IWT SBO PROJECT 120003 "SEARCH"

Archaeological heritage in the North Sea

Development of an efficient assessment methodology and approach towards a sustainable management policy and legal framework in Belgium.

Archeologisch erfgoed in de Noordzee

Ontwikkeling van een efficiënte evaluatiemethodologie en voorstellen tot een duurzaam beheer in België.

DIGITAL SURFACE MODELLING OF THE INTERTIDAL ZONE (LIDAR)

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Table of abbreviations

ALB	Airborne Laser Bathymetry
ALS	Airborne Laser Scanning
DSM	Digital Surface Model
EDM	Electromagnetic Distance Measurement
FLEPOS	FLEmish Positioning System
GCP	Ground Control Points
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
INS	Inertial Navigation System
LRM	Local Relief Model
MBES	Multi-Beam Echo Sounder
MTLS	Mobile Terrestrial Laser Scanning
MVS	Multi View Stereo
POS	Position and Orientation measurement System
RTK	Real Time Kinematic
SAR	Synthetic Aperture Radar
SfM	Structure from Motion
STLS	Static Terrestrial Laser Scanning
TOF	Time Of Flight
UAV	Unmanned Aerial Vehicle

DIGITAL SURFACE MODELLING OF THE INTERTIDAL ZONE (LIDAR)

Abstract

Digital Surface Models (DSMs) are an indispensable data source for the management and protection of archaeological relicts and cultural heritage. In many applications, DSMs are used as base layer in combination with many other types of maps. If the resolution and accuracy of the models are sufficient, DSMs will also enable the detection of new relicts using advanced elevation enhancement algorithms. In coastal areas, especially in intertidal zones of beaches, the construction of DSMs that meet these resolutions and accuracy requirements is a challenging task.

In this paper, different data acquisition techniques are presented, aiming at the construction of DSMs with a resolution of at least 1 m and with a vertical accuracy of at least 25 cm. Different types of laser scanning, image based modelling and conventional topographic measurement techniques are covered and analysed. The research is mainly focussed on the first technique, covering both airborne approaches (Airborne Laser Scanning (ALS) and Airborne Laser Bathymetry (ALB)) and terrestrial approaches (Static Terrestrial Laser Scanning (STLS) and Mobile Terrestrial Laser Scanning). However, the use of GNSS, total station measurements, conventional photogrammetry and structure from Motion and Multi-View Stereo (SfM-MVS) are also discussed in the context of intertidal surface modelling. The advantages and disadvantages are carefully considered for the implementation within a project on the development of a sustainable management policy for maritime cultural heritage at the Belgian North Sea coast. The most constraining parameters in this context are the water turbidity and hard weather conditions. Not only are the environmental conditions very difficult for various sensors, also the gap between bathymetric and topographic methods hampers the full coverage of beaches by DSMs. Other more practical issues also play an important role in the selection of an appropriate data acquisition technique. Based on the findings of this research, it becomes clear that MTLS is very suitable for this purpose. Using this technique, the requirements on accuracy and point density are met, as well as the requirements on the flexible deployment under rapidly changing conditions. Besides, the use of Unmanned Aerial Vehicles (UAVs) in an image based processing workflow will result in DSMs with textures or orthophotos.

1 Introduction

1.1 Paper outline

The SeArch project aims to develop a reliable and cost-efficient survey methodology, based on remote sensing and geophysical techniques, which allows the assessment of the archaeological potential of areas at sea affected by industry or infrastructural works. This paper will focus on different state-of-the-art sensors and techniques to generate Digital Surface Models (DSMs) of intertidal zones of beaches. For these models, spatial data with a high quality and a 2.5D or 3D geometry are essential. Figure 1 presents an illustrative overview of a Belgian beach. The width of 50 to 100 meters between the low water level and high water level is very typical for this coast line. The amplitude of a tidal cycle is between 4 to 5 metres.

Figure 1. Overview of one of the areas with high archaeological potential

A special focus is laid on the adapted use of different types of laser scanning, but conventional onshore techniques (Global Navigation Satellite System (GNSS) or total station) and image based techniques will also be discussed for intertidal zones. The dimensions of most relicts are often limited, implying high resolution and highly accurate DSMs. Consequently, only surface modelling techniques with a reachable Ground Spacing Distance (GSD) lower than 1 m (possibly after gridding the point cloud) and a vertical accuracy of 25 cm or higher were selected. As a result, no space borne sensors are included in this paper, like QuickBird or GeoEye. It is important to mention that no full discussion on the sensors, working conditions and error sources can be presented. The authors refer to the large number of references for further readings.

1.2 Surface modelling of intertidal zones of beaches

Coastal modelling heavily suffers from gaps between land and shallow waters. On the one hand, common onshore techniques are not able to measure the surface topography under water, due to significantly different medium conditions. On the other hand, bathymetric techniques cannot be applied in intertidal zones, due to the limited draft and the disability to operate outside the water. A thorough maritime and coastal management system requires full coverage with detailed DSMs. It is obvious that this area may be considered as the link between hydrography and topography, where the environmental conditions involve different incompatible or difficult physical parameters that have to be fathomed. In the context of laser scanning, different parameters are already discussed in literature, like the influence of sun elimination and sand parameters [*Křemen et al.*, 2006] or the influence of range, local slope and surface parameters [*Soudarissanane et al.*, 2011]. However, a study fully dedicated to the difficulties on the surface modelling of intertidal zones is hard to find. Notwithstanding these difficulties, it can be shown that onshore acquisition techniques may be adapted in order to fill the gap.

