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Review and rebuttal of the paper

Field measurements of very oblique wave run-up and overtopping with laser scanners

P. Oosterlo et al.

Editor handling the paper: Miguel Esteban

We thank the reviewers for their reviews and comments. We have addressed them all. The way in which we incorporated the suggested changes is indicated below. For the few cases we did not make a change the reason is also explained.

Reviewer 1:

1.1 It would be better to explain more about the advantages of using expensive radar to measure overtopping waves.

We assume the reviewer meant laser instead of radar. Actually, the laser set-up is cheaper than constructing and placing an overtopping tank in the dike slope in a safe way.

We added explanations to lines 20 - 29:

Author (2019b, 2021) developed an alternative innovative and more flexible solution, using two terrestrial laser scanners. They showed that the system can measure the run-up heights, run-up depths (flow depths, layer thicknesses) and front velocities of up-rushing waves on a dike in field situations with oblique wave attack. From these measurements the virtual wave overtopping can be calculated at any height level as well. Furthermore, an estimate of the (peak) wave period and angle of incidence can be obtained from the data. Determining these two parameters from the run-up signals could alleviate the need of additional measurements offshore. Another advantage of the system is that more insight is gained into certain parameters than with the conventional measurement techniques, e.g. into the depths and velocities, which are measured with high resolution. Since the system is mobile, it can measure at several dike locations by moving the system every few years. The present paper builds on the system calibration of Author (2019b, 2021).

And changed lines 65 - 67:

The present system still uses two SICK LMS511pro HR laser scanners, cost efficient laser scanners with a near-infrared (905 nm) laser beam, which is the newest version of a commonly used laser scanner in previous research (e.g. in Hofland et al., 2015; Streicher et al., 2013).

1.2 This is a field test conducted on a specific experimental beach for a specific storm. Are there any strong generalities in the results of this study? If the results are not applicable to other locations, it will be an experiment only for this location.

The measurements were conducted on a dike with a typical profile, with asphalt on the lower slope and grass on the upper slope. Theoretically, the laser scanners can be applied at any dike.

We added (lines 560 - 569):

The laser scanners can be applied at any dike; the performance of the system was confirmed for both asphalt and grass dike slopes. Some of the generic results, obtained from the measurements during storm Ciara, are that relatively shallow water oblique wave run-up is Weibull-distributed, and that the run-up depth equation (Van der Meer, 2011) based on lab measurements also predicts the depths for an actual storm with oblique wave attack quite well. Furthermore, the trend of the EurOtop (2018) equations agrees quite well with measurements of very oblique wave overtopping, but measured discharges were smaller than according to the equations. Accurate measurements of the Tm-1,0 wave period and angle of incidence are important for further verification of the EurOtop (2018) equations and laser scanner system, and further measurements with the system during storms are expected to provide more insight into both the performance of the system and the understanding of oblique wave run-up and overtopping.

1.3 It would have been better if the characteristics of oblique waves were shown as a comparison with normal incidence waves at this site because the readers cannot understand what the standard is.

Unfortunately, no measurements of normally incident waves are available at this location, since the location is characterized by (very) oblique wave attack during storms. The performance of the laser scanner system was confirmed previously, for normally incident waves generated by the wave run-up simulator, at a different dike but with a similar profile. The results of these calibration tests were published previously. We refer to this previous work in the paper, although we had to remove the actual references for the double-blind peer review.

Added lines 101 – 102:

The laser scanner system was previously tested for normally and obliquely incident bores (Author, 2019b, 2021).

1.4 Please explain how the overtopping tank works.

Added to lines 85 - 89:

The overtopping tanks are placed inside and flush with the dike slope and collect water through thin openings in the dike slope at elevations of 4.4 m+NAP and 5.3 m+NAP. The tanks are approximately 0.8 m deep and 1.3 m wide, and have a 4 m-wide opening for entering by overtopping waves. The collected volume of water in the tanks is monitored by measuring the water level in the tanks by pressure transducers, and the water can flow out freely through a gate in an outflow channel (Author, 2019a).

1.5 Please explain more about NAP, e.g., is NAP=0 the chart datum line or average water level?

Added to lines 78 - 79:

(Normaal Amsterdams Peil, Dutch ordnance level, roughly corresponding to mean sea level).

1.6 Figure 3: Please indicate the location of the wave measurement pole on the map.

Changed as proposed. Pole indicated by a triangle.

1.7 Figure 5: There appears to be a positive correlation between water level and wave height. Is there any reason for this?

