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COASTSCAN: CONTINUOUS MONITORING OF COASTAL CHANGE USING TERRESTRIAL LASER SCANNING

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Abstract

Sandy coasts are vulnerable to predicted climate change, but also need to safeguard coastal housing, recreation, safety and ecology. "Building with Nature" is an important approach for resilient coastal maintenance, but corresponding predictive modelling tools are partly inconclusive, due to a lack of measurements over multiple spatial and temporal scales. The aim of the CoastScan project is to develop a monitoring system to measure and understand dry coast topography over multiple scales with a permanent laser scanner. A field campaign was setup at Kijkduin, The Netherlands to monitor a kilometre of beach for up to 6 months. The first permanent laser scanning results show a promising ability to monitor the coast over multiple scales: hourly topography is obtained with a quality at the millimetre range, while time series at four different locations lasting 10 days show subtle variations that could not be compared before.

Key words: Coastal morphology, change detection, storm impact, continuous monitoring, beach, laser scanning

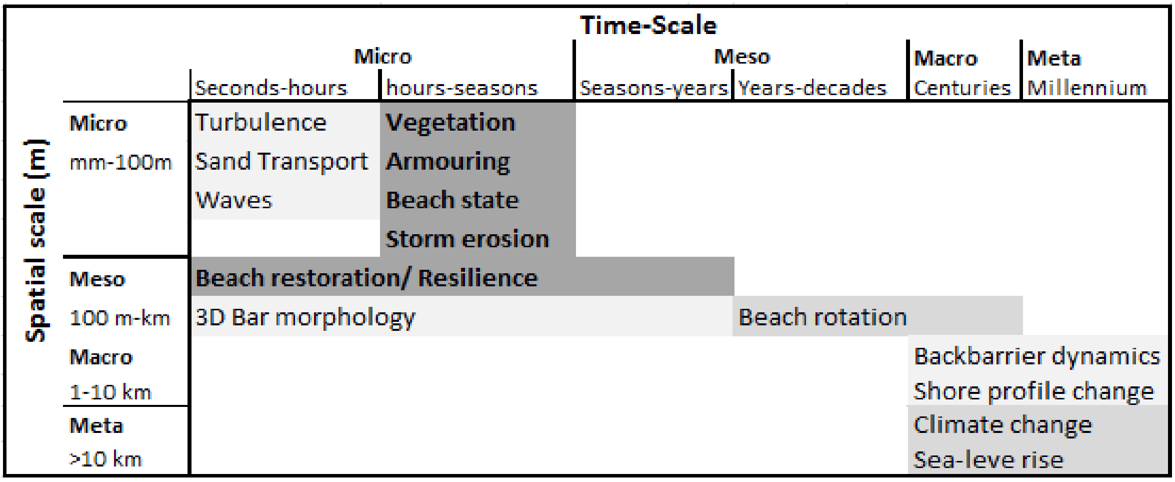
1. Introduction

1.1 Sandy coast dynamics

Sandy coasts have been inhabited by humans since ancient times (Bartlett 2006) and people have used many techniques to survive these sometimes hostile environments. Until early modern age nature was seen as the opposite of society and something to be challenged or besieged (Knottnerus, 2005). Many solutions aimed at fixing and/or anchoring coastal processes and defending society against the rigors of nature. This has resulted in numerous dikes, terps and other fixed coastal structures since the last Iron Age. However the effectiveness of these coastal structures had varying degrees of success (Stive et al, 2013).

Coastal areas in general have nowadays become so attractive that about 44% of the world population lives within 150 km of the coast (UN, 2016). This makes a significant part of the population vulnerable to the effects of predicted climate changes, including sea level rise and weather extremes (IPCC, 2012). An extreme event like hurricane Katrina (2005) flooded the main part of New Orleans, displaced about 1 million people, killed more than 1000 people and cost the American economy 135 billion dollar in damages (Plyer, 2016). The expected sea level rise (S. Rahmstorf et al., 2012) may result in trillions of costs in the next decades.

In order to safeguard sandy coastal areas against climate change it is important that sustainable coastal strategies are developed and implemented in near future. In recent years "Building with nature" solutions (Vriend, 2014) have been proposed as a climate proof and sustainable solution for coastal protection. Recent examples which are meant to provide long term protection (>20yrs) are the Sand Engine (Stive 2013) near the Hague, and the mega-nourishment before the Hondsbosche Seawall in the northwest of the Netherlands.



