

Spatio-temporal measurement of laboratory wave fields using LiDAR

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ABSTRACT

Accurate spatio-temporal measurements of the free-surface elevation are essential for understanding wave evolution, wave breaking, and wave-structure interaction. In laboratory studies, conventional wave gauges provide reliable point measurements but become intrusive and impractical when extended to dense spatial arrays. This study evaluates the capability of a commercially available 3D LiDAR system to resolve the spatio-temporal evolution of regular and irregular waves in a wave flume, through direct comparison with high-resolution camera and wave-gauge measurements.

The LiDAR is deployed non-intrusively to capture free-surface elevation over a spatial extent exceeding two wavelengths with high spatial and temporal resolution. Regular and irregular wave conditions are investigated over a sloping bathymetry, including breaking waves. Quantitative comparisons are conducted in the time, frequency, and spatial domains, as well as individual wave statistics. For irregular sea states, significant wave height, individual wave heights, periods, and crest heights derived from LiDAR measurements show close agreement with wave gauge estimates, with root-mean-square errors typically below 6% of the significant wave height and correlation coefficients exceeding 0.97 outside the immediate vicinity of the LiDAR.

Systematic deviations are observed directly beneath the LiDAR. Under breaking conditions, the LiDAR preferentially captures the densest part of the overturning crest and aerated surface, revealing inherent differences between optical and probe-based definitions of the free surface. These effects are quantified, and practical guidance on sensor placement, data processing, and interpretation is provided. Overall, the results demonstrate that LiDAR offers a robust and efficient alternative to dense wave gauge arrays for laboratory studies requiring spatio-temporal resolution of wave fields.

1. Introduction

The expanding offshore and coastal engineering sectors, including fixed and floating wind turbines, wave energy devices, and coastal defense structures, place increasing demands on accurate measurements of ocean waves. Beyond bulk parameters such as significant wave height or peak period, many contemporary engineering problems depend critically on the spatio-temporal evolution of the free surface, including wave shape (Karpadakis and Swan, 2020; Huo et al., 2025a), crest geometry (Karpadakis and Swan, 2022), kinematics (Millar et al., 2025), and the development of wave breaking (Al et al., 2025a). These aspects are central to understanding extreme wave loading, wave-structure interaction, run-up, overtopping, and the validation of advanced numerical models.

In laboratory environments, wave measurements are traditionally

obtained using resistance or capacitance-type wave gauges, which provide reliable and high-frequency point measurements of surface elevation (Shepherd, 1997). When spatio-temporal information is required, arrays of closely spaced wave gauges can be deployed (Le Page et al., 2024; Swan and Sheikh, 2015). While effective, such arrangements rapidly become intrusive, expensive, and logistically complex. Large arrays may alter the local flow field, require repeated experimental runs, and remain limited in their ability to resolve three-dimensional wave evolution over extended areas. These limitations are particularly acute for steep and breaking waves, where air entrainment and complex free-surface geometries challenge the physical definition of the “true” surface elevation measured by probe-based instruments (Babanin, 2011; Na and Son, 2021; Wang et al., 1986). In addition, point measurements inherently fail to capture spatial variability across areas comparable to the footprint of offshore structures, where wave statistics and crest

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extremes are governed by spatio-temporal variability rather than single-point behavior.

Alternative approaches for resolving the free surface in laboratory wave flumes have therefore been explored. Camera-based methods using side-wall imaging have been applied to reconstruct wave profiles and kinematics (Almalki et al., 2025a; Govender et al., 2002; She and Cannings, 2007; Blenkinsopp et al., 2008) but require intricate setup. Laser-induced fluorescence techniques have also been used to extract surface elevation (Erinin et al., 2023), though at the expense of substantial experimental complexity, calibration effort, and post-processing requirements. More broadly, remote sensing methods such as radar, infrared imaging, and stereo imaging have demonstrated strong potential for wave measurements in both laboratory and field settings (Marom et al., 1990; Dankert et al., 2003; Kabel et al., 2024; Jessup et al., 1997; Benetazzo, 2006; De et al., 2011), motivating further investigation of optical, non-intrusive measurement technologies.

LiDAR (Light Detection And Ranging) systems offer a particularly attractive alternative for spatio-temporal wave measurements. By emitting short laser pulses and measuring their time of flight, LiDAR systems can rapidly sample the position of the water surface over large spatial extents with high resolution. Their non-intrusive nature avoids flow disturbance, while recent advances driven by the autonomous vehicle industry have improved availability, robustness, and cost-effectiveness. LiDAR-based wave measurements have been successfully demonstrated in laboratory flumes (Allis et al., 2011; Blenkinsopp et al., 2012; Kristoffersen et al., 2024, 2025; Baker et al., 2023; Vousdoulas et al., 2014) when compared to wave transducers.

The LiDAR has also been widely utilized in coastal and nearshore environments to assess splashes and bubble plumes from breaking waves, estimate wave runup and wave shape in the surf zone (Brodie et al., 2015; Martins et al., 2016, 2017a, 2017b, 2020; O'Dea et al., 2021; Carini et al., 2021; Blenkinsopp et al., 2010; Fiedler et al., 2021; Kabel et al., 2019). Brodie et al. (2015) validated LiDAR-derived wave and setup measurements against pressure sensors in a full scale setup, establishing confidence in remote sensing of inner-surfzone processes, while Martins and colleagues (2016, 2017a, 2017b, 2020) advanced 2D LiDAR applications to capture individual wave characteristics, swash-zone reflection, and undular bore structure on a wave-by-wave basis.

The conditions for LiDAR operation in laboratory settings differ substantially due to the absence of instantaneous wind fields and salinity that leads to faster dissipation of bubbles in breaking wave foam and reduced surface roughness. As a result, water reflectivity is assumed to be lower in laboratory conditions, potentially complicating LiDAR-based surface mapping. However, increasing water turbidity through seeding can improve measurement conditions, as demonstrated in earlier laboratory studies applying LiDAR for wave measurements (Blenkinsopp et al., 2012; Baker et al., 2023; Vousdoulas et al., 2014). The laboratory studies have demonstrated that LiDAR can accurately resolve time-varying free-surface elevations and detailed wave processes under controlled conditions. Blenkinsopp et al. (2012) first showed in a wave flume that LiDAR can capture high-resolution, time-dependent surface profiles comparable to traditional gauges, validating its use for laboratory hydrodynamics. Vousdoulas et al. (2014) evaluated laser scanning and video techniques to monitor swash-zone processes to study the morphological changes. The two latter studies validate the LiDAR wave measurements for the surface elevation in the time domain and individual wave characteristics. More recently, Baker et al. (2023) advanced LiDAR applications by comparing stereo imaging and LiDAR, namely, two highly resolved spatial signals. It focused primarily on directional waves, with validation forming a secondary aspect. The objective was to estimate directional parameters, along-crest length, and the number of crest ends. To achieve broader coverage, the LiDAR was positioned at a relatively high altitude, and with the addition of relatively large trackers in the water, this appears to have reduced spatial resolution and accuracy.

This study provides a systematic evaluation of scanning LiDAR for resolving the spatio-temporal evolution of laboratory wave fields. While LiDAR has previously been applied in both laboratory and field environments, most existing studies rely on limited point comparisons or focus primarily on specific processes such as surf-zone dynamics or directional wave breaking. The present work extends this body of research through a comprehensive validation of a 3D scanning LiDAR system against a densely spaced array of wave gauges and synchronized video measurements in a controlled wave-flume environment. The analysis examines LiDAR performance across time, frequency, and spatial domains and includes wave-by-wave comparisons of key parameters such as wave height, crest height, and period. Particular attention is given to irregular wave conditions and breaking processes. By quantifying measurement accuracy, identifying systematic deviations, and assessing performance limits under different wave conditions, this study provides practical guidance for the effective deployment and interpretation of LiDAR measurements in laboratory wave research.

2. Methodology

2.1. Experimental setup

An experimental setup was designed to provide a comparison between a LiDAR-system and a traditional measuring system, which were mainly resistive wave gauges and video recordings having a side view of the tank. The experiments were conducted in the Coastal Flume at the Hydrodynamics Laboratory of Imperial College London (ICL). The flume is 22.0 m long and 0.60 m wide and is equipped with a piston-type wave paddle with active absorption operated in force control. A constant-depth section of 0.50 m extends from the wave paddle to 3.8 m along the flume, followed by a 1:30 uniform bed slope extending to the far end. A side view schematic of the experimental setup is shown in Fig. 1 (top).

An Ouster OS1 LiDAR was placed 1.0 m above the still water level (SWL) and 6.9 m from paddles, with the LiDAR's local z-axis pointing across the tank i.e. with an angle of 0.0° from horizontal (see Fig. 1, bottom and Fig. 2). This means that when the LiDAR is scanning 360° around its z-axis, it is capturing the blue area marked in Fig. 1, bottom. The coordinate conversion from the LiDAR's local coordinate system to the global coordinate system of the tank, is explained in detail in the next section.

