Feasibility Study of the Use of Bathymetric Surface Modelling Techniques for Intertidal Zones of Beaches

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Key words: DSM, laser scanning, mobile mapping, sensor integration, comparison

SUMMARY

This paper elaborates on the use of different 3D data acquisition techniques for the construction of Digital Surface Models (DSMs) of intertidal zones of beaches to detect archaeological relicts. DSMs are an indispensable tool for the development and sustainable management of cultural heritage and archaeological relicts and in many applications, these models are used for the analysis of existing archaeological features or the detection of new features. This is also the case in the presented project on archaeological research in the Belgian North Sea. Obtaining a sufficient resolution and accuracy for these models is a challenging task, especially for intertidal zones of beaches. Specific difficulties in these transitional areas require a thorough study of available spatial data acquisition techniques, focussing on the various system properties and measurement methods.

A field campaign was organized at the intertidal zone of the beach of Raversijde (Belgium) in the early summer of 2013. Various techniques were deployed during this campaign in order to define the advantages and disadvantages for archaeological research. Based on this study, the use of MTLS appears to be very useful for the construction of the required DSMs. An ARGO, which is an amphibious vehicle, was used in combination with a series of positioning and orientation sensors (GNSS, INS,…). Using this system, the requirements concerning the resolution and accuracy were respected. Besides, the ARGO enables a fast and flexible usability, which is important for the varying weather conditions and tide. As a result, further development of het ARGO based acquisition platform is planned and additional campaigns for a more extensive systematic surface modelling of the intertidal zones of the Belgian North Sea coast will be organised.

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1. INTRODUCTION

The knowledge of the underwater cultural heritage in the Belgian North Sea is rather limited. Yet these submerged relicts form an important aspect of our cultural heritage and offer huge possibilities for scientific and (inter-)cultural purposes. However, this unique underwater archive is in danger due to increasing economic activities at sea such as aggregate extraction, wind farms, dredging, fishing, etc. These are not the only threats. Due to the complexity of the state structure in Belgium, a solid regulation regarding underwater cultural heritage is still lacking, notwithstanding the awareness of the need to take responsibility for this heritage in danger at the political and administrative level. The project SeArch (www.sea-arch.be) offers solutions to these challenges via the development of an efficient assessment methodology and an approach towards a sustainable management policy and legal framework. This project involves a close collaboration between the following partners: Flanders Marine Institute (VLIZ), Flemish Heritage Agency (FHA), Deltares (Department of Geology and Geophysics) and Ghent University (Renard Centre of Marine Geology, Maritime Institute and Department of Geography). The contribution of the Department of Geography is the selection and application of an innovative survey methodology which allows accurate and cost-efficient evaluation of the archaeological potential in the intertidal zones of the Belgian beaches.

Conventionally, bathymetric techniques make use of different approaches compared with topographic techniques, like the use of acoustic versus electromagnetic signals for distance measurements. The limited draft of intertidal zones, as well as the turbidity and tempestuous weather conditions are additional limiting factors to map the Belgian North Sea coast. Different data acquisition techniques are discussed for the construction of Digital Surface Models (DSMs) on the intertidal zones: Airborne Laser Scanning (ALS) from a flying platform, Airborne Laser Bathymetry (ALB) as a combination of ALS with a water penetrating electromagnetic signal, Static Terrestrial Laser Scanning (STLS) (scanning from a fixed position on the ground), Mobile Terrestrial Laser Scanning (MTLS) (terrestrial laser scanner mounted on a driving platform). Moreover, image based reconstruction techniques and conventional topographic techniques, like a total station and Global Navigation Satellite System (GNSS), are already examined. These techniques were selected based on a required ground resolution of at least one metre and a vertical accuracy of a few centimetre. Finally, several of the descripted techniques are applied on a test site on the base of the received knowledge of the comparison analyses.

At the end of spring 2013, a field campaign was conducted at the beaches of Raversijde, near Ostend, Belgium (Figure 1). This area was chosen for its high archaeological potential. The Belgian coast is situated in the northwest part of Belgium and borders the North Sea. It extends over 67 km and includes up to 500 m wide sandy beach and up to 2.5 km wide dunes behind the beach. The test site in Raversijde is located approximately in the middle of the Belgian coast and consists only of about 300 m wide sandy beach. About every 350 m, a breakwater is situated straight across the waterline, which divides the beach in several parts (Figure 2). The beach is enclosed by a sea front with a height of 2 to 4 m. The test site consists of five areas (known as zone A to E) which are separated from each other by breakwaters. In this described field campaign, only the first three areas were surveyed (A, B and C).