For bathymetric modelling, acoustic systems are frequently applied, like Multi-Beam Echo Sounders (MBES). The transducers of these systems require fully humid environments and most systems require a minimum draft of around 2 meter. Thus, these systems do not meet the requirements of intertidal surface modelling and will not be discussed in this paper. It must be mentioned that shallow water MBES systems also exists, but these systems require a very calm water surface. Photogrammetry and topography are classical techniques to acquire onshore DSMs, but the use of laser scanning [*Doneus et al.*, 2008; *Oude Elberink and Vosselman*, 2011], Synthetic Aperture Radar (SAR) [*Simarda et al.*, 2008] and digital image based modelling [*Rottensteiner et al.*, 2007; *Tack et al.*, 2012] are also more and more applied since a few decades.

The combination of different systems is also appreciated in both onshore applications [*Briese et al.*, 2012; *Haala and Kada*, 2010] and coastal applications [*Wübbold et al.*, 2012]. The integrated use of different sensors is also combined with abstract modelling parameters for the validation of coastal environmental and morphological prediction [*Scott and Mason*, 2007]. It is important to understand the working principles and operational parameters of the different techniques. The selection of a specific sensor or series of sensors is obviously an equilibrium between different requirements, like resolution, accuracy, speed, price, … The comparative study presented in this paper is motivated by this requirement, and is also an update of the work of Mason et al. [2000] and Gao [2007].

Within the project, the data acquisition campaign and processing will result in a DSM of the intertidal zone of the beach, supplementing the bathymetric and topographic measurements. The use of DSMs is already common practice for a various range of onshore applications, like environmental modelling [*Dubovyk et al.*, 2011; *Hape and Purps*, 1999], spatial planning and management [*Kolbe et al.*, 2005; *Smart et al.*, 2011; *Stoter et al.*, 2008], as well as in archaeology and cultural heritage [*Hendrickx et al.*, 2011; *Koller et al.*, 2009; *Remondino*, 2011]. The DSM will be used for the calculation of different derivative products, like Local Relief Models (LRMs), contour maps or hillshade maps [*Hess*, 2010; *Stal et al.*, 2010]. The integration of these products in a Geographic Information System (GIS) is an extra added value to the management of the coastal area of Belgium, with a special focus on maritime cultural heritage. Besides, the GIS-based use of a DSM enables further shape and pattern detection, data integration and interoperability between different stakeholders [*Finkl et al.*, 2005; *Lam and Yip*, 2008].

This paper is structured as follows: section 2 is fully dedicated to laser scanning. After a discussion on the general principles of laser scanning with special attention to the different distance measurement techniques, regular Airborne Laser Scanning and Airborne Laser Bathymetry are discussed. Static and Mobile Terrestrial Laser Scanning are presented as alternatives for the measurement of intertidal zones. Section 3 will focus on the use of conventional topographic measurement techniques like GNSS and total station. The last spatial data acquisition technique that is presented in section 4 covers photogrammetry and Structure from Motion and Multi-View Stereo as image based surface reconstruction methods. The four techniques are further compared in section 5, where recommendations on the surface modelling of intertidal zones on Belgian beaches are presented.

2 Laser scanning

2.1 General principles

Laser scanning is also known as LiDAR, an acronym that stands for 'Light Detection And Ranging'. The term is a generic term for all techniques, in which (laser) light is used to derive the distance between a sensor and an object or surface [*Wehr and Lohr*, 1999]. A large number of distance and angular measurements will result in a very dense point cloud within a limited time frame. All types of laser scanning systems use active, optical, reflection based and contact free scanning methods [*Galantucci et al.*, 2006]. Using the electromagnetic distance measurement (EDM) technique, a distance is derived by means of measuring the circulation time of a pulse or the wavelength difference of a continuous wave. The electromagnetic signals are situated in the visible, near- or short-wave infrared range (500-1600 nm). In addition to the backscatter based distance measurement, horizontal and vertical angles are recorded. By transmitting signals from a measuring instrument of which the orientation and the coordinates are known or fixed in three dimensions, polar coordinates can be calculated based on the measurements of angles and a distance. Polar coordinates are usually directly converted to Cartesian coordinates.

To be more precise, the acquisition of a point cloud by laser scanning is based on the registration of horizontal angles, vertical angles and on the (direct or indirect) measurement of distances. Absolute coordinates $r\ (X_R, Y_R, Z_R)$ of an object R are determined in relation to the position $p\ (X_P, Y_P, Z_P)$ of sensor P and the distance and direction of vector a from the sensor P to the object R [*Katzenbeisser*, 2003]. The object R can be any properly reflecting object within the range of the sensor (Figure 2).

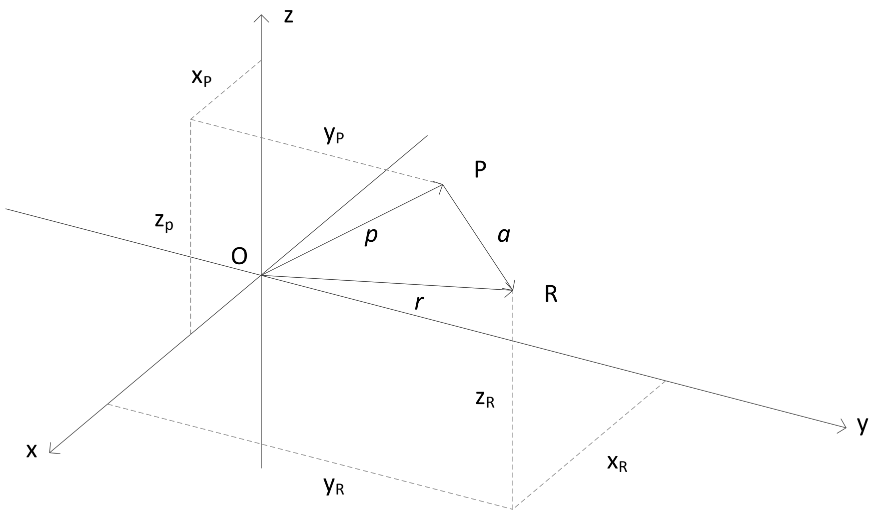

Figure 2. Determination of the coordinates of object R [Katzenbeisser, 2003]