The water in this flume is clear as in similar laboratories, hence reflectivity is low and return signals can drop out. In testing various techniques (Kristoffersen et al., 2024) to increase reflectivity and surface roughness without affecting the hydrodynamics, it was found that addition of spherical, glass hollow bubbles was most optimal. In the first tests 20 L of spherical bubble seeding (concentration in the flume 1:300) was thus added, but since the seeding was not sufficiently buoyant, some of it dropped to the bottom, and further 20 L was added throughout the last tests (concentration in the flume 1:150).

A Canon5D Camera was placed 6.9 m from the paddles with a side view of the waves recording through the glass wall of the flume. In the camera's field of view, there is a chess-pattern board with 0.05 m × 0.05 m squares to calibrate the surface elevation of the waves within the frame, which is recorded with 20 Hz. The frames of the camera recordings are converted to grayscale, then edge detection and line tracking are applied to track the surface elevation of the waves (Almalki et al., 2025b).

At first the tests cases were run with a setup including both LiDAR and camera, but without the wave gauges installed, ensuring that the LiDAR had a clear Field of View (FOV) for these tests and efficiently scanned over 6.0 m along the tank. The test cases were repeated in another seed with 80 resistance-type wave gauges installed along the centerline of the flume (Al et al., 2025b; Bellos et al., 2024). Each wave gauge comprises two thin steel wires of diameter 1.5 mm, spaced 10 mm apart. The sampling frequency was $f_s = 128$ Hz, which is sufficiently

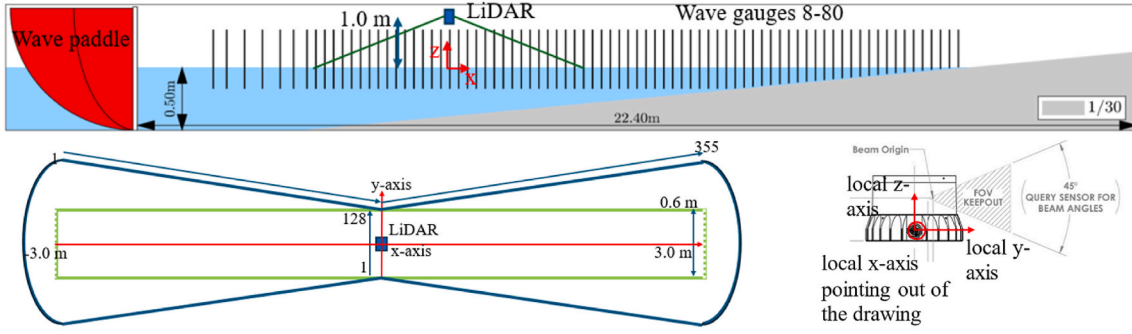


Fig. 1. Top: Schematic side-view of experimental setup in the coastal wave flume at Imperial College. The LiDAR position, the wave gauges and the sloping beach dimensions are shown. Bottom, left: Schematic top view of the LiDAR's scanning FOV (blue) in a section of the flume (green) with x-axis origin in the center of the LiDAR (NB: the bottom sketch is drawn on a larger scale). The LiDAR scans one line in the tank from point 1 to 355 of a bow-tie-shaped area, next its laser jumps across the tank, scans another line of this shape, and proceeds accordingly up to 128. Bottom, right: LiDAR's local coordinate system.

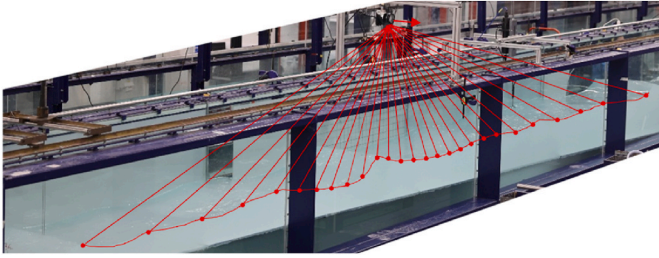


Fig. 2. Photo of LiDAR setup with markup of its local z-axis as a red arrow and conceptual plot of one central line (however drawn at the side wall to ease visibility) scanned along the length (all 355 points are not drawn to keep the sketch simple).

large to resolve the water surface elevation accurately without the need for post-processing or filtering, while daily calibration ensures an accuracy of ± 0.5 mm (Karpadakis et al., 2019). Wave gauges 8-80, spaced at 0.20 m intervals from 4.0 m to 18.4 m from the wave paddle, span the measurement domain of relevance in the present study. Their positions can be seen in Fig. 1.

Tests with regular and irregular wave cases were conducted for 4 min and 10 min, respectively. The wave cases included in this study are regular wave A-B and irregular waves A-E (see Table 1). The cases with regular waves are included to have a clear definition of the wave profile at least for non-breaking waves as in case A. The irregular sea states were generated based upon the standard JONSWAP frequency spectrum defined by (Hasselmann et al., 1973). The spectral density function is given by

$$S_{\eta}(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} \exp \left[-\frac{5}{4} \left(\frac{f}{f_p} \right)^4 \right] \gamma^{G(f)}, \quad (1)$$

where

Table 1
Wave characteristics for regular wave A-B and irregular waves A-E.

Setup 1, Regular waves	A [m]	f [Hz]	
A	0.04	1.0	
B	0.08	1.0	
Setup 1, Irregular waves	H _s [m]	f _p [Hz]	S _p [–]
A	0.086	0.71	0.028
B	0.139	0.71	0.046
C	0.156	0.71	0.051
D	0.124	0.83	0.055
E	0.167	0.63	0.042

$$G(f) = \exp \left[-\frac{1}{2} \left(\frac{f/f_p - 1}{\sigma} \right)^2 \right] \quad (2)$$

is the peak enhancement function, α the Phillips parameter, γ the peak enhancement factor, $g = 9.81 \text{ m s}^{-2}$ the gravitational acceleration, f_p the spectral peak frequency, and $\sigma = 0.07$ for $f \leq f_p$ and $\sigma = 0.09$ for $f > f_p$ the peak width parameter. The adopted spectral shape with $\gamma = 2.5$ represents realistic storm conditions in intermediate water depths (Jonathan and Taylor, 1997) and is consistent with previous experimental campaigns conducted in this facility (Al et al., 2025b; Bellos et al., 2024). The steepness, listed in Tables 1 and is defined as $S_p = 2\pi \frac{H_s}{g T_p^2}$.

2.2. LiDAR – coordinate transformation and geo-referencing

The LiDAR system scans a point on the water surface by transmitting a light pulse, which is next reflected when encountering a reflective surface and finally received by the LiDAR. The location of the surface is determined by the time of flight, Δt

$$r = c\Delta t/2, \quad (3)$$

where c is the speed of light ($\sim 3 \cdot 10^8 \text{ m/s}$). The range, r is by application of a direction vector (inherent LiDAR operation) transformed into a vector $[r_x \ r_y \ r_z]$ with x-, y- and z-components corresponding to the local axis of the LiDAR. This vector can then be transformed into a global coordinate system appropriate for the flume. The coordinate conversion for this setup is simplified since the LiDAR's local z-axis, r_z only points in the direction across the tank of the wave flume, which is converted to global y-axis. The LiDAR's local x-axis is pointing in vertical direction and is therefore converted to global z-axis. The last conversion is from LiDAR's local y-axis to global x-coordinate. The transformation matrix going from local LiDAR coordinates $[r_x \ r_y \ r_z]$ to global coordinates is

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} \quad (4)$$

The global z-coordinates can now be shifted with the distance from still water level to the LiDAR device to achieve estimates of the free surface elevation

$$\eta(x, t) = z_{\text{LiDAR}} - |z| \quad (5)$$

The position and angling of the LiDAR was carefully measured and leveled out to ensure that the conversion from the local LiDAR coordinate system to the global coordinate system is valid. To ensure the designed position and angling of the LiDAR, the side wall of the tank and

a support beam, is detected and used in geo-referencing.

