Assessing the Error Budget for Permanent Laser Scanning in Coastal Areas

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SUMMARY

An increased preference for building with nature solutions to mitigate possible negative effects of predicted climate change urges to acquire additional knowledge on coastal variability and resilience. Permanent laser scanning is a new and promising tool to observe and analyse natural variations at short (i.e. hourly) time-scales for extended periods of time (i.e. years). In order to establish an error estimate over both space and time, a six months period of daily laser scans obtained at Kijkduin was analysed. The scans were obtained from a permanent laser scan set-up on top of a hotel. We provide an overview of possible spatiotemporal error sources and of errors associated with a permanent laser set-ups for this particular example data set. In addition, some quantitative insights in the data quality are derived by assessing the variability of several parameters in space and time. Our analysis shows, that we can establish possible errors due to deformations in the laser scanner set up as well as small changes in range to reference objects at larger distances. Analysis of ranges within the point cloud shows that the range changes over time are in the order of centimetres indicating minimal deformation of the point clouds over time.

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1. Introduction

Sandy beaches are dynamic parts of our coastal areas that undergo continuous change. In previous times, these beaches were stabilized against external forces with fixed objects like dikes, groins and other solid structures with varying degrees of success (Stive et al, 2013). In recent years a more flexible approach is chosen with so-called building with nature solutions (de Vriend et al., 2015) where natural materials are used to shape and protect our coasts. Examples are the sand engine near The Hague, the Hondsbossche Dunes and the Prins-Hendrik dike on the island Texel. These solutions allow for more diverse coastal management, which can adapt easier to future changing environmental and societal needs. However, natural solutions inhibit more natural variation and present knowledge about relevant coastal deformation processes is still incomplete.

Permanent laser scanning (PLS) is a relative new and promising technique to monitor coastal processes (O'Dea(1) et al., 2019, Williams et al., 2019 and Brodie et al., 2012). It delivers a 4D spatio-temporal representation of a part of the coast at hourly temporal and centimetre to decimetre spatial resolution, (Vos et al, 2017). A laser scanner is mounted on top of a high building close to the beach to acquire point clouds of a section of the coast of about 1 km length over a period of several months. It is especially useful for assessing deformations of the beach over time. Recent locations are Kijkduin (The Netherlands) (Lindenbergh et al., 2019, Vos et al., 2019 and Anders et al., 2019), Duck, North Carolina (USA) (O'Dea(2) et al., 2019) and Mariakerke Bad (Belgium) (Brandt et al., 2019).

To assess the accuracy of the observed deformation processes it is essential to understand the error sources and error budget of the PLS data set. Possible error sources include measurement errors due to inaccuracy of the scanner and small deformations in the frame or building on which the scanner is mounted. Also atmospheric effects, changes of the properties of the observed objects or objects blocking the line of sight of the scanner are relevant. Previously error analysis of laser scanning data was performed for example by Riveiro et al. (Riveiro et al., (2020)), Lindenbergh et al. (Lindenbergh et al. 2011) and Soudarissanane et al. (Soudarissanane et al., 2011). Atmospheric effects have been studied by Friedli et al. (Friedli et al.2019), who demonstrated a significant effect of atmospheric refraction. However, the derived error budgets for terrestrial laser scanning do not provide long term analysis of the stability and error development over time. The assessment of the error budget of permanent laser scanning considering time dependent errors and the stability of consecutive measurements is essential to derive accurate and reliable parameters and statistics about coastal deformation processes.

In this study we explain possible error sources and relate them to PLS data from our experimental set up in Kijkduin, the Netherlands. For this purpose, we first explain the geometry of the set up and list possible error sources. Then we show some data examples on stable reference planes within the observed part of the beach to study the stability over time. Long range errors based on the detection of reference objects are analysed in a third step.

2. Permanent laser scan setup

Our permanent laser scan system consists of a Riegl VZ 2000 laser scanner, mounted on a specially designed frame (see **Fejl! Henvisningskilde ikke fundet.**). It consists of a stainless-steel main column on four legs supported by cross-legs. The frame is buffered on rubber and weighted down with floor tiles. The system is protected by a double protection case equipped with special borafloat glass with a 1% reflection factor for the 1550 nm wavelength of the scanner.

