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AN OVERALL VIEW OF LIDAR AND SONAR SYSTEMS USED IN GEOMATICS APPLICATIONS FOR HYDROLOGY

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Abstract

The paper presents an overall view of LiDAR and Sonar systems used in geomatics applications for hydrology, this branch of science concerning with the properties of the earth's water, and especially its movement in relation to land. LiDAR sensor provides an efficient, rapid, and low cost tool for hydrological application, especially for coastal and river water management. For example, in Romania the hydrographic organizations need accurate bathymetric maps for near coastline area of the Black Sea, for the Danube River and the inner riversides. Nowadays, airborne LiDAR bathymetry is an accurate, capable, and highly cost-effective alternative to traditional waterborne Sonar in areas with appropriate depth and water clarity Water hydrology modelling and watershed management is based on constant monitoring of the water volume over a long time for modelling water dynamic behavior. Flood prediction and flood extend modelling is one of the most important issues in the watershed management and usually the primary interest would be coastal area and rivers hydrodynamic modelling especially in the event of the flood. Using echo sounders would be dangerous, not accurate enough in shallow waters, time consuming, and do not give a continuous water depth. Alternatively, using bathymetric LiDAR system provide accurate, continuous, fast depth information from a large region, without a contact directly with the water body and this ability resolves many of the industrial and military needs for accurate and precise geospatial information from water body in shallow area in a very rapid manner.

***Key words**: bathymetry, geomatics, hydrology, LiDAR, sonar.*

INTRODUCTION

LiDAR is a light detection and ranging sensor that uses a laser to transmit a light pulse and a receiver with sensitive detectors to measure the backscattered or reflected light. Distance to the object is determined by recording the time between transmitted and backscattered pulses and by using the speed of light to calculate the distance travelled. In addition to mapping of land and water surfaces, LiDAR systems can be used to determine atmospheric profiles of aerosols, clouds, and other constituents of the atmosphere.

In general, LiDAR systems used for gathering geographic information can be classified in the following ways:

- measurement techniques;
- target scanning techniques;
- sensed phenomena.

There are three main types of laser sensing systems (Figure 1). They include pulsed and continuous wave (CW) laser ranging systems as well as light-striping/video-profiling systems. A pulsed laser system transmits laser pulses, senses the light that is scattered back through an optical telescope and amplifies the returned signal using a photomultiplier tube. The time required for the transmitted pulse to travel to the target and back is recorded and used with the speed of light to determine the distance to the object.

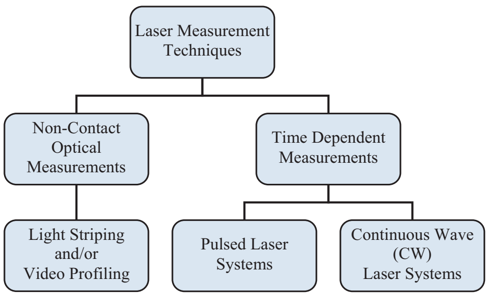

Figure 1. The basic laser measurement techniques

On the other hand, the CW laser system transmits a continuous signal. Ranging can be carried out by modulating the light intensity of the laser light. Typically, the modulated signal is sinusoidal and that sinusoidal signal is received with a time delay. The travelling time

is directly proportional to the phase difference between the received and transmitted signal.
Currently, the pulsed laser systems are most widely used because they can produce high power output at a very high pulse repetition rate.
There is one type of laser measurement that is based on a combination of a laser light stripe generator and a video camera. It is so-called „non-contact" optical measurement. The laser source is apart from the video camera, which can be digital. The laser light is visible on the target surface as a continuous line. This line is considered as a surface profile. Then, during the movement of a carrying platform, the profiles are registered to a 3D coordinate system by an iterative surface-matching algorithm. The digital image processing is based on a projective transformation between the image plane of the camera and the plane of the laser sheet, and also the direction of the scanning with respect to the plane of the laser sheet. The refinement is obtained through weighted least squares matching of multiple profile maps acquired from different points of view, and registered previously using an approximate calibration.
Sonar is a sound transmittal and detection sensor that uses one or more transducers to transmit sound pulses with one or more receivers that measure the reflected sound pulses along with backscatter information (signal to noise ratio). The calculated depth is determined by recording the time interval between transmitted and received sonar pulses. The speed of sound as described in sound velocity profiles is used to calculate the travel distance. By combining the known velocity of sound (c) in water with the time the echoes were received (t), the sonar can calculate the distance the sound has travelled (d). As sound must travel from the Sonar to the target object and then back again, the range (r) between the Sonar and target is half of the total distance travelled, shown in formula 1.