2.3. LiDAR operation and configuration

The LiDAR was configured with a sampling frequency of 20.0 Hz. The scanned area in the wave flume is marked as two blue wedges in Fig. 1, bottom. The wavelength of the LiDAR's laser is 865 nm (near-infrared), which enables the detection of surfaces with moderate reflectivity. The LiDAR's resolution consists of 128x1024 points for each frame. The 128 subdivisions of the LiDAR is a complete scan of 45° across the tank. The 1 024 subdivisions of the LiDAR correspond as standard to a 360° clockwise rotation of the light pulse with the local z-axis as normal vector. In this case a full rotation would result in measurements of the roof and other surroundings besides the water surface, and the scanning angles were thus set at -80° to 80° from vertical, which results in 355 measurement points along the tank (further explanation on scanning specification can be found in appendix). The duration for the LiDAR to perform one rotation when scanning is 0.05 s. This means that for the 355 (out of 1 024) points there is a delay of 0.017 s from the time where it measures furthest downstream to furthest upstream of the LiDAR device. For the waves of this study, this delay has an insignificant influence considering the low wave celerity. The flume is narrow compared to the wedges in the FOV of the LiDAR, which means that only the central lines 60–64 are included in the analysis of the data (see Fig. 4 for an example of LiDAR-scanned wave profiles). These central lines are chosen since they are nearly parallel with the x-axis, and the surface is consistently scanned over 6.0 m. Over these five lines only small variations across the tank are observed.

2.4. Post-processing of LiDAR data

The post-processing of the LiDAR data follows the steps illustrated in Fig. 3. In the first two steps, the LiDAR point cloud coordinates are transformed from the local LiDAR coordinate system to the global flume coordinate system using the previously defined transformation matrix, including a vertical shift of the z-coordinates. In the third step, the data are screened for outliers using a Hampel filter with a window size of seven data points. Detected outliers are subsequently replaced through linear interpolation. Next, the transformed x-, y-, and z-coordinates for lines 60–64 are fitted using surface interpolation, covering approximately 0.08 m across the center of the tank and 6.0 m along the tank (see

Fig. 4). Because the waves propagate uniformly without noticeable cross-tank modes in the flume, any variations across the tank are assumed to originate from the LiDAR measurements themselves, as discussed in the next section. To reduce these variations, the interpolated surface is averaged across the tank in step five, resulting in a surface elevation profile along the x-coordinates at each time step. This procedure produces a more consistent representation of the wave profile along the tank in case of dropouts. When seeding particles are added to the water, the reflectivity of the surface improves, leading to a lower drop-out rate. This can be observed as more consistent occurrences of valid surface elevation measurements along the tank in Fig. 4. Following the surface interpolation and averaging across tank, the data are defined on a fixed grid. In step six, time series are extracted at each x-coordinate. In the final step, spectral filtering is applied using a trapezoidal band-pass filter with cut-off frequencies of $(0.3\text{--}0.4) f_p$ and $(2.9\text{--}3.0) f_p$.

3. Results

3.1. Regular waves

Initially the performance of the LiDAR is assessed for regular waves to have a deterministic reference frame. The tests are run for regular waves with a frequency of 1.0 Hz and an input amplitude of 0.04 and 0.08 m, respectively. The mean wave height is calculated over 4 min along the tank in all locations in the tank containing either wave gauges or LiDAR measurements. The mean wave height is plotted in Fig. 5 as a function of the x-coordinate. It can be seen that mean wave heights along the tank show good agreement between the LiDAR and the wave gauges measurements. The largest discrepancies appear in the vicinity of the LiDAR i.e. around $x = \pm 1.0$ m, where the LiDAR overestimates the wave height. For the regular waves of highest amplitude (Fig. 5b), the decrease in mean wave height downtank can be observed for both the LiDAR and wave gauge measurements.

The wave profiles along the tank are plotted at 4 time instants in Fig. 6. There is very good correlation between the wave gauges and LiDAR measurements for the spatial profile of the surface elevation for the regular waves in the range $x = [-3.0:3.0]$ m. The LiDAR overestimates the surface elevation in certain areas in the range $x = [-1.0:1.0]$ m with about 0.01 m in both crest and the trough. The LiDAR-measured waves exhibit slightly longer wavelengths than the signal of the wave gauges; a modest discrepancy that is partly explained by the delay in the LiDAR from measuring upstream to downstream.

3.2. Irregular waves

3.2.1. Qualitative assessment of LiDAR

The performance of the LiDAR is assessed based on tests with irregular waves of five different sea states to investigate the dependence on storm steepness (sea state A–E listed in Table 1). The ability to detect the surface elevation and the significant wave height is compared against estimates from wave gauges in Fig. 7 for all sea states A–E. The significant wave heights are estimated along the tank in x-coordinates containing LiDAR data or wave gauge data. Here it is observed that the estimate of the significant wave height from the two devices are comparable besides from in the interval of $x = \pm 0.75$ m. As with regular waves, the LiDAR slightly overestimates the H_s in this interval. The reduced accuracy in the immediate vicinity of the LiDAR is attributed to near-field optical/geometric effects at the air–water interface rather than to a single identified cause. Our data show that the discrepancy is spatially localized beneath the sensor, where wave heights are overestimated and the time series indicate a tendency for troughs to be underestimated while some crests are captured more accurately. In the raw data series, there was an apparent negative bias in the near-field measurements, which decreased with increasing incidence angles. Previous studies of LiDAR measurements over water have shown that the returned signal is sensitive to incidence angle, specular versus diffuse

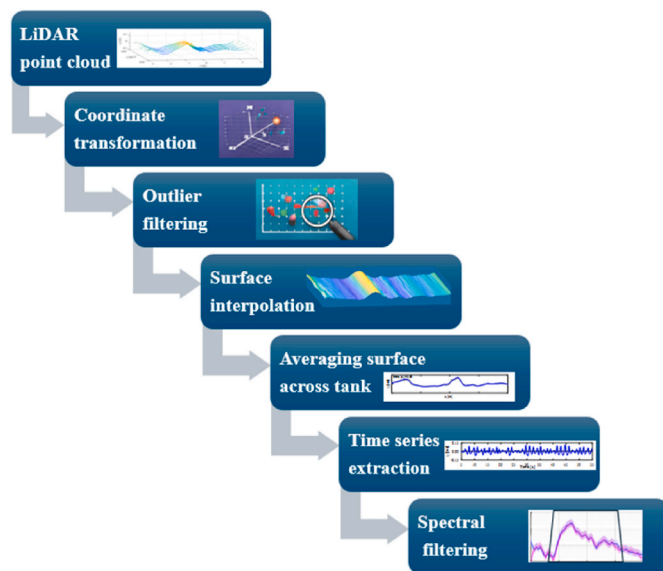


Fig. 3. Workflow of the LiDAR data-processing procedure used to reconstruct the spatio-temporal free-surface elevation field.

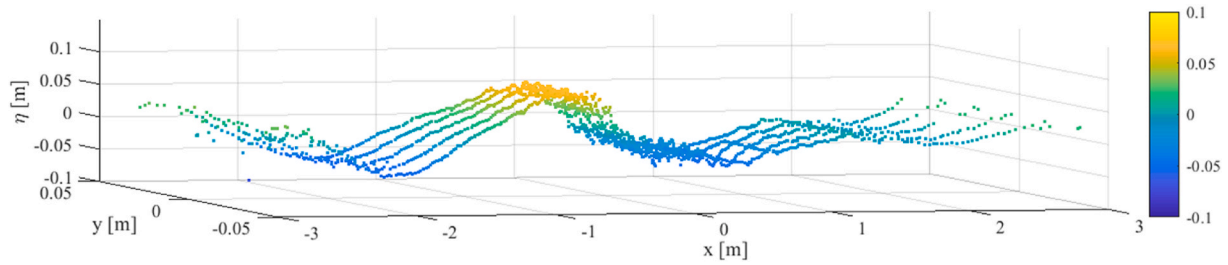


Fig. 4. Example of LiDAR detected surface of a wave along and across tank in one scanning frame within FOV. Along the tank the tracked surface is shown from ± 3.0 m, whereas the y-axis contains the y-coordinates of the lines from 60 to 64.

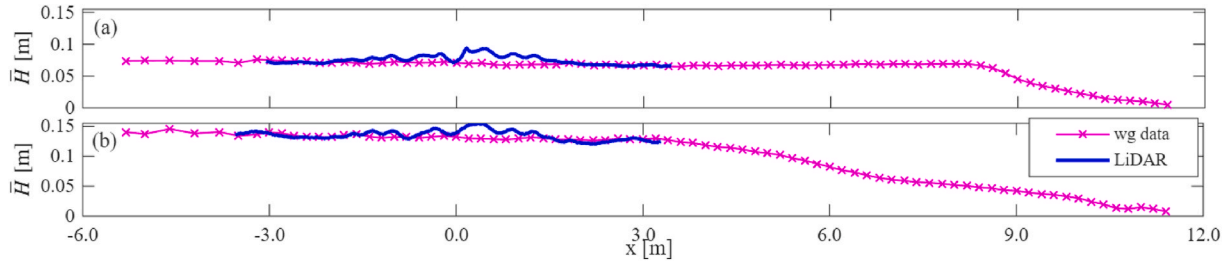


Fig. 5. Mean wave height along the tank for LiDAR and wave gauges measurements for regular waves with $f = 1.0$ Hz, $A = 0.04$ m in subplot (a), and $A = 0.08$ m in subplot (b) on a sloping beach (1:30).