The laser scanner is set up on top of the NH Hotel Atlantic in Kijkduin, The Netherlands, right behind the dunes next to the beach. It is programmed by a command computer which sets the atmospheric conditions (pressure, humidity and temperature) and the scan range, resolution and settings for each scan. Weather data is obtained from an online weather repository (openweathermap).

A total of six months of daily low waters scans (from 11 November 2016 to 25 June 2017) is used with small gaps in the data due to instrumentation problems and maintenance activities (17 days) and low visibility because of fog or heavy rain (5 days).

3. Geometry of the PLS Data Set

The data set acquired with permanent laser scanning at Kijkduin consists of one point cloud per day (obtained at low water) showing a part of the beach and dunes in front of the hotel. The laser scanner on the hotel roof is at about 37 m above sea level and the distance to the water line at low tide is about 250 m. Assuming the ranges and distances as shown in figure 2,

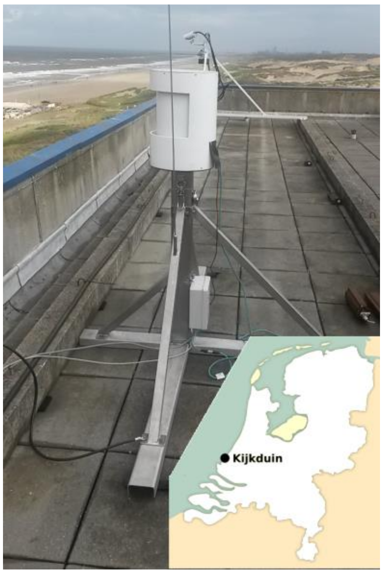


Figure 1: Experimental set up: A Riegl VZ2000 laser scanner is mounted on a steel frame on the roof of a hotel near the beach in Kijkduin, NL. The scanner is covered with a protective casing to shield it from wind and rain while not operating.

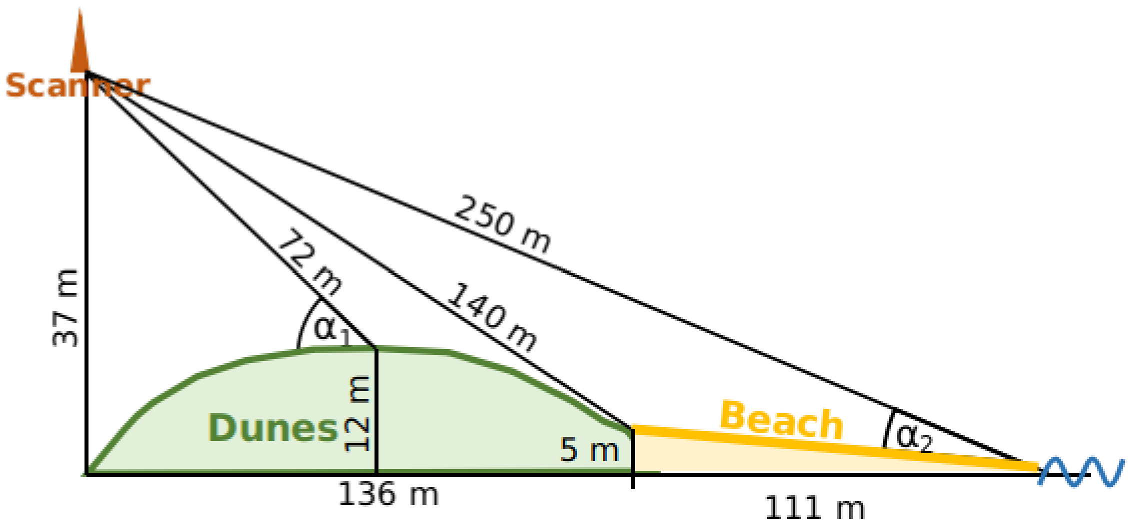


Figure 2: Sketch of the measurement scenario as a cross-section orthogonal to the beach at the location of the laser scanner.

the grazing angle (90° minus the incidence angle) for a beam orthogonal to the coastline is 31° on top of the dunes (α_1 in **Figure**) and 8.5° on the beach near the water line (α_2). Both angles are calculated with the assumption that the surface on top of the dune as well as next to the water line is nearly flat without inclination.

