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# Height Information from Laser-Altimetry for Urban Areas

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## Abstract
The need for height information for approaching urban problems has grown rapidly the last decade. The needs include design and inspection of utilities such as water mains, sewer systems, tunnels, bridges, roads, railroads and power lines, and the creation of 3-dimensional digital city models, in which the shape of buildings and other objects have been reconstructed with high spatial detail, for city planning and development purposes. In the past, one could usually suffice with contour lines. At present, the demands with respect to accuracy and level of detail are far beyond this point. In addition, the processing of huge amount of data requires automation. New remote sensing techniques have emerged which are able to respond to these demands. They include Laser-altimetry, matching of stereo pairs of imagery and radar-based systems (INSAR). They sample the terrain blindly by automatic means, while being able to carry out data capturing with high point density. In particular, Airborne Laser-altimetry Systems (ALS) have many beneficial properties. The automation rate is large, while time-efficiency and cost effectiveness are high. This paper examines the suitability and possibilities of ALS for fulfilling parts of the height information needs in urbanised areas. Our considerations are partly based on an inventory study about height needs carried out among local authorities in the Netherlands. The local authorities involved cover both small and large cities. Our overview is interesting for many involved in urban planning, design, inspection and monitoring.

## Introduction
Approaches to urban problems demand geodata, which represent in a highly detailed form the environment in its full spatial and time dimensions. Before being ready for use, geo data need to be acquired. This seems trivial, but isn't. Too many take the existence of geo data for granted. Acquisition of geo data has long been and is still continuing to be a cumbersome, labour-intensive and expensive task. It can be readily envisaged that within the establishment of national or regional geo-information infrastructures (GII), the availability and collection of data will be one of the main limiting factors. A favourable development, the last decade has witnessed, is the rise of new remote sensing techniques, which are able to collect geo-data in an automated way. For example, techniques to collect highly automatically 3-dimensional geo data in the form of Digital Elevation Models (DEMs) have rapidly emerged. In particular, those data acquisition techniques, which are able to deliver accurate and detailed 3-dimensional geo-data in a highly automatic way are forming the leading edge. They include Airborne Laser-altimetry Systems (ALS), matching of stereo pairs of (aerial) imagery and interferometric SAR (INSAR). For being operationally attractive, desirable properties, which these techniques have to fulfil, include:

- High data capture rates
- High automation degree of the entire process, up to the creation of the desired 3-dimensional terrain surface
- Low cost per point
- Final solution largely independent of terrain type and terrain characteristics

Because of the above features, ALS stands at the front end of the emerging 3-dimensional geo-data acquisition techniques. The automation rate is substantial, whilst data capture rates of 100 km2/h are possible. Consequently, time-efficiency and cost effectiveness are prohibitive. Forests and dunes can be captured accurately at high level of detail. The detailed mapping capabilities enable monitoring of electric powerlines from the air. Risk management of coastal and river zones is an important application. In built-up areas, reliable, accurate and detailed 3-dimensional digital city models can be reconstructed is input for, amongst others, virtual reality systems.

The present paper elaborates upon the possibilities, which ALS has to offer for approaching space related problems in urban areas. Our considerations are partly based on an inventory study about height needs carried out among local authorities in the Netherlands. The local authorities involved cover both small and large cities. Because a large part of the Netherlands is located below sea level whilst the landscape is relatively flat, the accuracy demands of height information are at the cutting edge of technology. Our experiences are interesting for many involved in urban planning and monitoring processes. To date the possible fields of applications are far from being thoroughly scrutinised, so it is important to have insight into the principles and characteristics of the technique to arrive at a comprehensive understanding of the yet unexplored abilities. Therefore, we reserved also space to treat these features.

## Principles of Laser-altimetry

Laser-altimeters operate usually from an aircraft or a helicopter, although also orbiting satellites are used (laser pulses can bridge long distances.) Airborne Laser-altimeter Systems (ALS) are multisensor systems consisting of a reflectorless laser range system and a positioning system. ALS was first tried out in the 1960s. In the 1970s experimental systems were developed. Accurate positioning remained one of the bottlenecks until a decade ago GPS became operational. A laser ranger determines the distances from the platform to arbitrary points on the earth's surface by measuring the time interval between transmission of a train of pulses (up to 80,000 per second!) and the return of the signals (Figure 1). A rotating or nutating mirror enables scanning perpendicular to the flying direction, resulting in a swath width, which lies in the order of half the flying height of the platform. A flying height of 1000 meter is typically used during operational flights.