Spatial scale (m)	Time-Scale					
	Micro		**Meso**		**Macro**	**Meta**
	Seconds-hours	hours-seasons	Seasons-years	Years-decades	Centuries	Millennium
Micro mm-100m	Turbulence Sand Transport Waves	**Vegetation** **Armouring** **Beach state** **Storm erosion**				
Meso 100 m-km	**Beach restoration/ Resilience**					
	3D Bar morphology			Beach rotation		
Macro 1-10 km					Backbarrier dynamics Shore profile change	
Meta >10 km					Climate change Sea-leve rise	

Figure 1. Coastal processes operating at different spatial/temporal scales are as introduced by the Coastal Tract concept (modified from Cowell, Stive 2003).

Building with nature solutions requires a thorough knowledge of the natural behavior of the coast. The complexity of coastal behavior (Figure 1) with multiple temporal and spatial scales makes it hard to accurately predict the behavior over all scales. The quantitative accuracy of the predictions have a reliability problem (Lesser, 2009) which result in an inability to predict long term shoreline changes accurately. This makes it hard to accurately predict the resilience of the coast which is an important factor in the coastal safety assessments. Especially the dune ward transport of sand and the restoration of the coast after a storm are a present challenge. Restoration of the shoreline is a long term event driven process which includes many mechanisms over multiple spatio-temporal scales.

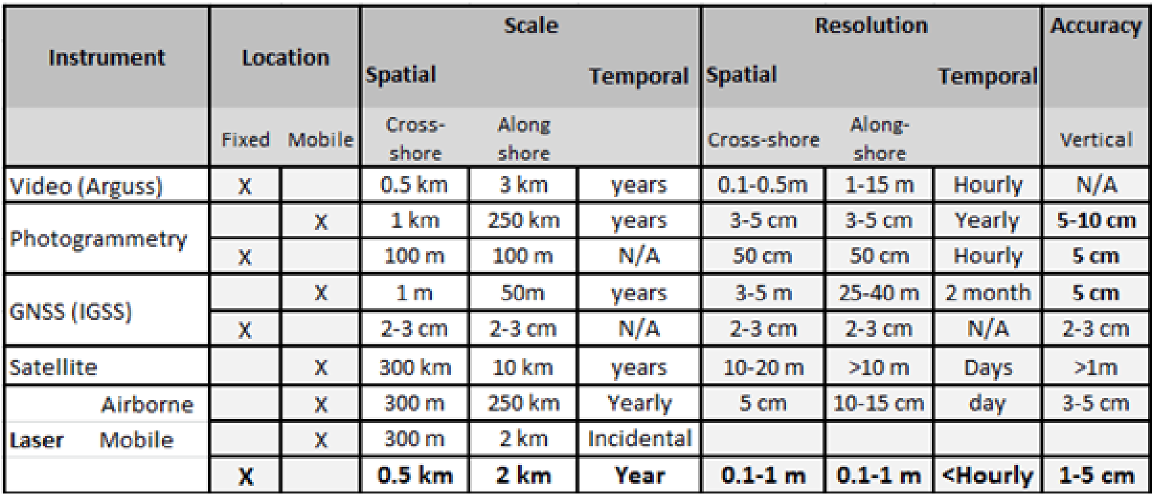
The resilience of the coast is heavily dependent on the ability to bounce back after an after hazardous events such as hurricanes, coastal storms, and flooding – rather than simply reacting to impacts. The ability of the coast to recover after hazardous events is dependent on many mechanisms. Sand stored underwater has to be transported landwards during calm periods, deposited on the beach, dried and thereafter transported to the dunes where it is stored more permanently. The long term recovery of the coast is difficult to measure and model due to the small fluxes (centimeters) and is strongly dependent on the circumstances. This makes it hard to measure in regular field campaigns. Special campaigns are currently being organized, e.g. the so-called Quick reaction Force (Ministry of Public Works, The Netherlands). With a lack of good measurements it is more difficult to effectively and efficiently tune and use the present numerical forecast models.

1.2 *Measuring techniques*

Obtaining information over all spatio-temporal scales over long term periods is a huge challenge. Present strategies miss either the spatio-temporal detail or quality to provide sufficient information. Figure 2 gives an overview of several long term large scale measuring campaigns. Although campaigns cover large areas and long time periods, the spatial and temporal resolutions are quite low thereby omitting all kind of micro and mezzo scale phenomena. Recent developments with X-band radar (van Gils, 2014) make it easier to monitor the hydrodynamic part of the coast, but the dry part is harder to monitor. Satellite data misses the spatial detail in combination with a high revisit time while airborne laser scanning cannot be employed at hourly interval, compare Figure 3). There are video systems (Argus, Holman 2007) that operate at the required scale, but these miss metric quality. A permanent laser solution is proposed to provide the data for the necessary multiple spatial and temporal scales.

