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RECOMMENDED OPERATING GUIDELINES

Lidar surveys

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Summary:	This document proposes a procedure to survey the coastal zone using Lidar sensors, in both topographic and hydrographic modes, for the intertidal zone and the shallow water area, respectively. It also deals with post-processing of the data towards delivery of DTMs (Digital Terrain Models).
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MESH MAPPING EUROPEAN SEABED HABITATS

Recommended operating guidelines for Lidar surveys

1. General principles of operation

1.1. General facts about the Lidar technique

Light Detecting And Ranging (Lidar) is an airborne mapping technique which uses a laser to measure the distance between the aircraft and the ground. Since the 1970s the application of airborne Lidar for topographic and bathymetric mapping has matured at a rapid pace, with the first commercial Lidar systems appearing in 1993. Much of this growth has directly followed advances in high-speed digital and analogue electronics, along with increases of several orders of magnitude in computer memory, storage capacity and processing speed.

The basic components of a topographic Lidar system are a laser scanner with a cooling system, a Global Positioning System (GPS) and an Inertial Navigation System (INS) (Figure 1). The laser scanner is mounted in an aircraft and emits infrared laser beams at a high frequency. The scanner records the difference in time between the emission of the laser pulses and the reception of the reflected signal. A mirror is mounted in front of the laser. The mirror rotates and causes the laser pulses to sweep at an angle, back and forth along a line. The position and orientation of the aircraft is determined using a phase-differenced kinematic GPS. The GPS is located in the aircraft and several ground stations (differential GPS) are situated within the area to be mapped. The orientation of the aircraft is controlled and determined by the INS.

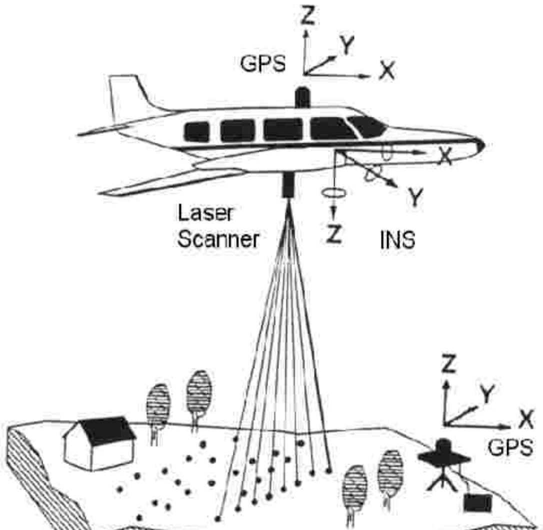

Figure 1: Lidar georeferencing system (from Earth Observation Magazine, February 1997 – see http://www.personal.psu.edu website).

The principles of topographic and bathymetric Lidar mapping rely on the accurate round-trip travel time of a laser pulse transmitted from the Lidar system to a surface target. Travel times of the laser pulses from the aircraft to the ground are measured and recorded along with the position and orientation of the aircraft at the time of the transmission of each pulse.

In operation, successive laser pulses are sequentially scanned across the water surface to produce, when combined with the aircraft's forward velocity, a swath of nearly evenly spaced soundings. Firing the laser at thousands of pulses per second, and scanning the beam across the terrain using a scan mirror, generates a dense distribution of ranges to the surface. After the flight, the vectors from the aircraft to the ground are combined with the aircraft position at the time of each measurement and the three dimensional X, Y and Z coordinates of each ground point are computed. Different approaches are used to resolve the return in time, including simple ranging to the first or last detected return, ranging to the first and last return, ranging to multiple returns, or digitising the entire backscatter return amplitude as a function of time.

With a given system having a fixed frequency, the dot spacing is a function of the flight altitude only. Since accuracy decreases with altitude (owing to atmospheric content), the flight parameters will be dictated by the project requirements in terms of both accuracy and dot spacing Another constraint, in the case of visible light, is the regulation of the particular laser for eye-safe range.

Typical operating specifications permit flying speeds of 75-250 km per hour, flying heights of 100-5000 m, a scan angle up to 20 degrees and pulse rates of 2000-50,000 or more pulses per second.

These parameters yield enough data points to create a highly accurate digital terrain model (DTM). Users of this technology have typically achieved accuracies of 15 cm RMS in terms of elevation on regular surfaces and 50 cm for horizontal positions in the case of a topographic Lidar.

There are two main types of systems operating with different light frequencies

(Figure 2):

- •Topographic Lidar uses only one near-infrared (IR) wavelength, between 1047 and 1540 nm according to manufacturers;
- • Airborne Lidar Bathymetry (ALB) uses two rays at different wavelengths: blue-green (532 nm) and near-infrared. Usually ALB systems are also geared to survey in dual topographic and hydrographic modes.

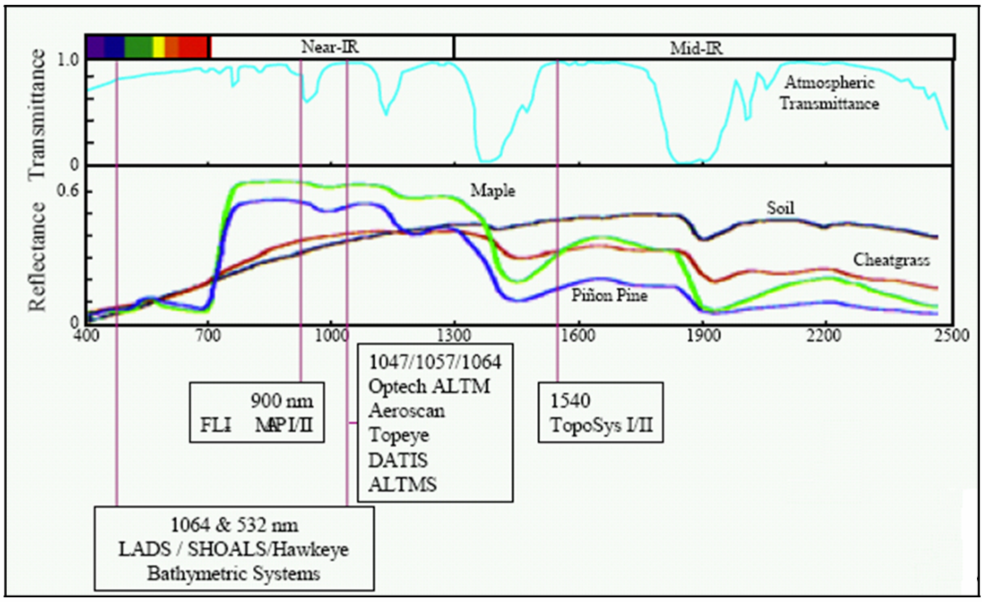

Figure 2. Wavelength ranges for different Lidar sensor systems (from Colorado State University website: http://www.cnr.colostate.edu)

In addition to surface height, Lidar systems can also provide information on surface reflectance for the corresponding spectral wavelength at which the laser emits. Reflectance is defined as the ratio between the returned energy (intensity) and the emitted energy. It varies with material characteristics, as well as the light used. Consequently, reflectance may provide useful information for the classification of land and seabed cover.