The scans are acquired with a vertical and horizontal angular spacing of 0.03°. The beam divergence is 0.27 mrad, (Riegl, 2019). This leads to a footprint size of about 2 cm on top of the dunes and a point spacing of ~5 cm. However, close to the water line on the beach, the footprint resembles an ellipse with diameters of about 7 cm across and up to 45 cm along (see **Figure**). This is mostly due to the small grazing angle (and therefore large incidence angle). As illustrated in **Figure** also the point density varies a lot depending on the distance to the laser scanner. At a shorter range of around 72 m the point density is ~350 points per square meter and close to the water line (~250 m range) around 10 points per square meter.

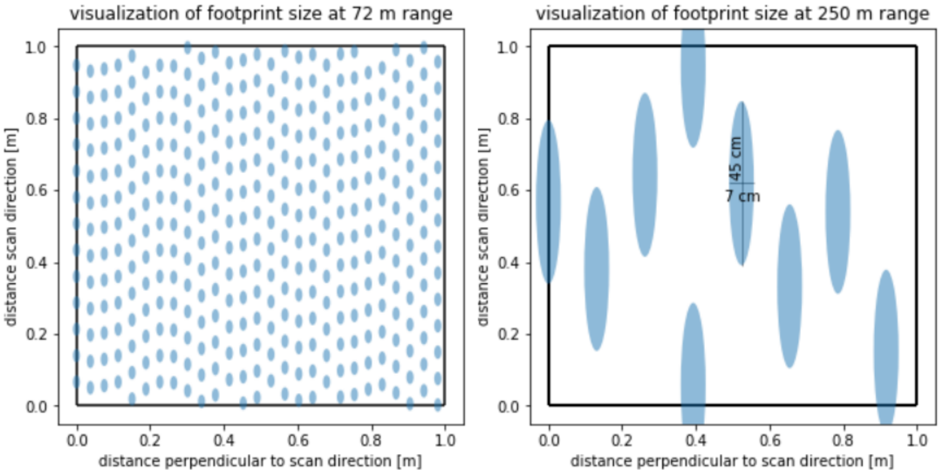


Figure 3: Laser footprint size and shape and point density per square meter at a short range (72 m) on the top of the dunes and at a long range (250 m) close to the water line.

Note that the point cloud data is acquired in a spherical coordinate system, that is, at a given horizontal and vertical scan angle the scanner determines the range distance to the scene. In addition to the range, also the amount of backscatter is stored, as an intensity value, (Kashani et al., 2015), as well as the amplitude, reflectance, deviation and multiple-time-round capability (Riegl, 2019), and if instructed, the full waveform.

4. Overview of error components

The PLS data set, as a nearly continuous collection of point clouds from one position, provides unique opportunities for data analysis and applications. However, it is also subject to absolute errors per point for each point cloud as well as relative errors over the entire period in time. We are especially interested in geometric changes over time and therefore focus on relative errors between point clouds. Assuming that absolute errors can be established for a reference point cloud, for example the scan on day one of the observation period, the error budget for all remaining point clouds can be established in relation to this reference point cloud.

According to Soudarissanane et al. (Soudarissanane et al., 2011) there are four main influences on the quality of a point cloud in terrestrial laser scanning:

1. Scanner mechanism
2. Atmospheric conditions and environment
3. Object properties
4. Scanning geometry

An overview of mechanical errors affecting terrestrial laser scanning and associated calibration methods is presented in (Lichti, 2010). In our case the fourth factor, scanning geometry can be split up in scanning geometry and platform stability, since the building that our scanner set-up is placed on, can also be subject to movement. It is possible that thermal expansion due to temperature variations affects the scanner mechanism somehow, and that as a consequence the measurement quality is affected as well.