Location	Spatial Scale		Temporal Scale	Spatial Resolution		Temporal resolution
	Cross-shore	Along shore		Cross-shore	Along-shore	
Duck, North Carolina, USA	Macro (1 km)	Macro (1 km)	Macro (22 yrs)	10 m	50 m	Forthnigthly
Dutch coast: JARKUS I	Macro (1 km)	Meta (250 km)	Macro (49yrs)	10 m	250 m	Annual
Dutch coast: JARKUS II	Macro (3.5 km)	Meta (250 km)	Macro (49 yrs)	10 m	1000 m	Every 5 years
Narrabeen, New South Wales, Australia	Micro (100 m)	Macro (3 km)	Macro (32 yrs)	10 m	500 m	Monthly
Moruya, New South Wales, Australia	Micro (100 m)	Macro (2 km)	Macro (34 yrs)	10 m	N/A	Monthly
Dutch coast: Nemo	Macro (1km)	Macro (20 km)	Mezo (5 yrs)	3-5 m	50 m	Every 2 month's

Figure 2. Historical macro-scale (temporal and /or spatial) coastal field measurements.



Instrument	Location		Scale			Resolution			Accuracy
			Spatial		Temporal	Spatial		Temporal	
	Fixed	Mobile	Cross-shore	Along shore		Cross-shore	Along-shore		Vertical
Video (Arguss)	X		0.5 km	3 km	years	0.1-0.5m	1-15 m	Hourly	N/A
Photogrammetry		X	1 km	250 km	years	3-5 cm	3-5 cm	Yearly	**5-10 cm**
	X		100 m	100 m	N/A	50 cm	50 cm	Hourly	**5 cm**
GNSS (IGSS)		X	1 m	50m	years	3-5 m	25-40 m	2 month	**5 cm**
	X		2-3 cm	2-3 cm	N/A	2-3 cm	2-3 cm	N/A	2-3 cm
Satellite		X	300 km	10 km	years	10-20 m	>10 m	Days	>1m
Laser Airborne		X	300 m	250 km	Yearly	5 cm	10-15 cm	day	3-5 cm
Mobile		X	300 m	2 km	Incidental				
	X		**0.5 km**	**2 km**	**Year**	**0.1-1 m**	**0.1-1 m**	**<Hourly**	**1-5 cm**

Figure 3. Indicative overview of different measurement techniques.

Laser scanning emerged as a surveying technique in the nineties of the last century using the LIDAR (LIght Detection and Ranging) sensor technique.. A laser is used to emit a focused pulse to a spot on the beach, say, and the two way travel time of the pulse is easily converted in a range distance at mm accuracy. In combination with the known position and orientation of the laser system 3D coordinates of the spot on the beach are obtained, (Vosselman and Maas, 2011).. In the beginning LIDAR technology was notably implemented in airborne platforms and became very successful, in the Dutch setting, for obtaining the Actueel Hoogtebestand Nederland (Dutch topographical height map, see: www.ahn.nl), a national airborne LIDAR elevation archive, and for obtaining part of the so-called JarKus measurements, yearly coastal elevation measurements, applied to assess yearly erosion and sedimentation rates.

After the airborne success, LIDAR technology got also implemented on vehicles, referred to as mobile mapping systems, (Bitenc et al., 2011), and on static platforms, referred to as terrestrial laser scanning, (Lindenbergh et al., 2011). A terrestrial laser scanner integrates a LIDAR sensor with a rotating head and mirror, resulting in a near 360x360 deg coverage of the 3D environment of the scanner. One such scanner is shown in Figure 4. The range of such scanners is anywhere between 1 m and ~5 km.

Typically a LIDAR system internally extracts one range from the return pulse, by selecting e.g. the time of maximal energy, or the time half of the significant return energy is received. Except for the range, also the strength of the return signal is stored as an intensity value. Some scanners are in addition able to sample and store the raw full return signal as function of time. Such full waveform return contains additional information on the scattering elements in the cross-section of the laser pulse, such as vegetation, pebbles or surface roughness, (Mallet and Bretar, 2009).

1.3 Permanent Laser Scanning and CoastScan project

Often Terrestrial Laser Scanning (TLS) is used from different station positions. Consecutively, the different point clouds, obtained from each standpoint are combined to form a common point cloud. Alternatively, the scanner is kept stationary and the same scene is scanned repeatedly to detect changes. If this repeated scanning is automatized we obtain what we call a Permanent Laser Scanning system (PLS). It is permanent in two ways: spatially, in the sense that it always scanning from the same standpoint. And temporarily, in the sense that such system can be employed in a near continuous way, that is, once the surroundings of the scanner is scanned once, it automatically starts over again. First reported experiments with PLS were performed in open pit mining (Little, 2006), where PLS was used to monitor excavation volume. Very recently, initiatives have been taken to use PLS for monitoring landslides (Kromer et al., 2015) and (Canli et al., 2016).