$$d = c \times t \quad \Longrightarrow \quad r = d / 2 = (c \times t) / 2 \qquad (1)$$

Typically, the velocity of sound (c) is about 1500 m/s, but this can vary depending on the water temperature, water salinity and sonar operating depth. To calculate this, Sonar contains a sensor that continuously measures the operating depth and water temperature, and combines this with an appropriate salinity value for the body of water that it is operating in, entered by the user in the control software.
Sonar can also determine bottom types (mud, gravel, rock, sand etc.) by using backscatter as a measure of hardness determined by comparison to classification catalogues. Multiple pulses transmitted and received by multibeam sonar create 100% coverage surfaces of the sea bottom. The sonar error footprint is dependent on depth and sound frequency. Sonar systems achieve the following measurements:

- Time taken for the emitted pulse of sound to travel from the sensor to the ground and back (in milliseconds);
- Backscatter - measure of the reflective intensity of the reflected sonar pulse;
- Sonar footprint - usually represented by measurements in square meters.

Usually, for classical detailed bathymetric survey, there is echo sounder and GNSS equipment with continuous recording papers or recordable digital devices. This has some inconveniences because includes: mounting and demounting the equipments on each site; transporting the equipments to the site and between the working places; accommodation and daily allowance for the staff etc.
In this context, the paper present an overall view of LiDAR and Sonar systems used in geomatics applications for hydrology, this branch of science concerned with the properties of the earth's water, and especially its movement in relation to land.

MATERIALS AND METHODS

Nowadays, LiDAR/LaDAR and Sonar have been accepted as ones of the important sensors providing accurate and dense 3D point cloud from earth surface terrain and water bathymetry. The basic idea of using LiDAR stems from the problem of measuring water depth without direct contacting with the water body or without any instrument mounted on the water surface in shallow regions. Bathymetric LiDAR that uses two different laser beam mounted on a flying aircraft/drone above the water surface has proved to be a good solution.

This ability resolves many of the industrial and military needs for accurate and precise geospatial information from water body in shallow area in a very rapid manner. This technology has been used in the cases which would be solved with serious difficulties using alternative solutions. In addition to hydrology and oceanography, there are other important application areas which mainly are urban mapping, forestry, and photogrammetry. In this paper, an overview to the use of LiDAR technology in the hydrology is discussed. In hydrography, various subjects are tackled such as: dunes and tidal flats measurement, coastal change and erosion, flood mapping and prediction, snow and ice measurement, water bathymetry in depths up to 70 m. Airborne LiDAR systems are rapidly developing and expanding in new applications. Integration of LiDAR with imaging sensors, efficient using of waveform information and better processing algorithms would make a great development in obtaining more realistic and accurate 3D models of the geospatial objects (Mohammadzadeh and Valadan Zoej, 2008).

RESULTS AND DISCUSSIONS

LiDAR systems can be classified on the basis of scanning techniques as is shown below in the Figure 2.

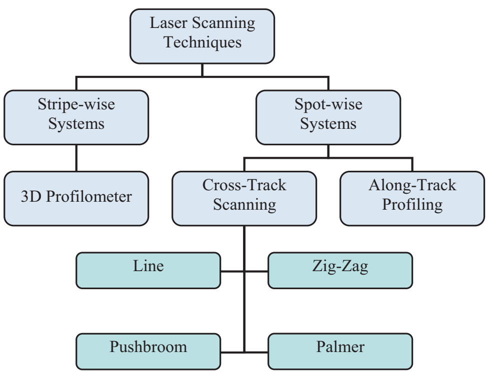

Figure 2. The laser scanning techniques of LiDAR

Laser scanners are typically cross-track or push broom scanners. An airborne laser profiling system is a laser altimeter.

