LASER ALTIMETRY FOR RIVER MANAGEMENT

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ABSTRACT:

Laser altimetry seems to be an attractive method for the fast acquisition of up to date height data which can be useful for various river management tasks. The Geo-information and ICT department of the Ministry of Transport, Public Works and Water Management gathered many experiences in this field during the recent years. The topic of this paper is to give an overview of the use of laser altimetry for different river management applications. The first subject is floodplain vegetation classification for hydraulic modelling. Laser data adds useful structure information on spectral information for vegetation classification. Furthermore, the potential of laser altimetry for soil volume determination concerning costs and accuracy is discussed. Laser altimetry also offers new possibilities for monitoring of groynes and realistic visualizations of innovative river structures. In addition, the benefit of laser altimetry for the acquisition of detailed DEM's of the shallow parts of the riverbed in case of extreme low-water level is shown. Finally, laser altimetry has been investigated for measuring continuous water levels and wave characteristics such as amplitudes and wavelengths.

1. INTRODUCTION

One of the core tasks of the Dutch Ministry of transport, public works and water management (Rijkswaterstaat) is to guarantee citizens safety with regard to flooding and to enable and facilitate shipping along the great rivers. To fulfil these objectives a variety of underlying river management tasks has to be performed which requires different kinds of up to date geo-information. The demand for up to date geo-information is even expected to increase because of higher river discharges in the future due to climate change. In addition, a new concept of river management will be performed in The Netherlands: in the future both, the river and the vegetation in the riparian forelands, will be allowed to behave in a more natural and dynamic way as long as safety and shipping are not affected.

For the regional departments of Rijkswaterstaat laser altimetry seems to be an attractive method for the fast acquisition of up to date height data. The role of the Geo-information and ICT Department is to advise the regional departments about such new techniques and the use of geo-information. The department is quite experienced with laser altimetry because of the co-ordination of the acquisition of the new country wide digital elevation model (AHN), which has been completed in 2003. Furthermore, the quality control of the laser altimetry data was done by the Geo-information and ICT Department. For this quality certification task a new height error description scheme was developed for DEM's acquired by laser altimetry, allowing the quantification of error effects at different scales (Crombaghs et al., 2002).

In the recent past a number of tailor made laser altimetry flights have been organized for specific water management objectives. The topic of this paper is to give an overview of the use of laser altimetry for various river management applications. Among them are:

- Floodplain vegetation classification in combination with hyperspectral images for hydraulic modelling.
- Acquisition of detailed and precise DEM's for soil volume determination concerning construction works in the floodplains.
- Monitoring of groynes for maintenance and management tasks.
- Acquisition of detailed DEM's of the shallow parts of the riverbed in case of extreme low water level.
- Continuous water level determination along the river axis.
- Wave amplitude and wavelength determination to verify ship wash modelling.

Related work over river flood modelling with laser altimetry can be found in (Mandlburger and Brockmann, 2001), (Cobby et al., 2001) and (Kraus, 2003). In the following paragraphs the above mentioned applications will be described in more detail. The required flight specifications and achieved accuracy will be discussed.

2. FLOODPLAIN VEGETATION

Floodplain vegetation influences the rivers discharge capacity in high water conditions through its hydraulic resistance (flow resistance). This is expressed by hydraulic roughness parameters which depends on many different factors like vegetation height, density, stem diameter and spatial patterns within vegetation among others (Asselman, 2001). The main input data for the hydraulic models for water level forecasting consist of these roughness parameters in combination with morphological data of riverbed and floodplains (see paragraph 5). Both data have to be up to date. Therefore, mapping of the floodplain vegetation is crucial and has to be done regularly.

There are different possibilities to gather the required vegetation roughness information of the floodplains. One possibility would be to directly derive the roughness information from laser altimetry data. Asselman did some investigations on this topic using (geo-)statistical characteristics of the data (see (Asselman, 2001) and (Asselman, 2002)) but concluded that it is difficult to distinguish lower types of vegetation including grass lands, bare arable land and herbaceous vegetation. However, there are other studies which show that vegetation height, which can be derived from laser altimetry data, can be used as a surrogate for the product of stem density and flexural rigidity (Mason, 2003) and thus would be sufficient for the water level forecasting model which they use.