The CoastScan project aims to use PLS for the first time in coastal engineering and provide measurements over multiple spatio-temporal scales. The initial results are presented in this paper.

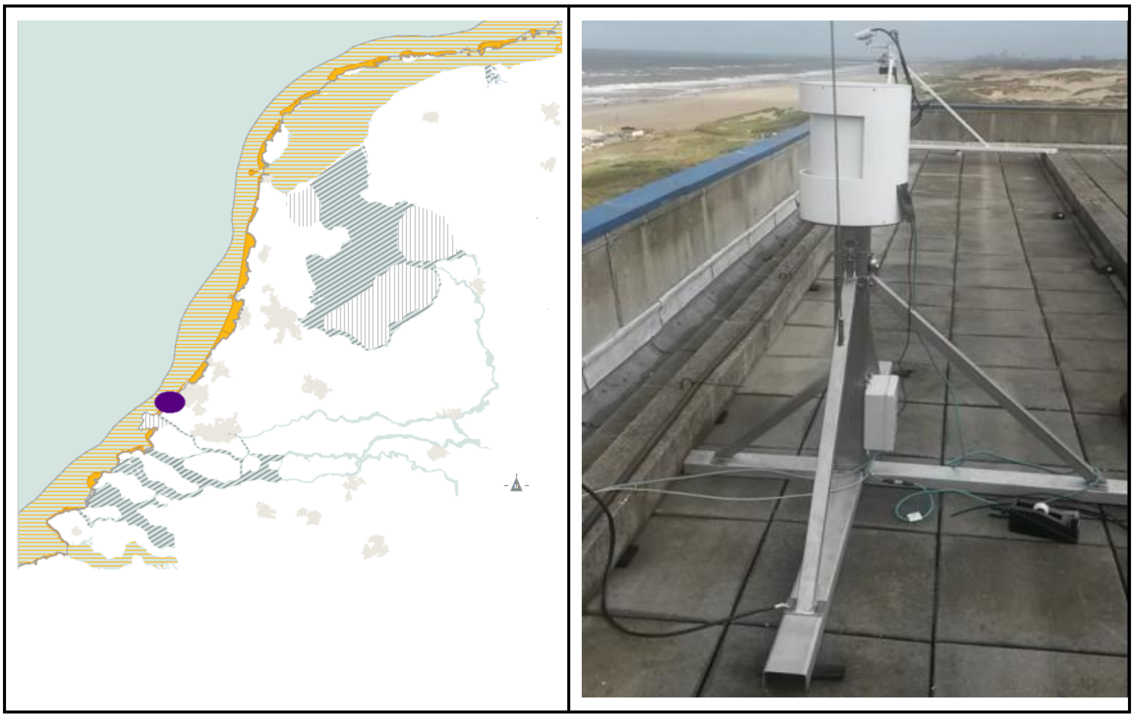


Figure 4. Left panel: Sandy coasts along the Dutch Coast (indicated by filled yellow areas) with their region of influence indicated by the while yellow striped areas. The test location in Kijkduin is marked by a purple dot. The right panel shows the Riegl VZ2000 laser scanner on top of NH Hotel Atlantic Den Haag at the test location.

2. System Setup

The Permanent Laser Scanner (PLS) setup consists of a Riegl-VZ2000 laser scanner mounted on a stable measuring frame (see figure 4, right panel). The scanner is shielded by a custom made all weather protective housing and steered by a command computer with attached storage. The command computer runs a task scheduler which retrieves the latest weather information, corrects the laser scanner and instructs a scan. The laser scanner is located on top of a hotel overlooking the beach at Kijkduin, just south of The Hague, The Netherlands, (see also figure 4, left panel).

A total of six 5-centimeter reflectors are more or less evenly spread over a 180 degrees window on both the building and the beach. The field of view was reduced to ~180 degrees due to the protective housing and the fact that the beach is the object of interest. With the reflectors it is possible to determine the location of the laser scanner with a precision of about 3-5 cm. The location of the laser scanner was checked separately with GNSS (Global Navigation Satellite System) and the differences are in the range of 5 cm. As the laser scanner is not moved during the measuring campaign this falls within the required specifications.

Figure 5. Scan result where each xyz point is colored by RGB information obtained from the built-in true color camera system. The sandy beach on the left is clearly distinguishable from the green dune vegetation on the right.