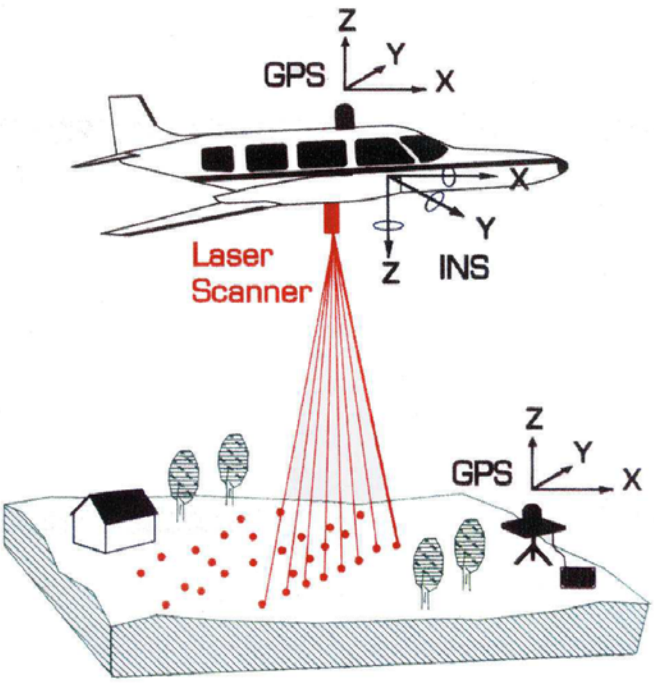


*Figure 1, Principle of Laser-Altemetry (Courtesy: Survey Department Rijkswaterstaat, Netherlands)*

The positioning system determines the position and attitude of the laser ranger. This is necessary for geo-referencing purposes, i.e. to determine the coordinates of the sensed points on the terrain surface in a local or national system. Usually one uses DGPS for position determination and an inertial navigation unit (INU) for the determination of the roll, pitch and yaw of the platform. The INU is autonomous and does not require any ground support. The sampling rate of GPS is low compared to that of the laser ranger and the INU. Transformation from the WGS84 coordinates to a local reference system requires a geoid. During flight a (digital) video records the terrain. The quality of the video limits its use to documentation and visual inspection. The final accuracy to be achieved depends on many factors, including the properties of the entire measuring system, flying height, terrain characteristics and applied processing software. During typical operational airborne surveys the accuracy values, to be achieved, are five centimetre systematic error and ±15 centimetres random (root mean square) error, both in the vertical. For a review of accuracy-aspects and issues refer to (Lemmens, 1997, 1999, 2000).

## Properties

Depending on the system, the flying height, the speed of the platform and the merging of data stemming from multiple flyovers, densities up to various dozens of height points per square meter can be acquired. Helicopters are better suited for high resolution coverage, because they can easily limit their speed. Since ALS is an active system, data acquisition is independent of sun illumination, while no shadows are generated. Weather and sight conditions do only slightly affect flight surveys, making the technique fairly well independent of season and daytime. For many countries, these are beneficial properties. Contrary to photogrammetry, height values in areas with low texture such as beaches and dunes are obtained effortless. The used wavelengths (visible and near infrared) do not penetrate material. Consequently, when transmitted in the direction of a forest stand or bushes, pulses will reflect on the foliage cover.

Nevertheless, depending on the density of the vegetation and the footprint size, parts of the signal will reach the ground; the footprint size depends on the characteristics of the ALS and the altitude of the carrier above ground surface, but is typically between 20 and 100 cm. By recording the last part of the return signal the distance to the ground is obtained. By recording in addition the first part of the return signal, canopy heights can be derived. Some systems are able to record the entire signal characteristic of the reflected pulse. Using advanced signal detection and processing techniques, information can be derived about the vertical structure of the surface, such as roughness, height and shape of objects, canopy density and height of trees, and the reflectivity of the surface. The amount of accompanying ground surveys is usually modest. Problematic accessible areas can be mapped relatively easy.

When waterbodies are hit, parts of the pulses may penetrate water and reflect on the bottom of the waterbody, enabling the measurement of water depths.

However, when waters are troubled, depth measurement fails. The pulse may also reflect on suspended layers causing spurious values. The absorption of pulses hitting water-bodies is rather high. Many pulses may be also subject of specular reflection, especially when the surface of the water body is smooth, yielding reflection of the signal in the direction away from the recording platform. Nevertheless, when choosing small scan angles sufficient signals may return to map water surfaces, in particular when the surface has a certain roughness. Experiments in the Netherlands have shown that laser-altimetry is able to map water levels of rivers. In urban areas, spurious height values may occur when a pulse is specularly reflected on a ground point, e.g. on the paved road surface. The reflected pulse moves away from the recording platform, but may hit next the face of a building. When this multipath signal reflects in the direction of the carrier, it may be picked up by the receiver of the ALS. Because the measured travel path will be longer than the actual distance, a false height value, up to several meters below the real surface, will show up in the data.