In the Netherlands, it is common practice to derive the roughness parameters from vegetation structure classes. Rijkswaterstaat employs a list with the hydraulic resistance values for about 30 different vegetation structure types which normally appear in Dutch riparian forelands (Velzen et al., 2003). Up to now, these vegetation structure classes are manually mapped from aerial stereo-photographs. This is a time consuming and expensive method. Therefore, we are investigating the possibility of automatically or semi-automatically deriving the vegetation structure classes from remote sensing images such as airborne hyperspectral data in combination with laser altimetry data. For this purpose we investigated the benefit of fusing hyper-spectral data from the airborne line-scanner CASI (10 bands ranging from 440 nm up to 870 nm, pixel size 2 x 2 m^2), acquired in summer 2003, with very dense laser altimetry data (30-40 points per m^2). The laser data was acquired in March of 2003 with the helicopter borne FLI-MAP system from Fugro Inpark (see also paragraph 4). The test area was the floodplain Gameren along the river Waal which comprises about 160 ha.

Before land use classification a quite labour-intensive geometric correction of the CASI data was necessary which has been done with the 'rubbersheeting' algorithm of ERDAS Imagine. To get the vegetation structure classes from the spectral and laser data a classification was performed using the software eCognition (see fig. 1). It follows the concept that important semantic information is not represented in single pixels but in meaningful image objects and their mutual relations. Therefore, the image classification is based on image segments rather than individual pixels. In a first step, the software extracts homogeneous image segments in any chosen resolution which are subsequently classified by means of fuzzy logic.

As input layers we chose all 10 CASI bands, a NDVI-layer (NDVI = Normalized Difference Vegetation Index) which was computed from the red and nearby infrared band, the unfiltered laser heights and a band comprising maximal height differences

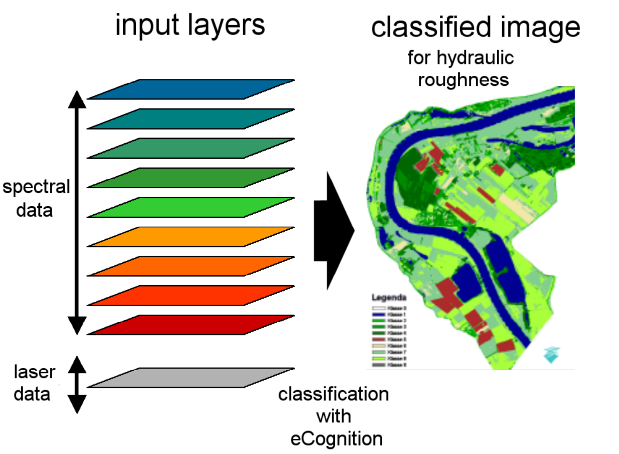

Figure 1. Principal of vegetation classification with eCognition based on spectral and laser altimetry data.

of laser points within one pixel indicating the vegetation height. All data were resampled to 1.5 x 1.5 m^2 pixel size.

After segmentation into small segments, a top down tree structure approach (hierarchical network) for classification was pursued. First, two main classes ("land" and "water") were distinguished. These two classes were further subdivided into more detailed classes, e.g. the class "land" was subdivided into the classes "vegetation", "bare soil" and "shadow" and the class "water" into "water-plants/duckweed" and "water without plants". Totally, 15 classes have been distinguished. The classification was done by a combination of a standard supervised Maximum Likelihood classification and rules (constraints) translated into membership functions. Ecognition also allows using shape parameters of the segments for classification, but up to now we did not use this option. The overall classification accuracy unfortunately has not yet been quantified, but is estimated to be around 70-80%. A thorough evaluation of the achieved results still has to be done. However, it is already apperent that the combination of spectral and height data is very promising, especially for distinguishing the lower vegetation structure classes which seemed to be difficult with laser altimetry alone (Asselman, 2002).

3. VOLUMES

For construction works in the floodplains, such as dyke displacements and lowering parts of the floodplains in order to give the river more space for discharging especially with high-water conditions, detailed and precise DEM's are required for soil volume determination. The volume of the soil which have to be moved or digged up is an essential parameter for the contracts with the construction firms. In addition, DEM's are measured after termination of the work (so called 'end models'). Currently these DEM's are measured with tachymetry or GPS with about 140 points per ha. The question was whether laser altimetry could be an alternative with regard to quality and costs.