3. Measuring Campaign

3.1 Introduction

After several initial tests the PLS setup has been running continuously since the beginning of November 2016 (see figure 6). Around Christmas 2016 a severe bug in the command computer prevented the acquisition of data. Apart from this period and one day in February 2017 the laser scanner has since November 2017 functioned for about 100 days acquiring about 2400 scans.

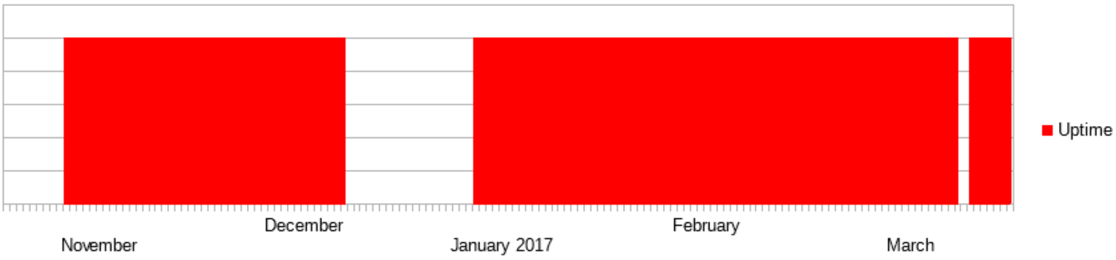


Figure 6. Uptime of the lasers scanner over a period of 100 days.

3.2 Permanent Laser Scanning vs GPS measurements

In order to compare the Permanent Laser Scanner with GPS data a GPS survey of 19th February 2017 was compared with a laser scan at the same time. Figure 7 shows an overview of the GPS track and the laser data. The GPS survey consists of two longitudinal and perpendicular survey lines on the beach and two paths to approach the beach.

A nearest neighbor search routine was used to search the nearest laser point near a GPS location in horizontal direction. The maximum allowed distance was 1 meter. The results of the comparison are presented in figure 8. The figure shows a very good fit between the laser data and the GPS data. Still some outliers are visible at around 7m and 14 m height. Possible explanations for these outliers are temporary objects like people.

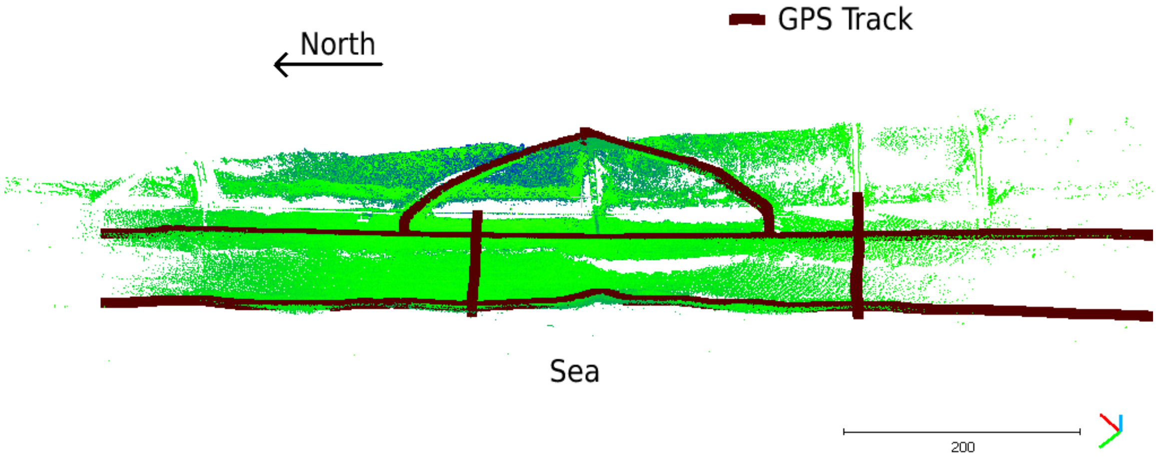


Figure 7. Comparison of the laser and GPS data. The GPS data is indicated in black and the laser data in green.