In the same time, all LiDAR systems can be classified on the basis of the different physical phenomena that they are designed to detect.
So, we have the following main types of LiDAR:

- **Aerosol LiDAR** directly measures the optical properties of atmospheric aerosol distributions.
- **Coherent Doppler LiDAR** is usually used for remote sensing of the distribution of wind velocity and aerosol backscatter within three-dimensional volumes in the troposphere and lower stratosphere. Coherent LiDAR is considered to be more sensitive and to provide better wind measurements at aerosol levels consistent with the boundary layer and lower troposphere, as well as from atmospheric ice and water clouds.
- **Differential absorption LiDAR (DIAL)** transmits two closely spaced wavelengths. One of these wavelengths coincides with an absorption line of the constituent of interest, and the other is in the wing of this absorption line. During transmission through the atmosphere, the emission that is tuned to the absorption line is attenuated more than the emission in the wing of the absorption line. The concentration of the species can be determined based on the relative optical attenuation.
- **Raman LiDAR** uses the Raman-shifted component that is a transition that involves a change in the vibrational energy level of molecules. Since each type of molecule has unique vibrational and rotational quantum energy levels, each has a unique spectral signature.
- **Rayleigh LiDAR** measures the intensity of the Rayleigh backscatter, which is used to determine a relative density profile. This is used in turn to determine an absolute temperature profile.
- **Resonance LiDAR** uses the resonant scattering that occurs when the energy of an incident photon is equal to the energy of an allowed transition within an atom. As each type of atom and molecule has a unique absorption and fluorescent spectrum, this effect can be used to identify and measure the concentration of a particular species.

The resolution of a sensor is distinct from the resolution of an image. The resolution of a

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sensor is the smallest difference that can be detected by a sensor. Sensor resolution is a measure of the ability of a sensor to detect differences between sensed objects and it may be expressed in many ways depending on the sensor.

The immediate outputs of a digital sensor are digital numbers (DNs). Prior to deployment, a sensor is calibrated in a laboratory using standard radiation sources. Using a calibration curve, DNs are mathematically converted to sensor input radiances.

The resolution of a sensor is defined by several quantities. The band structure for a sensor determines its spectral resolution. The radiometric sensitivity of a sensor for a specific band is the radiance increment for a single bit change in the DN. The spatial resolution of the sensor is the solid angle for which the sensor measures radiances.

Sensor descriptions are organized by the type of energy sensed by the sensor: optical, microwave, LiDAR and Sonar for example.

With the use of aerial drones with LiDAR or Unmanned Surface Vessels (USV) and Sonar technology, it is able to construct georeferenced point clouds from which accurate water body volume estimations can be created. This is a safe and cost efficient alternative to manual or aerial bathymetric surveys that may not be feasible for smaller water bodies.

Recent developments in sensor technology yielded a major progress in airborne laser bathymetry for capturing shallow water bodies. Modern topo-bathymetric small foot print laser scanners do no longer use the primary near infrared (NIR) signal (λ=1064 nm) but only emit and receive the frequency doubled green signal (λ=532 nm). For calculating correct water depths accurate knowledge of the water surface (air-water-interface) is mandatory for obtaining accurate spot positions and water depths. Due to the ability of the green signal to penetrate water the first reflections do not exactly represent the water surface but, depending on environmental parameters like turbidity, a certain penetration into the water column can be observed (Gottfried Mandlburger et al., 2013).

In Figure 3, is shown below LiDAR bathymetry which is used to measure water depth for shallow water with depth not more than 30 m.

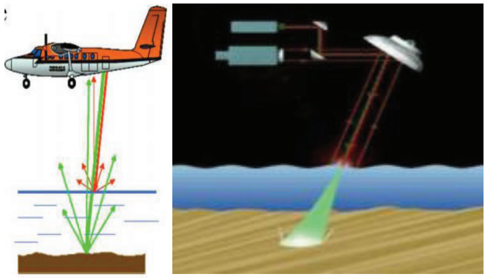

Figure 3. Green pulses (532 nm) reflected from bottom, NIR (1064 nm) laser pulses reflected from water surface (Elhassan I., 2015)

As against LiDAR and photo bathymetry, the disadvantages of echo sounding are:

- measurements are the time and cost associated with making measurements from a ship in deep waters or a small vessel in shallow waters;
- in order to build up coherent images at high resolution many survey lines with overlapping tracks must be run;
- because the swath width decreases in shallow water, many more ship or glider tracks are required in large rivers' confluences or rivers flowing into the sea, in coastal bays with shallower water.

Detailed surveys in coastal regimes require considerable time and effort to cover relatively small portions of the sea bed. Ship time is costly even in deep water and because of increasing time and effort to operate in shallow waters, acoustic systems are not ideal for such tasks as monitoring bathymetric changes and shoreline.

Airborne laser scanning technology to survey both land and coastal waters in a single approach, employing a technique known as Airborne LiDAR Bathymetry (ALB) or Airborne LiDAR Hydrography (ALH) which uses state of the art LiDAR technology to measure sea bed depths and topographic features rapidly and accurately (Figure 4).