Volumes can be calculated by multiplying the mean height with the concerned area: volume = length × width × height, see fig. 2. Thus the precision of the volume is closely related to the precision of the mean height of an area. Therefore, the effect of for example laser scanner point noise can be neglected. The volume precision also depends on how much soil has to be digged up or moved, the so-called digging depth (h). A maximal volume error of 5% is requested. This yields for the precision of the mean height:

$$2\sigma_h \le (h/100)\cdot 5 \text{ or } \sigma_h \le (h/100)\cdot(5/2).$$

Tabel 1 shows the required precision for the mean height as function of the digging depth.

digging depth [m]	1	2	3	4
σ_h [cm] <	2.5	5	7.5	10

Tabel 1. Required precision of the mean height depending on the digging depth.

The determination of the mean height precision of an area acquired with laser altimetry is based on error propagation of four error components with different amplitudes and spatial resolutions. This is described in detail in (Crombaghs et al., 2002). With increasing area size, the precision of the mean height decreases because then more error components are averaged. Our computations showed that the previously mentioned FLI-MAP system meets the demand of 2,5 cm height

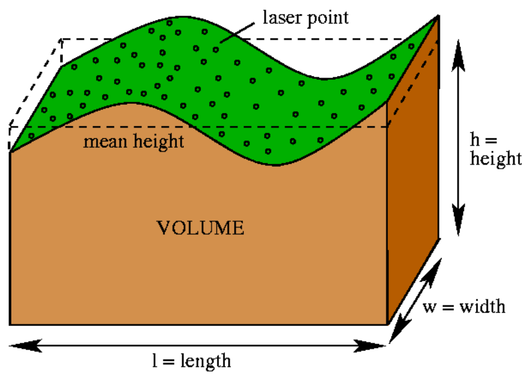

Figure 2. Soil volume determination for construction works in the floodplains.

precision (for 1 m digging height) for areas of about minimal 50 ha in case of *no* vegetation. This applies for point densities of 15 and 30 pt/m^2. The disturbing effect of (low) vegetation on laser measurements still is difficult to quantify but is estimated to be 2-3 cm (systematic error). For areas *with* vegetation, the FLI-MAP system is satisfactory for digging depths from minimal 2 m. Laser data acquired from an airplane with a point density of about 1 point per 16 m^2 can be used for digging depths from minimal 2 m in case of no vegetation and minimal 3 m in case of vegetation. Concerning the costs, helicopter borne laser altimetry is about 30% cheaper than terrestrial measurements for small areas (50 ha) and about 50% for larger areas (200 ha). This applies for an extreme high point density of 30 pt/m^2. Another advantage of laser altimetry is the possibility to survey large areas in short time.

4. GROYNES

Along the river banks of the large Dutch rivers we find numerous groynes (see fig. 3). These are structures of sand and stone extending from the river bank into the water, built transverse to the flow direction. Their main purpose is flow acceleration to minimize sediment deposits in the main channel (fairway). This way the required depth of the riverbed for shipping is maintained. Monitoring of groyne shapes is important because different kinds of damage may occur which affect the performance of the groynes, for example collisions with ships and deformations by the current.


Figure 3. Groynes along a Dutch river.

The present way of monitoring the above-water parts of groynes is with terrestrial measurements and visual inspections. The measurements consist of levelling profiles (one profile across the ridge of the groyne and two profiles perpendicular to the main axis) and slope measurements with a 3 m rod. In addition, visual inspections are performed for damage control and acquisition of the number and approximate heights of trees and bushes growing on groynes. In fact, groynes must be free of (high) vegetation. These activities are time-consuming and therefore expensive. Thus they are carried out not more than once per three years. The below-water parts are measured with a multi-beam echo-sounder system.

Concerning costs and acquisition time laser altimetry seems to be a good alternative for the terrestrial groyne measurements. The main question, however, was: what is the precision of the laser altimetry data and could groyne deformations be measured with laser altimetry? Therefore, a test was performed with the FLI-MAP system. This is a helicopter borne laser scanner which acquires laser altimetry data with extreme high point densities: 15-20 points per m^2. In our test the point density was even higher: 30-40 points per m^2. This could be achieved by flying all strips two times. In addition, the FLI-MAP system acquired video data (pixel size 30 x 30 cm^2) and digital photographs (pixel size 6 x 6 cm^2) during the flight. Figure 4 gives an impression of the dense laser data and to what extent morphologic details can be recognized. Apparently, there are very few laser reflections from the water surface (black pixels).