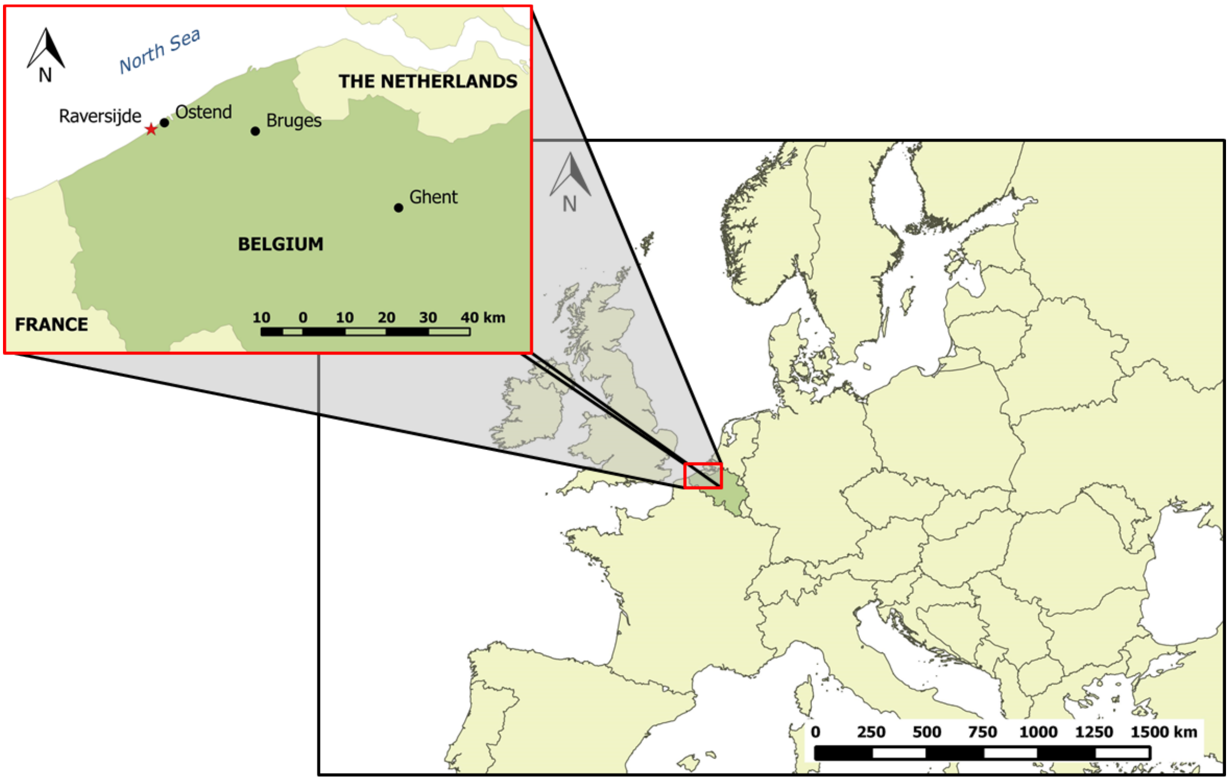

Figure 1: Location of Raversijde, Belgium, Europe

Figure 2: Topographic map of the coast of Raversijde

2. MEASUREMENT TECHNIQUES AND PLATFORMS

One of the objectives of the SeArch project is to select an accurate and time- and cost-efficient acquisition technique to verify the archaeological potential of the intertidal zones. Modelling coastal areas of the Belgian North Sea has to be executed in difficult circumstances. First, the tide cycle of about twelve hours needs to be taken into account. Therefore, high tide alternates with low tide every six hours. Between the tides, the sea level differs approximately 4 m. However, the beach of Raversijde has a limited slope of about 0.95° (1,7%). This results in a high and fast variation in horizontal motion of the waterline. Secondly, the surface near the waterline can be very humid which influence the accessibility and the ability to model the area with a specific sensor. Third, the weather conditions play a huge role in the selection of the acquisition techniques. The Belgian coast suffers from strong winds and frequent rain fall during the entire year. Finally, the turbidity of the North Sea is very high. Even in shallow water, the surface is hardly visible. As a result of these characteristics of the Belgian coast, the survey has to be performed in difficult circumstances. Besides, the intertidal zone is the border between land and shallow waters. On the one hand, common onshore techniques are not able to measure the surface topography under water. 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. Therefore, several techniques have to be evaluated to create coastal DSMs.

The choice of acquisition techniques encloses the different types of laser scanning, conventional topographic measurements and image based modelling. In case of the laser scanning technique, both the aerial techniques (ALS and ALB) and the terrestrial application

(STLS and MTLS) are presented. Furthermore, the use of GNSS, total station measurements and Structure from Motion and Multi-View Stereo (SfM-MVS) are also discussed. The selection of a specific acquisition technique is finding an equilibrium between a set of different requirements, like accuracy, resolution, speed, price, needed time, etc. in the actual environmental circumstances. Assuming common acquisition conditions, the achievable values of the point density and the vertical accuracy are presented in Table 1 for the different techniques.