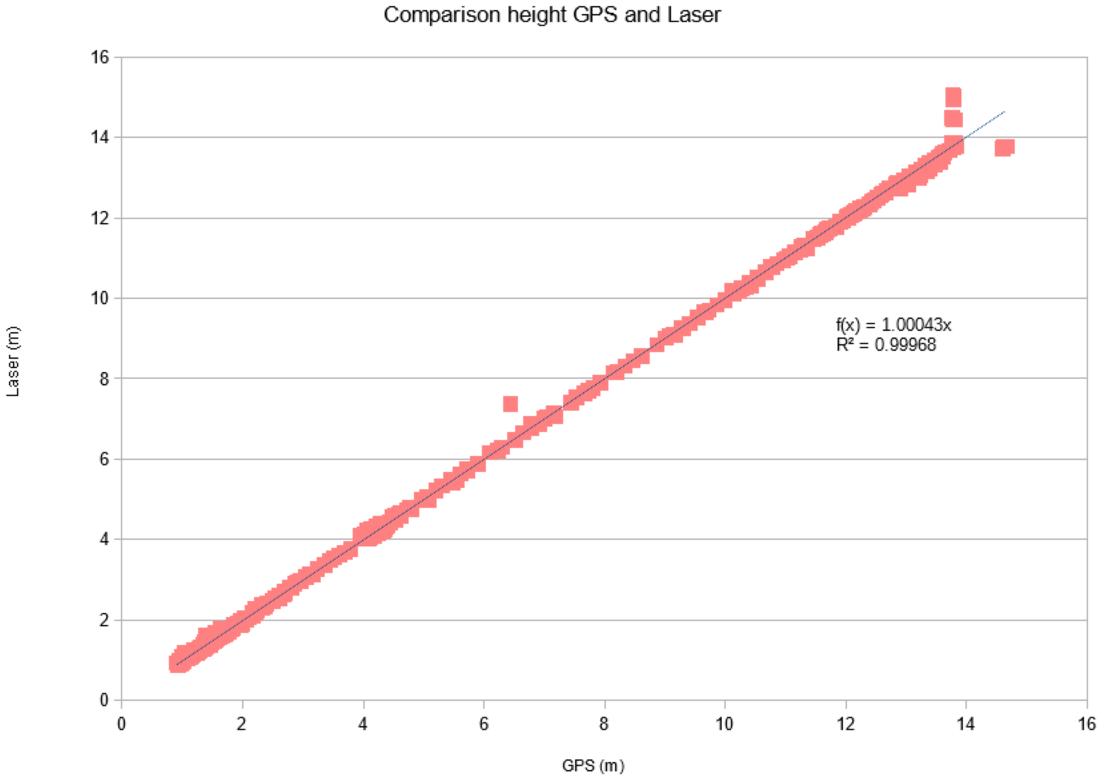


Figure 8. Comparison of the measured height of the laser and the GPS

3.3 Relative accuracy

In order to determine the smallest detectable difference of the PLS setup two consecutive scans were compared obtained at the 14th January 2017 at 21h and 22h respectively. The scans were taken during low tide with mild weather. A selection on the upper part of the beach (figure 9, indicated in yellow) was compared using a Cloud-to-Mesh tool. The average difference was less than one millimeter with a standard deviation of about 1.5 cm (see figure 10).

Compared to the accuracies of other measuring techniques, compare Figure 3, the PLS is able to differentiate much smaller differences. Compared to a high accuracy GPS with an accuracy and standard deviation of about 1-2 cm the PLS is able to distinguish a factor 10 more than the GPS. The main advantage over GPS of PLS is the much better spatial coverage though.

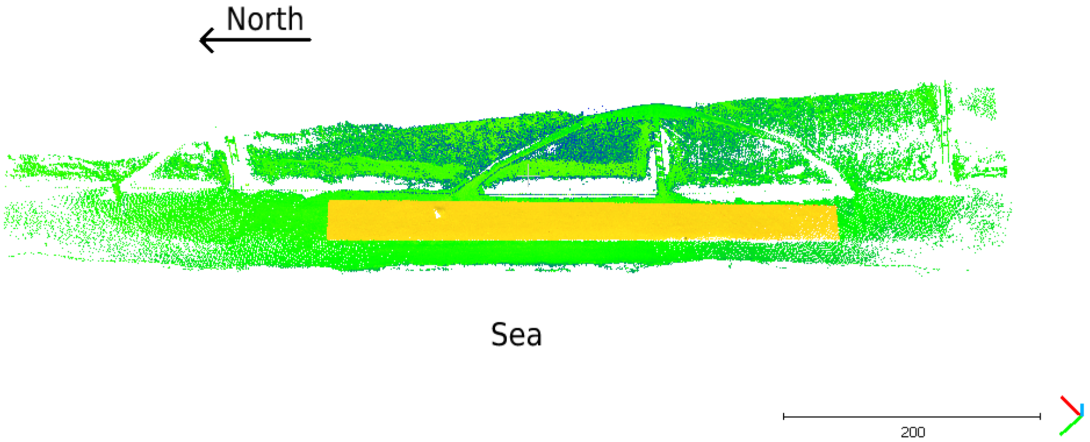


Figure 9. Comparison area indicated in yellow on the upper part of the beach.