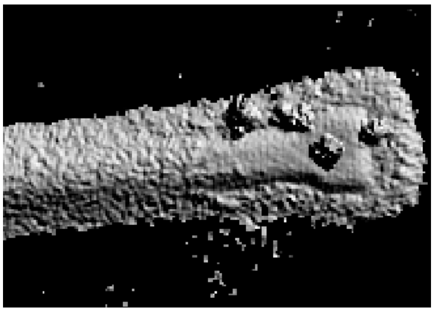
Figure 4. Hillshade of laser data grid of a typical groyne with some bushes on it (grid cell size: 20 x 20 cm^2).

The laser data were compared with dense GPS measurements on four groynes (about 200-400 measurements per groyne) with varying grid cell size and point density. The main conclusions of this comparison were:

- The height differences showed standard deviations of about 7 cm. This contains not only the laser scanner point noise (in this case about 4.5 cm), but also the error of the GPS measurements and the roughness of the groyne surface.
- The systematic error lay between –0.1 cm and –7 cm. Several centimetres height shift of laser strips can be caused by positioning errors of the helicopter.
- The extreme high point density of 30-40 points per m^2 is not necessary: 15-20 points per m^2 would be sufficient and does not affect the achieved accuracy.
- A grid cell size of 50 cm is recommended because of the roughness of the groyne surface and the averaging of laser point noise (several points per grid cell).
- The laser data is not suitable for monitoring deformations per *single* grid cell. The deformations must be considered for at least some neighbouring grid cells or the whole groyne surface.
- Absolute deformations can be detected from about 10 cm, relative deformations (comparing one laser data set versus another) even from about 5 cm.

Considering the costs of terrestrial measurements even about 40% of the total costs can be saved using laser altimetry. This applies for a point density of 15-20 points per m^2.

In addition, information is required about the vegetation on groynes, such as trees and bushes, which dissipate a great deal of flow energy in case of flooding. The number of stems and rough height classes (0-3 m, 3-5 m, 5-7 m) are necessary information. We did not perform much research on this item because of the lack of ground truth data. However, it is obvious that the number of trees and bushes and their approximate heights can easily be measured manually in the dense laser data (15-20 points per m^2, see fig. 4), even when the laser data is acquired in the leaf free period. Automation of this process is probably possible with image processing algorithms. Further tests on this topic have to be performed.

Whereas the dry parts of groynes and the floodplain topography can be measured with laser altimetry, the riverbed and the below-water parts of groynes are usually measured with echo-sounder systems, in our case a multi-beam system. For the monitoring of the groyne state as well as for forecasting of water levels with hydraulic models, a continuous DEM of the whole watercourse between the dykes, thus of riverbed *and* floodplains is required. Fig. 5 shows a combination of both datasets: laser and multi-beam data. However, in spite of measuring the multi-beam data with high-water level and the laser data with low-water level, there still remain some no-data gaps which must be interpolated. This must be taken into account using the continuous DEM for water level forecasting models.

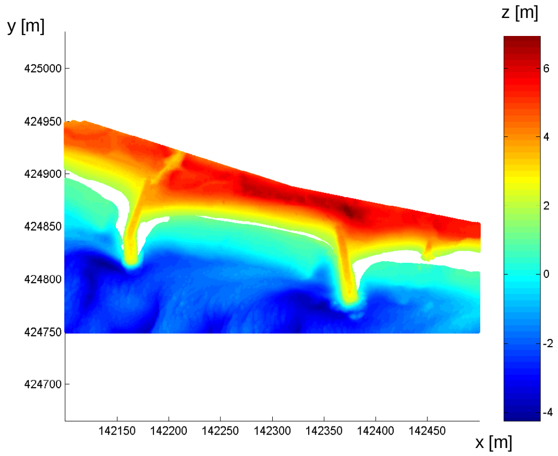

Figure 5. DEM of laser altimetry data in combination with multi-beam echo-sounder data at the river Waal.