## Height Demands in Urban Areas

Since ALS provides high resolution height data with an accuracy level slightly above the decimetre level, the technique is particularly suited for planning, monitoring and control purposes. Other applications like construction of e.g. traffic tunnels and bridges, and deformation control purposes, which require a dense and well-distributed network of bench marks with centimetre precision, remain to rely on trigonometric levelling. In the remaining part of this paper a number of applications are treated, which are needed by City Administrations. The treated applications are already operational, have passed successfully the piloting stage or are in the phase of experimental investigation.

## Flood Risk Management

Floods cause nearly one third of the economic losses resulting from natural hazards. The role of floods as cause of natural catastrophes is increasing due to amongst others rising sea levels and increased urbanisation. The last issue results in a substantive growth of the earth's surface, even river-beds- covered with asphalt and concrete. Flood prevention and river management tasks are therefore important activities in urbanised areas of lowlands, such as the Ganges Delta, the Yellow River Delta, the Rhine Delta and the Mississippi Delta. For these purposes, detailed and accurate knowledge is required concerning the variations in elevation of the river-bed and surrounding area, height of dikes, flood waves, along-and across-track slope of the river and the water resistance of different vegetation areas. Studies in the Netherlands have shown that high resolution ALS is able to provide detailed information about the water level and the along- and across-track slope of the river Rhine (Bollweg, 1999). In the UK the applicability of ALS data has been studied for quantifying flood risk for insurance purposes (Murtagh & Cheesman, 1999). By incorporating the DEM in a GIS as input for a flood model, insight into which areas are susceptible to inundation is obtained. The height data provided by ALS is so detailed and accurate that they enable verification and even refinement of the input parameters of hydraulic models used in these simulations.

## Rain Water

The heights of areas in many cities are subject to natural or man-induced changes. Man-induced changes may for example result from the development of a new living area. What will be the effect on the flow of rain water, once having reached the paved surface? Is the sewerage system still able to deal with the drainage of the all water, even in periods with heavy rain falls? Is the rain water still streaming in the direction of the river or reservoirs? Should the drainage layout be improved? These are all question a City Administration may be confronted with and which can be answered with the help of height information derived from airborne laser-altimetry.

## Urban Planning and Development

The need for easy evocation of the environment is as old as is the human capacity of constructing buildings, bridges and roads. For example, integration of an architectural design with its surrounding, represented by a 3-dimensional landscape model that includes existing vegetation, facilitates highly the design process and gives engineers and planners an accurate impression of how their design interacts with its surrounding (Figure 2). Maps, scale models and later on, also aerial and satellite imagery, have always represented an essential tool for serving these purposes. However, these analogue media often give a rather poor backdrop. In addition, this type of representation is often hard to understand for the general public, especially when complex spatial structures are involved. Furthermore, urban planning and development requires increasingly 3-dimensional urban topography models.

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*Figure 2, Part of a 3-dimensional City Model of Mannheim created by using Laser-altimetry (Courtesy: Toposys Germany)*

Computer technology has been for some time capable of creating 3-dimensional virtual fantasy worlds for entertainment purposes. This technique can also be used to support the urban planning and development process. When creating a 3-dimensional virtual world of existing or proposed reality, real data is needed. This data should not only be 3-dimensional, but also very accurate and highly detailed. The direct acquisition of 3-dimensional information is very time-consuming and expensive. This is one of the main problems to be overcome in the advancement of virtual reality for monitoring and design purposes. ALS, providing highly automatically spatially highly detailed geo-data, is a promising technique to tackle this data problem.

## Reconstruction of Buildings

The reconstruction of buildings from high resolution ALS data, seems to become a promising option. The high point density enables the proper determination of the position and orientation of planes, which put together the building, although it may appear that planes with similar orientations are merged (Maas, 1999). For mapping purposes one is usually interested in the outlines of buildings. These have to be determined by intersection of the planes. In ALS data, edges at height discontinuities are difficult to locate, while other structures near the edges of roof faces cause problems in reconstructing the outlines. Therefore, a manual correction step is required. To improve the automation level, a combination of ALS and aerial imagery, from which building outlines can be extracted rather reliable and accurately by (semi-) automatic means, seems to be promising. Also combining ALS and 2D digital map data may be appropriate, although the latter may be often quite out of date. Detailed reconstruction of buildings, like historical monuments, both from above as well as from the faces is becoming a realistic option by combining ALS data with laser mapping data acquired from terrestrial stations.