Yes, the conditions at this location are typically depth-limited, so higher water levels allow for higher waves.

Added (lines 114 - 115):

Note the positive correlation between water level and wave height, due to the depth-limited conditions at the measurement location.

1.8 Figure 6: The slope is uniform. Is it possible to use the laser measurement method even when there are undulations? In other words, what is the generality of the method?

Figure 6 shows a schematized version of the dike slope and laser scanner system. The actual dike slope is convex and has undulations. The coordinate system accounts for the irregularities and the system works on any dike (also see our response to comment 1.2).

Added to lines 139 - 144:

The final maximum difference in x-coordinate between the GPS-measured dry slope and the dry slope as calculated from the laser data was 0.04 m, the same order of magnitude as the scan resolution and laser footprint. The maximum difference in z-coordinate between GPS and lasers was 0.05 m, which can be considered accurate, given the convex and irregular shape of the dike slope, the accuracy of the GPS and the maximum accuracy that the laser scanners can be mounted with.

Added to lines 560 - 561 (see comment 1.2):

The laser scanners can be applied at any dike; the performance of the system was confirmed for both asphalt and grass dike slopes.

1.9 Figure 6: Looking at Fig.2, the heights of the two lasers seem to be slightly different; in Fig.6, the height is only hs. Is the error negligible?

This is true, the heights of the laser scanners above the slope are not the same, see lines 81 - 83:

The laser scanners are located at heights of 5.55 m and 6.04 m above the slope, hence at 10.55 m+NAP and 11.04 m+NAP.

Each laser scanner has its own h_s, which is used in the coordinate transformation. To indicate this, we changed h_s to $h_{s1,2}$ in Figure 6 and its caption (lines 148 - 149).

1.10 L143-144: Why do different lasers have different criteria for depth?

Lines 154 - 156 explain this:

Run-up depths smaller than a certain threshold, depending on the data quality of the specific laser scanner and storm peak, were removed to remove noise from the signal and prevent the detection of unrealistically high run-up values.

Furthermore, we added (lines 156 - 157):

The threshold is chosen in such a way that realistic and accurate run-up depths and heights are obtained.

1.11 L254: The shape factor b is 2. What is the value of the scale factor a?

The value of the scale factor a is approximately 1.1 m for both storm peaks.

Added (lines 290 - 296):

Determining the tangent to the curves gives the shape factor b. The scale factor a can be determined by locating the value on the horizontal axis, which corresponds to an exceedance probability of 1-0.632=0.368 on the vertical axis. Here, shape factors b = 2.2 (laser scanner 1) and b = 2.4 (laser scanner 2) were found for the first storm peak, whereas b = 2.1 was found for both laser scanners for storm peak 2. The value of the scale factor a was approximately 1.1 m for both storm peaks. The run-up thus follows a Weibull distribution that is quite close to a Rayleigh distribution.

1.12 Figure 9: Why are the results of peak1 and peak2 almost the same? Is it just a coincidence that these two peaks have the same value, or is it due to the small sample size?

Both peaks are from the same storm (Ciara). This storm was fairly long-lasting, without much change in the wind direction, and with similar water levels and wave heights during both peaks. Hence, the conditions during both peaks were quite similar. Also see Table 1.

Added (lines 254 - 256):

The data of both storm peaks lie closely together (a result of the similar conditions during both peaks) and fall just above the lower 90%-bound of the EurOtop (2018) equations.

Reviewer 2:

2.1 The following sentences in the abstract should be deleted, as they are repeated by sentences afterwards "This paper presents the first field measurements with an innovative laser scanner system, during an actual severe winter storm with very oblique wave attack. The goal of this paper is to validate this innovative system for measuring wave run-up and wave over-topping parameters during storms with very oblique wave attack."

The first sentences were changed to (line 6):

This paper presents the first field measurements with an innovative laser scanner system, during a severe winter storm. The goal of this paper is to validate this system for measuring wave run-up and wave overtopping parameters during storms with very oblique wave attack. To this end, the paper describes the analysis of the data obtained during storm Ciara (10 - 12 February 2020) and validates the results with data from overtopping tanks and video recordings.

2.2 Abstract, the following sentence is unclear. Please rephrase and improve. "Larger deviations were found for the 2D front velocities and wave angle of incidence, which could not be determined as well for storm Ciara."

Changed to (line 6):

The 2D front velocities that were derived from laser data deviated more from a commonly used equation. The wave angle of incidence could not be determined as accurately for storm Ciara, as in previous calibration tests and numerical simulations with less oblique wave attack. This arose from the very oblique wave attack during storm Ciara.

