric measurements on the other hand offer a high flexibility in the selection of measuring mode (raster, profiles, contours, spots heights, characteristic lines, hybrid modes), a selective measurement (much less and almost nonredundant points) and an explicit modelling of characteristic geomorphologic lines and points, which are crucial for a high quality DTM. Automatic methods, if they are dense, measure these points only explicitly and partially, and at the cost of a high and redundant data volume. Automation of breakline detection is easier with images than just the range data, as grey level edges can also be used as indicators of surface discontinuities. The high redundancy of automated methods can be useful in better object modelling, detection and classification, filtering of errors, etc.; however, after these processes have been performed, an intelligent data reduction and/or compression is necessary. Otherwise, data amounts explode, and in addition they cannot be processed by most commercial packages (e.g., assuming that a DTM interpolation programme can handle up to 5 million points, and a typical laser pulse rate of 10 kHz, only data of 500 s can be processed!).

3.4. Error budget and accuracy

In manual photogrammetric measurements, the height accuracy, assuming an image measurement accuracy of 15 μm for an image of average quality and texture, mainly depends on the flying height and the accuracy of the sensor orientation. With ALS, there are much more factors that can influence the results (see Baltsavias, 1999a for a short discussion) thus making derivation of theoretical accuracy models, prediction of the achieved accuracy and error propagation much more complicated. Furthermore, with POS the behaviour of planimetry and height is quite independent of each other and can be analysed separately. In addition, with ALS the error budget has a substantial constant term which in photogrammetry is lower (Baltsavias, 1999a). Accuracy with POS is also more homogeneous within the image format, while with ALS, attitude errors lead to a rapid height accuracy decrease with increasing scan angle, especially for high flying height.

Accuracy estimates for ALS, given by service providers, seem to be optimistic. It is interesting to note that the given height accuracy is 2–5 times better than the planimetric one. This implies that these results refer rather to flat surfaces. Independent investigations (Hoss, 1997; Kraus and Pfeifer, 1998; Murakami et al., 1999) have shown that, depending on terrain slope and cover, lower accuracies, especially in planimetry, than those specified by service providers, may be achieved. Kraus and Pfeifer (1998) report that with increasing terrain slope and roughness, the height accuracy deteriorates to 0.5–1 m for 1000 m flying height. These authors also mention that the accuracy of ALS corresponds for open and forest areas to that of 1:7000 and 1:10 000 scale photogrammetric measurements respectively, while if systematic errors can be modelled, then ALS becomes more accurate than photogrammetry for terrain slopes less than 30%. Ignoring the effect of terrain slope and target reflectivity on the laser accuracy, the expected height accuracy from a laser scanner consists coarsely of a fairly constant error of 5–20 cm (mainly due to GPS and ranging) and an error of ca. 0.5–2 cm per 100 m of flying height for typical attitude errors and a scan angle of 30° (in reality the height error is not linear but rather exponential; for medium to large scan angles, it increases rapidly with increasing flying height). Photogrammetry also has a constant term due to limits in the accuracy of GCP coordinates (assumed to lie at 2–5 cm) and their image coordinate measurement (3–4 μm). Assuming a 60% overlap, 15 μm accurate image measurements, 15 cm camera constant and flat terrain, there is an additional error of 1.6 cm per 100 m of flying height. For a given flying height, the spreading of the accuracy values for ALS (see Baltsavias, 1999a) is much larger than for photogrammetry and is increasing with increasing flying height. Comparing the accuracy values for identical flying height in the range 400–1000 m, the photogrammetric accuracy is on the average slightly better than the ALS one, although the latter can in good cases be more accurate. It is in the higher flying heights where laser could outperform photogrammetry, if attitude determination is accurate enough and the received target reflection is sufficient. However, there are no published tests with ALS for flying heights more than 1000 m.