Strong atmospheric effects such as rain and fog can affect the quality and amount of stored points in terrestrial laser scanning, (Hejbudzka et al., 2010). Part of the effects can be

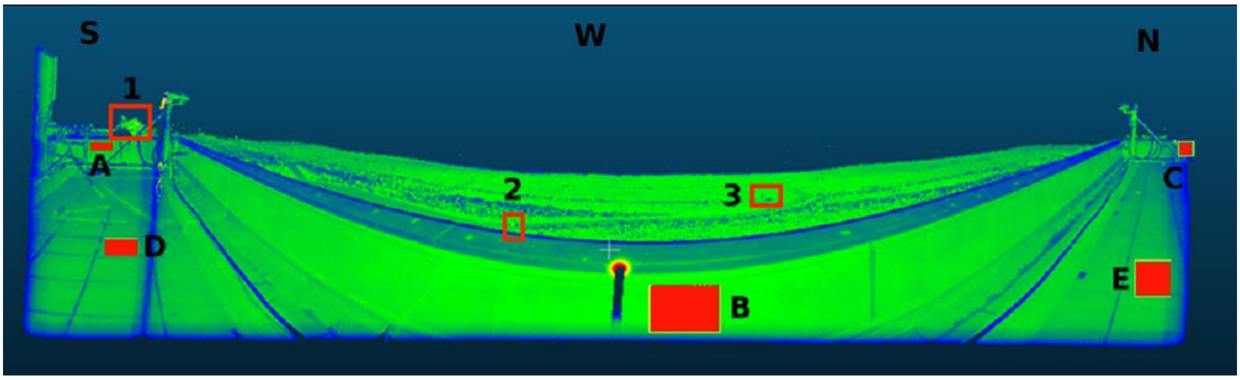
compensated (Wang et al., 2016) but laser ray refraction due to fog or temperature gradients is a problem (Friedli et al., 2019). As a consequence, the laser beam may not hit the surface in the expected beam direction, which in many cases will affect the range distance. In our set-up, a combination of a relatively long range of up to 1km and near-continuous day and night scanning, the effects of atmosphere variation are expected to be important. It is expected to be in the centimeter range (although the number is not consolidated here) as atmospheric effects become more prominent over longer distances and more atmospheric variation is expected between day and night.
Object properties can be influenced by several factors. Rain and wet surfaces (like for example the beach) can influence object properties as wetness, as well as droplets in the air, are known to reduce the backscatter and unfavorably affect the signal to noise ratio (Rasshofer et al., 2011). Ambient light and reflections may influence the return signal and negatively influence the measurement quality. Additionally, the laser scan foundation (here a hotel) is sensitive to thermal expansion of the building and wind moving the building (Kijewski-Correa et al., 2007), both affecting the laser scan position and orientation of the laser scanner. Although we keep the location of the laser scanner and therefore the scanning geometry fairly stable, small variations in the scene will directly affect the local scanning geometry (Soudarissanane, et al., 2011). In addition, factors 1-3 are expected to vary due to the extended observation time.

In the following sections we present a brief analysis of three different ways to establish errors from deviations in the scanner set up and/or the building.

5. Results

5.1 Motion and rotation variations

The motion and rotation of the laser scanner through time is determined by analyzing range measurements on five reference planes (RP) (see **Fejl! Henvisningskilde ikke fundet.**) and the scanner's internal inclination sensors. The reference planes were obtained by segmenting the areas in spherical space and were selected in such a way that movement of the laser scanner in the N-S and W-E direction and in height can be detected. The calculated ranges are based on the mean XYZ-coordinates of each reference planes.