2.3 What is the purpose of having the following phrase in the abstract? "The mobile system is now ready to be used at several different locations in the measurement campaign in this area over the coming years."

We removed the sentence from the abstract. We kept it in the conclusions, but slightly changed it (lines 559 – 560):

The mobile system will be used at several different locations in the measurement campaign in the area over the coming years.

2.4 Figure 1a. Where is this satellite image from? If it is from google earth then this needs to be acknowledged. Please read the terms and conditions of google, and follow their instructions regarding attribution. If it is from another source then it should be stated.

Added to caption of Figure 1 (lines 40 - 41):

Satellite image: ©2021 GeoBasis-DE/BKG, ©2021 Google. Data: SIO, NOAA, U.S. Navy, NGA, GEBCO.

2.5 L67, it is not usual for figures to be mentioned out of order.

We added the laser scan lines to the right panel of Figure 1 and changed the cross-reference to (line 75):

... blue and red dashed lines in the right panel of Figure 1 …

Added to the caption of Figure 1 (lines 40 - 41):

Right: Drone overview of measurement location, with the laser scanner pole (left), the approximate laser scan line locations (blue and red dashed lines), the painted grid on the slope, and two of the overtopping tanks (right).

2.6 L70-71 repeats information given earlier. Please delete here and consolidate any additional information in previous sentences.

Removed lines 70 - 71 and changed lines 61 - 63 to:

In October 2019, the new system was placed on the dike at Uithuizerwad in the Eems-Dollard estuary, next to two of the overtopping tanks. See the right panel of Figure 1 and Figure 2 for an overview of the measurement location and the system set-up.

2.7 Figures 1 and 3, north direction should be indicated on the maps with an arrow.

Changed as proposed.

2.8 Table 1, table captions should be placed above the table, not below.

Changes as proposed for both tables.

2.9 Figure 5 caption, what do the authors mean by "moments of the spectrum"?

See the table with notations (line 574). We clarified the definition of the $T_{m-1,0}$ in the table, added the definition of the spectral moments and added the definitions of frequency and spectral density.

2.10 L105, what do the authors mean by "The wave overtopping was compared to data from the overtopping tank and EurOtop equations". What is the "wave overtopping" (the two words at the beginning of the sentence) that was compared to the data acquired?

We meant the virtual wave overtopping discharge as determined from the laser data. Changed lines 117 - 119 to:

The (virtual) wave overtopping discharge, as determined from the laser data, was compared to overtopping data from the overtopping tank and the EurOtop (2018) equations.

2.11 L108-112, how reliable are these estimations of the likely error, and how were they derived? (given the double blind nature system of the journal, this reviewer cannot go back to the paper of the authors… well, maybe in truth it would not be so hard to find out, but that would infringe the spirit of double-blind review). It might not be necessary for the authors to modify their paper here, though some private comments of the method used would be welcome (it would be interesting also to eventually access the video that is now blocked).

The relation was based on previous storms in the area, for which both wind and wave direction measurements were available. We calculated the differences between the relation and the measurements (e.g. Root-mean-square error RMSE), which provided an estimate of the accuracy of the relation.

No changes made in the text.

2.12 L140, "Run-up depths smaller than a certain threshold, depending on the data quality of the specific laser scanner and storm peak, were removed to remove noise from the signal and prevent the detection of unrealistically high run-up values". This reviewer is slightly confused, why would

this be the case? (shouldn't the maximum run-up height be independent of any noise in the lower parts of the dyke?)

The noise (below the threshold value) has to be removed from the run-up depth/layer thickness signal. The run-up height is derived from the run-up depth signal, by taking the highest value on the slope where the run-up depth is larger than the threshold value (see lines 168 - 169). If this removal of noise using a threshold depth is not performed, then the results will (often) show a certain (small) run-up depth along the slope, even when no water is present. This is due to the noise in the distance measurement of the laser scanners. Not removing the values below the threshold would then thus also (often) result in high run-up values (outliers), even when no water is present on the slope.

No changes made in the text.

2.13 L145, "If a valid run-up depth value occurred higher on the slope after more than 10 straight NaN values, these values were removed as well." Why was a "valid" run-up depth removed? This is confusing

If 10 straight NaN-values occur (no water on the slope), then there likely is no water/wave/run-up present on the slope above those (NaN-)locations either. Therefore, a valid (non-NaN) value after 10 straight NaN-values, is likely an outlier or caused by noise in the signal, and is therefore removed.