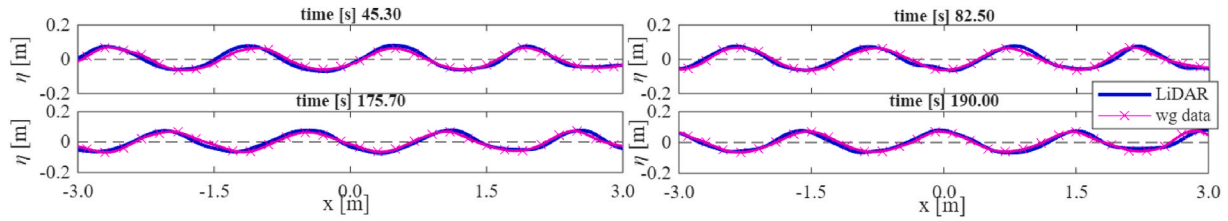


Fig. 6. Spatial profile of regular waves of $A = 0.08$ m along the tank measured at four different timestamps with the LiDAR and a wave gauge array.

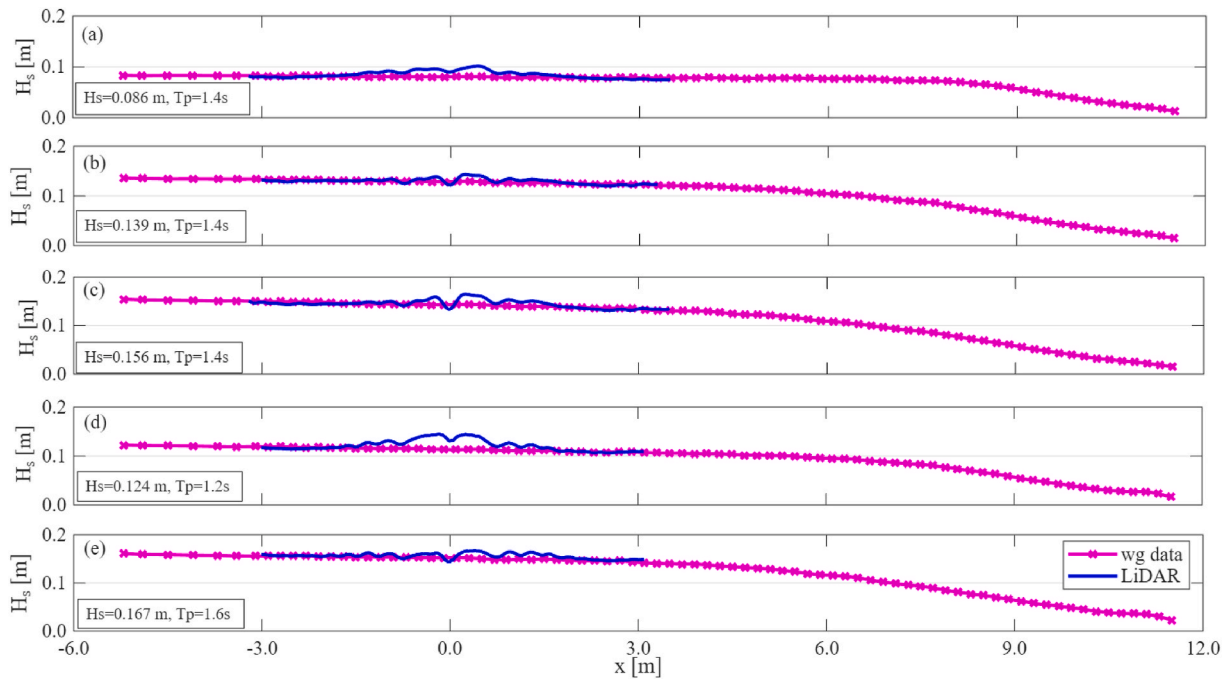


Fig. 7. Significant wave height along the tank with a sloping beach for LiDAR- and wave gauge measurements. The significant wave height is calculated by integrating spectral densities from 0.3 Hz to 2.0 Hz. Sea states A-E are plotted from the top to the bottom.

reflection, surface roughness, turbidity, and subsurface backscatter, all of which can vary rapidly over steep or breaking wave facets (Tamari et al., 2016). Penetration depth is likely dependent on the incidence angle (Streicher et al., 2013), as the Fresnel reflection tends to decrease at smaller incidence angles. The local incidence angle varies with the instantaneous wave slope and crest geometry. These effects along with surface disturbances as present for breaking waves can lead to a penetration depth that varies in both time and space. The near-field bias observed here is therefore consistent with a combined effect of geometry-dependent surface reflection, short-range subsurface scattering, and local footprint/shadowing effects, although the present dataset does not allow these contributions to be separated quantitatively.

The largest deviations in this area appear for the sea states of smallest significant wave height (cases A and D). The deviation in the nearest vicinity of the LiDAR is obvious in the time series of sea state C (Fig. 8b), where it is observed that particularly the troughs (/crests) are underestimated (/overestimated). Therefore, the recommendation is that the measurements of the surface elevation should only be considered on the x-axis in the intervals of $[-3.0: -0.75]$ m and $[0.75: 3.0]$ m given that the LiDAR performs best away from the area right below the sensor. If necessary, the LiDAR mount can be shifted along the tank to cover a larger area with reliable data. The significant wave height for both the wave gauges and LiDAR measurements decreases as the depth decreases with the presence of the beach. This is caused by the occurrence of breaking waves, which dissipates some energy.

Investigations of the LiDAR performance for the individual sea states were carried out and are presented here for sea state C, which is representative of all cases. The LiDAR and wave gauge measurements are first compared qualitatively in the time domain over 50 s at three positions along the tank (Fig. 8a–c), and subsequently in a spatial frame in Fig. 9 also including video-detected surface elevations for 4 time instants. The LiDAR measurements agree well with the wave gauge signals at the locations of 1.5 m upstream and downstream of the sensor (Fig. 8a and c). The breaking wave events, highlighted with green boxes, show a tendency for the LiDAR to capture slightly higher crest elevations, likely due to its ability to detect splashing and droplets associated with the overturning crest. In contrast, larger discrepancies occur in the nearest vicinity of the sensor at $x = -0.24$ m (Fig. 8b), where both crest and trough heights of particularly the largest waves are overestimated relative to the wave gauge measurements. One possible explanation is a small penetration depth of the laser signal into the water that varies with

the incidence angle, which again varies with local wave slope. The discrepancies can be explained, if the laser beam for the near-field measurements penetrates the water and detects subsurface scatter, thereby leading to underestimation of the trough, while the occurrence of breaking waves increases surface roughness and hinder the subsurface detection and lead to measurement of a realistic surface elevation. This results overall in an overestimation of the wave height.

If the breaking events contain overturning or splashing, the LiDAR and wave gauges will gain different outputs for the surface elevation. Additional distortions may also arise from specular reflections and multi-path returns.

In Fig. 9 the qualitative comparison is made for both video-tracked, LiDAR and wave gauges measurements of the surface elevation along the tank at four different time instants containing breaking waves. There is very large consistency between the surface elevation measured for all devices, nevertheless there are some discrepancies around the crest for these breaking waves. The video-tracked surface elevation profiles are in general following the trend of the LiDAR measurements better than the wave gauge measurements. Despite the video and LiDAR data origin from one test run and the wave gauges measurements from another run, this is of secondary importance, since the facility is thoroughly tested with respect to high repeatability for the wave generation and performs well (Huo et al., 2023, 2025b). Another factor can be that the wave gauges have difficulties in capturing the overturning process with droplets and bubbles. In fact, the video-tracking detects the surface as steeper than the LiDAR (and wave gauges) at the positions where the wave crest is overturning. This indicates that the LiDAR does not necessarily capture the outmost peripheric events of splashing and droplets, but most likely detects the densest part of the overturning crest. Another source of error is that the wave front is not necessarily breaking uniformly across the tank, which will cause deviation since the wave gauge and LiDAR are measuring in the center line of the flume, whereas the camera detects the wave from a side view, so the detected profile corresponds to the side wall of the flume.