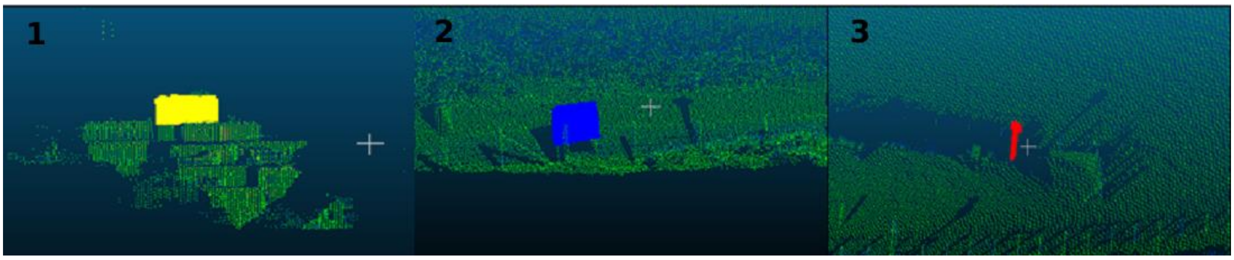


Figure 4: Top image: Spherical view of a Kijkduin point cloud (coloured according to reflectance) with a South-West-North orientation. The edge of the roof can be seen in the foreground, while the observed part of the coast up to the water line is in the background. The position of reference planes A-E is indicated by red rectangles and a capital letter and the locations of the reference objects in the surrounding of the building are marked by a red box and a number. Low surface reflectance is indicated by blue colours while high surface reflectance is indicated by green colours.
Bottom image: Detailed images of the reference objects in the surrounding of the building, to the South of the laser scanner (1, part of a neighbouring building) and to the West (2, information sign) and North-West of the laser scanner (3, sign on a post).

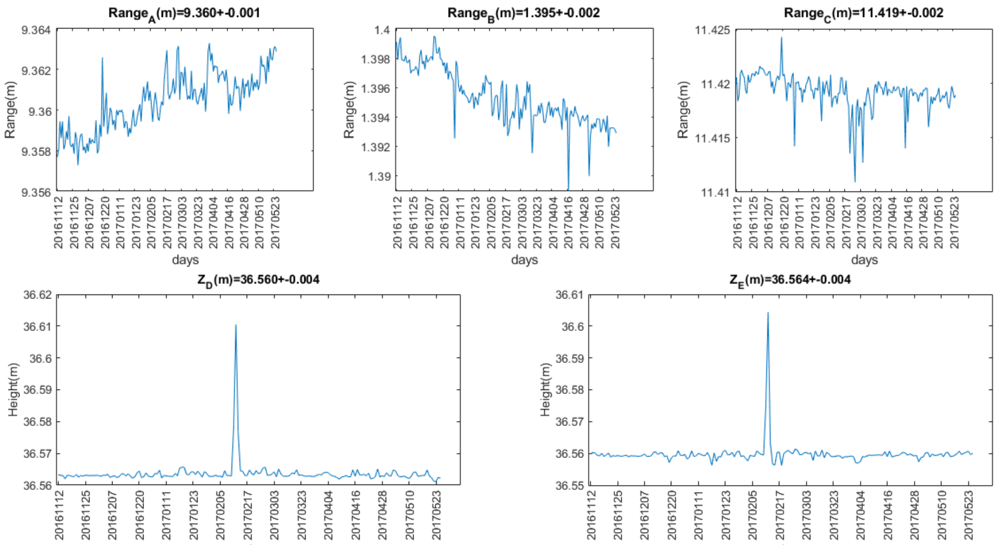


Figure 2: Top row: Mean range versus time, shown for the three reference planes (RP) in N-S- and W-E-direction (A-C). Bottom row: Mean elevation over time for reference planes D and E as indication of the stability in Z-direction. The captions above the graphs indicate the calculated mean value and standard deviation (of the range for RP A-C and height for RP D-E) over the six month period.

The variability in range to the five reference planes on the roof of the building, where the laser scanner is mounted, is analyzed for all available days over the six months period. It gives an indication of movements of the scanner relative to the borders of the roof on which it is mounted. Planes A,B and C are located on the border of the roof. They are used for determining movement in N-S and W-E-direction. The planes D and E are part of the roof itself and are used to determine movement in Z-direction.
The calculated ranges from the laser scanner to the reference planes over time are visualized in **Figure**5. Variations in the horizontal plane are small showing a small drift of about 0.5 cm over time. Calculated standard deviations are in the order of millimeters. A cause for the small drift is not known at the time of writing and will be investigated in the future. The measured range towards the reference planes on the roof show smaller variations with no visible trend

and one clear outlier. This outlier is caused by snow covering the roof. Calculated standard deviations are in the order of millimeters and less than 2 mm when the outlier is removed.