The position *p* of sensor P is measured by the combined use of GNSS and INS (Inertial Navigation System) in mobile applications, or by point cloud registration in static applications. The actual angular and distance measurements of vector *a* are performed by the laser scanner. The angle, from which this distance is measured, is measured by the registration of the rotation of a rotating mirror. This mirror must be perfectly aligned and calibrated with respect to a reference orientation. The pulse frequency varies with different topographic airborne units from 20 to 300 kHz (pulse frequency, sampling interval per pulse), where between 5 to more than 400 scan lines per second (scan frequency) can be recorded [*Lemmers*, 2007]. For terrestrial applications, these values may increase strongly up to 1 GHz, when a phase-based laser scanner is deployed. Pulse-based and phase-based laser scanning are the most common techniques for the distance measurement [*Baltsavias*, 1999] and will be discussed in more detail. Pulse-based systems are most common in airborne laser scanning applications, whereas phase-based systems may be implemented in fast and accurate terrestrial laser scanners. In both cases, the incidence angle and the reflecting object play an important role in the accuracy of the distance measurement, which will be discussed later in this paper.

Pulse-based measurement

Pulse-based laser scanning systems, also called Time-Of-Flight (TOF) scanning systems, are frequently used for airborne applications [*Hug et al.*, 2004] and terrestrial applications with relatively long ranges (e.g. over 100 m). Using this technique, the distance between the sensor P and the reflecting object R is directly calculated by counting the time delay *t* between an emitted and received pulse. This delay is multiplied by the speed of light *c* and divided by two:

$$d = \frac{1}{2} c\, t$$

Equation 1: Pulse-based distance measurement

The time of flight of the signal is registered by a counter, which multiplies the number of cycles *n* by a given frequency *f*. The resolution of the counter has a linear relation with the range resolution of the measurement system [*Wehr and Lohr*, 1999]. A constant time factor should compensate the time delays, inherent to the electronics of the system and should be carefully calibrated.

Phase-based measurement

In many short range terrestrial applications (< 100 m), phase-based laser scanners are used. This type of laser scanners is known for their high scanning speed and accuracy in comparison with pulse-based laser scanners [*Nuttens et al.*, 2010]. A continuous electromagnetic wave is emitted and its backscatter is received. This returned signal will have a phase shift with respect to the same signal that has been recorded by the scanner. Based on this phase shift and the number of entirely elapsed waves, the distance can be determined [*Baltsavias*, 1999]:

$$d = \frac{1}{2} c \left(\frac{1}{2\pi} \frac{1}{f} \varphi \right) = \frac{1}{4\pi} \frac{c}{f} \varphi$$

Equation 2: Phase-based distance measurement

As demonstrated in Equation 1, the calculated distance *d* is directly related to the time of flight of the signal. Using a phase-based scanner, this travelling time is calculated as a function of the frequency *f* of the signal and the phase shift . The resolution of the system is then limited by the extent to which this phase shift can be measured [*Wehr and Lohr*, 1999].

2.2 Airborne Laser Scanning (ALS) and Airborne Laser Bathymetry (ALB)

In contrast to conventional photogrammetry, Airborne Laser Scanning (ALS) is a relatively new technique in surveying and engineering for topographic surface modelling. Although the acquisition technique itself is known for several decades, much research is still performed on different applications, accuracy improvement and processing performance. Especially in geo-sciences and engineering, ALS is frequently used to generate 2.5D and 3D models. The main advantages of ALS are the fast and relatively accurate acquisition of topographic point sets, with a wide range of possible point densities. This density is related with the flying height. Besides, recent research on processing ALS data enabled a reliable and straightforward workflow for the generation of DTMs and DSMs [*Podobnikar and Vrecko*, 2012].

The ALS systems deflect the laser beam across a flight path in order to acquire a certain field of view (Figure 3). Each separate distance and angle measurement is combined with synchronized observations of a position and orientation measurement system (POS). This enables the direct georeferencing of the measured points in a common coordinate frame. The POS typically consists of a GNSS and an INS [*Mallet and Bretar*, 2009]. As with all other mobile and integrated spatial measurement systems, the calibration of these different sensors is very important. This calibration consists of the determination of the lever-arm and bore-sight parameters, representing positional and angular offsets of the different local coordinate systems of the sensors [*Skaloud and Lichti*, 2006].

