Simulation-based Measurement Strategies for Dune Tracking with Multi Beam Echosounders

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Key words: Dune tracking, Hydrography, Concept of Measuring, Multibeam Echosounder, Geometrical Simulation

SUMMARY

The static as well as the morphodynamic component of the river bed are of great importance for the maintenance of waterways. Such maintenance is in the responsibility of the German Federal Waterways and Shipping Administration (WSV). Water currents can cause parts of the riverbed sediments to move in the form of dunes. By the dune tracking method, the shape, migration and finally bedload transport rates of dunes are determined. Using multibeam echosounders on vessels, area-covering measures of the river bed can be conducted in a certain time.

Therefore, the single stripe like measurements have to be merged to an overall image. Besides technical and environmental conditions, especially the morphodynamic component imposes certain requirements on the measuring strategy. Due to the dune migration during the measurement of one measuring stripe the overall image can be distorted. This paper deals with the development of an optimized measuring concept in order to achieve the best possible measurement data. Using a geometrical simulation of known river bed form data, suitable measurement settings can be found. In this work, the considered measurement settings are the along track point distance, the direction and length of trajectory. The measurement strategies concerning the described measurement settings are combined in a measurement concept.

The development and findings are based on surveys of the river Rhine, where a coherent and consistent 3D point cloud of the river bed for a limited river area has been obtained. Based on a simulation and further considerations, a procedure has been developed, to refine the measurement concept during the actual survey. Using the presented methods and approaches, knowledge about a suitable measurement concept can be transferred to other measurement epochs and other waterways with their own environmental conditions.

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1. Introduction

As waterways like the River Rhine being important parts of the traffic infrastructure, the safety and ease of navigation has to be guaranteed. In Germany, this job is done on behalf of the German Federal Waterways and Shipping Administration (WSV). The WSV is responsible for maintenance measures including traffic safety soundings, maintenance dredging or bedload input in terms of sediment management. Being the supreme authority within the Federal Ministry of Transport and Digital Infrastructure (BMVI), the Federal Institute of Hydrology (BfG) supports the WSV with research and development (R&D) and consulting. The MAhyD project (morphodynamic analyses using hydroacoustic data) is one of those R&D projects. The aim of the project is to derive new strategies for the actual measurements and their analysis as well as to improve the morphodynamic analyses and understanding of river bed transport.
Both the static and morphodynamic components of the river bed are of great interest in terms of maintenance surveys and sediment management. Under the action of a current, parts of the river bed can move in forms of bed forms (Bechteler 2006), also called dunes, and lead to short-term changes in depth within the fairway. In terms of sediment management, the knowledge of sediment transport is important. Due to an incomplete understanding of the morphodynamic processes (Bradley and Venditti 2019), regular monitoring measurements using multibeam echosounders (MBES) are necessary to ensure the safety and ease of navigation. The dynamic characteristics of the bed forms are challenging to the measurement. Measurement settings have to be well suited in order to generate measurement data with a high level of geometrical consistency, which represents the river bed accurately. A specific orientation of measurement lines is required to reduce dune migration induced offsets. Single swaths of MBES measurements are merged together in order to obtain a 3D point cloud of the observed dune field. During the measurement of one stripe, the dunes migrate. While measuring the next stripe, the dunes have a horizontal shift compared to the measured dunes in the previous stripe. This ends up in a distorted inconsistent 3D point cloud. Furthermore, if measurement settings, such as the vessel velocity or the sampling rate of the echosounders are chosen inadequately, the dune shapes are inaccurately represented. In order to generate informative measurements, which can be used in further dune tracking analysis, such as examined in (Claude et al. 2012), a workflow has to be established.
In this work, a workflow concerning a measurement concept for dune tracking is presented. Based on premeasurements of a dune field, fine measurement settings are adapted to the existing morphodynamic characteristics and optimal measurement lines are derived. Subsequently, dune information is derived from these measurements and a simulation is performed in order to estimate thresholds of specific measurement settings.

Bed forms can be characterized by their geometrical parameters height and length. The dimensions strongly depend on the hydraulic (e.g. water depth, velocity) and morphological (e.g. grain size, sediment supply) conditions. The bed form length can be defined as the distance between two adjacent troughs while the height can be defined as the height of the triangle formed by two adjacent troughs and the crest between them. According to (Flemming 1988) there is a highly correlated exponential relationship between the two parameters which is defined as $H=0.0677\ L^{0,8098}$. However, depending on the water depth and a grain size-dependent critical erosion velocity for sediments above the bed form crest, the bedform growth can be terminated before the expectable height is reached, which can lead to deviations from the relationship shown.