The laser scanner contains two inclination sensors with an accuracy of ±0.008 degrees (Riegl, 2019), which we use to assess the rotational stability of the laser scanner position over time. The inertial compass was unfortunately not available for data analysis. The data from the internal inclination sensors provide mean pitch and roll as well as standard deviation in pitch and roll for every scan (based on about 250 pitch and roll measurement per scan). **Fejl! Henvisningskilde ikke fundet.**6 shows the roll and pitch variation over the six months period. These values are compared to the PLS range data to stable reference planes on the roof of the building. In general the roll values show a larger variation than the pitch values, which matches our findings from the analysis of the range on reference planes. There is more movement in the W-E-direction than in the N-S-direction. We still need to establish if the observed magnitude and timing of

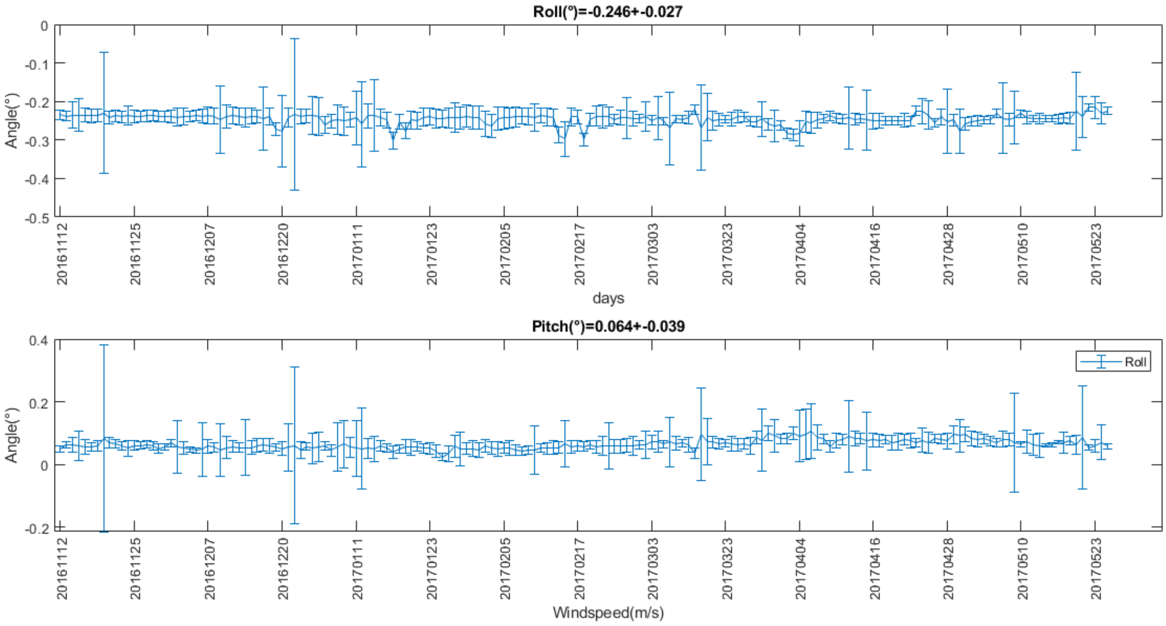


Figure 6: Calculated mean roll and pitch values per scan over time. The calculated standard deviations are based on about 250 individual pitch and roll measurements during a scan. Larger standard deviations indicate larger movements of the laserscanner during a scan.

the movement matches between the two methods. Larger inclination values could indicate movement of the entire building on which the scanner is mounted.

5.2 Reference object variations

We use several reference objects (RO) (see **Figure**) to establish the variations of point cloud data over a longer range. The number of stable reference objects was limited around the hotel and three objects were deemed suitable. These objects were large enough to be detectable

with enough scan points (between 20 and 300 per object) and sufficiently spread around the hotel. They were assumed stable in terms of position and material properties.
The three objects (1-3) consisting of a vertical wall on a building (S), an information board (SW) and a sign on the beach (NW). The reference objects were isolated from the data based on position, height, laser angle and range. An averaged XYZ coordinate in national coordinates was calculated per object and angles (here referenced as Theta (0-360°) and Phi (-90-90°)) were calculated in relation to the position of the laser scanner.

The detected angles and ranges are shown in Figure 7. Ranges to the objects change little over time apart from a couple of isolated cases. The horizontal angle shows a clear jump around the 22th of February. No clear explanation has been found other than there has been a power shutdown around that date. A possible explanation is that a reboot around that time, could have reoriented the coordinate system of the laser scanner.
Variations in range from the laser scanner towards reference objects, which are not part of the same building, can indicated influences of deformations of the building itself. To draw a clear conclusion on error sources additional data from external measurement systems is needed.