1.2. Topographic Lidar

The topographic Lidar emits pulses of light in the near-infrared. The measurement of the time lapse between emission and return provides a way of measuring the distance between instrument and ground. Laser pulse backscatter return energy resolved in time provides a measure of the distance to vertically separated features, including canopy layers and the ground, which are illuminated with laser energy. Ground resolution is typically within the metre, while vertical resolution lies within a few decimetres depending on the type of target. In the coastal zone, only a few types of human-built objects are erect; e.g. mussel poles or metal structures for oysters. A sufficient number of rays hit both the top of these structures and the ground below, producing two pulses which can be separated by the instrument gating. Water theoretically absorbs IR radiation; however, in reality the high sensitivity of the telemeter allows detection of surface returns even in slightly turbid waters. Vertical accuracy is expected to be better than 15 cm on flat, hard, well-defined surfaces, free of objects. This value, however, is degraded at higher altitudes and flying above 1200 m is not recommended.

1.3. Airborne Laser Hydrography

While topographic Lidar is widely used for multiple applications, bathymetric Lidar only recently increased the number of uses in coastal applications, such as mapping the morphology of shallow-water coral reefs (Costa et al., 2009), shoreline detection and delimitation (Boak and Turner, 2005), predicting fish communities with seafloor features (Kuffner et al., 2007), defining benthic habitat complexity (Wedding et al., 2008), and estuarine habitat mapping (Chust et al. 2010).

Airborne laser hydrography systems, also termed bathymetric Lidar, accurately determine water depths by measuring the time of flight of two laser pulses at different wavelengths: one is backscattered by the sea surface, while the other travels through the air-water interface into the water column and, depending upon water depth and turbidity, will reflect off the seafloor. An optical receiver on the aircraft detects the pulse reflections from both the seabed and the sea surface (Figure 3).

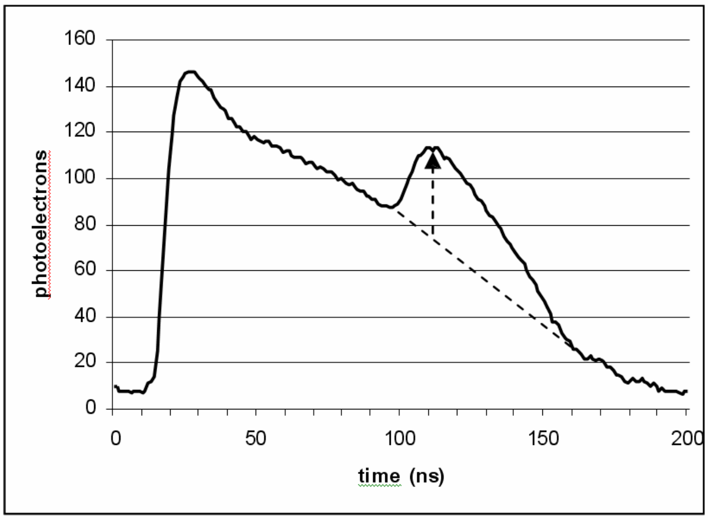

Figure 3: SHOALS green APD (avalanche photodiode) waveform and bottom peak signal shown as arrow (from Tuell & Park 2004).

The water depth is determined by the elapsed time between these two reflection and scattering events, after accounting for the system's operating geometry, propagation-induced biases, wave height and tide effects. The horizontal coordinates of the soundings are determined from the aircraft position, altitude and attitude, the direction of the laser beam with respect to the aircraft, and the measured water depth. The laser beams are swept in either an arc or a rectilinear scan across the direction of travel, with a swath width typically half of the altitude. The footprint on the seabed is usually around 3m in diameter. Dot spacing ranges from 2 to 5 metres and the typical flying altitude is below 500 m.

The Lidar bathymetric technology utilises the reflective and transmissive properties of water and the seafloor to enable measurement of water depth. When a light beam hits the water, part of the energy is reflected off the surface, and the rest, unless absorbed by particles in the water, is transmitted through the column (Figure 4).

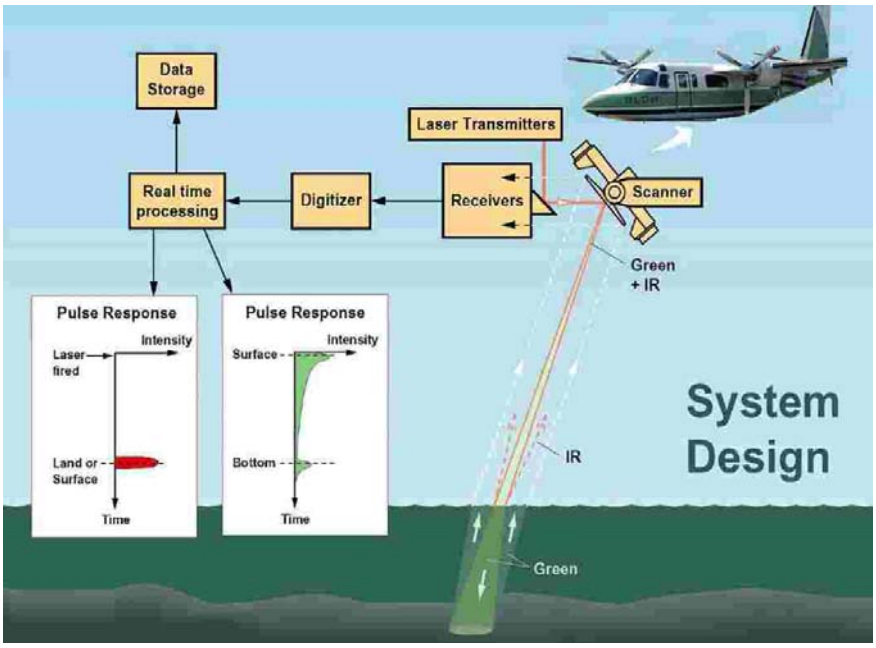

Figure 4: SHOALS green APD (avalanche photodiode) waveform and bottom peak signal (shown as arrow) (from Tuell & Park 2004).

Turbid water, weather-related phenomena and bottom structures can limit depth determination. As the light travels through the water column and reflects off the seafloor, scattering, absorption and refraction all combine to limit the strength of the bottom return, and therefore the system maximum extinction depth. This depth is a function of water clarity and is generally about 2-3 times the Secchi depth (Smith et al. 2000). It can reach 40 to 50 m in very clear tropical waters but would geberally be limited to less than 20m in European coastal waters. Heavy bottom vegetation and ‘fluid mud’ may limit system performance as well.