Due to the flow around the bed forms, grains are eroded on the bed form stoss side and deposited on their lee side. Based on the resulting migration of the structure, bedload transport rates can be estimated by applying a cross-correlation analysis to two temporally offset measured datasets. Figure 1 presents collected values for migration celerities based on measurements from different rivers. These depend on hydraulic and morphological conditions and the resulting bed form dimensions. For small structures, high values of more than 1 m/h can be found. In addition to the higher celerities, smaller structures also decay more rapidly, so that very small time increments between successive measurements are required for an accurate determination of migration rates.

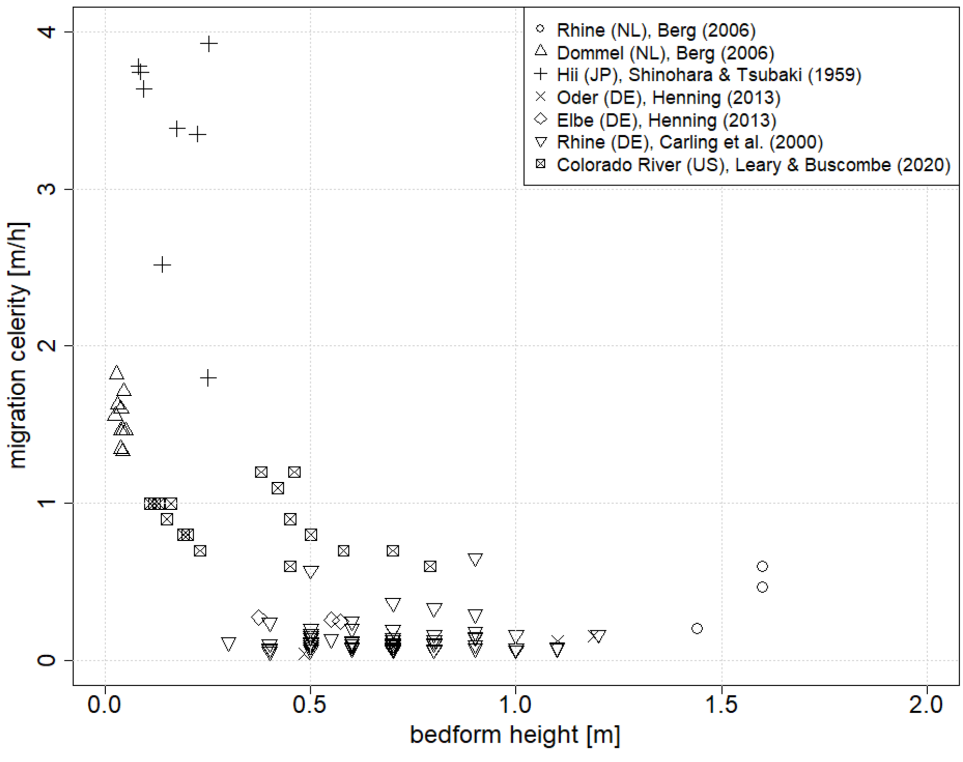

Figure 1. Migration celerities of bed forms.

2. Methods

2.1 Data Acquisition

In bathymetry, MBES is an established method to measure the river bed accurately and area covering. Depending on the intention of the measurement, several measurement settings have to be chosen. Dune tracking measurements require a detailed sampling of the river bed, while the dune field in a certain section of a river is observed in the complete cross direction. This is necessary in order to generate knowledge of the dune driven bedload transport in this specific section of the river.

In this work, Kongsberg Maritime multibeam echosounder EM3002 are used. Combining the echosounder with a GPS antenna (Trimble SPS185) in PDGPS mode and an inertial measurement unit (MRU5+) and an estimation of heading by a Seapath 330 system, measurement points in a consistent reference frame can be obtained. The measurement lines are directed against the flow in order to enable low velocities over the ground. A certain velocity of the vessel is necessary to preserve the maneuverability. With a technically limited sampling rate of the MBES, the along track point distances can be reduced by low vessel velocities. On the River Rhine, a velocity of 1 m/s can be considered low.