Changed lines 160 - 162 to:

If a (non-NaN) run-up depth was measured higher on the slope after more than 10 straight invalid measurement points (NaN values), these values were also removed, as they were likely caused by noise in the data.

2.14 L177, "showing the run-up signals based on both measured distance R and laser reflectance RSSI for both laser scanners". This is reviewer might have missed something. However, what is the exact meaning of the difference between the measurement of R and RSSI? Both of these are measured with the same instrument… what is the meaning of plotting them in the same figure? (this reviewer confesses he has never used such instruments, so there might be a gap in understanding here).

The lasers measure both the distance and the laser reflectance (reflected signal intensity RSSI). The latter is given as a dimensionless value between 0 and 255. A more reflective surface gives a higher value. Hence, this provides information on the type of surface (e.g. wet or dry, asphalt or grass). The run-up height can thus be determined from the observed differences in RSSI-values as well. See lines 168 – 169 (and our previous work, which we unfortunately cannot share due to the double-blind peer review system).

Added to lines 70 - 72:

(Received Signal Strength Indicator, a dimensionless value between 0 and 255), which provides information on the type of surface.

2.15 In Figure 7, 8 (and others) parameters should be in italics, whenever possible

Changed as proposed throughout the paper.

2.16 L208, it is unclear whether the authors can really conclude here "making them accurate". Suggest deleting these words.

Changed as proposed.

2.17 L246 delete "as well" (here it does not add anything to the sentence…). In other instances this reviewer would recommend the authors to avoid use such grammatical construction and instead use "also" somewhere in the middle of the sentence. Essentially, "as well" is more common in speech than in writing (particularly in academic writing). See: https://dictionary.cambridge.org/grammar/british-grammar/also-as-well-or-too

Changed as proposed throughout the paper.

2.18 L378, "EurOtop (2018) predicts a 10 times larger discharge for both storm peaks than measured by the laser scanners and tank, see Table 2". Actually, Table 2 provides a range of discharges, as indicated also by the authors in the text. The lower ranges are not 10 times larger. Note also next point

This is not completely true. The table does not provide a range of discharges. The table shows the discharges at the height level of the overtopping tank (4.4 m+NAP), for both storm peaks. The discharges calculated based on the data of both laser scanners are given, based on the EurOtop (2018) equations, and based on the overtopping tank. Two values are given for the EurOtop equations, using the actual measured $T_{m\text{-}1,0}$ value and using the ratio $T_{m\text{-}1,0} = T_p/1.1$ (so based on the measured T_p instead of the $T_{m\text{-}1,0}$). The values based on the measured $T_{m\text{-}1,0}$ are 10 times larger than the values of lasers and overtopping tank. The values based on the ratio $T_{m\text{-}1,0} = T_p/1.1$ agree much better with lasers and tank.

Changed lines 397 - 403 to:

EurOtop (2018) predicts a 10 times larger discharge for both storm peaks than measured by the laser scanners and tank, also see Table 2. Here, a ratio Tp/Tm-1,0 = 0.9 occurred, while a more common ratio for a JONSWAP spectrum is Tp/Tm-1,0 = 1.1. Therefore, the laser data were also plotted using Tm-1,0 = Tp/1.1 in Figure 12. Using this ratio, the lasers, tank and EurOtop (2018) agree much better. See also Table 2, where the EurOtop (2018) overtopping volumes and discharges using Tm-1,0 = Tp/1.1 have also been given. Hence, the large deviations in the overtopping discharges mainly seem to stem from the Tm-1,0 wave period.

2.19 L379 "The ratio Tp/Tm-1,0 = 1.1 for a JONSWAP spectrum. As described in section 3, a ratio of 0.9 occurred here." This is confusing from a grammatical point of view. It could be that some nuance related to the previous point was trying to be explained here? (the following sentences indicates that this is likely the case)

Apparently the spectrum in the storm was not a JONSWAP spectrum. See reply to previous comment.

2.20 L457 "Hence, the wave peak periods were determined from the auto-spectral densities of the run-up signals, and the angles of incidence were based on the cross-spectral density of both run-up signals and the resulting 'angle of incidence spectra'." Not fully clear what the authors mean (probably better explained in their earlier paper… which this reviewer cannot check).