Fig. 10 provides comparisons between the LiDAR and wave gauges measurements in the frequency domain, where the power spectral densities are plotted for six different locations in the tank. The power spectral densities, which are determined by Welch-averaging with a window size of 30 s, show large similarities in the range $[0.4\text{--}2.0]$ Hz for the LiDAR data and wave gauge measurements at all six positions along the tank. The peak of the spectral densities for the LiDAR is nevertheless larger for $x = -0.6$ and 0.6 m, and additionally there is slightly more

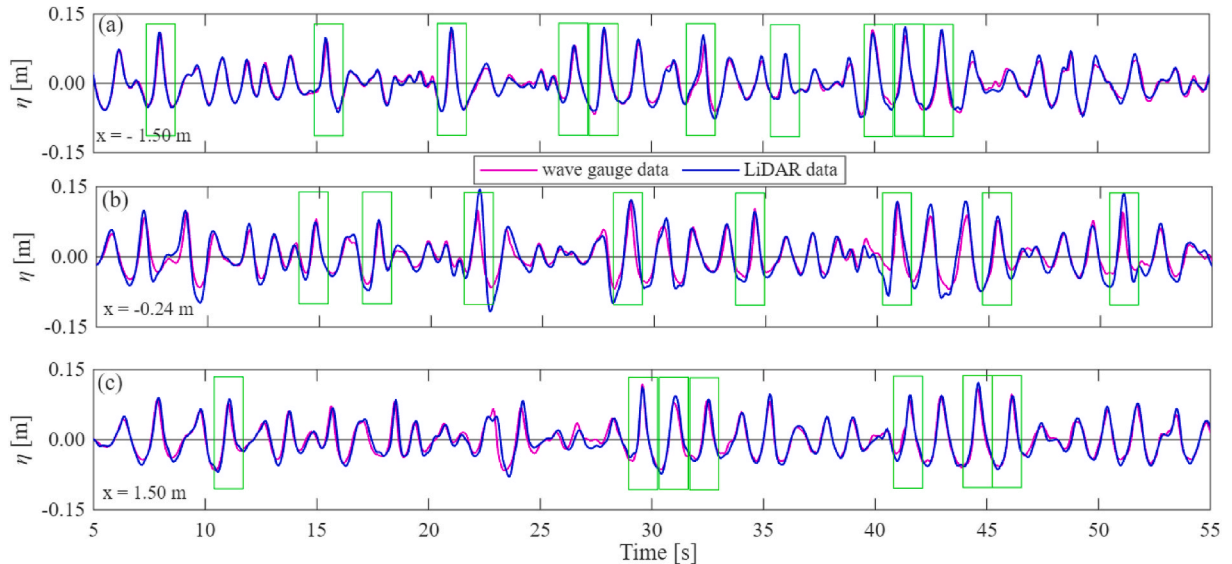


Fig. 8. a–c: Time series of wave gauge- and LiDAR measurements for irregular waves of sea state C at three different positions along the tank, $x = -1.50$ m (top plot), $x = -0.24$ m (center plot) and $x = 1.50$ m (bottom plot). The green boxes mark breaking waves.

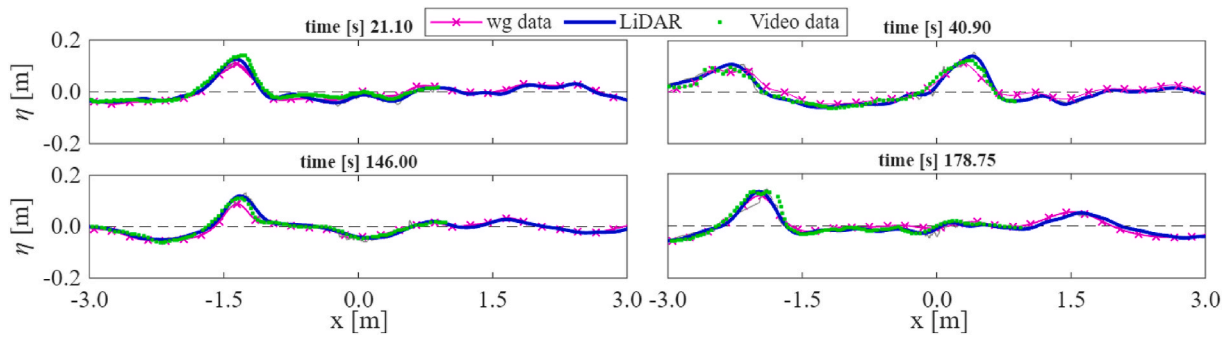


Fig. 9. Spatial profile of four breaking wave events of irregular waves at four different time instants for video-tracked, LiDAR- and wave gauge measurements of the surface elevation.

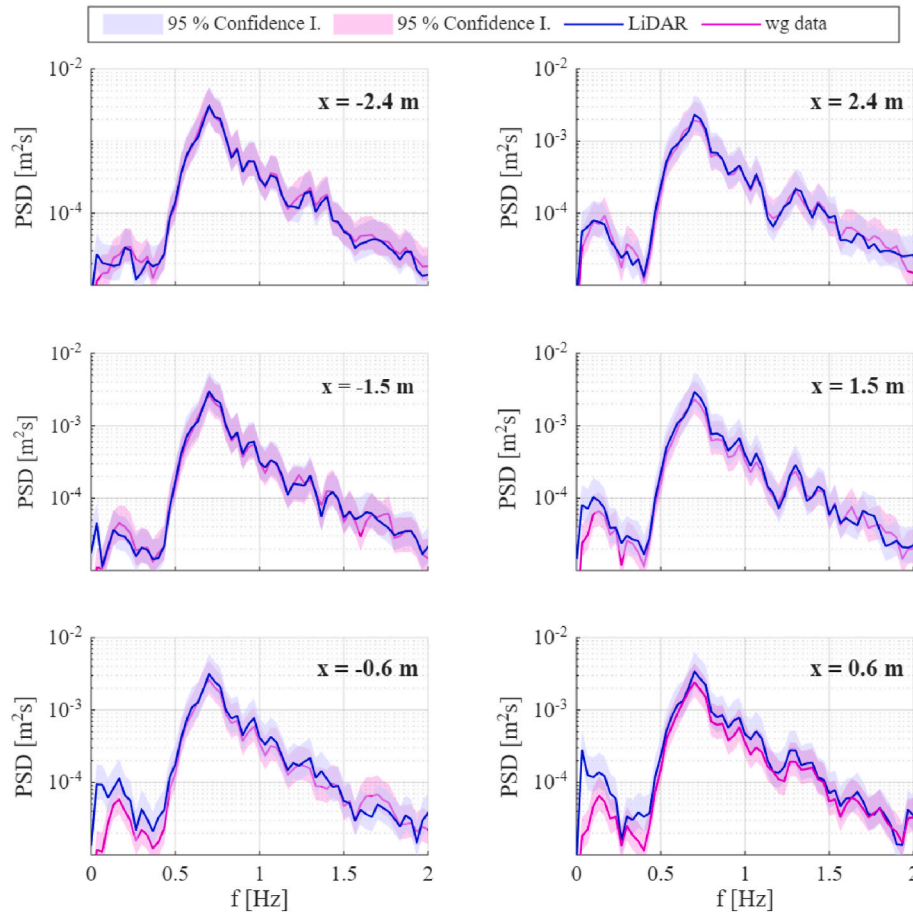


Fig. 10. Power spectral densities for LiDAR- and wave gauges measurements at six different positions along the tank.

energy in the high-frequent area. This confirms the observations in the time domain, that the LiDAR detected larger variances of the surface elevation right below the device than the wave gauge measurements. In the range [0.0-0.4] Hz it is observed that the LiDAR data at $x = \pm 0.6$ m contain some low-frequent energy, which could be caused by movements of the support, energy spreading for diffuse reflection, optical contamination or changing reflectivity. The low frequent energy is present at the same frequencies as the subharmonics of the spectrum, which makes it difficult to filter out without filtering out relevant wave energy. Nevertheless, the LiDAR time series has been bandpass filtered in the frequency domain from 0.3 to 2.0 Hz at all locations along the tank. The energy at the peak of the spectra decreases when going from $x = -2.4$ m to $x = 2.4$ m, which is caused by breaking dissipation.

3.2.2. Assessment of individual wave characteristics

To compare characteristics of the individual waves, the wave height, period and crest height are plotted for LiDAR and wave gauge measurements in a q-q plot in Fig. 11. The q-q plots show that the crest- and wave heights are attached with some scatter around the 1:1 line. The crest- and wave heights are particularly overestimated for the largest waves. From observations of the spatial profile, it was apparent that the LiDAR measured larger crest heights with the occurrence of breaking, which could be an explanation of why the LiDAR assesses the highest crest heights as larger than the wave gauges.