Laser altimetry data in combination with digital photographs and echo-sounder data can also be useful to illustrate new river structures. For the visualization of an innovative groyne type an animation has been made. Figure 6 illustrates some stills of this animation: a traditional groyne and two examples of the innovative groynes consisting of a row of pales. These visualizations are giving a much more realistic impression of the future landscape to the citizens and to policy-makers than technical line drawings alone.

5. RIVERBED MORPHOLOGY

Usually, the riverbed morphology is measured with a multi-beam echo-sounder system during high-water level and the floodplain with aerial stereo-photographs during low-water level. The two datasets are not connected by an overlapping zone, but with a no data zone over the groyne fields. Normally the groyne fields are mostly covered with water and cannot be measured with multi-beam nor with stereo-photogrammetry.

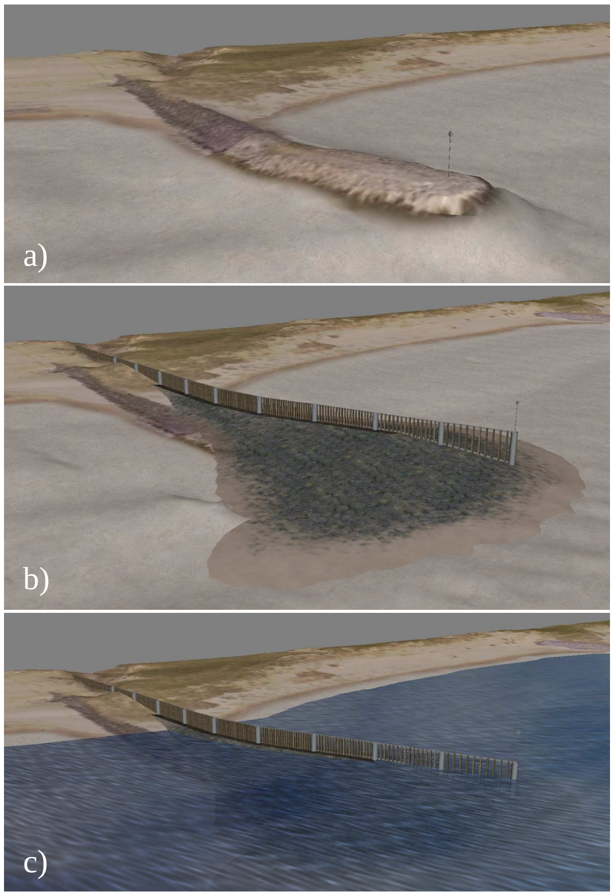

Figure 6. Visualization of traditional groyne (a) and innovative groynes (b + c).

During the summer of 2003 the water level in de main Dutch rivers reached the lowest level ever, see fig. 7. On 29th of September the minimum water level of +6.91 m NAP at Lobith (where the Rhine enters the Netherlands) was measured. The normal low-water level at Lobith is between +9 and +10 m NAP. During this extreme low water level period the dry groyne fields have been measured by laser altimetry with a point density of 1 point per m^2, see fig. 8, with an Optech scanner used by TerraImaging.

Figure 7. Harbor during extreme low-water level in Waal river.

Now the whole watercourse DEM (between both dykes) is available. In the past the gap between the wet and dry parts was much bigger than shown in figure 5. In addition the laser data of the dried up floodplains can contribute to the floodplain DEM for the normally wet ditches and lakes. However, the riverbed morphology, the groyne fields and the floodplain undergo big changes due to the water displacements. The laser DEM thus is a single moment representation. This instantaneous, actual and precise DEM of the watercourse

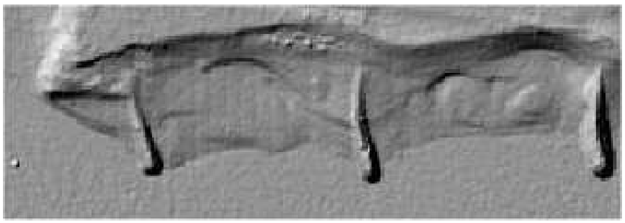

Figure 8. Laser altimetry data of an extreme low-water level in a Dutch river. The dry groyne fields are clearly visible in this hillshade DEM.

between both dykes is now at our disposal to compute the volumes of the high-water level reservoirs.

Up to now, the floodplains have been measured by aerial photogrammetry. Whether laser altimetry data is useful as input for the hydraulic model still needs to be researched, but seems to give a positive contribution given this extreme low-water level data. Most important for the hydraulic computations are the line elements in the floodplain, such as dykes, terrain height steps, drainage ditches and hedges. The quality of these items derived from the laser data has also to be further investigated.