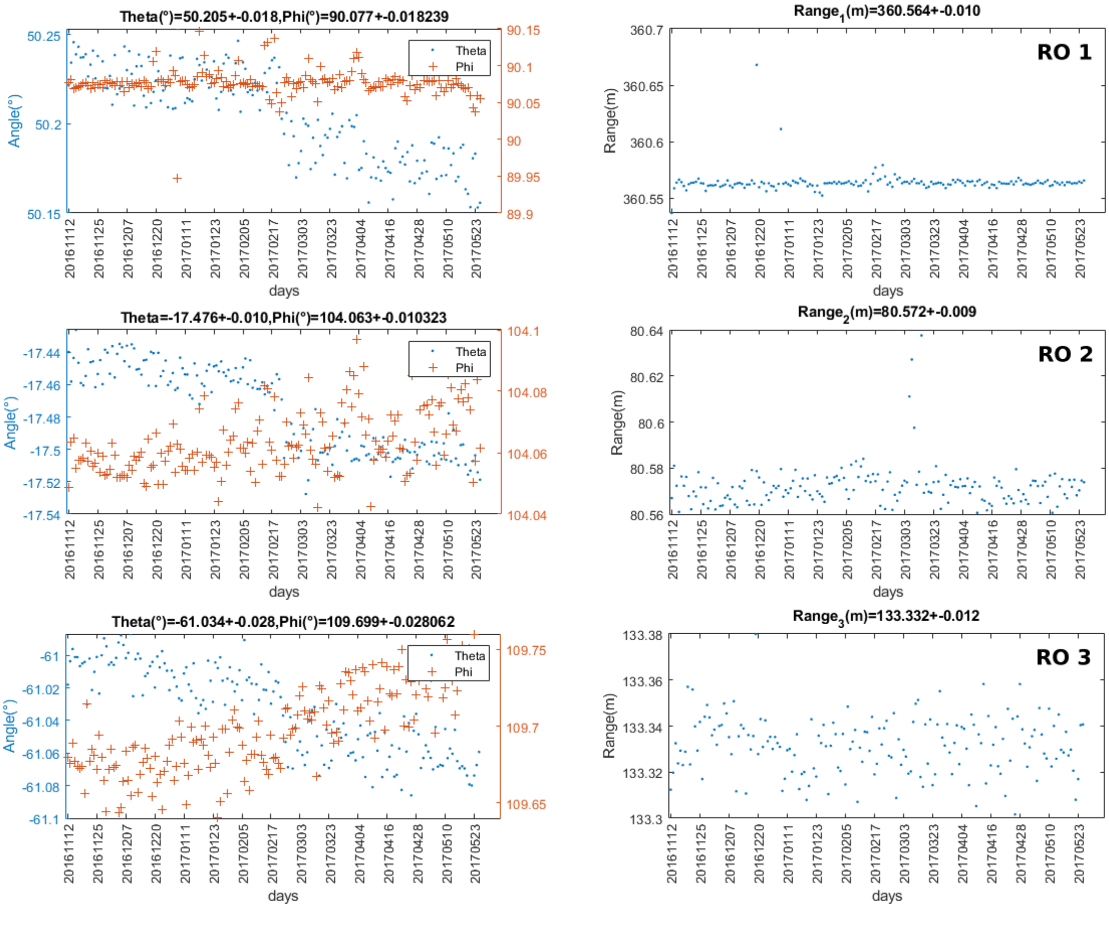


Figure 7: Daily measurements of horizontal (theta) and vertical (phi) angles over time per reference object (left column) and range measurement over time per reference object (right column).

Deformations within each point cloud are analysed by measuring the distances between the three reference objects. The results are shown in Figure 8. Distances vary in the order of centimetres or up to 0.01% of the distance between the reference points and don't show any obvious trend. The observed variations could be the result of small movements of the reference objects themselves, for example the information signs do not necessarily have to be stable during strong winds. Other reasons could be issues in the object detection method, movement of the scanner during a scan or refraction effects due to varying atmospheric conditions.