To compare the statistics of irregular waves of sea state C the exceedance probability curves for crest and wave heights are plotted for both wave gauge and LiDAR measurements in Fig. 12. The curves at the position of $x = -1.5$ m are similar, and only smaller differences are

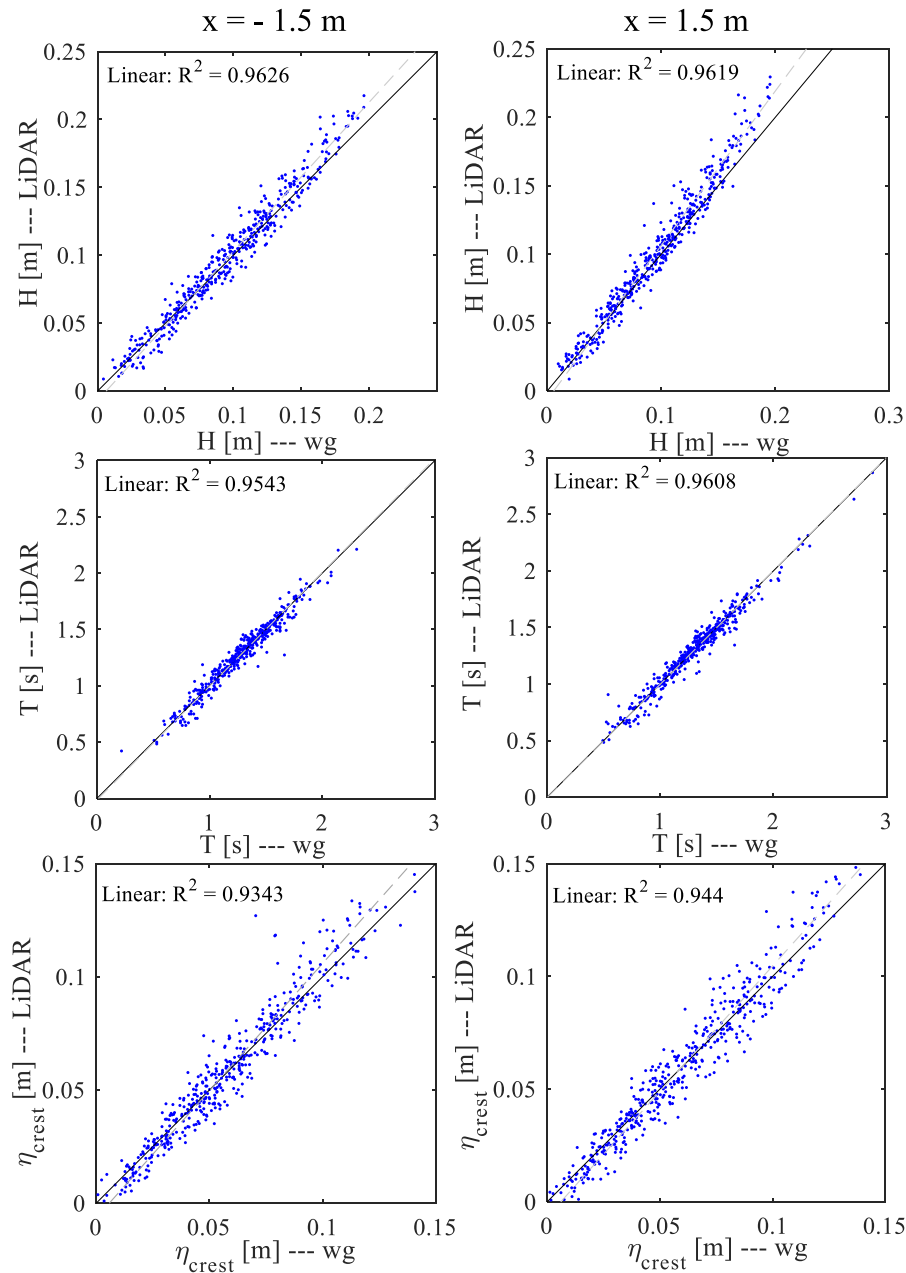


Fig. 11. q-q plots of wave heights, wave periods and crest heights for wave gauge measurements against LiDAR measurements at two different locations along the tank, at $x = -1.5$ m (left plots) and $x = 1.5$ m (right plots).

observed in the tail. The exceedance probability curves for wave and crest heights at the location of $x = 1.5$ m are deviating around H/H_s larger than 1.0 and η_{crest}/H_s larger than 0.8, where the LiDAR captures larger wave and crest heights consistent with the observations in the q-q plots and spatial profiles. The sloping bed causes more breaking waves at 1.5 m than at -1.5 m, which can explain why the deviation in the tail of the exceedance probability curve for crest and wave height is most pronounced downstream of the LiDAR.

3.2.3. Quantitative assessment of LiDAR

In this section the performance of the LiDAR dependence on the height of the waves is evaluated. Thus, error metrics are found for comparison of wave gauge and LiDAR measurements for sea state A-C, which have the same peak period but increasing significant wave heights. The comparison is made for both the entire surface elevation, the wave height and the wave period at different locations along the

tank (see Fig. 13, top). The RMSE-values are less than 0.010 and 0.015 m for respectively the surface elevations and wave heights along the tank besides from the area right below the device, i.e. $x = \pm 0.75$ m. This error is reasonable and is comparable to previous findings, which will be presented in the discussion. In the x-range from -0.75 to 0.15 m, the RMSE-values are increasing in particular for the wave heights. The RMSE-values for wave heights and surface elevation are for most locations along the tank increased, when the significant wave height is increased from $H_s = 0.086$ m to 0.156 , but the difference is insignificant relative to the significant wave heights.

The correlation coefficients for the surface elevation measured with LiDAR and wave gauges are plotted in Fig. 13, bottom. There is overall a high correlation for the surface elevation, when comparing the two time signals at all locations along the tank containing wave gauge measurements and corresponding LiDAR data. There is a decrease in the correlation coefficient at the two central points. The best correlation is

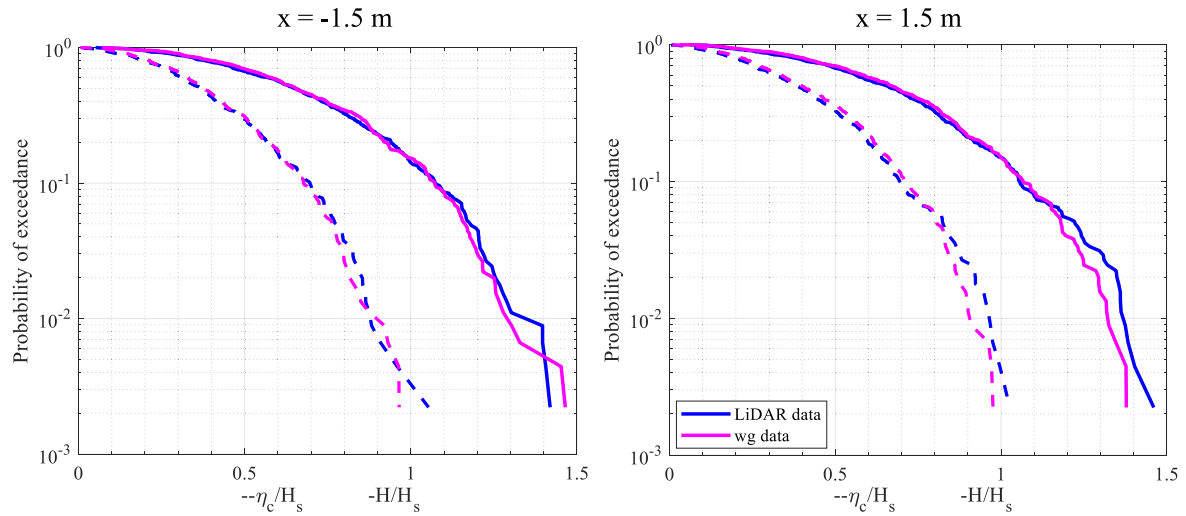


Fig. 12. Exceedance probability curve for crest heights (dashed line) and for wave heights (solid line) at two different locations at $x = -1.5$ m (left) and $x = 1.5$ m (right) determined from wave gauges- and LiDAR measurements.