Table 1: Different acquisition techniques with their vertical accuracy and Ground Spacing Distance (GSD)

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

At first sight, the STLS method can be selected as the most suitable technique because of its high vertical accuracy and high achievable point resolution of the Digital Surface Models (DSMs). However, the range of STLS is limited to a few metre since the accuracy heavily depends on the incidence angle. Therefore, a large number of scanning setups is required to survey large areas such as beaches, which is very time consuming. Besides, the tide of the North Sea has to be taken into account. This makes the STLS method less suitable for surveying intertidal zones. The mobile counterpart of STLS, MTLS, is also influenced by the limited incidence angle of the laser, although, it is less time consuming to survey the area in parallel stripes (MTLS) than to have a large number of static setups of circular data acquisition (STLS). For the MTLS method, the point density depends on e.g. the speed of the moving platform. Nevertheless, a higher point resolution can be acquired by overlapping the parallel driven stripes. More importantly, the moving platform can drive parallel to the water line, follow the tide and thus guarantee a full coverage of the intertidal zone. Next to the tide, the weather conditions plays an important role in the selection of the suitable technique. On the Belgian coast, the weather conditions can change suddenly and remain unpredictable. In contrast to the MTLS method, the wind conditions are relevant for the airborne platforms (ALS and ALB). The use of ALS and ALB are not only very expensive, it would also be difficult to use these technique. Furthermore, the turbidity of the North Sea is very high (even in shallow water) which makes the sea bottom in shallow water not or hardly detectible for the ALB method. On the other hand, airborne platforms have a high acquisition speed. Furthermore, the conventional topography technology is not eligible as it is an unrealistic job to create DSMs of a beach with a point density of less than 15 cm with this technique.

The comparative analysis of the different acquisition techniques has made clear that MTLS is the most suitable methodology for the surface modelling of intertidal zones of beaches. The relatively high accuracy and the high point resolution of the Digital Surface Models (DSMs) are the main characteristics to select MTLS technique as most sufficient method. Besides those characteristics, MTLS is also an innovative and cost-efficient survey methodology which is an important factor for the SeArch project. In comparison with the STLS method, the MTLS technique is less time consuming and covers the whole intertidal zone. Previous feasibility studies have also demonstrated that the MTLS method is very promising for intertidal surface modelling in comparison with other measurement techniques. It appears to close the spatial incompleteness between land measurements and measurements in shallow water.

For intertidal zone modelling, the driving platform of the MTLS method needs to perform in shifting sand and very shallow water. Therefore, an amphibious or all-terrain vehicle (ARGO) was used. The ground pressure of the eight-wheeled vehicle is very low (about 14.5 kPa or 0.145 bar). Furthermore, the system configuration on the driving platform is very similar to an ALS setup: a terrestrial laser scanner (Leica HDS6200) in profiler mode, an Inertial Navigation System (INS) (iXSea LandINS) and a RTK Global Navigation Satellite System (GNSS) (Ashtech Magellan Proflex 500) (Figure 3 (left)). Furthermore, a PC with real-time project management software and storage capacity provides the operation of the MTLS configuration. The combination of the INS and GNSS measurements by the Position and Orientation measurement System (POS) provides highly accurate positioning. At the same time, the laser scanner produces a very precise point cloud. As in airborne applications, the prior calibration of the devices is indispensable for the correct use of MTLS [Skaloud and Lichti, 2006]. The operation of the MTLS method is presented in Figure 3 (right).

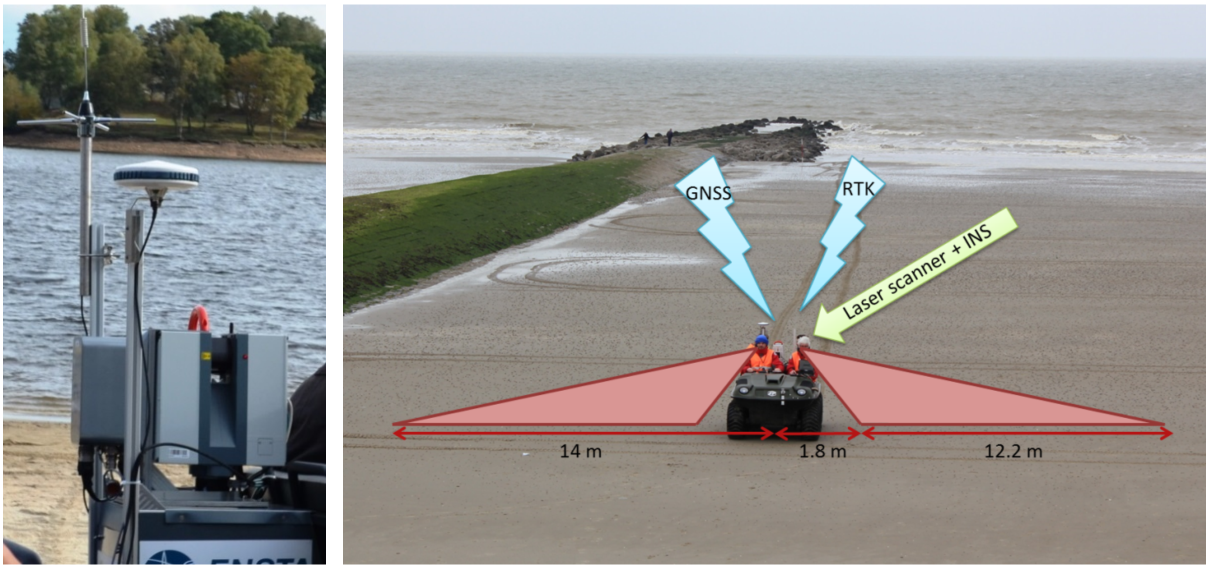

Figure 3 : Side-view of MTLS set up (left) – Performance principle of MTLS method (right)