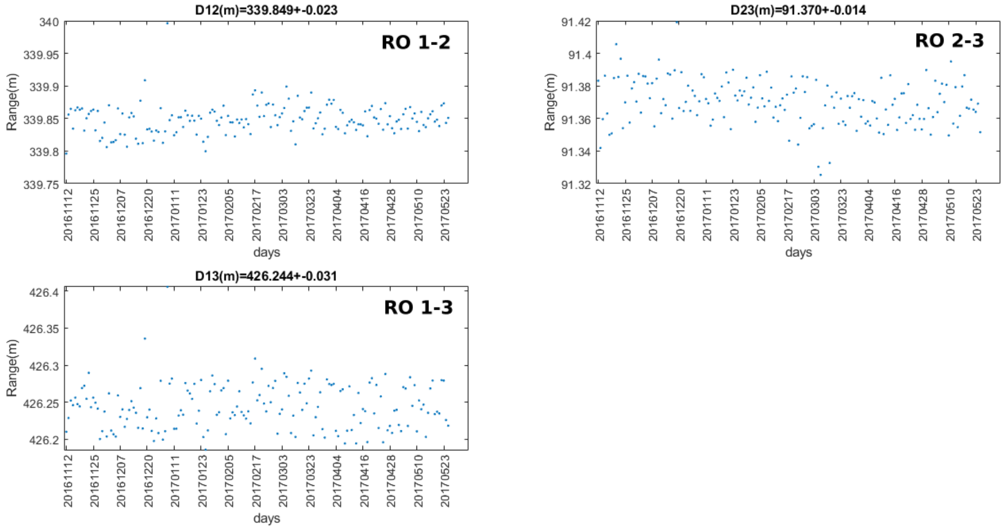


Figure 8: Distances between reference objects over time.

Summary of standard deviations			
Item		**Max per day**	**Entire period**
Range to reference planes (A,B,C) [mm]		6	2
Z-coordinate of reference planes on the roof (D,E) [mm]		0.2*	0.18*
Angles [°]	Roll	0.17	0.025
	Pitch	0.3	0.04
Reference objects (1,2,3)	Range [m]		0.012
	Theta [°]		0.03
	Phi [°]		0.03
Distance between reference objects [m]			0.03

Table 1: Summary of standard deviations of all considered measurements. The variations in the Z-coordinate (marked with *) are reported without the day where snow covered the roof, to indicate possible errors in the set-up, not derived from known weather conditions.

4.3 Error Summary

Six months of permanent laser scanning data provide the unique opportunity to continuously monitor deformations and changing properties of the coast. However, these observations are subject to errors due to various factors. We make a first attempt at determining the time dependent errors of the permanent laser scanner setup. The results in **Fejl! Henvisningskilde ikke fundet.** show movement of the laser scanner in the order of millimeters and below centimeter level. The whole laser scanner set-up tilts towards one side, with respect to the hotel that it is mounted on, in the course of six months. The inclination sensors in the laser scanner show rather large standard deviations in the detected inclination angles but no clear trend to one direction. Otherwise calculated ranges towards references objects at larger distances from the scanner vary around 1 cm. Deformations within the laser scan point clouds are detected with range errors in the point cloud up a couple of centimeters.

6. Conclusions

We reviewed possible error sources in a data set from permanent laser scanning and demonstrated, which errors can be found by purely analyzing the point cloud data set. There are time dependent errors in a data set from permanent laser scanning. Without taking into account the effects on selected reference objects and the observed scene, we found small variations and indications on their order of magnitude (in the order of millimeters to centimeters and less than 1 degree), which gives a first estimate of the data quality. Considering the five factors that influence the relative errors in laser scanner data (scanner mechanism, atmospheric conditions, object properties, scanning geometry and platform stability) we suggest that scanning geometry, platform stability and atmospheric conditions are the most likely causes of the detected errors. In one case, we identified the source of one outlier in the otherwise stable elevation on two reference surfaces as a result of snow (changed object properties). Changes in distances between reference objects are likely influenced by platform instability, changed scanning geometry as well as object properties (slight deformation of the building and/or slight movement of the information sign and post due to wind). The observed changes of the position and orientation of the laser scanner could result from temperature changes, as well as wind or other atmospheric effects. To establish these relations, more data from independent measurements are needed. This will be subject of our future work.

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BIOGRAPHICAL NOTES

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