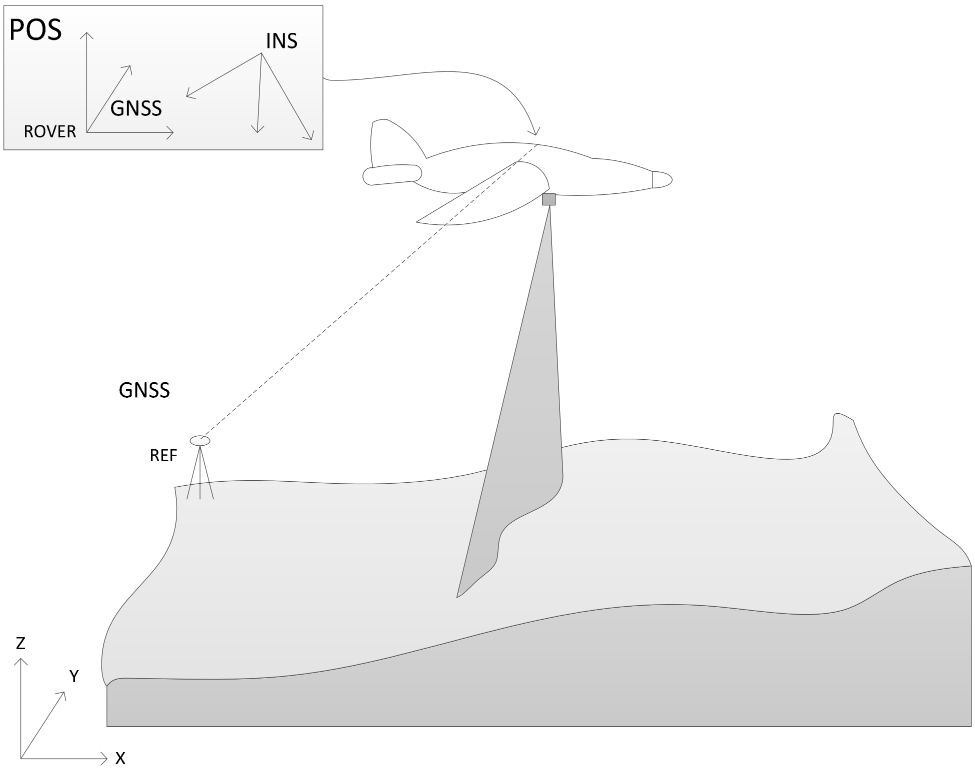

Figure 3. General operation principle of an ALS-system

Airborne Laser Bathymetry (ALB) is a new remote sensing technique that has known a very fast development over the last few years. In most aspects, ALB is very similar with regular ALS systems. However, a common ALB system is equipped with a pulse-based dual wavelength signal emitter and receptor, typically with wavelengths of 1064 nm (near infrared, like in ALS) and 532 nm (green). The first signal is reflected by the dry ground and the water surface; the second signal penetrates into the water and is reflected on the sea bottom (Figure 4).

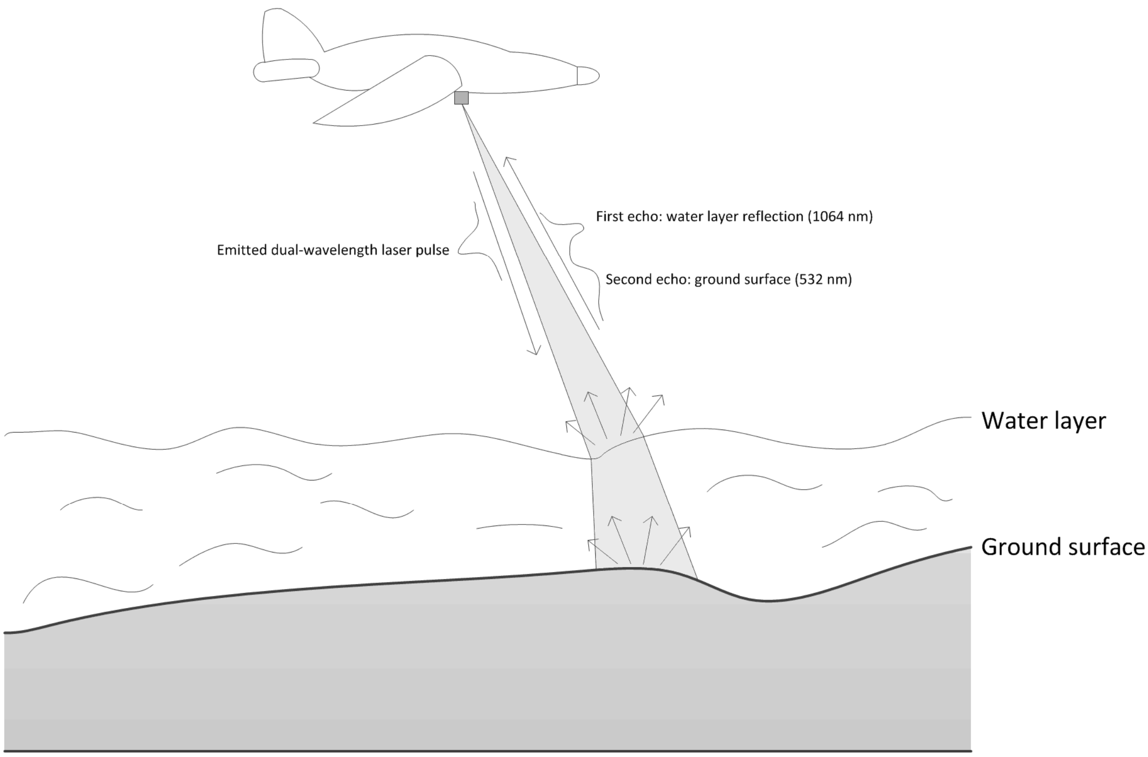

Figure 4. Operational principle of Airborne Laser Bathymetry (ALB)

The technique is used for bathymetric surveying of shallow coastal waters and in the right environmental conditions, it will provide significant efficiency advantages over survey by regular multibeam vessels. The most recent advances have enabled the recovery of reflectivity information from the seabed footprint, leading the way to seabed classification and advanced feature detection. Earlier research has demonstrated the potential of ALB in areas with water turbidity of 2-3 secchi depths [*Pastol*, 2011; *Pe'eri et al.*, 2011]. In clear water, this corresponds with approximately 50 m. Due to the active billow and strong tidal current in the near shore North Sea coast, high water turbidity occurs, limiting this secchi requirement to only a few decimetres. Using ALB, it is possible to cover both the dry beach, as well as the sea bottom. The technique does not necessarily provide a full coverage of the area, because of interference of the two signals in very shallow waters (approximately 20 cm). The automatic detection of the current shoreline will be hampered and additional campaigns have to be performed to overcome this problem [*Pe'eri et al.*, 2011]. Multiple scan campaigns during different tidal situations could solve this data gap issue as well.