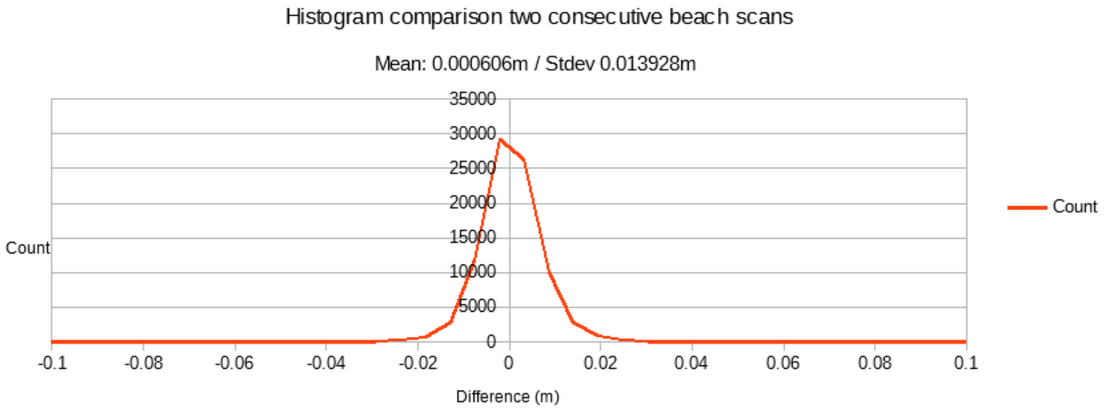


Figure 10. Histogram of the difference between corresponding points in two consecutives scans of the beach areas. As only negligible actual change is expected in one hour, these differences merely represent the measurement quality.

3.4 Time series analysis

To further demonstrate the possibilities of Permanent Laser Scanning, time series were extracted at four different locations in the region of interest (Figure 11). For each of these locations time series of hourly mean elevation (+associated standard deviation) were obtained. For each time step all PLS points within a 50 centimeter radius at the four points were selected. For each interest point the ordinary mean of their Z values is reported as the elevation of the considered interest points, while the spread in the Z values is used to determine a standard deviation. The resulting time series are shown in Figure 12.

The time series obtained over asphalt appears very stable, the mean st.dev. = 0.017 [m]. As expected, no significant linear trend is visible. A peak on the 11-th day is probably caused by a walker. This peak comes together with a high standard deviation of ~20 cm. This peak shows the need of a filter to remove temporary objects from the scan data that could affect their interpretation. Apart from this peak, the st.dev. is close to the precision reported above. Note that some small jumps in the time series appear to be present at all four interest points. Therefore these jumps could be interpreted as small instabilities in the horizontal positioning of the laser scanner. This will be checked in the future by an analysis of the target data.

The second interest point is located on a vegetated dune slope. This is clearly visible in the reported st.dev value of 0.105 [m]. This st.dev. is expected to rise further in summer, when beach grass is thicker. More analysis is required to assess when and how it is possible to separate the signal from the sand below the vegetation from the signal of the vegetation itself, e.g. to estimate dune-ward aeolian sand transport. The Riegl VZ2000 is able to store multiple returns for each outgoing pulse. Future analysis of this multiple signal is expected to at least partly solve this vegetation terrain separation issue. In addition, note that a small downward trend is visible at this location. At the time of this writing, we have no good explanation for this.

The third interest point is on the dry part of the beach. The time series shows a small downward trend of -0.003 [m/day] and the mean of the epoch wise standard deviations equals 0.008 [m], which is the smallest of the four points. In some contrast the point of interest on the intertidal part of the beach shows more variations, with also a bit higher st.dev. value. Indeed the mean of the epoch wise st.devs in this case equals 0.011 [m]. Apparently this location is more affected by dynamics. The higher st.dev. could be caused by higher local topography variations or by a higher incidence angle, which is known to affect the noise level, (Soudarissanane et al., 2011).What is also apparent in this time series is that more often epochs with missing data occur. During high tide, this point of interest is located in the water, and not enough return energy is received by the laser scanner to estimate a Z value.

Figure 11. Four different interest points, picked to illustrate differences in time series. From right to left, the yellow dot indicates the location of the laser scanner; the first red point is on asphalt, and assumed to be stable. The second red points is located in the dune vegetation, and is characterized by a high local roughness. The third and fourth point are on the dry part and the intertidal part of the beach respectively.