## Powerlines

High resolution DEMs are suited for inspection surveys of powerlines (Figure 3). From the randomly distributed points hitting the wires the wire-lines can be reconstructed by using 3-dimensional line detection and modelling software.

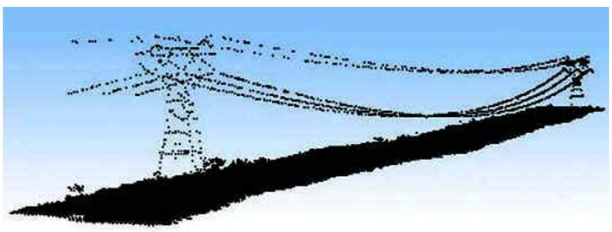

*Figure 3, Representation of a Powerline from high resolution Laser-Altimetre data, acquired by helicopter(courtesy: Eurosense)*

However, inspection does not only include the determination of deformations of the wires, but also the identification of obstructions present in the corridors, for example caused by trees or illegal buildings standing too close to the powerline path. Their rapid detection and evaluation allows maintenance crews to react fast and to prevent disasters. Also, the inventory of damage after bad weather circumstances can be done easily from Laser DEMs. The required high resolution mapping necessitates the use of helicopters operating at low altitudes as recording platform.

## Telecommunication

Detailed DEMs are essential to tower planning and micro-wave network design for example to answer the question where antennas for mobile cellular networks should be placed for optimal coverage. As bandwidth increases and higher frequencies are used the task of locating transmitters and receivers and minimizing the number of repeaters becomes critical. ALS data is well-suited for telecommunication purposes. For this application, the city does not need to be reconstructed with great accuracy. Often it suffices to model the buildings by a rectangular block with the base dimensions, orientation and the height of the building at meter level accuracy. An effective building height determination algorithm by combining high resolution ALS data and a 2D digital map has been developed by Lemmens et al. (1997). Additionally, high resolution imagery can be collected to facilitate further the design and planning process.

## Infrastructure

Laser DEMs are beneficial for planning, design, inspection and maintenance purposes of infrastructural works. In the planning process corridor planning and environmental impact simulations can be carried out. The use of detailed DEMs enables to design a solution, which will have the least undesirable effects on the city landscape, vegetation, and hydrology. The DEM provides also accurate terrain information to optimise the construction process, and logistics, like optimal movement of earth works. Major road surface, runway surface, and railroad track deformations can be traced on the fly. Under special conditions, for paved surfaces even potholes deeper than 5 cm can be detected. Large obstructions like fallen trees after storms can be detected and registered.

## Change Detection of Buildings

In many urban areas buildings are often subject to changes because of public construction works or reconstructions carried out by the owners. For tax purposes or subsidy arrangements, where money flows from the central government to local authorities or visa versa, it is often necessary to trace these changes.

Automation of the change detection process is highly desirable to reduce the costs of tax collection. Although automated detecting of building changes from aerial and satellite imagery have been investigated intensively, they have never become operational. ALS seems to present new opportunities. Murakami et al. (1999) carried out experiments to trace automatically building changes by subtracting time sequences of ALS DEMs. The areas where changes are traced can be checked by field inspections or inspection of aerial photographs. Another application is the detection and measurement of sub-urban growth, in particular in cities where expansion is a highly uncontrolled process.

## Pollution and Subsidence

In principle, high resolution DEMs are suited for detection of changes of any heights and volumes. In particular, when time series are applied height and volume changes can be traced. So, it could be an appropriate tool to detect the dumping of waste for example in ditches or to monitor (growth of) waste belts. Some cities, like Mexico city are subject of severe subsidence due to groundwater extraction. By regularly carrying out airborne laser-altimeter surveys, the level and rate of subsidence can be estimated and modelled.

## Concluding Remarks

The main property of ALS is that it is able to determine accurately and detailed the 3-dimensional terrain shape. We have identified in this paper some of the abilities of ALS for urban areas. ALS has passed a rapid and successful development. At present, it has reached the stage of being an established, although still rapidly evolving technique. The only restriction for new applications seems to be unfamiliarity and unawareness among users about its full potentials. Although the method is operationally applied, it still is not a settled technique. Much has still to be investigated, including accuracy improvement of the measuring system and accompanying processing software, filtering techniques for automatically processing of the height data set and proper integration with other data sets. The determination of its suitability for a particular application requires a piloting stage.

Much recent information on Laser-altimetry can be found on Martin Flood's Airborne Lasser Mapping Website: www.airbornelaserscanning.com

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