In contrast with the high pulse frequency of ALS systems, ALB systems operate with a frequency of only 1 kHz. In order to penetrate a water column with the green signal, a significantly longer and more powerful laser pulse is required. Complex interactions occur between the emitted laser signal and the environment. After emission, attenuation takes place on the beam by absorption and scattering. Signal losses, caused by diffuse reflection, occur on the water layer, but also the influence of refraction is very important to mention and has to be taken into account. The green signal will penetrate the water layer until it is fully absorbed or until it reaches the ground surface, where a second diffuse reflection takes place. During the return of the signal, the same phenomenon occurs, but in the opposite direction [*Mitchell*, 2008]. Increasing the emitted energy of the signal will clearly increase the penetrating capacity and thus the maximal depth of the water layer. The signal-to-noise ratio will also increase with higher power levels. Nevertheless, this power level is limited by legal void for security reasons: high energetic green light may cause irrevocable eye damage. Besides, officially preparatory permission is required to perform the flight, reducing the flexibility of measuring the intertidal zones under acceptable weather and tidal conditions. Based on this theoretical comparison of ALS and ALB, it becomes clear that ALB campaigns will result in coarser digital surface models with lower accuracies, as an ALS acquisition campaign under the same acquisition circumstances. However, the quality of the ALB data could be comparable with MBES data in near shore areas [*Pastol*, 2011]. Besides, the acquisition time and cost of ALB are lower in comparison with conventional bathymetric acquisition techniques, when very large surfaces are covered [*Lam and Yip*, 2008].

2.3 Static Terrestrial Laser Scanning (STLS)

Static Terrestrial Laser Scanning (STLS) is a variant of the above mentioned laser scanning techniques, where a huge amount of accurate detail points is acquired from a fixed laser scanner position. STLS is frequently used to model objects of a limited size or at a limited distance from the scanner [*Pieraccini et al.*, 2001]. The type of application and the range is in this context mainly related to the type of distance measurement (i.e. phase-based with a range up to 100 m or pulse-based with a range up to 1 km) [*Pertrie and Toth*, 2009]. High resolution STLS is more and more being applied for measuring and monitoring geometric deformations of civil technical constructions [*Nuttens et al.*, 2010], but also in cultural heritage [*Pesci et al.*, 2012; *Stal et al.*, 2012] or earth sciences [*Brodu and Lague*, 2012; *Jaboyedoff et al.*, 2012] STLS offers a non-invasive solution for the need for 3D data in a short time frame and in difficult field conditions. This data recording leads to an accurate 3D model which offers a point based representation of the object or site and offers a complete data set ready for archiving and detailed processing in the future with possibly more powerful processing techniques [*Laefer et al.*, 2012].

The technique can be used for topographic surface modelling [*Slob and Hack*, 2004], but it is obvious that STLS suffers from some important drawbacks for intertidal zone mapping. The number of scans is related with the size of the area that has to be scanned. Because of the lack of topographic variability of the terrain, a target based registration is required [*González-Aguilera et al.*, 2009]. Since each target, or materialised reference point, has to be positioned a coordinate system, the campaign can be very time consuming. An even more important drawback of static measurements is the fact that on flat terrain, the angle of incidence will be very large. A scanner is often placed on a tripod, meaning that the scanning height is around 1.5 to 2.0 m. Even with a range of 8.5 m, there will be an incidence angle of 80^o, resulting in large beam spots or radiation angles. Thereupon, lower signal to noise ratios will occur and lower point accuracies will be reached [*Soudarissanane et al.*, 2011]. Summarizing, it can be concluded that STLS will be very useful for the detailed modelling of small surfaces, but attention on the speed and accuracy has to be paid for the mapping of larger areas.

2.4 Mobile Terrestrial Laser Scanning (MTLS)

With Mobile Terrestrial Laser Scanning (MTLS), the system configuration is very similar to an ALS setup. A laser scanner, GNSS and INS are the main components, mounted on a driving platform. As in airborne applications, the combination of GNSS and INS measurements from the POS provide high accurate positioning, whilst the laser scanner produces a very precise point cloud. The accurate determination of the calibration parameters is also essential for the correct use of MTLS. However, the required power level for the laser scanners is much lower, reducing the dimensions of the system and therefore improving the usability on compact platforms.

MTLS has already been applied for river bed mapping [*Vaaja et al.*, 2011] and also on beaches for coastal protection applications [*Bitenc et al.*, 2011]. For intertidal beach modelling, the driving platform needs to perform in very shallow water, but also in shifting sand. An amphibious vehicle, like the ARGO (Figure 5) is then an obvious choice. Although 2D profile scanners can be used for MTLS, it is also possible to deploy regular STLS systems configured as a profiler. Nevertheless, the centimetre accuracy of both systems is comparable. STLS has the advantage of generating point clouds of the surface in a strip-wise manner as with airborne scanning. Using the ARGO, the scanning height will be more or less equal to the height of a scanner on a tripod. The previously mentioned issue concerning the large incidence angles can be reduced by limiting the scanning range and allowing enough overlap between subsequent strips [*Vosselman and Maas*, 2001].