As shown in Figure 5, for turbid water the extinction coefficient is smallest in the green part of the spectrum close to 600 nm. The presence of organic matter in the water tends to displace light penetration towards higher wavelengths..

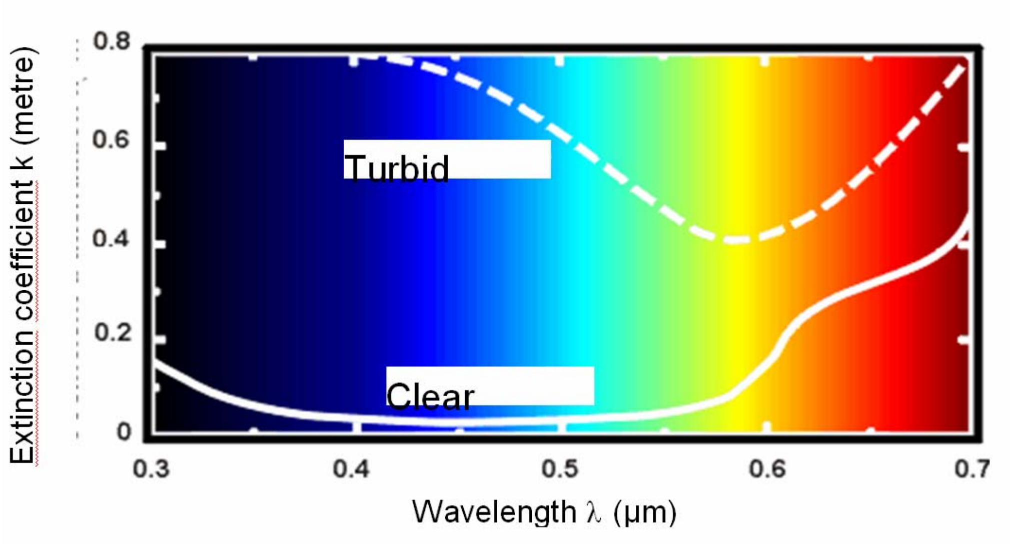

Figure 5. Evolution of the seawater extinction coefficient according to the wavelength (from http://isitv.univ-tln.fr/~lecalve/oceano/figures/fig310.htm website).

Hydrographic Lidar can be used to complement acoustic survey techniques in several ways. While acoustic multibeam systems have revolutionised bathymetric data acquisition in medium and deep waters, they are generally much less effective in shallow waters (less than 20 m below LAT – lowest astronomical tide) and not easy to use in complex environment. In contrast, Lidar systems have been specifically designed for use in such challenging environments and can provide uniform and dense data in even the shallowest water (Figure 6). Unlike multibeam systems, Lidar swath coverage is independent of the water depth. Because of its ability to achieve coverage rates several orders of magnitude higher than any of the acoustic methods, Lidar is likely to be a cost-effective tool for surveying large and shallow or complex rocky areas with generally good water clarity. In very clear water it can be effective to depths of 50 m, but in turbid water it is only successful to depths of 2-3 times the Secchi disk. In general, Lidar systems will not be applicable in areas with chronic moderate to high turbidity. In areas where the turbidity may be variable over a wide range of values, it is critical to schedule Lidar operations during a period when conditions are favourable, e.g. low discharge from coastal rivers and neap periods.

Furthermore, sea surface roughness has a strong influence on light penetration into the water. It is believed than both a very smooth surface and a very rough one may result in beam reflection and decreased penetration, which is going to condition surveys.

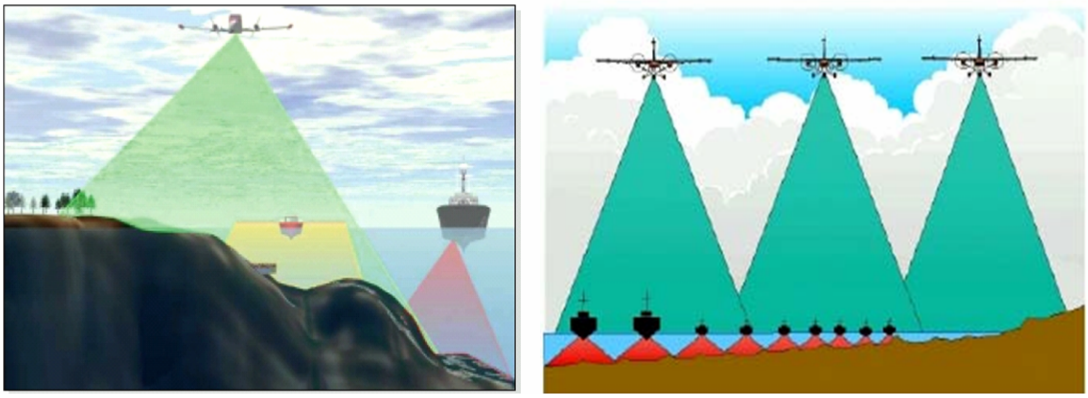

Figure 6. Depiction of Lidar and multibeam sonar operation in shallow water to emphasise Lidar capabilities and efficiency (from Banic & Cunningham 1998 and Guenther et al. 2000).

The advantages and constraints of Airborne Lidar Bathymetry are given below:

- The speed with which data can be collected for large areas provides a snapshot on a regional scale. Consecutive surveys can be compared to monitor changes in bathymetry and topography that occur over time, such as beach, cliff erosion and coral reef damage. ALB is ideally suited to undertake repeat surveys of mobile or critical seabed areas.
- Considering Lidar is non-intrusive, remote shallow waters, rocky shorelines and coral reefs that present extreme hazards for survey vessels can be easily surveyed in a time-efficient manner.
- A significant advantage of airborne laser bathymetry is its ability to work in dual mode; i.e. surveying very shallow water (<10 m) across the shoreline and up onto land (topographic elevation). There is no degradation in vertical accuracy, no change in sounding density, and no adjustment in aircraft track to match the shoreline direction. It is therefore a suitable tool for the study of coastal zones in their continuity.
- Acquisition can be done by day or by night, but daytime is preferred as a digital camera is usually run simultaneously (for reasons of data control). The Lidar flight plan is similar to that of a classic aerial survey. A 40% overlap between flight lines must be ensured to provide proper georeferencing. Of course, for tidal zone acquisitions these flight lines must be positioned with respect to the varying water levels. Operation time is therefore reduced to a few hours around low water. Typically, the surface range covered per hour is between 20 and 30 km².
- One feature shared by all bathymetric Lidar systems is the need for non-turbid water conditions.