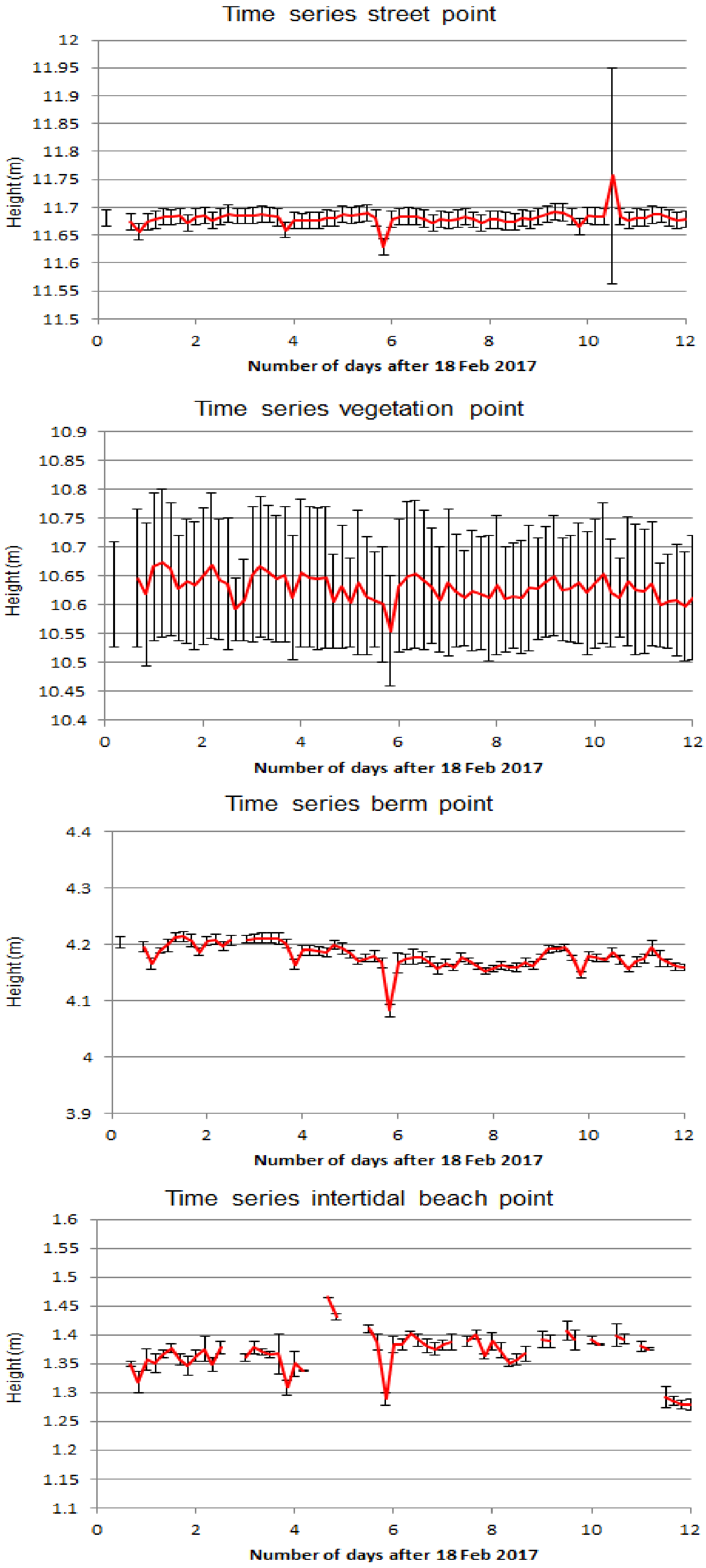


Figure 12. Time series for the four different interest points. For each interest point, an elevation and standard deviation of that elevation is given for each hourly interval.

4. Conclusions

Resilient coasts become more and more a necessity to safeguard sandy coasts against future climate changes. Obtaining suitable measurements over multiple spatio-temporal scales is an important addition to the improvement of present modelling tools needed for Building with Nature solutions.

The CoastScan project aims to provide these measurements over multiple scales with a Permanent Laser Scanning setup. The initial results show a great promise to provide valuable measurements for model and coastal knowledge improvements.

During a first experiment, the Permanent Laser Scanner setup was able to scan for 100 days in a row with one larger and one smaller interruption. First analysis shows that data is stable between consecutive epochs, with differences at the millimeter level, mainly caused by sensor noise. Time series at different points of interest located on asphalt, on dune vegetation and on the dry and intertidal part of the beach behave as anticipated. At the same time a first data analysis of the data shows the need of a variation of solutions, e.g. to remove temporary objects, to separate terrain from vegetation, and notably to cluster and interpret small but varying spatial patterns of topographic change and their relation to dynamic processes as resilience.

Acknowledgements

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