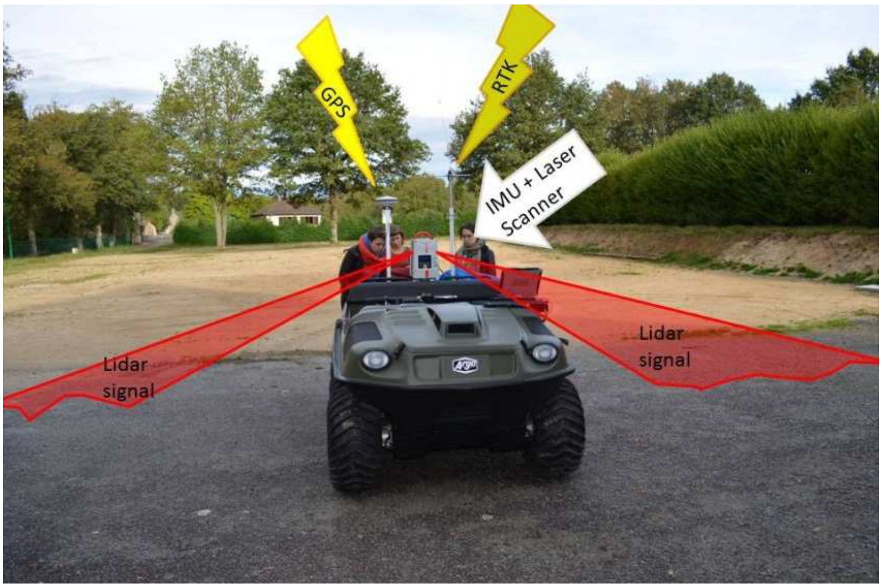

Figure 5. Main components of a mobile laser scanning system, mounted on the ARGO

3 Conventional topographic measurements

GNSS measurements or measurements with a total station are probably the most well-known techniques to generate DSMs. In contrast with the mentioned laser scanning techniques and image based modelling, which will be discussed in the next section, the measurements for a DSM are a mainly manual process. The theoretically possible point density of conventional topography is equal to the other techniques, but this is hardly feasible for practical reasons. Consequently, these techniques are mainly applied for low resolution surface modelling with high accuracy, e.g. for the calculation of reference surfaces which can be used for quality evaluation of DSMs acquired by more automated techniques. Besides, conventional topography is frequently applied for the measurement of Ground Control Points (GCPs) or reference points as input for the georeferencing of laser scan or image based modelling DSMs.

3.1 GNSS

Until a few years, it was very difficult and expensive to measure single points with cm accuracy. Moreover, these measurements were extremely time-consuming. The ability to use data connections over mobile networks have speed up the development of Real Time Kinematic (RTK) GNSS measurements with cm accuracy. The Flemish Positioning Service (FLEPOS) is the implementation of such a system in Flanders, consisting of a network of 40 permanent reference stations. Users can use this FLEPOS service by downloading real time correction messages for their own GNSS measurements [*De Wulf et al.*, 2006]. By using FLEPOS, point precisions between 1 and 4 cm (67% or 1 sigma) can be reached for planimetry and altimetry [*AGIV*, 2008]. This easy access to very accurate GNSS measurements has opened a lot of possibilities to use GNSS for the fast and accurate generation of DSMs. However, the technique is still limited by the achievable resolution of the measurements. For the application of GNSS measurements in the intertidal zone of a beach, an extra error source can be introduced when the pole on which the GNSS antenna is mounted is not perfectly positioned on the beach's surface.

3.2 Total station measurements

Recent developments towards robotic total stations make it possible to perform reflectorless distance measurements (EDM) by only one operator, significantly increasing the performance of total station measurements. The use of such a total station for surface mapping may result in an accuracy of 1 or 2 cm, although sub-centimetre single point precisions can be reached. Another interesting development is the integration of total stations with imaging sensors [*Sakimura and Maruyama*, 2007]. Nevertheless, the same remarks have to be made as with the GNSS measurements. Due to the slower measurement speed (in comparison with e.g. laser scanners) and the higher degree of manual intervention by the operator, only a lower point density is achievable.

4 Photogrammetry and image based modelling

In contrast with the discussion on laser scanning, image based modelling techniques can be distinguished by processing algorithms, rather than by the used acquisition techniques and platforms. Photographs can be taken during an airborne or terrestrial campaign or on a mobile or static platform. In all cases, the initial data for the surface reconstruction are two or more digital images. As with ALS, airborne photogrammetric campaigns also require predatory permission and are therefore not advisable for intertidal zone modelling. The use of an Unmanned Aerial Vehicle (UAV), like a drone or kite, could be an alternative, notwithstanding the fact that favourable weather and tidal conditions are required. The presence of salt water can be disastrous for the fine electronics on the platform, so a watertight construction is preferred. On terrestrial images, it is very difficult to define corresponding points between different images. Large incidence angles away from the acquisition point of an image result in very large GSD, so terrestrial photogrammetry and image based modelling is only advisable for very small and characteristic areas.

4.1 Conventional photogrammetry

A conventional photogrammetric workflow can be subdivided into two main processes. The chain starts with the aerial triangulation for which aerial images, camera details, orientation files and GCPs are required. If this process is successful, the triangulated images and generated tie-points make it possible to extract detailed and accurate DSMs. Conventional digital photogrammetric software packages process stereo couples one by one. This means that different images are aligned with each other in a pair-wise way. Although recent software may merge different stereo-based DSMs in the last step of the processing workflow, the calculated elevations are only a function of single image pairs, averaged over all available stereo couples. Since this technique is also very well documented, we refer to [*Kraus*, 2007] and [*McGlone et al.*, 2004] for further readings.

4.2 Structure from Motion and Multi-View Stereo (SfM-MVS)

New 3D photo modelling software is able to generate 3D models based on a large series of images using SfM-MVS. SfM-MVS is a technique to reconstruct the camera acquisition parameters and a sparse point set of the scene (SfM), as well as a technique to acquire the 3D geometry of an object, or a series of objects (MVS), using a series of 2D images [*Lourakis and Argyros*, 2009]. The projection of a real 3D object on a 2D image plane and the inverse transformation of the resulting 2D image coordinates into a virtual model in a 3D space, result in the determination of the extrinsic parameters and require the intrinsic camera parameters for the initial iteration [*Robertson and Cipolla*, 2009]. This is also applied in conventional photogrammetry, but in this case, multiple images can be used instantly. The intrinsic parameters, like the image format, the principal point and the focal length of the images are extracted from the metadata of the images. The extrinsic parameters are calculated by the projection of the images in the 3D space. Characteristic points or feature points are detected on different images and matched with each other. In order to recover the position and orientation of the different camera positions, a system of geometrical projective matrices, based on the 3D coordinates of these points, has to be solved [*Pollefeys et al.*, 2000]. The first step in this process is the (automatic) detection of these feature points. Using the resulting parameters, the extrinsic transformation parameters of the images in a virtual 3D space are calculated. For the absolute orientation of the images, the derived feature points and model, GCPs are required. As with conventional photogrammetry, these points must be unambiguously detectable. The temporal scene structure, the orientation and position of the images are illustrated in Figure 6. The numbered rectangles, representing the images, their recording positions and the feature points, give an impression about the correctness of the image alignment. This first scene visualization also enables the selection of a part of the study area for further processing by defining a bounding box around this area. In Figure 6, the GCPs measured by RTK GNSS are visualized as flags with numbers. The rather equal spatial distribution of the GCPs becomes clear in this figure.