Besides the MTLS method, two other acquisition techniques are applied on the field campaign as reference datasets. First, a grid of almost a thousand points with a density of a few metre is measured with conventional GNSS in RTK mode (Trimble R8). These points were collected for a smaller part of test area A (Figure 2) and with a 2.35 m high pole. This GNSS has a vertical accuracy of 15 mm + 1 ppm in RTK mode [Trimble R8 GNSS System Datasheet, 10/03/2014]. Secondly, the STLS method (Leica HDS6100) is also applied, only for a small part of the test site parallel to a breakwater in order to cover the intertidal zone as well. Contrary to the GNSS method, the STLS technique acquires a huge amount of accurate detail points from a fixed laser scanner position. The accuracy of the laser scanner depends on several factors and is described further in this paper. In the end, only the STLS data will be used as a reference surface to verify the accuracy of the MTLS data as the STLS method has a higher point density.

The quality of the DSMs of laser scanning techniques (MTLS and STLS) is influenced by various factors. The first influencing factor refers to the surface properties. It concerns the reflectance parameter of the sand which depends on the grain size and the sand moisture [Leu, 1977]. The sand properties on the intertidal zones of the Belgian beaches are similar, which means that the grain size has a constant parameter (about 120 µm or 'Well sorted very fine sand' according the Gradistat method [Blott et al., 2001]) and the influence can be omitted for this survey. However, the humidity of the sand, which is related to the beach environment and tide, has an influence on the point density and the accuracy of the data. These are the results from a preliminary study which is described below. Secondly, the quality of the data (accuracy and point density) decreases with an increasing range, i.e. the distance from the scanner to the object, and increasing incidence angle, i.e. the angle between the normal and the incoming laser beam [Soudarrissanane, 2011]. As the surface of the beach is more or less flat (limited slope of approximately 0.95°), the incidence angle increases fast by increasing range, according to the following formula:

$$tg(incidence\ angle) = \frac{scanning\ height}{range}$$

A scanning height around 1.4 m and a range of 10 m results in an incidence angle of 76°. Therefore, the scanning range need to be taken into consideration when using laser scanning. The third factor is only applicable for the MTLS method: the speed of the driving platform. The following rule is valid: the higher the speed of the ARGO, the less accurate and the lower the point resolution. Therefore, in this project, the speed was fixed at 6 km/h.

A laboratory experiment was executed in a controlled environment to estimate the errors of the key parameters which will influence the data quality. The test focused on the influence of the increasing range and the humidity of the sand on the data accuracy and point density. In total, seven sand samples were taken from the beach, each with a certain gravimetric moisture content (1% (dry), 7% (slightly wet), 21% (wet), 24% (shinny sand), 25% (liquid sand with thin water layer), 26% (water layer) and 28% (water layer of 3 mm)). Each sample was placed at seven different positions from the laser scanner: 1.8 m, 5 m, 8 m, 11 m, 14 m, 18 m and 21 m. Since it was an indoor controlled experiment, the sun effect was simulated with two lamps which reaches a value of 15 kLux, which simulates a cloudy day. In this experiment, the Leica HDS6100 laser scanner was used on a height of 1.4 m which is the same laser scanner height as for the MTLS method. The scanning resolution was set on 0.072°. Table 2 reveals the results concerning the mean point density. The point number per square decimetre decreases very fast with the increasing range. Furthermore, the point number is also decreasing in function of the gravimetric moisture content of the sand samples, nevertheless, this counts for a range > 5 m. A Ground Spacing Distance (GSD) less than 10 cm (or a point density less than 1 point/dm²) can be declared as unsuitable to model intertidal zones, as DSMs with high resolutions are demanded. Table 2 demonstrates that the point density is still acceptable up to a range of 11 m. For the range of 14 m, the gravimetric moisture content needs to be taken into account: as soon as there is a water layer on the sand (26 % or more), the point densities were low. The acquired values for the ranges of 18 m and 21 m were too low and are left out of the table.