2. Variety of systems available

2.1. Airborne Laser Terrain Mapper (ALTM)

Airborne Laser Terrain Mapper (ALTM) is an Optech topographic Lidar system. The ALTM 1225 (Table 1), with a frequency of 25 kHz at a maximum operating altitude above ground of 2000m (Figure 7), can survey up to 80 km² per hour. The latest sensor, the ALTM 3100, offers area coverage rates as high as 100 kHz at 1100 m altitude and can fly as high as 3500m with coverage rates even higher. Additional options include a 4kx4k integrated metric frame digital camera for georeferenced (x,y,z) colour or colour-IR images with sub-pixel accuracy.

Table1. Optech ALTM 1225 characteristics (see http://www.optech.on.ca).

Aircraft altitude	1000-5000 ft
Aircraft velocity	85-110 knots
Swath width	approx. 2/3 Aircraft Altitude
Laser wavelength	1064 nm
Laser pulse rate	25 kHz
Laser scan rate	20 Hz
Laser scan angle	+/- 20 degrees
IMU frequency	50 Hz
Number of returns recorded	2
Laser footprint	10-20 cm

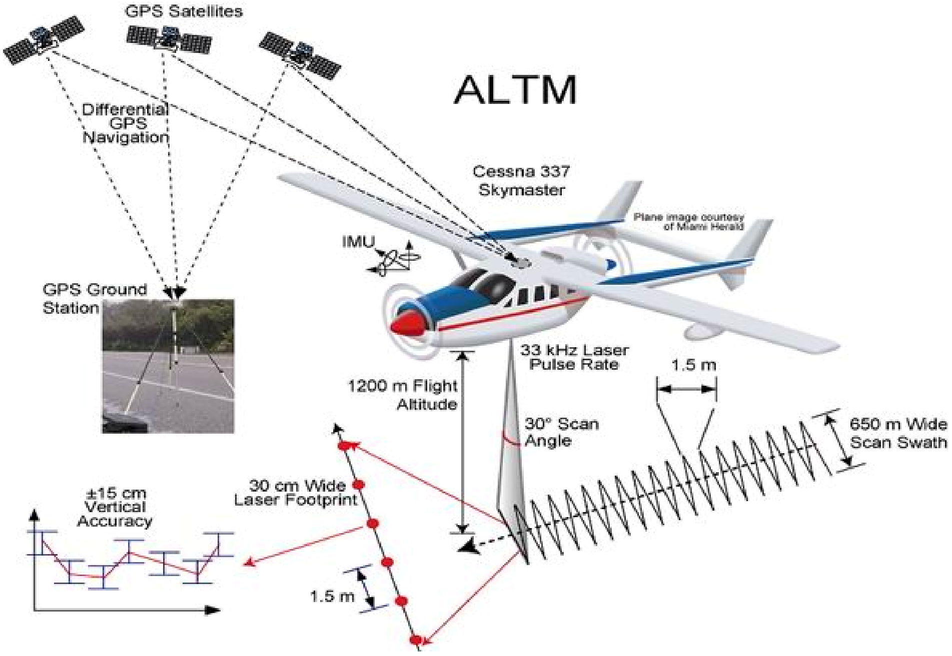

Figure 7. Schematic diagram showing ALTM data acquisition parameters to record topographic data (from http://ihrc.fiu.edu/lcr/research/airborne_laser_mapping).

2.2. Laser Airborne Depth Sounder (LADS)

Mettre, comme dans 2.1, un schéma du LiADR bathy avec le doublé tir IR + Bleu/vert.

The original Laser Airborne Depth Sounder (LADS) has been in routine survey operation with the Royal Australian Navy Hydrographic Service since February 1993, and has surveyed more than 75,000 km^2 (22,000 nm^2) in eight years of operation.

The manufacturer, Tenix LADS Corporation, now uses the new generation LADS called LADS Mk II (Table 2). The Airborne System (AS) is fitted into the Dash 8-202 aircraft, which flies eight-hour survey sorties. The AS comprises a solid state, 900 Hz pulsed Nd:YAG LASER mounted on a stabilised platform. Depth data is generated by firing laser pulses into the ocean and recording sea surface and seabed reflections. LADS Mk II normally surveys on a 5 m² rectilinear grid across a 240m swath during mainline sounding; higher sounding densities to 2 m² are available if required.

Table 2. Summary of LADS MkII's performance characteristics (from Tenix website: *www.tenix.com*)

Sounding Rate	900 Hz (3.24 million soundings/hour)
Area coverage	19 sq nm/hour (64 km2/hour)
Sounding density	5 m x 5m (2 m x 2 m, 3 m x 3 m, 4 m x 4 m capability)
Swath width	240 m
Bathymetric depth range	-70 m to -0.5 m
Maximum topographic height	+ 50 m
Depth accuracy	S44 IHO Standard for Hydrographic Surveys Special Publication of 4th Edition 1998, Order 1
Position accuracy	5 m CEP 95%
Data processing to data collection ratio	Better than 1:1
Output	Fairsheet plots and digital data in ASCII formats

2.3. Hawk Eye systems

In 1985, the Swedish Defence Research (FOI) was ordered by the Swedish government to develop a laser system for submarine hunting. FOI named the system FLASH and engaged Saab in Sweden, Feary in Australia and Optech in Canada as subcontractors. FOI made the system design and the control software based on its own resources. Based on FLASH, Saab developed Hawk Eye. Saab is a subcontractor to Optech for the SHOALS system used by the US Navy. Saab has delivered Hawk Eye systems to the Swedish Navy, SMA (Swedish Maritime Administration) and Indonesia. SMA has employed a Hawk Eye system for a large share of their hydrographic surveys for many years.

Swedish experts with Airborne Hydrography AB (AHAB) have developed the Hawk Eye II – a lidar system that can offer images of extremely high quality and definition in clear water depths of up to 30 m plus (2.5-3 times the capability of the Secchi depth). Hawk Eye II Laser Bathymetry & Topography System (LBTS) is an airborne system using laser technology for fast and accurate surveying of shallow waters, coastlines, shores, land and islands. At less than 200 kg, the compact and light design can be used by just one operator and pilot in any small aircraft. The Hawk Eye system includes ground equipment for mission planning and hydrographic and topographic processing, all at considerably less than the cost of multibeam surveying.

The sounding density may be set at 0.1-10m (this fulfils the IHO S44 requirements). The flight altitude can be varied between 100 and 1000 m, and normal flight altitude is 200 to 300 m with a nadir angle of 15-20°. The minimum depth detection with the previous system, Hawk Eye I, was 0.3-0.4 m. Hawk Eye II should have better discrimination owing to shorter laser pulses, better receivers and better processing algorithms. The system is usually optimised around IHO Order 1 requirements. It may be possible to re-optimise around shallow depth detections for a particular task.