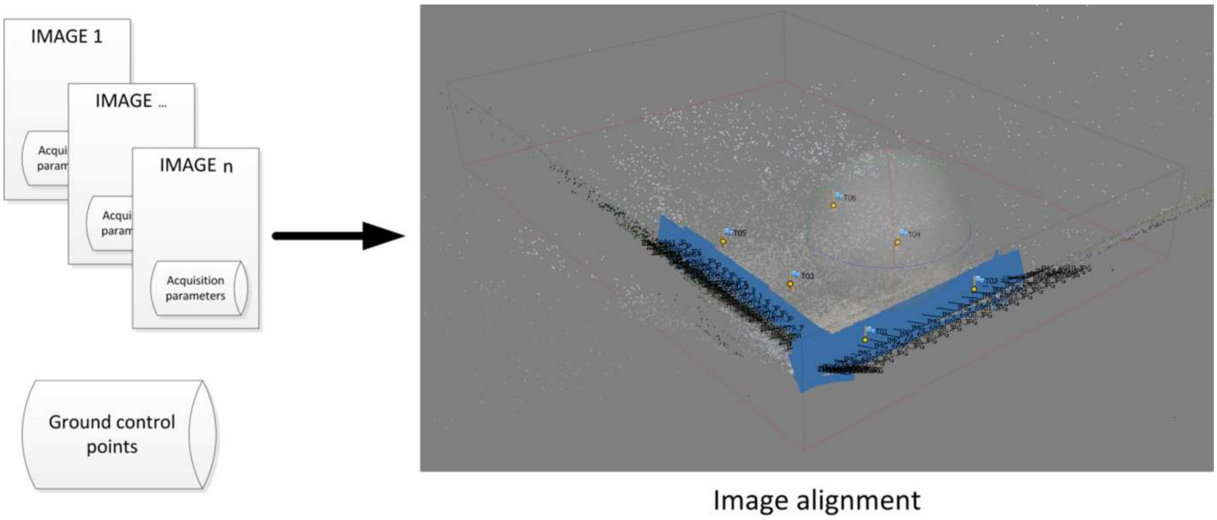

Figure 6. Scene structure with matched feature points and positioned and oriented images

Instead of using the 3D feature points, the positioned and oriented images are used for the actual 3D reconstruction after the image alignment. A 3D mesh is generated based on the intersection of perspective pixel rays. The linear projection parameters of these 2D image pixels in a 3D space are defined by the focal length of the used camera. This results in a series of depth maps, representing the distance between the intersection of perspective rays and the focal centre of the camera. Combining these depth maps from differently oriented positions enables the creation of a dense point set. This point set is hereafter triangulated into a mesh. This 3D reconstruction technique is extensively discussed by Robertson and Cipolla [2009] and Seitz et al. [2006].

5 Comparative analysis of the different techniques and recommendations

With the knowledge of the above mentioned surface modelling techniques and the comparative study, it is possible to define the most suitable methodology for the surface modelling of intertidal zones of beaches. For the detection of archaeological relicts in these areas, the suggested technique or techniques must result in high resolution data with a sufficient accuracy. The sole use of conventional topographic measurements is therefore impossible. However, these techniques can be used for the construction of supplementary data sets for the referencing and quality analysis of other data sets. Notwithstanding the low point density of conventional topography, it delivers the highest possible accuracy in comparison with the other surface modelling techniques presented in this paper. Achievable GSD and vertical accuracies of DSMs are presented in Table 1, assuming common acquisition conditions.

Table 1: Overview of different surface generating techniques

Acquisition technique	GSD	Vertical accuracy	Reference
ALS	10 cm	5 cm	[*Stal et al.*, 2013]
ALB	1 m	25 cm	[*Doneus et al.*, 2013]
MTLS	10 cm	5 cm	[*Bitenc et al.*, 2011]
STLS	2 cm	2 - 5 cm	[*Pertrie and Toth*, 2009]
Photogrammetry	8 cm	8 - 16 cm	[*Mason et al.*, 2000]
SfM-MVS	2-5 cm	2 - 15 cm	[*Ortiz et al.*, 2013]
Conventional topography	-	1 - 4 cm	[*Taaouati et al.*, 2011]

Since the ability to model intertidal zones is highly correlated with weather conditions and the tides, last minute decisions on the deployment of a sensor are required. Consequently, the use of airborne platforms (apart from UAVs) will be difficult, very expensive or even impossible. The use of MTLS also requires thorough preparation, but is not sensitive or at least much less sensitive to administrative complications. Other techniques do not suffer from these difficulties at all. Next to these practical considerations, some technical difficulties have to be taken into account for the selection of an appropriate method. In the context of intertidal zone modelling of the Belgian coast, the following difficulties occur:

- The turbidity of the North Sea is very high, so even in shallow water, the surface is not or hardly visible;
- The weather conditions are rough with strong wind and frequent rain fall during the entire year;
- The water and weather conditions of the sea can change suddenly and remain unpredictable;
- The beaches are very crowded during the summer season, especially in July and August.