Airborne LiDAR bathymetry is an accurate, capable, and highly cost-effective alternative to traditional, waterborne sonar in areas with appropriate depth and water clarity. With the production of high-density, three-dimensional digital bathymetric data, it offers a number of important products, services, and applications in coastal waters. It can also survey safely in areas where Sonar cannot, including, for some systems, above-water structures and dry land.

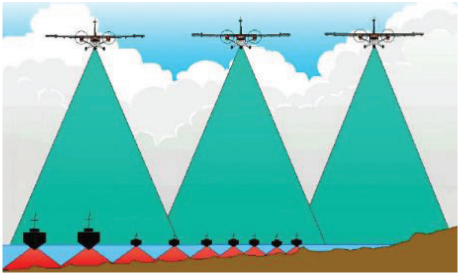

Figure 4. A graphic comparison of LiDAR and Sonar operations in shallow water (Guenther, 2004)

Airborne LiDAR bathymetry is, however, not a substitute for sonar because airborne LiDAR bathymetry surveys are limited by water clarity and depth. The maximum scanner nadir angles in use are 15° - 20° and larger angles would cause unacceptably large pulse timing errors in both surface and bottom returns due to the more extreme geometry. Coverage is dense and surveys are performed with soundings spaced in a regular pattern. The densities vary from system to system used.
LiDAR applications provide to hydrologists with one of the most advanced methods of visualizing river speed profiles. The data can be provided as 2D cross sections or 3D velocity fields. This data can be combined with LiDAR data to generate and analyze complete surfaces above and below the water surface.
The geopositioning of data collected with a sensor is made by a mathematical relationship between the position of an object on Earth and its image as recorded by a sensor. In order to algorithmically describe the data flow beginning with measurements by an individual sensor and ending with a geopositioned product, it is necessary to introduce Coordinate Reference Systems (CRSs). These CRSs are each defined with reference to a physical entity. They serve as a reference for related metadata and describe the steps required to convert the sensor measurements into geographical data. The flow of coordinate transformations, required to relate image coordinates to coordinates referenced to the Earth, is: Image CRS --> Platform CRS --> Global geodetic CRS --> National geodetic CRS --> Projected CRS (map grid).
We use as global geodetic reference system, and for vertical reference too, the WGS-84 ellipsoid, which is independent of the water surface. In the past, differential corrections for coordinates were applied during post-flight processing of recorded user data, but now DGPS systems not only generate the corrections but also utilize some type of wireless transmission system for getting the correctors to users in near real time. This communication may be VHF systems for short ranges (FM broadcast), low-frequency transmitters for medium ranges (beacons), and geostationary satellites (L-Band) for coverage of all continents.
In the figures below, are shown two types of Sonar systems, with single beam (Figure 5) and multi beam (Figure 6), which use GNSS for accurate measurements location.

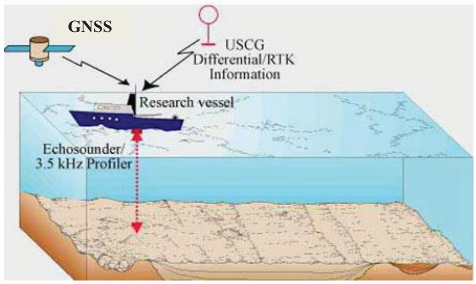

Figure 5. Single beam Echosounder (Elhassan I., 2015)

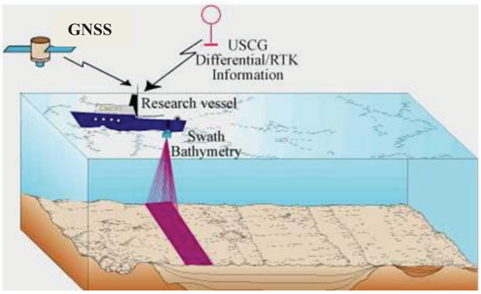

Figure 6. Multi beam Echosounder (Elhassan I., 2015)

As opposed to traditional single beam bathymetric survey techniques that produce soundings on discrete profiles, multi beam bathymetry affords the end user with a highly detailed, densely spaced grid of soundings in the form of a geographically referenced digital terrain model. This model can support engineering design, construction, and dredging projects. The key advantages to multi beam bathymetry, as opposed to single beam bathymetry, are: increased data coverage, greater data density, and greater survey production capacity.