The previous comparison refers to manual photogrammetric measurements. Matching can deliver in good cases equally or even slightly more accurate results than manual measurements. In addition, doubling of the pixel footprint (which can be generated by various methods) causes only a slight deterioration (by ca. 10%–20%) of the DTM accuracy. A preprocessing to support matching through manual measurements of breaklines, elimination of problematic areas, 'lake fill', etc. is possible. However, usually matching results include locally significant errors which require manual editing. Several problem cases that can occur with matching, like low texture, shadows, multiple solutions, geometric and radiometric differences between the images, poor approximate values, etc., do not affect ALS-derived DTMs. It should be mentioned, however, that matching algorithms have by far not exploited their potential, as important additional information by simultaneous use of more than two images or use of colour have not been exploited by commercial systems yet. Matching results are also less detailed and smoother, especially at discontinuities. Assuming a 1 mrad laser divergence, 5^2–15^2 patch size for matching, 20 μm pixel size and 15 cm camera constant, the area used for height derivation is for ALS $n^2 0.008$ m^2, for n (100 m) flying height, and for matching $n^2 0.005$–0.044 m^2. In matching, additional surface smoothing is caused by less dense measurements, and in some programmes, interpolation of poorly matched points from their neighbours and/or reduction of many measurements to one grid mesh. Furthermore, ALS can detect and measure objects much smaller than the laser footprint, like power lines, if these objects are good reflectors.

In photogrammetry, planimetry is typically 1/3 more accurate than height, while with ALS 2–6 times less accurate. Such planimetric errors will also severely influence the height accuracy on sloped terrain. For more details on the planimetric accuracy see Baltsavias (1999a).

It might seem a paradox, but this high degree of detail and the high accuracy over the whole imaged area can also be a disadvantage for ALS, as for example in applications where some objects, being a small portion in the area, need to be modelled very accurately, while the rest of the points should be ignored or modelled in a much less accurate or generalised fashion. A selective measurement and modelling process, as with manual measurements, cannot be implemented. In addition, if the accuracy and density requirements are lower than the ones typically provided by the ALS system, either the flying height must be increased (which for many systems is not possible), or the scan rate, and the scan angle or pulse rate, or even better both, should be variable within a quite large range.

3.5. Geomorphologic quality

Although the accuracy of the raw ALS data is high and their density too, the geomorphologic quality of the derived DTM is not always satisfactory. Apart from the lack of explicit modelling of characteristic lines and points, a major reason is also the filtering applied to the raw data (to reduce errors, filter out buildings, trees, etc.). The processing algorithms applied are generally nonintelligent image processing methods which cannot distinguish between signal and target objects to be filtered out. Thus, DTMs from ALS tend to be smooth and miss some important terrain features (see Kraus and Pfeifer, 1998). Manual photogrammetric measurements are still the best method for high geomorphologic DTM quality.

3.6. Production time

There is no doubt that with ALS due to the digital acquisition of the data and the direct range measurement, a DTM can be generated more rapidly than with photogrammetry. The generation speed relation will change with the advent of the digital photogrammetric camera, but ALS will still be faster. The question will be whether a rapid response is really required by the application at hand.

3.7. Costs

Photogrammetric costs are very well known. With ALS, they are not easy to find out. The technology is in a developmental stage and the market is not stable yet. Thus, some prices might be too low in order to attract customers. Each service provider has different means of calculating the costs, and there is partly a quite stiff competition among the service providers. Some prices mentioned are 300–1100 DM/km^2, but these vary a lot depending on the firm, size of the area and point density, type of postprocessing, and extra costs for mobilisation, platform, etc. Some papers have mentioned that ALS was cheaper, even by 70–75%, in comparison to photogrammetry (Gomes Pereira and Wicherson, 1999; Petzold et al., 1999). However, up to now there has been no publication of exact prices, deliverables and prerequisites, nor a thorough cost comparison. As an example, a customer, mentioning that ALS is cheaper, was using digital orthoimages and digital maps for editing of the laser data. A simple question is whether these necessary products were calculated in the costs, or assumed that they existed for free. The calculations become more complicated when, apart from the DTM, other products like high quality orthoimages, or even feature extraction, are necessary. An advantage of photogrammetry is that it can rely on an large existing image archive, while some of the images have been already oriented via aerial triangulation. Thus, DTM production can proceed faster and at a lower cost than with a new flight. If only a DTM is required, ALS might well be cheaper, but this depends also on the size, form and land cover of the area to be surveyed.