2.4. Scanning Hydrographic Operational Airborne Laser Survey (SHOALS)

SHOALS is a successor to Optech's first airborne laser bathymetry system, the LARSEN 500, which was developed for the Canadian Hydrographic Service. The LARSEN 500 has been in operation since the mid-1980s on all three coasts of Canada and internationally in areas such as Indonesia, Barbados and the Middle East. It was used to produce the world's first nautical chart based on airborne laser data.

The SHOALS minimum depth capability was limited to about 1 m. However, with the recent implementation of a special ‘shoreline depths’ processing mode, SHOALS can now provide continuous topographic and bathymetric mapping through the shoreline from water onto land.

The Lidar transceiver consists of a 200 Hz frequency-doubled Nd:YAG laser which produces both green (532 nm, 3-5 mJ, 5-6 nsec) and infrared (1064 nm, >5 mJ, 7-9 nsec) pulses. A two-axis, pitch/roll-corrected scanner is used to sweep the laser beam pointing direction across the aircraft in order to produce a nearly uniform distribution of laser spots on the water surface. In addition, the transceiver records laser energy return time series (waveforms) with four receivers. One receiver records the infrared energy reflected from the water surface (surface return) while two collect the blue-green energy reflected from the sea bottom (bottom return, Figure 3 and 4). A fourth receiver records Raman energy, at 645nm, which results from excitation of water molecules at the sea surface by the blue-green laser energy.

The Raman waveform and the infrared waveform yield direct ranging of the sea surface, while the two blue-green waveforms directly range the sea bottom from 0 m to 10 m and from 10 m to 60 m. The infrared waveform is also used to distinguish dry land from water.. Additionally, one blue-green waveform is used to directly range topographic elevations.

The signals from each of the channels are pre-processed using a sophisticated analogue processing module and are digitised (for each laser sounding) and recorded for use in off-line processing. All other required system parameters, as well as the scanner angles and the aircraft position and altitude, are also recorded for later processing. A down-look video system simultaneously records the area being surveyed below the aircraft. Global features of data delivered by SHOALS are given in Table 3.

Table 3. Nominal SHOALS System performance (from Cunningham *et al.* 1998).

Parameter	Value	Notes
Measurement rate	200 soundings/sec	
Altitude for data collection	200-400 m	
Sounding density	4 x 4 m 6 x 6 m 8 x 8 m	200 m altitude, 50 knots 300 m altitude, 70 knots 400 m altitude, 85 knots
Area coverage	3 nm²/hr >6 nm²/hr >10 nm²/hr	200 m altitude, 50 knots 300 m altitude, 70 knots 400 m altitude, 85 knots
Maximum depth capability $(Kd)_{max}$	>3.0 (day) >4.0 (night)	K : diffuse attenuation coefficient (1/m) d : bottom depth (m)
Maximum depth range	40-60 m	Depending on the water clarity
Minimum depth capability	0-1 m	Without the 'shoreline depth' mode of operation allowing continuous measurement from subsurface bottoms to onshore elevations
Horizontal accuracy	±4 m (DGPS) ±1.5 m (KGPS)	1 standard deviation
Vertical accuracy	±20 cm	1 standard deviation
Data processing ratio	1 : 1	

The SHOALS system also collects a directly downward-looking, georeferenced video concurrently with the Lidar measurements. In addition to offering a visual record of the survey area, the video is frequently used to position coastal features such as navigation aids, piers and other objects of interest.

Finally, it is worth mentioning the Fish Lidar Oceanic Experimental (FLOE) system that was built in the early 1990s from off-the-shelf components, in which improvements were made to signal processing techniques used to discriminate fish returns from small particles in the water. The FLOE system penetrates depths up to 50 m. It has been used off the coast of California to survey anchovy and sardine (Figure 8), and more recently to measure plankton, squid and marine mammals. Comparisons of Lidar with acoustic data have been very encouraging and these methods can produce similar results.

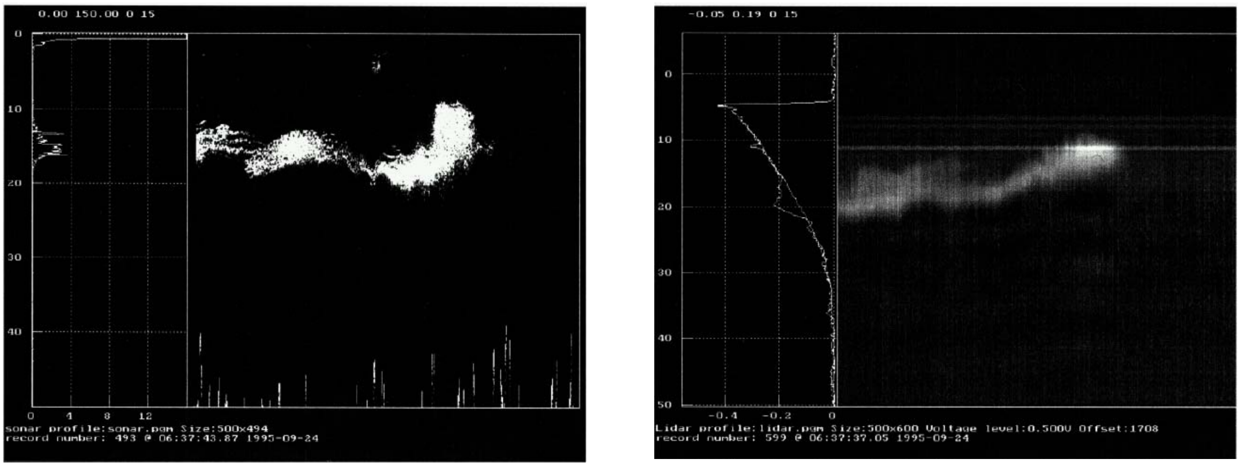

Figure 8. Comparison of synoptic acoustic (left image) and Lidar signal-return data (right image) for the same school of sardines observed off the coast of southern California (from Churnside et al. 2001 and Brown et al. 2002).

3. Review of existing standard and protocols

Very few guidance documents can be found today about Lidar. Many papers in journals partly describe operations (mostly for topographic Lidar) and processing; however, recommended operational guidelines are still needed.

3.1. Data acquisition

Lidar airborne operations are quite similar to those of other airborne surveys, with a few particular features:

- As it uses active light, the weather must be fair, though clouds are no problem provided they are located above the flight altitude with wind under 20 knots; as was mentioned above, the sea state should be fair so as to avoid too much glint and reduced penetration;
- Generally, the tide must be low, so time windows centred on low tide must be chosen. For tidal zone mapping surveys using with topographic Lidar should (standardly) be made from at the most two hours before to two hours after the spring low tide;
- For hydrographic Lidar, the neap cycle low tide can ensure reasonably low water levels combined with reduced currents and sediment bottom removal;
- Flight lines should be made as long as possible to optimise survey duration, and organised so as to survey the shallower parts when the water level is lowest. To avoid gaps due to breaking wave conditions, the survey during low water levels should be complemented with an additional one during during high tide levels;
- From experience, state-of-the-art coverage rates in complex shores are roughly 40 km² and 15 km² per hour for topographic and hydrographic surveys respectively; however, the resolution of the latter is typically 2 to 3 times lower.