Side scan sonar (Figure 7) is one of the „swath mappings" methods commonly used to map large areas of the seafloor. It consists of two transducers both of which produce a thin fan-shaped beam that is concentrated on a line that runs from below the transducer perpendicular to the direction of travel. The maximum range of the signal is determined by the frequency, power and transducer design. After processing, the resulting acoustic backscatter provides seabed. Side scan sonars are normally deployed within a towed body that is towed at a fixed height above the seafloor, although it can also be mounted on the hull of a vessel, or on the body of Remotely Operate Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs). Traditional side scan sonar provides only backscatter data and little information about depth. In the recent years, interferometric or bathymetric side scan sonar has been developed that provide accurate backscatter and bathymetry across a wide swath.

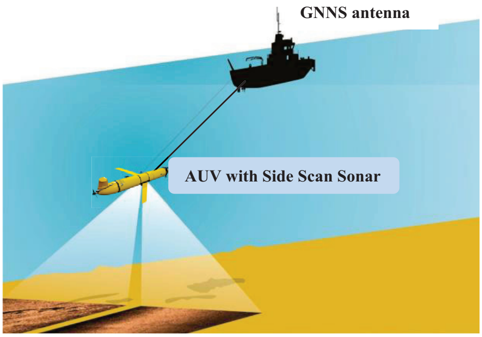

Figure 7. Schematic diagram of an AUV with a Side Scan Sonar (https://hiveminer.com/Tags/archaeology%2Csonar)

Like traditional bathymetric surveys, side scan sonar surveys produce data that are geographically referenced. The image-data are post-processed to create image mosaics that highlight bottom conditions and produce nearly seamless imagery. The image mosaics can be fed into a variety of computer-aided design (CAD) and geographic information system (GIS) packages, even ubiquitous visualization software such as Google Earth so that engineers, contractors, and even less technically experienced personnel may view the data and better understand underwater conditions.

In 1989, the International Maritime Organization (IMO) adopted a resolution adding a footnote to its resolution on Ships' Routeing Measures which states that „The minimum standards to which hydrographic surveys are to be conducted, to verify the charted depths in the traffic lanes are those defined in Special Publication No. 44 of the IHO" (Chris Howlett, 2010). So, „S-44 Edition 5", was published in 2008 and it is the International Hydrographic Organisation's standard for hydrographic surveys.

The maximum errors allowed by International Hydrographic Organisation (IHO) standard are: 0.25 m for depths between 0 m and 30 m; 0.5 m for depths between 30 m and 100 m; and 1 m for depths greater than 100 m. For harbours areas and associated critical channels, the minimum horizontal accuracy (with 95% confidence level) is 2 m. Principal aim for hydrographic surveys standard is that hydrographic data collected according to these standards is sufficiently accurate and that the spatial uncertainty of data is adequately quantified to be safely used by mariners (commercial, military or recreational) as primary users of this information. In the next figures are shown few examples of bathymetric maps from the Danube River (Figure 8) and the Romanian Coast of Black Sea (Figure 9).

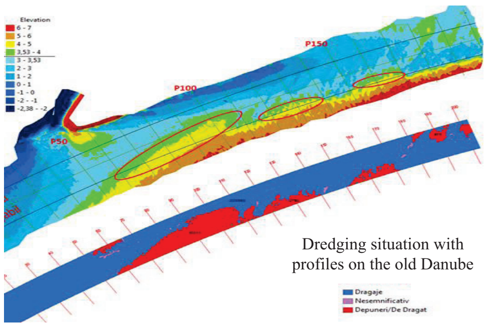

Figure 8. Bathymetric map on Danube River with cross profiles for dredging (Tehnogis Grup S.R.L., 2014)

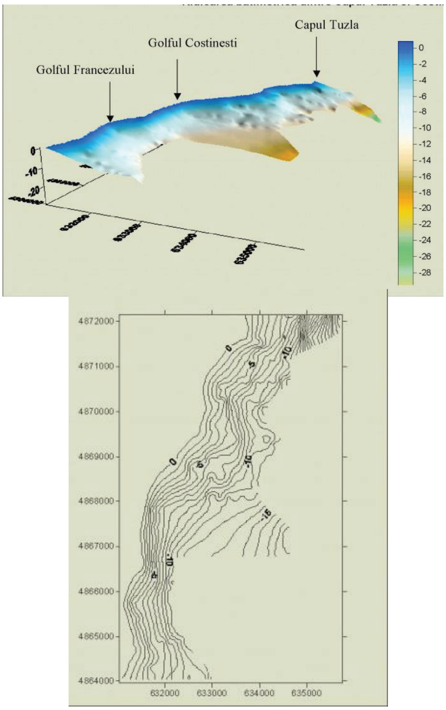

Figure 9. Bathymetric maps (3D and 2D) of the South Romanian Coast of Black Sea (Constantinescu Stefan et al., 2008)