Table 2 : Mean points number per dm², according to the range and the gravimetric moisture content

	Range (m)				
Moisture (%)	**1,8**	**5**	**8**	**11**	**14**
1	1550	150	41	13	3
7	1467	147	41	13	3
21	1477	150	42	11	3
24	1482	148	40	11	2
25	1498	142	40	8	2
26	1475	146	28	6	0
28	1513	148	18	5	0

Figure 3 (left) represents the standard deviation in altimetry in function of the gravimetric moisture content. The standard deviation in Z axis does not seem to be influenced by the moisture for the three lowest ranges. On the basis of this graph, the moisture content does not have a significant positive or negative influence on the standard deviation. The graph on the right (Figure 3) represents the same information in a different way: the moisture content (1%, 7%, 21%, 24%, 25%, 26% and 28%) in function of the incidence angle and the range. The graph shows that an increasing standard deviation in altimetry is mainly due to the increasing incidence angle of range, irrespective of the moisture content. On the basis of this graph, no significant conclusions can be drawn regarding a positive or negative influence of the moisture on the standard deviations. Nevertheless, the tide still need to be taken into consideration for modelling intertidal zones to avoid the surface with a higher moister content than 26%. Furthermore, it is important to notice the low standard deviation of maximum 1.2 cm in altimetry which is obtained in this controlled experiment.

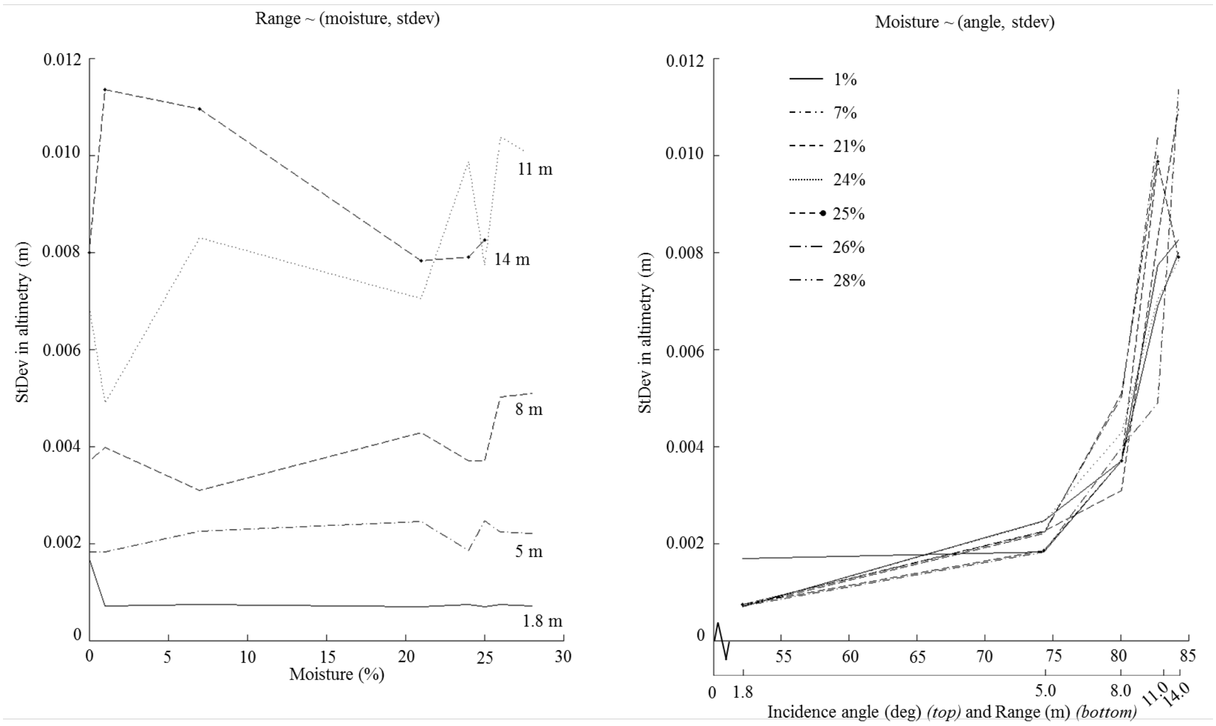

Figure 3: The range in function of the moisture and standard deviation in altimetry (left) and the moisture in function of the incidence angle (or range) and the standard deviation in altimetry (right)

3. DATA ACQUISITION AND PROCESSING

At the end of spring 2013, the MTLS method was applied on the test area (zone A, B and C on Figure 2). The survey of the intertidal zone was planned carefully to acquire data in the most efficient way. Besides taking the tide into account to avoid the most soaked sand and to survey an as large as possible intertidal zone, attention had to be paid to the laser range and incidence angle as well. The controlled experiment with the STLS method revealed that the data is sufficiently accurate until approximately a range of 14 m. The measurements were executed in parallel lines (parallel to the sea front) starting at the highest point of the beach (near to the sea front). Furthermore, as the laser scanner could not receive any data from the surface below the driving platform, which resulted in a blind angle, the distance between two consecutive lines was limited to 14 m. After surveying the whole area, the breakwaters were surveyed sideways and a transverse line (perpendicular to on the other lines) in the middle of each area was measured. The tracking lines are clearly visible on Figure 4, which presents the point density of MTLS data for one area between two breakwaters.

The STLS method was only executed on a small strip on the beach (area A on Figure 2) parallel to a breakwater which results in a small coverage of the intertidal zone. The deviations in altimetry of the STLS data on the beach are of cm-level, which is acceptable for the comparison of MTLS data.