3.2. Topographic Lidar data post-processing

Processing topographic Lidar data is made in two major steps: a) quality checking of the raw data to yield a point cloud and b) building the data into a user-friendly digital terrain model (DTM) for subsequent use. Some authors (e.g. Joinville et al. 2002, Daniels 2000) give a good account of their procedure and provide useful guidance. Operational documents fully describing these steps have not yet been produced. In short, quality checking mainly means checking three data attributes, density, horizontal accuracy and vertical accuracy.

Data density requirement may not be fulfilled if the survey navigation procedures were not properly carried out, resulting in gaps between adjacent swaths or over water patches (as water theoretically absorbs the infrared radiation). The operators usually provide a density map along with the data files.

Accuracy is checked by way of a high-quality DGPS (differential global positioning system) determination of reference surfaces. In practice, it is recommended that two of these references be surveyed per aircraft sortie, one at the start and the other at the end. Typically, reference surfaces should be smooth and rather flat, so that horizontal inaccuracy has a limited influence on vertical accuracy. The best surfaces are playing grounds, with a large flat area surrounded by vertical objects (hedges, railings, posts). The validation is a two-step process.

The horizontal positioning check should be carried out first by surveying a number (e.g. 30) of ‘vertical objects’ in the field, namely by their footprints on the ground. After horizontal accuracy has been shown to be within the specified limits (i.e. 0.5 m RMS), the vertical check can be performed.

A set of surveyed points distant from one another by more than the Lidar dot spacing (e.g. about 3 to 5 m) are selected. Lidar dots no more than 1 m away from these ground points are then chosen and paired with them. If there are enough of them, these pairs can then be processed statistically. The literature (e.g. Huising & Gomes 1998, Joinville et al. 2002, Populus et al. 2003) shows that on bare, smooth and moderately sloped terrain, accuracy of better than 0.15 m RMS is achieved at all times with topographic Lidar. These figures deteriorate with more rugged terrain types such as low-lying saltmarshes vegetation and slope, as is the case in cliff type shorelines.

Lidar data are extremely voluminous, leading to (x,y,z) ascii files in excess of 20 Mb per km². Building gridded DTMs has the advantage of dramatically reducing this size and providing raster files much easier to handle than point clouds in GIS.

Usually, the latest pulse data are considered first since they represent the ground. Unfortunately, these may also be generated by the top of objects, showing no double pulse (e.g. houses). In this case, only sophisticated filtering routines or visual inspection will allow the intended target data to be retrieved.

The procedure to process topographic Lidar data into a DTM involves several steps: elimination of duplicates and outliers, identification of water surfaces and interpolation to an adequate mesh size according to users requirements. This processing permits the generation of two types of models: 1) the ground (bare-earth) model called DTM (i.e. taking the last pulse) which excludes objects such as buildings, trees, and shrubs, and 2) the digital surface model (DSM) that represents the earth surface and includes all objects on it.

Regarding height reference, Lidar DTMs are initially expressed in a terrestrial system (WGS 84 or geoid level). Conversion to a tidal reference (LAT or lowest astronomical tide) is obtained by applying a shift between the LAT level and the geoid level (close to mean sea level)

Concerning Lidar reflectance information, images appear often heterogeneous and speckled (e.g. Brennan and Webster, 2006; Chust et al., 2008, 2010; and Costa et al., 2009), due to the excessive noise and artefacts caused by the sensor scanning. The main source of intensity noise is the angle of reflection of the land/sea floor surface, as some covers have different intensity values as the angle of reflection varies. In order to smooth this particular noise in the reflectance images, some filters can be applied and those preserving image sharpness, whilst suppressing noise, are recommended. The usefulness of the Lidar reflectance for habitat discrimination greatly depends upon the habitat type and the quality of the raw image (Chust et al., 2008, 2010).

3.3. Hydrographic Lidar data post-processing

Raw lidar bathymetric data are first processed using software designed by the manufacturer. In this section AHAB's proprietary Lidar survey studio (LSS) is taken as an example. LSS takes inputs in the form of a navigation file, a calibration file and the raw wave forms from the Hawkheye II. The output from LSS is .LAS files containing Latitude, longitude and point altitude data which can be imported to other processing and visualisation software.

Both hydro (green laser) data and topo (red laser) data are exported from LSS. The hydro data is broken down into 10 classes. Classes relevant to Lidar are Class 0 (outliers), Class 4 (land), Class 6 (shallow) and Class 7 (deep). Of these, two classes are exported, 6 - shallow and 7 - deep. These classes are exported at a confidence level of 0.6, meaning that only data points the algorithm is 60% certain of or better are included in the export and used in the next stage of data processing.

LSS processes the wave forms to produce values classified by laser into 'Bottom', 'Land' or 'No Bottom'. These values can be output as Ellipsoidal Heights or Depths, depending on the output required. Outputs can be set by the processor but currently all data variables are output into the CSS files.

Batch Processing of HEII files requires the input of 'confidence' settings and 'k' values by the Processor. These are initially set based on conditions experienced during the survey. Inspection of individual waveforms, especially those which return 'No Bottom' values, is carried out after batch processing to check the automatic interpretation of wave forms. Where wave forms show evidence of returns that have not been classified by the automatic processing, the 'confidence' setting can be adjusted. The effect of this can be to introduce more noise into the data but also more valid 'Bottom' returns. The Processor will adjust the 'confidence' value and reprocess when it is considered advantageous to the overall survey.

Each line processed in CSS is visualised to check for coverage, beam width and scan pattern, as well as a gross error check. Once lines are accepted they are exported as LAS files. It is possible to filter the 'no bottom found' values at this stage and they can be removed from the processed data set.

LAS files exported from CSS in the form of Point Latitude, Point Longitude, and Depth are then imported into CARIS HiPS to check coverage, data quality and navigation. Basic filtering of outliers, most notably those in the form of 'surface returns picked-up by Lidar, is then carried-out in the field and a base surface/ Fieldsheet produced. This is checked by the surveyor in the field.

A number of additional signal attributes are output by the software as can be seen in table 4 below. Whilst the seabed altitude is extracted from the green waveform with reference to the ellipsoid, the actual depth is extracted from the combination of the green and infrared waveforms.

More attributes can be extracted from the waveforms if adequate routines are developed in LSS (Table 4). One interesting attribute to assess lidar quality is wave height, obtained by averaging sea level from several returns.