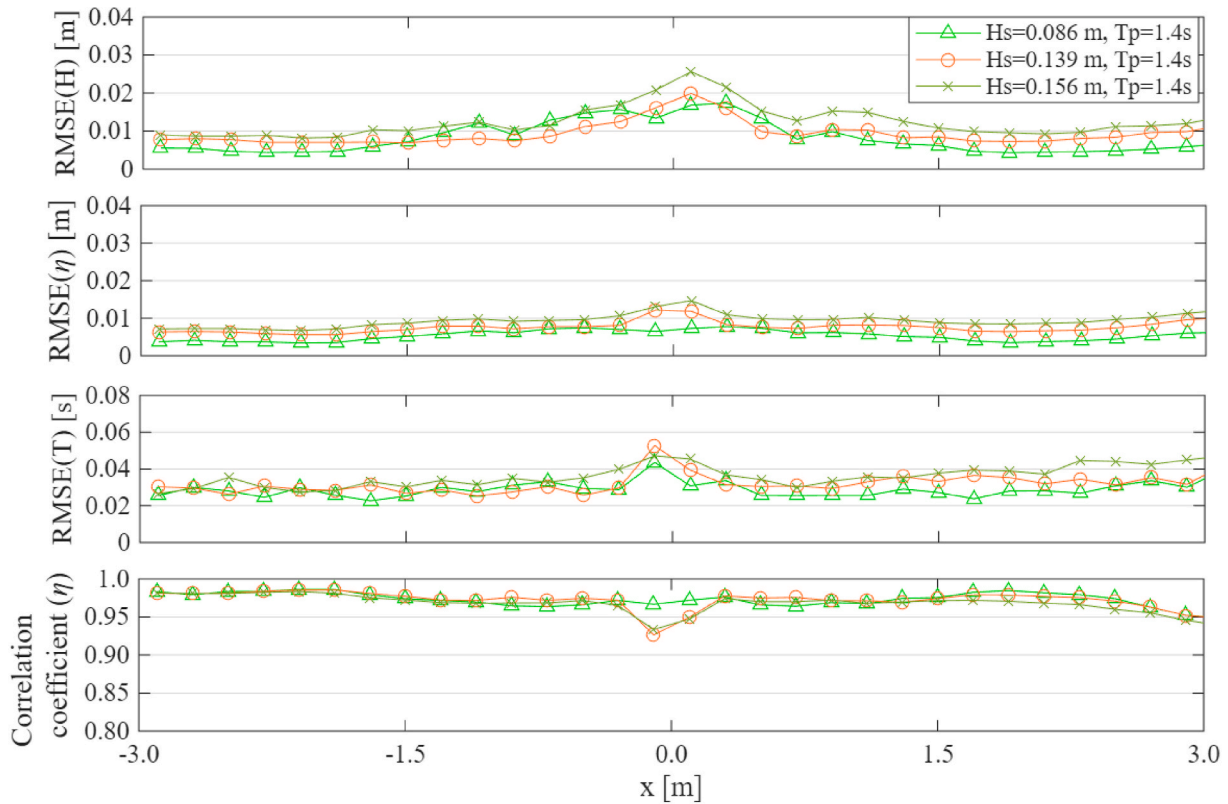


Fig. 13. Top: RMSE values for the surface elevation, for the wave-heights and -periods along the tank determined for the LiDAR and wave gauges signal at synchronized time. Bottom: Correlation coefficients between wave gauges- and LiDAR measurements of surface elevation at synchronized time in the interval of $x = \pm 3.0$ m.

achieved for the case with smallest significant wave height. Nevertheless, the differences in correlation coefficient for the three cases with different significant wave heights are minor except for the two central points. This indicates that the LiDAR is capturing a similar shape of the wave profile in time as the wave gauges even though the amplitude of the signals can deviate as apparent from the RMSE-values. The bottom plot in Fig. 13 indicates that the correlation between LiDAR and wave gauges measured surface elevation is not dependent on wave heights.

For the surface elevation, wave heights and periods normalized with

either the significant wave height or peak period, the RMSE-values between LiDAR and wave gauges measurement are determined at all coinciding locations along the tank except in the x-range of -0.75 to 0.75 m. These RMSE values are shown in box plot against the significant wave height for sea state A-E in Fig. 14, left. The boxplot shows the median and the 25 and 75 % percentiles of the RMSE values over the previously described positions in the tank for five sea states with different H_s . Since there are only minor variations of the median of the relative RMSE-values, this error metric reveals independence of the

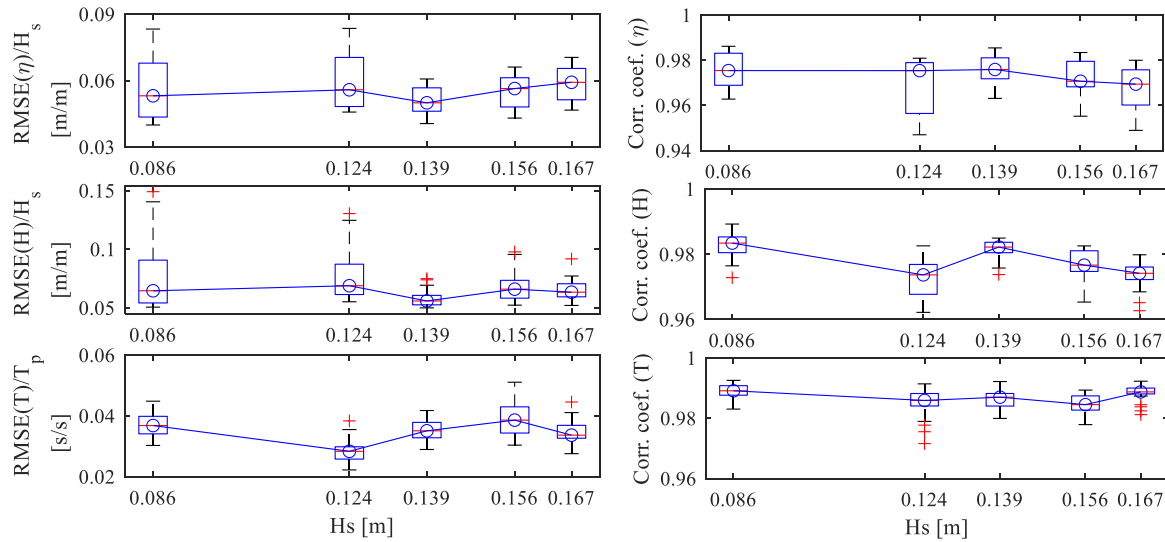


Fig. 14. Left: Boxplot showing median, 25 and 75 percentiles of RMSE-values of surface elevation, wave height and period with respect to significant wave height and peak period along the tank except in the x-range of ± 0.75 m and plotted against the significant wave height for sea state A-E. Right: Correlation coefficient of LiDAR-against wave gauges measurements for surface elevation, wave-height and -period in a boxplot showing the median, 25 and 75 percentiles along the tank except in the x-range of ± 0.75 m plotted against the significant wave height for sea state A-E.

significant wave height. The median of the RMSE-values along the tank are in percentage of the significant wave height around 5–6 % for the surface elevation and 6–8 % for the wave heights. For the wave period, the median RMSE-value in percentage is in the range 3–4%, which is reasonable since the accuracy of the LiDAR is larger in the horizontal plane than in the vertical relative to the extension of waves in x- and y-direction. For the cases with smaller significant wave height, there are larger variations of the RMSE values i.e. the 75 % percentile is larger for particularly the wave heights. This becomes evident when examining the relative RMSE values, as deviations appear as a larger percentage of the significant wave height.

The correlation coefficient between LiDAR and wave gauges measurement of surface elevation, wave heights and wave periods along the tank except in the x-range of -0.75 to 0.75 m is plotted in a boxplot in Fig. 14, right. The median of the correlation between the measurements of the two devices is high for all sea states, where the surface elevation has the lowest correlation, probably because it is more sensitive to higher frequency effects or other misalignments. No dependency on the significant wave height is observed for the correlation coefficient for neither surface elevation, wave height nor period.

4. Discussion

The present validation study of wave measurements obtained with a single scanning LiDAR system, is here contextualized with findings from previous studies. Before doing so, it should be noted that quantitative performance metrics may vary between LiDAR instruments due to differences in hardware specifications, including beam divergence, range accuracy, receiver sensitivity, and sampling frequency. However, the primary factors governing the measurement of water surface elevation by LiDAR in the present laboratory configuration are related to the interaction between the laser beam and the dynamic water interface, including incidence angle, surface slope, specular reflection, seeding material, bubble and foam coverage. These effects are inherent to LiDAR scanning of water surfaces and are therefore expected to influence different lidar systems in a similar manner, although the magnitude of the resulting errors varies.

In the present study, the LiDAR system is deployed relatively close to the still water level (SWL) in order to achieve a fine spatial resolution over the investigated range and to optimize measurement accuracy

outside the immediate vicinity of the sensor, which is better achievable with smaller footprint giving a stronger signal and smaller averaging area. Future work will investigate the influence of the vertical distance between the SWL and the LiDAR device. Increasing this distance will reduce spatial resolution but will expand the measurement coverage.

Increasing the elevation of the LiDAR above the water surface would enlarge the laser footprint and may enhance diffuse reflection from the surface. This could potentially reduce some of the near-field bias observed directly beneath the sensor. However, a higher mounting position would also modify the incidence angle and reduce the spatial resolution over the measurement domain. Because these effects act simultaneously, the present dataset does not allow a clear assessment of whether increasing the sensor elevation would improve the measurements overall. This should therefore be investigated in future work.