For performing scanning sonar surveys, it is necessary to utilize high-resolution scanning sonar units when very specific conditions require assessment, particularly in the vicinity of bridge piers, dams, and vessel mooring facilities. We must focus specifically on acquiring top-notch imagery and presenting it with interpretations or above-water imagery so that the images have perspective and are easily viewed and understood by lay personnel unfamiliar with the technique. Imagery can be qualitative (but scaled properly for dimensions) or quantitative in the form of high-resolution bathymetric datasets that can be integrated into 2D or 3D models of structures.

CONCLUSIONS

In conclusion, we can say that information that can be derived from Sonar sensor data includes:

- depth - time taken for the emitted pulse of sound to travel from the sensor to the ground and back, interpreted in meters;
- sound velocity profiles (m/s);
- digital elevation models;
- tide/current models;
- sea bottom texture maps based on backscatter;
- storm surge models;
- coastal erosion maps;
- free-air gravity maps (fusion of gravity and bathymetric maps);
- coastal flooding models and sea level rise;
- seabed classification;
- sediment's thickness.

Traditionally, old sonars were mechanical devices that operated by rotating their transducers (transmitters and receivers) to scan the sector in front of or around them. At each transducer position, a sound pulse would be transmitted into the water, and the echoes collected by the receiver before being plotted onto the display. Depending on the required resolution an image could tens of seconds to update, and any movement of the sonar during this period could smear and distort the imagery. Unlike mechanical sonars, which have moving parts, multi beam sonar has no moving parts, and an array of receivers collects echoes from a single transmission pulse and mathematically combines the data into an image using a process known as "beam-forming". This allows images to be produced many times per second and viewed in real time like the output from a video camera.

Another conclusion is that LiDAR sensor provides an efficient, rapid, and low cost tool for hydrological application, especially for coastal and river water management. But, there are still some weaknesses on the LiDAR data segmentation, visualization, very shallow depth measurement, water wave estimation etc.

Integration of LiDAR with imaging sensors and better processing algorithms would make a great development in obtaining more realistic and accurate 3D models of the geospatial objects. The most important factor for the combination of image and LiDAR data is the improvement of the accuracy of the flight trajectory of an UAV for example, which would lead to the real-time capability of data processing of such UAV platforms and the combined processing of the data. In this combination, first the images have to be oriented. In a second step using the enhanced image orientation the trajectory of the LiDAR data can be improved. Thirdly, the registered LiDAR point cloud can then be projected back into the images. Finally, in a combined adjustment the trajectory can be further improved and a DSM can be generated both from the LiDAR and image data. So, we can increase the real accuracy of the final mapping product.

As a conclusion, beside hydrographic measurements (e.g. bathymetry), typical applications of LiDAR systems can include:

- atmospheric monitoring and studies (e.g. aerosol profiling and ozone measurements);
- 3D terrain mapping [e.g. urban areas (3D city modelling), power lines, and mining];
- forestry and forest management (e.g. biomass, stem volume, tree heights);
- environmental monitoring (e.g. water quality and phytoplankton);
- pollution detection (e.g. pipeline leak detection like oil or gas);
- mapping organic pollution (e.g. oil and petroleum products on soil or in water);
- measuring industrial structures (e.g. bridges and tanks) and homeland security.

For many of these applications, LiDAR systems are flown together with other optical sensors such as photogrammetric cameras.

The latest trend in the development of LiDAR technology considers a different approach to aerial laser scanning point clouds, one that can create land cover maps more effectively than typical topographic methods, providing a tool for high-density topographic surveying which can be useful for land cover and land use classification. Such a data source can even be an alternative or a supplement to photogrammetric data collection and the potential of multispectral airborne laser scanning in land cover mapping was presented in few publications (Bakula, 2015; Wichmann et al., 2015).

Multispectral LiDAR system is a new promising research domain, especially in applications of 3D land cover classification, seamless shallow water bathymetry, forest inventory and vegetative classification, disaster response and topographic mapping. Further research is needed to combine multispectral LiDAR point clouds with other ancillary data such as digital surface model (DSM) and imagery in order to improve the associated precision.

All light and imaging techniques are dependent on the water clarity. So, all light and imaging techniques are susceptible to error with murky water. The disturbing restriction is the limited water depth that can be measured. This is due to the fact that optical light cannot penetrate even pure water for a depth more than 30m.

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