This is indeed explained in much more detail in the previous work. We attached the section from our previous paper, which explains this, as Appendix A to this rebuttal. As we do not want to repeat everything from our previous work in the present paper, we changed lines 476 - 483 to:

As described in section 4, the wave peak periods and angles of incidence were determined with the method as described in Author (2021). Hence, the wave peak periods were determined from the auto-spectral densities of the run-up signals. The angles of incidence were determined using the cross-spectral density of the run-up signals of both laser scanners, from which the time lag between both laser signals can be determined. The distance between the laser scan lines was then divided by the time lags, to determine the phase velocity of a projected wave travelling past the laser scanners. Using trigonometry and the incident wave celerity based on linear wave theory, the angle of incidence spectrum can be determined, see Figure 14. For the full description, refer to Author (2021).

2.21 L529 "The angle of incidence was more dike-normal than that estimated for the incoming wave field," This seems to disagree with the following sentence, which states that the waves were oblique.

The angle of incidence, based on the laser scanner data, was less oblique than the angle of incidence estimated with Equation 1. In other words, the angle of incidence based on the lasers was more dike-normal than according to the equation.

Changed lines 553 - 555 to:

The angle of incidence of the incoming wave field, based on the laser data, was less oblique than that estimated using an analytical relation, even though good results were achieved using the same method (Author, 2021).

2.22 L30 space between 80 and relative

Changed as proposed.

2.23 L120, there should be a "being" before the first "the" in this line

Changed as proposed.

2.24 L129, unclear what the authors mean by "accurate considering the convex shape of the dike slope", please rephrase ("which can be considered accurate given the convex shape of the dike slope"?)

See also our response to comment 1.8. Changed as proposed (lines 139 - 144):

The final maximum difference in x-coordinate between the GPS-measured dry slope and the dry slope as calculated from the laser data was 0.04 m, the same order of magnitude as the scan resolution and laser footprint. The maximum difference in z-coordinate between GPS and lasers was 0.05 m, which can be considered accurate, given the convex and irregular shape of the dike slope, the accuracy of the GPS and the maximum accuracy that the laser scanners can be mounted with.

2.25 Figure 6, change to "are indicated" (in various sentences in this caption)

Changed as proposed.

2.26 L184, change to "both laser scanners, based" (delete "and", add a comma)

Changed as proposed.

2.27 L346, change to "incident waves present during" (delete "as")

Changed as proposed.

2.28 L398, should be "some of the smaller overtopping waves…"

Changed as proposed.

2.29 L421, maybe also "numbers of overtopping waves…". Same for line 422 and 424.

Changed as proposed throughout.

2.30 L427 should be "than" (not "thank")

Changed as proposed.

2.31 L433 "somewhat more as well". This is not very elegant English. Suggest changing to "might have been slightly overestimated."

Changed as proposed.

2.32 L448 maybe "development over time"

Changed as proposed throughout.

2.33 L507 change to "to estimates the" (delete "determine")

Changed as proposed.

2.34 L535, change to "system can measure the wave"

Changed as proposed.

2.35 LL465 change "a lot" (casual English) to "much"

Changed as proposed.

Appendix A

From the time lag between the two laser signals, the angle of incidence can be obtained. Fig. 1 shows this schematically, providing the definitions for the analysis method. The solid lines represent an obliquely incident sinusoidal wave, with the wave direction indicated by the arrow, propagating towards the dike, with a phase velocity *c* [m/s] and a wavelength *L* [m]. The dike toe and crest are indicated with the thick solid lines. This wave causes a projected wave to travel along the dike, with a velocity *c'* [m/s] and a wavelength *L'* [m] (dashed lines). This projected wave is sampled at the two locations LS1 and LS2 (dotted lines), at a distance *D* [m] from one another.