Table 4: Raw data file content description (ACSAB, 2006)

Column	Description
1	WGS84 Bottom Longitude
2	WGS84 Bottom Latitude
3	WGS84 Bottom Altitude (m) , -100 = Not Found
4	Bottom Northing (m)
5	Bottom Easting (m)
6	Depth (m), without tidal correction
7	Pixel index
8	Timestamp (GPS-time in week seconds)
9	Depth class, 0 = Not Found, 4 = Land, 7 = Bottom
10	Wave height (m)
11	Depth Amplitude (amplitude of received pulse)
12	Extracted Waveform Attributes
13	Receiver Data Used
14	Manual Output Screening

On Figure 9 returns from adjacent shots clearly show the presence of canopy standing to a height of 1 to 1.5m. Some returns are generated either by the top of the canopy, others by the seabed itself. It should be determined whether this is bound to occur in dense kelp cover only or also by sparse cover.

Furthermore, as is the case with the well-known double pulse typical of topographic Lidar interaction with terrestrial vegetation, bathymetric Lidar is expected to yield more than just depth, provided more research and adequate processing are performed on the waveforms.

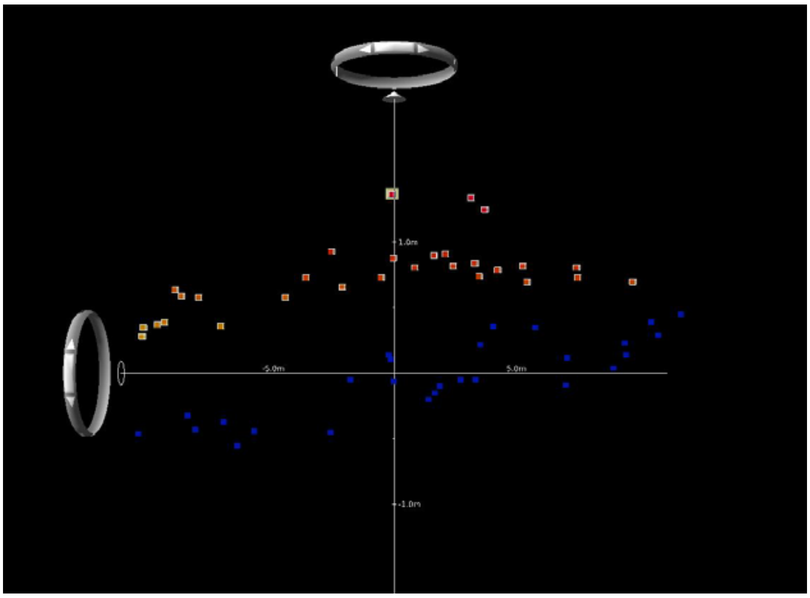

Figure 9: Bottom returns on kelp canopy - red dots - and actual seabed - blue dots.
(Courtesy of SHOM, France).

3.4. Data interpretation

A comprehensive review of surveying with Lidar and interpreting its data is given by Brown et al. (2002). For habitat mapping, Lidar-derived elevation data can be processed to generate several topographic features such as slope, aspect, and rugosity. Raster DTMs have to be displayed in such a way to aid orientation in the field for instance using shaded relief models. Slopes can also be computed and displayed. Specific height isolines are also useful (e.g. lower saltmarsh level). An example is shown below (Figure 10) of a Lidar DTM of one metre grid size (initial dot spacing was about 1.5 m) covering the Traict du Croisic, Loire-Atlantique, France. The elevation colour coding is every 0.25m. During field surveys, the elevation displayed on this map helped identify the main landforms and position the field sample locations (sediment and fauna). Interpretation can be undertaken in conjunction with other data. The DTM was exploited jointly with aerial photos and samples for final habitat mapping. Brown tones in the right side of the image are salt pans with similar water levels. White gaps are patches of clear water that absorbed the lidar beam and gave no return.

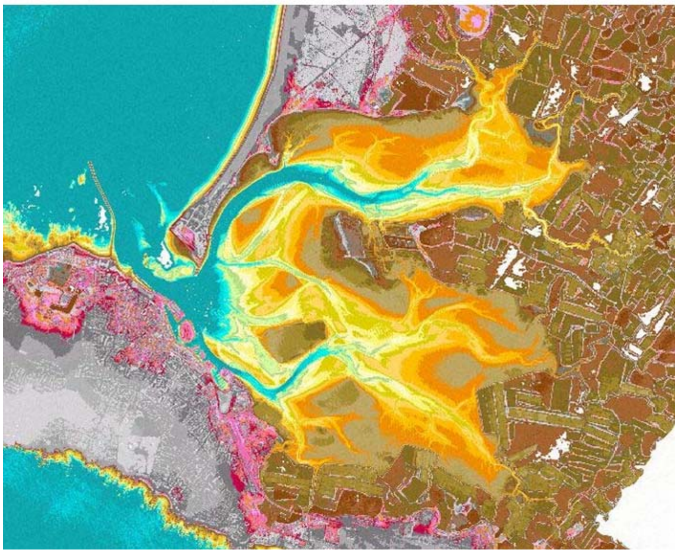

Figure 10. A topographic map of Traict du Croisic (Loire Atlantique, France) at spring low tide (Ifremer survey using Optech ALTM).

Another example on coastal habitat mapping is the assessment of the capabilities of the airborne bathymetric Lidar sensor (Hawk Eye system) in the Oka estuary (within the Biosphere Reserve of Urdaibai, SE Bay of Biscay, northern Spain), where water conditions are moderately turbid (see Chust et al. 2010). This study tested the discrimination potential of Lidar height, topographic features and reflectance information, together with multi-spectral imagery (three visible and near infrared bands), for the classification of 22 saltmarsh and rocky shore habitats, covering supralittoral, intertidal and subtidal zones. This study concluded that the combination of the Lidar-based DTM and derived topographical features with multispectral imagery permits high accurate habitat mapping, although somewhat limited by water turbidity and wave breaking.

This strongly supports the importance of Lidar integration with multi-spectral imagery to enhance coastal and estuarine habitat classifications since each information processed separately produced high habitat classification confusion. An example of this is given in Figure 11 showing the enhancement obtained in mapping *Zostera noltii* seagrass beds using data fusion.