6. WATER LEVELS

A new application of the laser altimetry technique is to measure the water level. Some laser systems do receive signals from water surfaces, in contrast with the FLI-MAP system which does not receive any signal from the water surface, see figure 4. The laser strip width decreases compared to land mainly due to the reflectivity characteristics of water. These water level heights, measured during a high water situation in the river including the flooded floodplains, can be used to verify the water level forecasting model for the Dutch main rivers. The high point density, continuous laser data and the flexibility of the system gives advantages above the single point data from the water gauges, located every 5-10 kilometres downstream.

In January 2003 a high water wave was expected in the Dutch main rivers (Rhine, Waal and IJssel). With an airborne platform laser data of at least 1 point per 4 m^2 was obtained. The quality was checked on two ways. A control of height differences between overlapping strips and between laser data and terrestrial measured ground control fields on dykes was performed. For the latter one the mean difference was between –5.1 cm and 3.6 cm, and the standard deviation ranged from 2.9 to 6.2 cm for reference areas of approximately 5 x 5 m^2.

From the laser data of the water surface a contour map was derived showing the details in acceleration and congestion of the water, see fig. 9. The red and blue lines are every 5 cm, the green lines every cm. The water level gradient going down-stream and the cross track gradient in river bends can be computed from the laser data. An expected downstream gradient in this river is approximately 10 cm per km, and for the cross track gradient 2 cm per 100 m.

Another application is to define the reference surface for dredging from the laser data. The water level gradient measured during a specific discharge along the river axis is the zero level for dredging. Dredging is necessary to keep transport by shipping optimal. The gradient line attained from laser data is a more realistic representation than using the single point water gauge measurements.

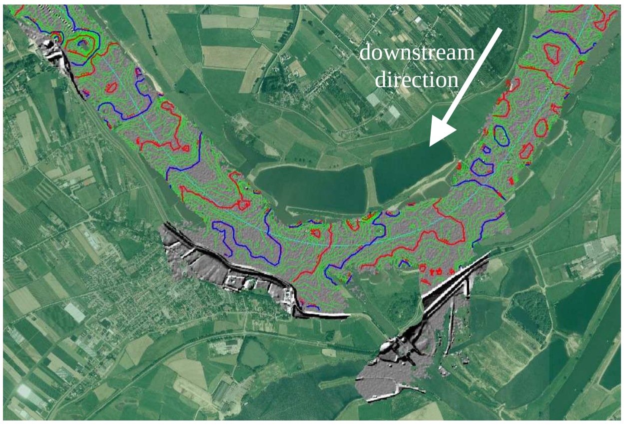

Figure 9. A contour map obtained from the low water level laser data, with an aerial photograph as background.

Finally, river experts denoted that in shallow water areas the water surface contains information about the structure of the underlying morphology. This phenomena can be recognized in case of extreme low-water in the riverbed and in case of high-water in the floodplains. Especially constructions in the riverbed and different foreland characteristics result in changes of the water level. Even the decrease of the water surface around a ship (squat) is visible in the laser data.

7. WAVE AMPLITUDES

Another application of laser altimetry is the determination of wave amplitude and wavelength. The Transport Research Centre of the Ministry of Public Works and Water Management is concerned with shipping. Fast ferries are restricted to produce little wash, but were still causing problems in some areas such as erosion to river shorelines, disturbing waves in recreation areas and undesirable motions of moored ships. To understand the wash of fast ferries a continuous spatial wash measurement, obtained by airborne laser altimetry, will improve this, allowing a better prediction in wash models, and checking on wash-limits. Most water level measurements are single point time series, not giving any information about wave direction and neighbouring water level heights.

A pilot was carried out to measure the wash of the Huizen-Almere fast ferry, moving with constant high speed over shallow and deep waters. The Toposys II laser scanner of TopoSys GMBH was used by Aerodata International Surveys in an airplane. A challenge in this pilot was tuning the exact time of measurement by the airplane of the fast ferry moving at constant speed (see fig. 10 for the course of both platforms). Communication between cockpit and bridge was essential. However, the standard communication frequency canals are different for both platforms. Therefore, communication with VHF was used.