These aspects make the dense and accurate modelling a challenging task. Initially, ALB seems to be the most obvious choice for the modelling of intertidal zones. This is mainly motivated by the high acquisition speed and the ability to close the gap between topographic and bathymetric surface models. Measuring the area during high tide and low tide is the only practical requirement for filling this gap. The previously mentioned issues imply some important difficulties, like the rapidly changing weather conditions and the high turbidity. The flexible deployment of the system is also limited by the required flying permission and the limited availability of ALB systems. Except for UAVs, the issues concerning flexible deployment hold for all other airborne techniques, and other terrestrial techniques have to be considered.

By using STLS, it is possible to generate very accurate point clouds. The point density of these point clouds can range to values of a few thousand points per square meter, but will decrease exponentially as a function of the distance to the scanner. Besides, the incidence angle plays a significant role in the accuracy, meaning that with a normal configuration (i.e. a scanner on a tripod), the range of the scanner must be limited to a few meters. For the measurement of the beaches, a large number of scanning setups is required, and even more reference points have to be materialised and measured for the registration of the scans. This makes the use of STLS on a larger scale time consuming, with is inconsistent with the tidal time constraint. The mobile counterpart, MTLS, is much less influenced by these issues. Naturally, the incidence angles and point density have to be taken into account with MTLS, but an equal distribution can be reached by acquiring points in overlapping strips. This method is very similar with ALS and enables a higher accuracy by performing strip adjustment. If the lines are driven parallel with the water line, the vehicle can follow the tide and a full intertidal surface coverage is guaranteed.

Concerning conventional photogrammetry and SfM-MVS, which can be used as image based surface reconstruction techniques, it has already been stated that a careful airborne flight planning is required, taking the official permissions and favourable weather conditions into account. With the use of UAVs, a higher degree of flexibility can be reached. UAVs also enable to fly in much lower altitudes, and may thus result in a higher GSD. However, good protection against water and salt is advisable for the durability of the system. In general, the use of these techniques can be hampered by the lack of feature points, or matching points in different overlapping images and on areas with a uniform appearance. Empirical research has to verify this statement for the specific case of the Belgian coast. If the image matching can be done in an appropriate way, airborne imagery using UAVs can be a good alternative for laser scanning techniques. The deployment of image based modelling does not only allow the construction of DSMs, it also enables to generate textures or even orthophotos of the covered area. These data sources are a valuable extension for the archaeological research.

Based on this comparison, it is obvious that MTLS is the most suitable technique to generate DSMs that meet the archaeological requirements concerning accuracy and resolutions. It must be kept in mind that this conclusion holds for the specific case of intertidal zones at Belgian beaches, where archaeological relicts are only visible by the analysis of very small and local differences in terrain elevation. The flexibility of MTLS is a big advantage of the technique, meaning that the data acquisition can take place during the most appropriate weather conditions. Moreover, by introducing the tidal conditions in the campaign planning, the gap between topographic DSMs and bathymetric DSMs can be filled. During high tide, the upper parts of the beach can be scanned by the vehicle, while a MBES vessel can measure the lower inducted parts of the beach. During low tide, the MTLS system can be used to measure the lower parts of the beach. This procedure ensures the full coverage of the beach by a DSM, and also enables a statistical quality assessment of the MBES data for the overlapping parts.

6 Conclusion

In order to detect, manage and protect archaeological relicts and cultural heritage in general, DSMs are indispensable. In near shore areas, these models are rather hard to generate, because of the difficult environmental conditions. Especially in intertidal zones, there is a gap between DSMs generated with bathymetric methods on the one hand and DSMs generated by topographic methods on the other hand. One of the main purposes of this project is to close this gap between land and shallow water areas, by finding a way to measure the intertidal and the very shallow water areas. Initially, ALB was selected as a variant of ALS to model this area. Based on the present state-of-the-art of ALB, the properties of this system seemed to be very promising. However, the Belgian coast suffers from various challenging difficulties, resulting in important practical and technical difficulties. For example, the weather conditions must be sufficient, but the beach must be as good as empty. Moreover, the water must be calm for a minimal turbidity. Even then, good results are not guaranteed and other techniques must be considered.

Next to ALS and ALB, the use of MTLS and STLS is discussed in this paper. STLS results in very dense and accurate point clouds, but in order to maintain this accuracy, the incidence angle and thus the maximal range must be limited. Thereby, a large number of scans have to be performed and an even larger number of reference points have to be materialised. MTLS overcomes this issue by measuring a point cloud in a systematic way. Point clouds with a high accuracy and with an equal spatial distribution can be achieved with this method. It also has a very flexible deployment, enable to measure the lowest water line on any favourable moment.

In case of a normal airborne campaign, image based modelling techniques (conventional photogrammetry and SfM-MVS) also have to deal with organizational issues and good weather conditions. Since terrestrial imagery can only be used for the modelling of limited areas, the use of UAVs can be a promising alternative for laser scanning-based techniques. Next to the reachable comparative accuracy, image based techniques enable to assign textures to the geometry, improving the interpretation of these models.

Conventional topographic measurements result in the highest possible model accuracies, but the point density is very low for practical reasons. Nevertheless, they are the most appropriate way to construct topographic maps of limited areas or to generate reference data for the quality evaluation of other surface modelling methods.

To conclude, it can be stated that MTLS is the most appropriate way to generate highly accurate and high density DSMs of intertidal zones of beaches. In case of the measurement of Belgian beaches, the flexibility of the system enables to acquire data as a function of the tidal conditions: during high tide, higher parts of the beach can be covered, during low tide, the lower parts. By doing so, the gap between topographic DSMs and bathymetric DSMs can be filled by re-measuring the lower parts of the beach during high water with bathymetric sensors. This approach also results in a data overlap and enables a qualitative comparison between these techniques.

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