4. RESULTS

The quality of the MTLS data can be effected by two criteria: the point density and the standard deviation. A map is created for both criteria for the same area (area A on Figure 2). The maps use WGS84 as coordinate reference system and are visualised in Figure 4 and 5. The point density decreases with an increasing range or incidence angle, which results in high point densities close to the tracking lines. Conversely, the point densities are very low on the tracking lines, as this line is surveyed from the two closest lines which are spaced by a distance of 14 m. This implies that the survey lines are clearly visible at the point density map. Furthermore, the minimum point density between two lines is 5 points/dm² which is good for creating an DSM of the intertidal zone. However, the point density is between 1 and 5 points/dm² on the tracking line, which can be seen as acceptable. In the future, a shorter range between two consecutive survey lines will be recommended to acquire higher point densities.

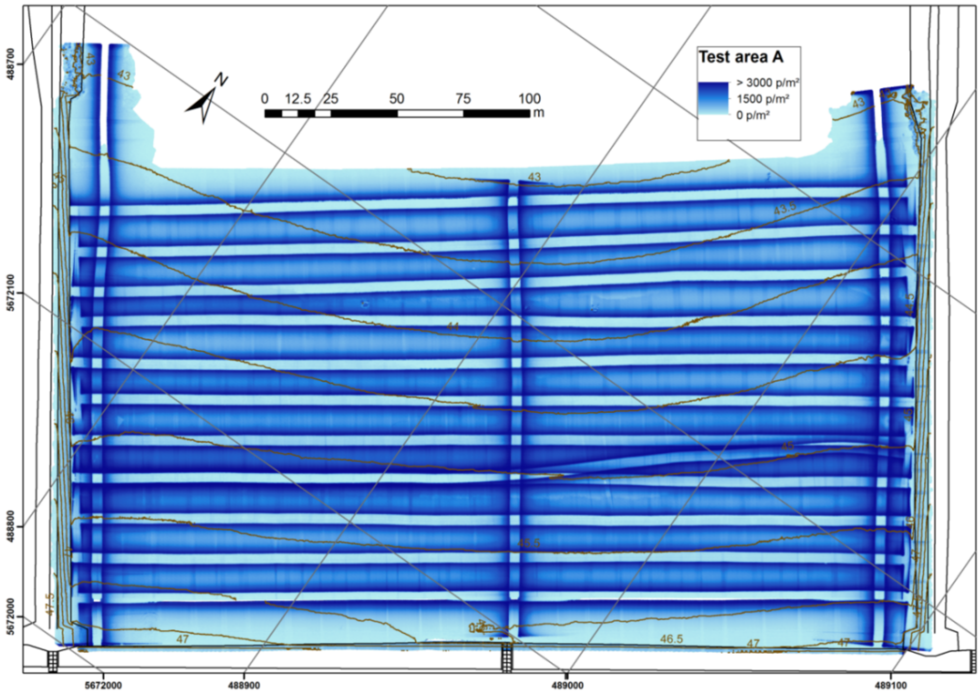

Figure 4: Point density map of the MTLS data (per m²)

The standard deviation results from two factors: the survey errors which are related to e.g. the incidence angle and the speed of the mobile platform and the micro-morphology of the beach. This last mentioned surface is actually more irregular in reality. For each survey point, the standard deviation is computed on the basis of a range of 50 cm. The standard deviation map (Figure 5) represents the dispersion of the errors between consecutive survey lines and between the parallel lines and the transverse line with a resolution of a square decimetre. Transverse survey line results in higher deviation values in the middle of the area. Higher standard deviations can be found on the survey lines due to the prints of the vehicle wheels. As the intertidal zone was surveyed in parallel lines starting from the sea front, the prints of the vehicle wheels were only present on the tracking lines at the side of the sea front. Besides, the standard deviation increases in the middle of two consecutive lines. Generally, the standard deviations are quite low, as the maximum value is below 0.035 m.