4. Advantages and main application areas of ALS

From the above made comparison, it follows that ALS has some strengths which can be favourably exploited in certain applications, the most important of which are listed below:

- Mapping of surfaces with very little/no texture or poor definition. There, image matching delivers very poor results, and manual measurements are also poor or slow/cumbersome. Examples include ice/snow surfaces, sand (coasts, dunes, desserts), swamps and wetlands.
- Mapping of forests and vegetated areas. ALS systems can provide measurements on the ground. The penetration rate mainly depends on type of trees (deciduous or coniferous) and season. Useful results, depending also on the terrain roughness, can be achieved even with penetration rates of 20–30%. Experimental systems (LVIS/NASA) using a very large laser footprint (10–30 m) have achieved results in dense tropical forests with a ground obstruction of 95%. In addition, through appropriate data process-

ing, both ground and tree height can be determined. ALS systems that record (a) first and last, or (b) even more than two echoes of each pulse, can more easily provide tree and ground height and those with more than two echoes can, in addition, measure a vertical object profile, thus enabling derivation of other important parameters like biomass estimation, tree type, etc.

- Mapping of long, narrow features. This includes road mapping, planning and design, powerline corridor planning and tower design, coastal erosion monitoring, coastal zone management, traffic and transport, riverways and water resources and traffic management, mapping of railway lines, fiber-optic corridors, pipelines, dikes, etc. Since ALS systems have a narrower swath in comparison to optical sensors, they are more cost-effective in capturing the information needed for such applications.
- DSM generation of urban regions for urban planning, roof-top heights for communication antennas, etc. Since ALS provides very dense and accurate measurements, detection, reconstruction and modelling of 3D objects with sharp discontinuities, especially buildings, is easier than in DSMs provided by image matching, or faster than manual processing.
- High point density, high accuracy mapping applications like monitoring of open pits or dumps, flood mapping, mapping of local infrastructures (e.g., airports), oil and gas exploration.
- Mapping of very small objects, e.g., power lines (probably THE killer application of ALS), which are hardly visible in optical images, or whose measurement cannot be automated.
- Fast response applications. Since ALS provides digital range measurements, this information can be quickly converted to 3D coordinates. This can be important in some cases, e.g., involving natural disasters.

5. Summary

With respect to future developments, ALS has a much higher potential. It is a newer technology and thus, has a greater margin for improvement, especially in the processing algorithms, and software and system development, while with its 'discovery' by users new applications will come up. Furthermore, laser is a technology with much broader base and interests, and the research in this field as well as the commercialisation of new findings are intense and advancing rapidly. Although many new developments are and will be in lasers that cannot be used in photogrammetry, some benefits will certainly result also for ALS, as laser-based earth observation from airplanes and satellites, as well as military applications, are important applications where improvements of the ranging and imaging capabilities of laser are expected. Furthermore, recording and exploitation of information with respect to signal properties like amplitude, polarisation, phase, frequency shifts and vertical profile can greatly improve the object classification and identification capabilities of ALS.

ALS is here to stay with us and hopefully flourish. It definitely has an overlap to existing photogrammetric processes, competes with them, and will also partly replace them. Its major advantages are density and accuracy of measurements, high automation and fast delivery times, the costs being a topic still to be resolved. However, to the greater extent, there is a complementarity between the two technologies. ALS can perform some tasks, which photogrammetry anyway could not [1] or very poorly perform and vice-versa. Furthermore, the use of ALS has concentrated up to now in large scale mapping and engineering surveys. Both technologies share similar methods for integration with GPS/INS and have the same nuts to crack, when it comes to automation of object recognition. An integration of ALS with digital POS and GPS/INS can open up new revolutionary approaches in the whole photogrammetric production chain.

The photogrammetrists have an important role to play in these developments. Laser, starting with light (Greek = phos) and dealing with measurements

[1] It would be an omission not to mention that currently, in certain applications, other technologies, e.g., interferometric SAR that has both advantages and disadvantages over the two technologies compared here, would be more suitable and cost-effective. An example is DTM generation in large cloud-covered areas, while P-band InSAR and radar tomography can compete with ALS in generation of DTMs and vertical profiles in forested areas.

(measure in Greek = metro), as much as a technology could possibly do, is nothing else than photogrammetry, and actually a subpart of it, dealing with a special type of sensor (sorry about the possibly misleading paper title!). It was photogrammetrists that played a major role in the exploitation and development of laser ranging for DTM generation. From the ca. 35 service providers, only one company comes from another field, ca. five are newly established, and the rest are firms involved in photogrammetry, surveying and mapping. Thus, ALS should not be mainly seen as a competition, but as an additional versatile tool to choose from. Photogrammetrists should decisively contribute, in close cooperation with open-minded firms, in the definition, standardisation and development of high-quality methods for the whole processing chain, and especially in the postprocessing phase of object filtering, extraction and classification, the integration with other sensors, and tighter coupling of technology and applications.

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