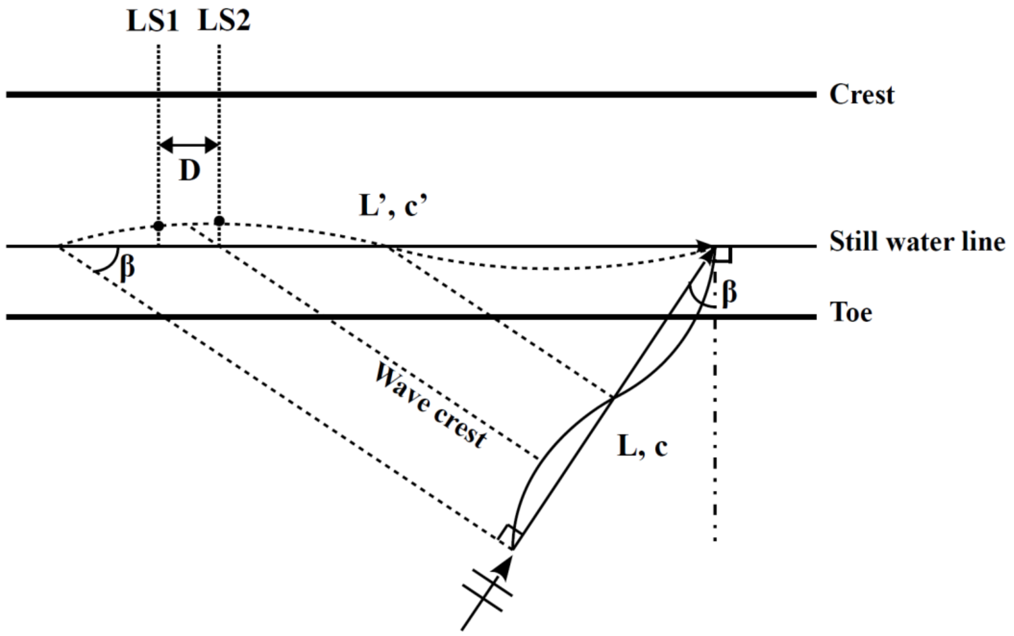

Fig. 1. Angle of incidence analysis definitions, with an obliquely incident sinusoidal wave (wave direction indicated by the arrow) propagating towards the dike (toe and crest indicated with thick solid lines), with a phase velocity *c* and a wavelength *L*. This wave causes a projected wave to travel along the dike, with a velocity *c'* and a length *L'* (dashed lines). β is the angle of incidence. Laser scanner scan lines indicated by the dotted lines (LS1 and LS2), with a distance *D* between them.

From the numerical simulations, the run-up was determined in the same way as for the actual laser scanner measurements, by determining the highest location on the slope where the run-up depth was larger than zero. The first step in the further analysis is to determine variance density spectra from the run-up signals of the (virtual) laser scanners, with finite and discrete Fourier transforms (e.g. Bendat and Piersol, 1971):

$$X_j(f, N\Delta t) = \sum_{n=1}^{N} R_{u,j}(n\Delta t)\, e^{-i2\pi f n\Delta t} \qquad \text{(Eq. 1)}$$

with $R_{u,j}$ (j = 1,2) [m] the run-up time signals for the scan lines, f [Hz] the frequency, Δt [s] the sampling interval, n integers and N the window length in samples. Next, the auto-spectral density is determined:

$$S_{jj}(f) = \frac{2}{N\Delta t} E\left[\left|X_j(f, N\Delta t)\right|^2\right] \qquad \text{(Eq. 2)}$$

with E[] being an ensemble average over the number of windows. Since these spectra are based on the run-up time series, they do not represent a real wave spectrum, from which e.g. a wave height can be determined. However, from the peak(s) of these spectra, the wave peak frequency f_p [Hz] can be determined. After that, the cross-spectral density is determined from both run-up signals for each pair of virtual laser lines at different distances from one another (1 m, 2 m, 4 m and 8 m apart):

$$S_{12}(f) = \frac{2}{N\Delta t} E[X_1{}^*(f, N\Delta t) X_2(f, N\Delta t)] \qquad \text{(Eq. 3)}$$

with X^* the complex conjugate of X. All previous equations in this section are defined for $0<f<1/\Delta t$. Martins *et al.* (2016) used a similar approach to determine wave peak periods and celerities based on data as measured by a single laser scanner. The 'time lag spectrum' $\zeta(f)$ is obtained from the cross-spectrum at each frequency, as follows:

$$\zeta(f) = \frac{Arg(S_{12}(f))}{2\pi f} \qquad \text{(Eq. 4)}$$

From the spectrum of time lags between these virtual laser scanners and the distance between both laser lines D, the phase velocity of the projected waves can be determined at each frequency:

$$c' = \frac{D}{\zeta(f)} \qquad \text{(Eq. 5)}$$

Next, the incoming wave celerity c is determined at each frequency according to linear wave theory. Finally, the 'angle of incidence spectrum' β can be found with trigonometry, see Fig. 1:

$$\beta = \sin^{-1}\frac{c}{c'} \qquad \text{(Eq. 6)}$$

E.g. the peak angle of incidence can then be determined by taking the angle of incidence corresponding to the peak frequency from the angle of incidence spectrum.

The method above was based on monochromatic, sinusoidal waves in deep water, whereby it was assumed that the wave angle of incidence is the same as the angle of the breaking wave on the slope.