The somewhat larger error in the nearest vicinity of the LiDAR device might be specific to this Ouster OS1 LiDAR or to the deployment. Instrument-specific properties, including emitted power, receiver sensitivity, beam divergence, and ranging algorithm, may also affect the balance between surface detection, subsurface scattering, and signal loss over water. However, the present experiments were not designed to isolate these effects. Penetration of the laser into the water can however play an important role, and since a negative bias was observed in the near-field raw measurements, the impact is discussed. The penetration depth of a laser in water depends on the angle of incidence in two ways. First, the Fresnel reflection i.e. the ratio of reflected to transmitted light decreases as the incidence angle becomes smaller. Second, at larger incidence angles, the laser travels more horizontally within the water, which reduces the vertical component of its penetration. Conversely, at small incidence angles, the laser penetrates predominantly in the vertical direction, having a stronger influence on subsurface scattering. As a result, penetration tends to systematically underestimate the actual surface elevation in particular at smaller angles of incidence, although this effect could be partially corrected through constant de-trending over time. However, accurately accounting for penetration is challenging because it is a dynamic process that changes over time. For example, instantaneous wave slope and crest geometry vary the local incidence angle, and an increase will thus reduce the risk of subsurface scattering. Similarly, breaking waves can disrupt the water surface and cause diffuse reflection, which gives a strong and accurate estimate of the surface elevation. Consequently, the penetration depth and specular

reflection directly below the LiDAR mount is not constant; some parts of the waves in space and time may be underestimated, while others are measured accurately or even slightly overestimated.

Incidence angles of up to 72° are applied in the present study, which may cause shadowing effects on the side of the wave facing away from the LiDAR, since the specular reflection on that side of the wave will be reflected opposite to the receiver. In addition, the laser footprint increases with increasing incidence angle, meaning that the LiDAR averages the surface elevation over a larger area. These effects accounting for larger inaccuracy further away from the mount are nevertheless considered to be of secondary importance for the measurements in this study, since the trend is inverse. A larger footprint also results in a higher likelihood of striking a reflective spot with either seeding material or any surface disturbance. This could partially explain the larger accuracy further away from the mounting point.

Based on the present results, it is recommended that surface elevation measurements obtained with this LiDAR configuration should primarily be considered at locations some distance away from the sensor mount, as the measurements directly beneath the device are associated with larger uncertainties. To capture wave transformation over a larger spatial domain, the LiDAR sensor may be repositioned further up- or down-tank and experiments repeated under identical wave conditions. Moreover, the water should contain buoyant seeding material that significantly increases turbidity, as buoyancy is particularly important for experiments of long duration.

The results obtained in this study are discussed in relation to previously published laboratory experiments, where RMSE values and correlation coefficients are summarized in Table 2. In the present experiments, RMSE values for surface elevation of irregular waves are below 0.010 m, which is comparable to those obtained in similar laboratory studies for LiDAR measurements compared to in-situ sensors, although reported for regular waves of comparable height (Blenkinsopp et al., 2012). Another laboratory investigation (Vousdoukas et al., 2014) reports RMSE values for irregular waves that, when expressed as a percentage of significant wave height, are comparable to those obtained here. In contrast, the percentage RMSE values reported by Baker et al. (2023) are relatively large compared with both previous studies (Blenkinsopp et al., 2012; Vousdoukas et al., 2014) and the findings presented in this paper. In that study, the correlation coefficient between LiDAR measurements and wave gauge observations was as low as 0.77 in the inner surf zone, whereas values around 0.93–0.97 were reported in (Vousdoukas et al., 2014) and in the present study. However, the results of Baker et al. were obtained for directional wave fields and, in some cases, shallower water depths with more frequent wave breaking. Such conditions inherently lead to larger deviations between remote sensing measurements and in-situ wave gauge observations.

Across the full-scale studies (Brodie et al., 2015; Martins et al., 2020; Fiedler et al., 2021), LiDAR is consistently validated as a highly accurate technique for measuring nearshore wave elevation, typically achieving RMSE-values in the range of 0.03–0.07 m and correlations coefficients of 0.87–0.98 when compared to traditional in-situ sensors.

Overall, these comparisons indicate that despite differences in LiDAR manufacturers, deployment configurations, and wave conditions, the accuracy of LiDAR measurements of water surface elevation is generally comparable and reaches a reasonable level in terms of error metrics such as RMSE and correlation coefficient.

This study advances the application of LiDAR for laboratory wave

measurements in three main ways. First, LiDAR observations are systematically validated against a densely spaced array of 80 wave gauges, enabling spatial comparisons rarely available in previous studies. Second, the analysis investigates the spatio-temporal evolution of irregular wave fields, including breaking waves, rather than relying solely on isolated point measurements. Third, the study quantifies the limits of LiDAR accuracy under laboratory conditions and identifies deployment constraints relevant for future experimental investigations.

5. Conclusion

This study has presented a detailed experimental evaluation of a commercially available 3D LiDAR system for spatio-temporal measurements of free-surface elevation in a laboratory wave flume. Performance was assessed through direct comparison with dense wave-gauge arrays and synchronized video measurements for regular and irregular wave conditions over a sloping bathymetry, including wave breaking.

Within most of the measurement domain, LiDAR-derived surface elevations and wave statistics show strong agreement with wave-gauge measurements besides from acquiring a low drop-out rate. For irregular sea states, root-mean-square errors in surface elevation and wave height are typically below 6% of the significant wave height, with correlation coefficients exceeding 0.97, which is comparable to findings of previous studies. This level of agreement is maintained across a range of wave heights and steepnesses, indicating that the LiDAR performance is relatively insensitive to the wave heights considered. Nonetheless, irregular waves with the smallest significant wave height for the same periods exhibit slightly lower RMSE values. However, when normalized by the significant wave height, this difference becomes negligible.

A well-defined region of increased uncertainty is identified directly beneath the LiDAR, arising from geometric and scanning constraints. The measurements in that range exhibited systematic errors and should generally be excluded from quantitative analysis unless additional corrections are applied. Outside this near-field zone, the LiDAR provides stable and repeatable measurements of the evolving wave field. From a practical perspective, this limitation can be addressed through appropriate sensor placement or by repeating experiments with the LiDAR positioned at multiple locations to extend spatial coverage without introducing intrusive instrumentation.

In breaking wave conditions, systematic differences between LiDAR and probe-based measurements are observed. The LiDAR preferentially captures the densest part of the overturning crest and aerated surface, whereas wave gauges provide a measurement influenced by air entrainment and probe wetting. These differences do not represent a failure of either technique but reflect fundamentally different definitions of the free surface in highly aerated flows. Recognising this distinction is essential when interpreting crest heights, breaking onset, and wave statistics derived from optical measurements.

Overall, the results demonstrate that LiDAR provides a robust and efficient alternative to dense wave-gauge arrays for laboratory studies requiring spatio-temporal resolution of wave fields. By reducing experimental complexity, avoiding flow disturbance, and enabling large-area measurements with a single device, LiDAR expands the scope of laboratory investigations into wave evolution, wave breaking, and wave–structure interaction. The performance bounds and limitations identified in this study provide a clear framework for the effective and informed use of the technology in future experimental wave research.

Table 2

Comparison of error metrics for present and previous studies on LiDAR application for wave measurements in laboratory.

Reference	Environment	Wave condition	RMSE [m]	RMSE/ H_s [%]	Correlation coef. []
Blenkinsopp et al. (2012) (Blenkinsopp et al., 2012)	Laboratory flume	Regular	0.006	4.0	
Vousdoukas et al. (2014) (Vousdoukas et al., 2014)	Swash zone	Irregular	0.017–0.032	3.4–6.4	0.93
Baker et al. (2023) (Baker et al., 2023)	Laboratory basin	Irregular, directional	0.019–0.067	6.3–9.0	0.77–0.90
Present study	Laboratory flume	Irregular	0.004–0.013	4.2–6.0	0.93–0.97

CRediT authorship contribution statement

Julie Carøe Kristoffersen: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Visualization, Writing – original draft. **Thomas Kabel:** Conceptualization, Data curation, Funding acquisition, Supervision, Validation, Writing – review & editing. **Christos T. Georgakis:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Vasileios Bellos:** Data curation, Software, Visualization, Writing – review & editing. **Ioannis Karpadakis:** Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. LiDAR scanning specifications

The LiDAR's resolution consists of 128x1024 points for each frame. The 128 subdivisions of the LiDAR is a complete scan of 45° across the tank. The 1 024 subdivisions of the LiDAR correspond as standard to a 360° clockwise rotation of the light pulse with the local z-axis as normal vector. In this case a full rotation would result in measurements of the roof and other surroundings besides the water surface, and the scanning angles were thus set at –80° to 80° from vertical, which result in 355 measurement points along the tank. The LiDAR scans in bow-tie shaped lines along the tank starting downstream of the LiDAR and continued upstream. This results in 355 measurement points along the tank (and not 1 024 as the standard setting with 360° rotation). The 355 points are located inside the two wedges, where line 1 and 128 constitute the outer lines in the wedges, and at 64-65 the lines are nearly parallel with the x-axis. Ideally, a matrix with measurements of the waves' surface elevation in 128x355 points had been obtained.

Data availability

Data will be made available on request.

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