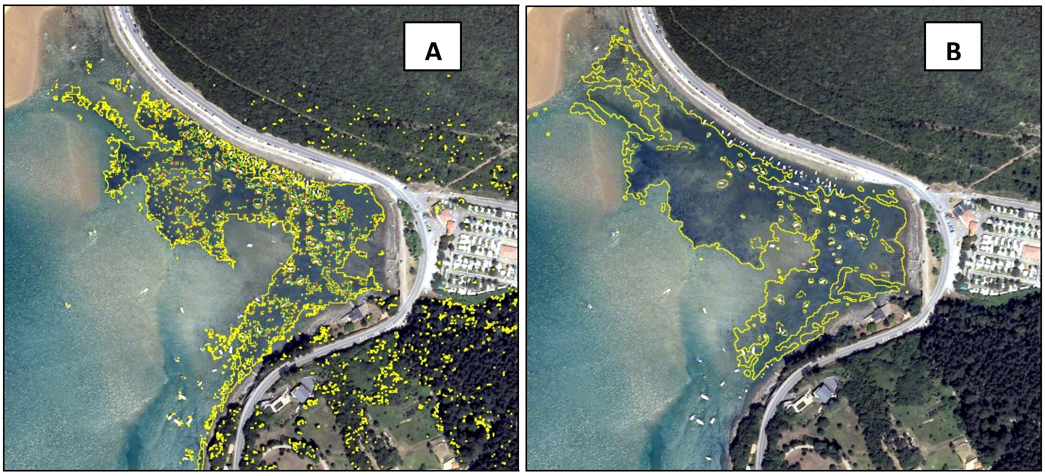

Figure 11. Classification improvement of *Zostera noltii* habitat in shallow waters, superimposed upon a RGB (Red Green Blue) colour composite image; classified with A) RGB, and B) Visible and Near InfraRed (VNIR) bands together with Lidar height, slope and shaded relief (with filtering at 3x3 pixel size).

Concerning topographic features, slope contributed to habitat discrimination on rocky shores while it was less significant over plain saltmarshes (e.g. mudflats). Overall, this showed the importance of elevation and topographic features in habitat classification as a function of landscape type and species traits. Moreover, this study revealed that when comparing Lidar and multibeam data, Lidar presented higher height deviations in rocky substrates than in sediment bottoms (see Figure 12).

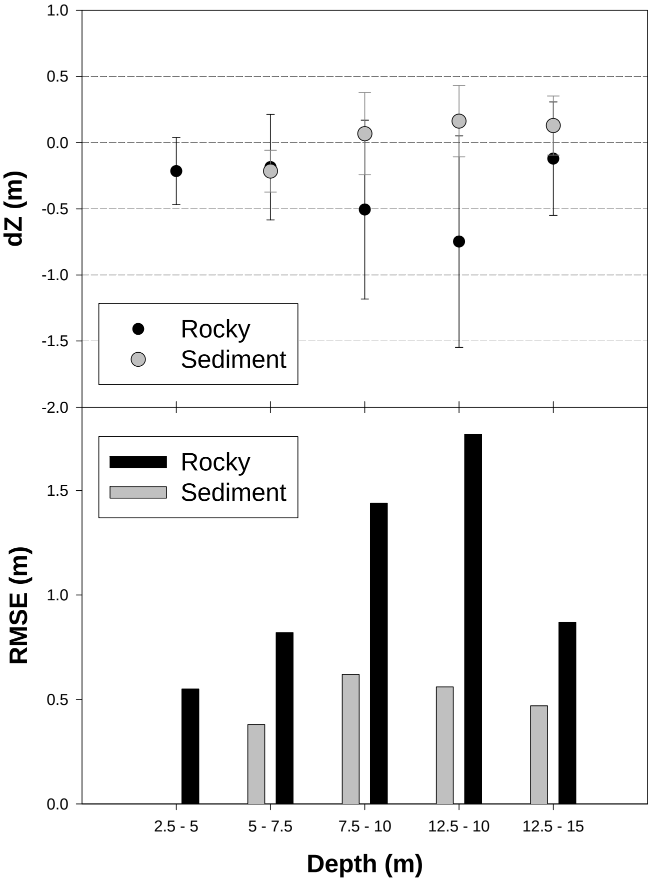

Figure 12. Comparison between multibeam echosounder and Lidar as a function of depth for two seafloor types. RMSE is the root mean square error and dZ the mean height difference. Error bars represent the SD/2, where ±SD is the standard deviation. Source: Chust *et al*. (2010).

Recent developments make use of the dual-wavelength Lidar intensity data (red and near-infrared) to derive vegetation indices useful for estimating the amount of saltmarsh vegetation (Collin et al. 2010).

Figure 13 shows a subset of the seamless DTM across the coastline of the Roches de Penmarc'h site in Brittany obtained by stitching together topographic and hydrographic lidar data surveyed with a Hawkeye dual laser system. As both data sets were rerefenced to the ellipsoid no tide correction was necessary.

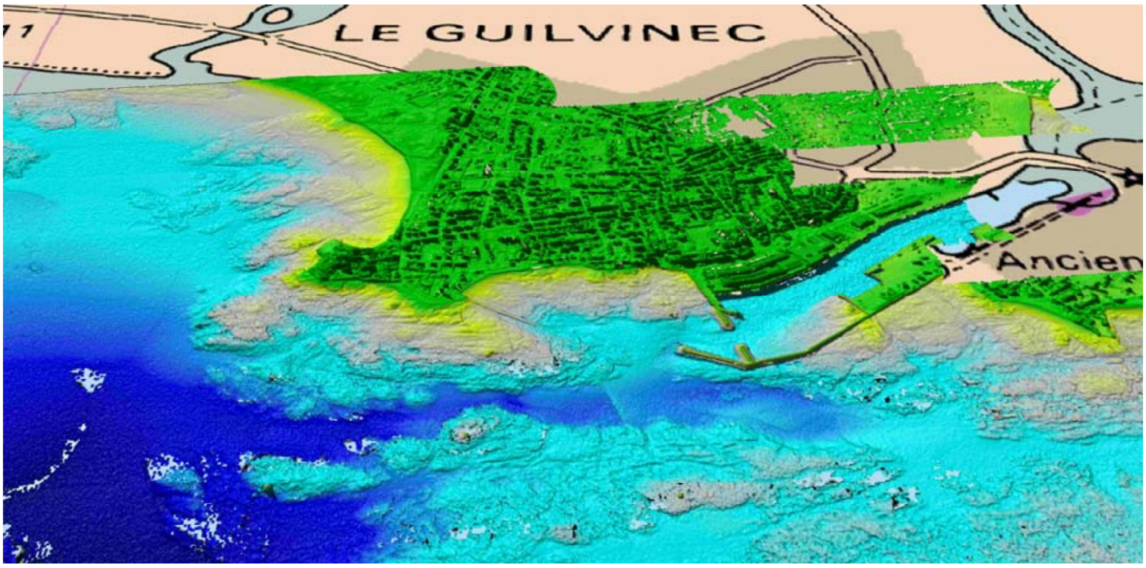

Figure 13. Combined topographic and hydrographic digital elevation model of Le Guilvinec harbour, south Brittany (Courtesy of the Intereg IV MeshAtlantic project).

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