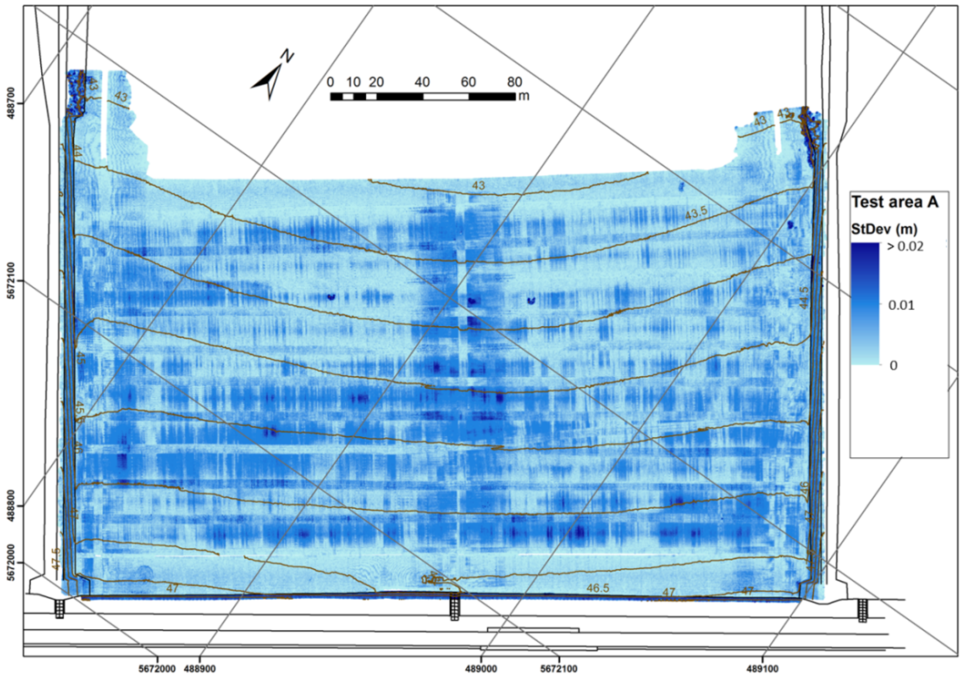

Figure 5: Standard deviation map of the MTLS data (per dm²)

A comparison between the DSMs from the acquired MTLS and STLS data is executed to verify the accuracy of the MTLS method. The STLS technique is the most suitable method for the comparison, because the only difference between both methods depends on the mobility of the devices. The results of the *point to mesh* computation of the data is presented in the WGS84 coordinate reference system (Figure 6). The deviations in altimetry are only a few cm. This indicates that the MTLS data are relatively accurate, which ensures that the MTLS method is reliable in this kind of approach.

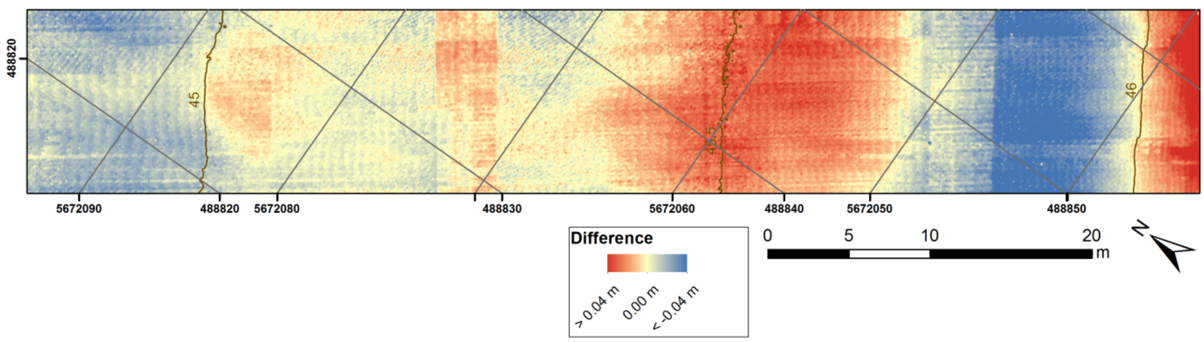

Figure 6: Differences in altimetry between MTLS data and STLS data for the small area on the beach

The main objective of the SeArch project is to map the archaeological potential in the Belgian part of the North Sea, including the intertidal zones. The use of the MTLS method on the beaches provides DSMs with a relative high point density which can reproduce the presented topography. Therefore, a zoom has been executed to one particular survey line to analyse the morphology of the MTLS method. The elevation map represents the heights on a level of centimetres (Figure 7 (top)). The white horizontal line on the map is due to the blind angle of the MTLS method and represents the driving path of the vehicle. A cross-section of the elevation map is visualized in Figure 8. The curve shows a minor gradual increase in altimetry and represents the micro-morphology of the beach. The intensity map is also an interesting figure in the field of archaeology (Figure 7 (bottom)). The map unveils changes in surface properties. Based on those changes, archaeological features or structures can be discovered. In the case of the presented survey line, an decrease in intensity value is visible at the left side of the map at right angles to the driving path. This change can refer to a former gully which cannot directly observed with the naked eye at the test area.