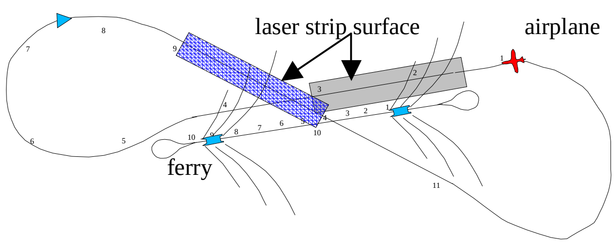

Figure 10. Course track and corresponding positioning numbers for both platforms.

The area chosen is the 'Gooimeer'-lake in the Netherlands. No disturbing wave reflections were expected due to the gradually shoaling and sufficient large distance to the shoreline. For the weather two specific restrictions were formulated: no clouds below 500 m and optimal wind conditions causing a smooth ribbling water surface. Thus, a maximum of 3 Bft was allowed, and a minimum of at least 1 Bft was required. The airplane altitude was chosen at 1500 ft, mainly because of the restrictions of Schiphol Air Traffic Control. To be sure to receive enough reflections of the laser scanner, and to be able to detect the wave pattern, wave amplitude and wavelength, a minimum of 8 laser points per square meter on water areas was specified. The laser strip width was about 180 m on the water surface. With approximately 4 strips the total wave pattern was obtained.

For getting wave amplitudes and wavelengths only relative heights have to be validated. To be able to validate the laser data all strips had to start and end over land. The relative validation consists of two parts. Over land the relative height differences between strips were checked and on the water part the variation of the laser points was computed. The variation of the laser data on water is higher than on land. For an area of 25 by 25 m^2 the standard deviation over 3300 points was 7.5 cm, primarily caused by laser point noise and the influence of wind waves.

The wave pattern from the laser data is not a single moment representation, which would have been optimal, but according to (Bolt, 2001) this is neglectable. The best way of representing the wave pattern with the laser data is a 2 x 2 m^2 grid. By averaging most wind waves and laser point noise were eliminated, whereas the ferry waves were still visible. By combining the strips the complete wave pattern can be reconstructed, see fig. 11. In this figure the upper part lies in a part with a constant water depth of 2.5 m, showing a wave pattern starting with a crest of the leading wave. For more details see (Bolt, 2001). In the lower part of the figure the depth increases steeply from 2.5 m up to 8 m. In the wave pattern a change of propagation angle appears and the leading crest disappears in the deeper part. The deep water waves have a longer wave length and run faster. These wave characteristics can be used as input in the numerical models for the prediction of wash patterns.

8. CONCLUSIONS

River managers need up to date geo-information. In this paper we showed that laser altimetry can be useful for a variety of river management applications. Time consuming terrestrial measurements, visual inspections and mapping from stereo-photographs can often be replaced by laser altimetry and even yields a reduction in costs. Fusing laser data with spectral information is very advantageous for some applications, e.g. vegetation classification and visualizations. In case of exceptionally occurring extreme low-water levels laser altimetry enables us to gather very fast detailed morphologic information about the groyne fields which usually cannot be measured with any technique at all. This way a valuable complementation of echo-sounder measurements to a continuous watercourse DEM can be obtained. Furthermore, laser altimetry has shown to be a new and valuable technique for measuring water levels and wave pattern parameters, such as wave amplitude and wavelength.

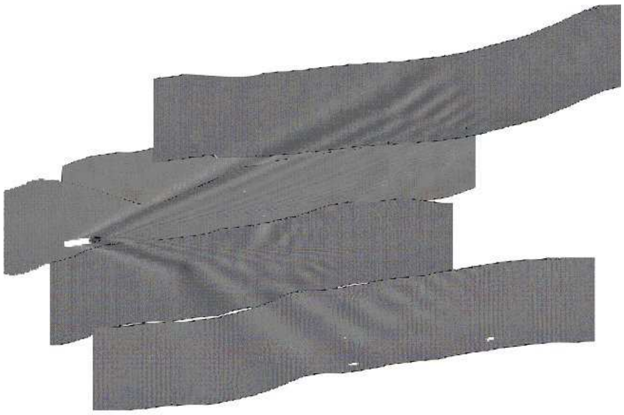

Figure 11. Composition of five laser strips presenting the wave pattern of the fast ferry (from (Bolt, 2001)).

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