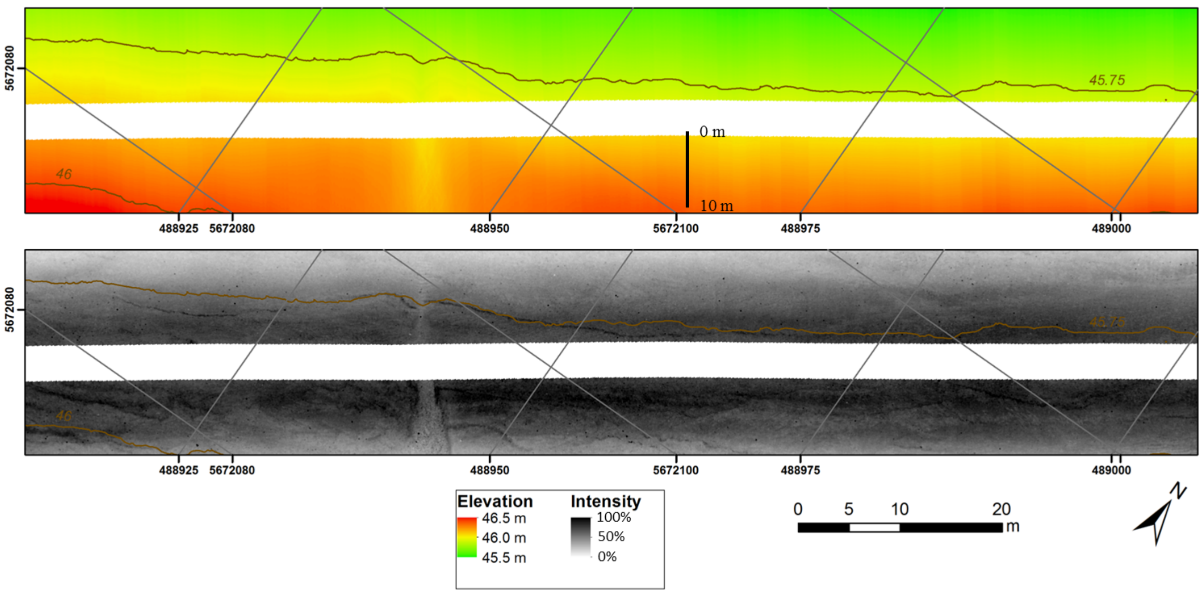

Figure 7: Elevation map (top) and intensity map (bottom) acquired from the same track line

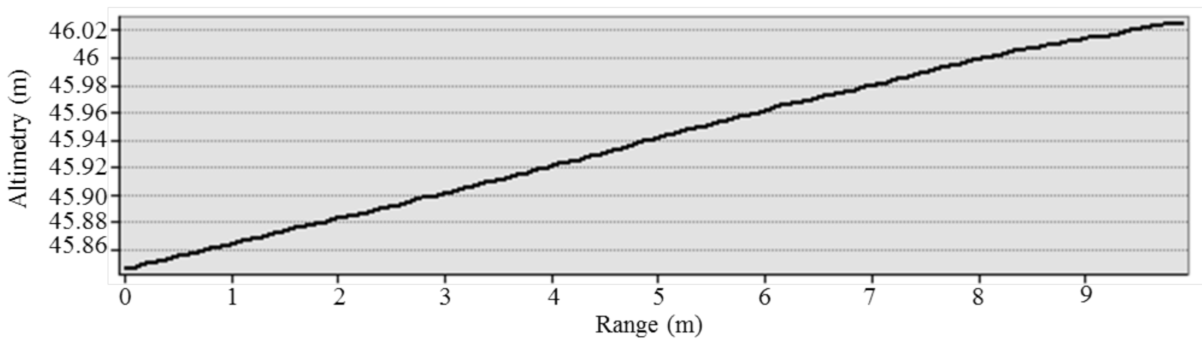

Figure 8: Cross-section of the elevation map (Figure 7)

CONCLUsSIONS

A comparative study of the different acquisition techniques showed that the MTLS method seems to be the most suitable method to model intertidal zones as part of the SeArch project. Therefore, an equilibrium is made between a set of different requirements, like point density, accuracy, survey time, cost, etc. Besides, the typical adverse weather and environmental conditions of the North Sea were taken into account as well to select the method. Preliminary experimental research with a laser scanner and sand samples showed that an increasing range or increasing incidence angle is related to higher standard deviations of the laser scanning data. A moisture content of the surface up to 26% seemed to have no significant influence on the standard deviation. Nevertheless, the beach survey was planned according to the twice-daily tide to avoid the most soaked sand. The results of the MTLS survey shows that the method is a very promising acquisition technique for intertidal zones. Within a range of 14 m, the received data had a point density of at least 1 point/dm², which is acceptable for modelling intertidal zones. The standard deviation values in altimetry were also very satisfying. Furthermore, STLS data was taken to compute a reference surface to verify the accuracy of the MTLS method, which resulted in deviations in altimetry of cm-level. The main advantages of the MTLS method are the low survey time, the high point density and the high accuracy. Moreover, the amphibious vehicle Argo proved its usability in all terrain conditions. In the future, research will be focused on the intensity value gradient of the data and its correlation with the geometry and micro-morphology of the surface.

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Trimble R8 GNSS System Datasheet
http://www.trimble.com/ (10/03/2014)

BIOGRAPHICAL NOTES

Prof. dr. ir. Alain De Wulf is MSc. in civil construction, MSc. in informatics and MSc. in Industrial Management. He is full professor at Ghent University, working on quality aspects of geodesy and land surveying in general. Within his research field, he plays a key role in topographic campaigns for archaeological projects (Malta, Altai (Russia), Thorikos, Titani (Greece), etc.). He has special interest in hydrography and he is vice-chairman of the Hydrographic Society Benelux. Moreover, with his expertise in hydrographic surveying, he is developing specialised software for the processing and quality assessment of hydrographic 3D acquisition sensors.

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