2.2 TPU

As depicted in Sect. 3.3, the achievable measurement uncertainty can be used to define an upper limit of a horizontal shift of two neighboring measurement stripes. In this work, the measurement uncertainty is computed in terms of total propagation uncertainty (TPU) of the vessel measurement system. The TPU computation is based on an enhanced approach of (Hare, 1995) and considers 42 components, which contribute to the uncertainty of a measured point and is described in (Wirth 2011). As the direction of all measurement lines is orientated against the flow and considering the relative approach of dune tracking analysis, uncertainty components, which do not differ in two measurement stripes, are removed from the uncertainty propagation. These are e.g. assembly coordinates of the GNSS antenna and the inertial measurement unit, and systematic GNSS deviations.

The TPU of a measured point can be separated in an along track and an across track uncertainty component. Both components are depicted in Fig. 2 in relation to the Beam angle for a measurement with an average depth underneath the echosounder of 3 m. Considering the increasing TPU of the along track component at high beam angles, a consistent 3D point cloud requires a properly chosen direction of measurement lines.

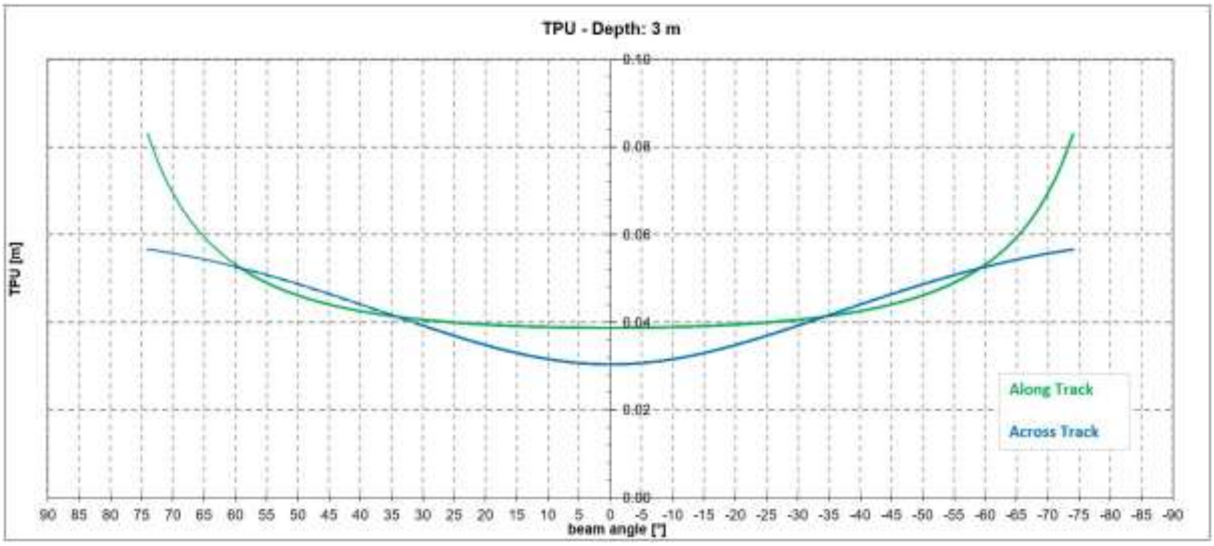

Figure 2. TPU of along track and across track component.

2.3 Dune Simulation

In order to evaluate effects of measurement setting variation on the measurement, a simulation of a synthetic reference dune field is analyzed. Figure 3 presents the procedure of simulation. The synthetic dune field serves as reference and enables the accurate estimation of deviations induced by a variation of measurement settings.
A dunes shape is mainly described by the height and length (see Sect. 1). Synthetic dune profiles can be constructed using these parameters. The simulated dunes are adapted to dune shapes of real measurements. Further parameters that describe the course of the stoss and lee side, the skewness and curvature of the dune, and the height difference of two adjacent dune troughs are applied in order to represent realistic dune shapes. The dune profile consists of the dune main points (trough, crest, trough) and condensing points among these main points. A dune profile with various dune parameters is arranged along a single profile and extended along a third axis to retrieve a 3D point cloud. Finally, the 3D point cloud is transferred to a surface using a Delaunay Triangulation (Fig. 3, right side).
By applying various transformations, the echosounder position in relation to the GNSS antenna position is calculated. The measurement points are projected for every echosounder ping from the echosounder center onto the triangulated surface, calculating the intersection with the Visualization Toolkit (Schroeder et al. 2006). The distance from one to another ping is given by the parameters vessel velocity and sampling rate of the echosounder.
A specific sonar measurement principle is not considered, as no effects during the measurement process like the footprint, but the geometric point distribution of realistic dune shapes is of interest.

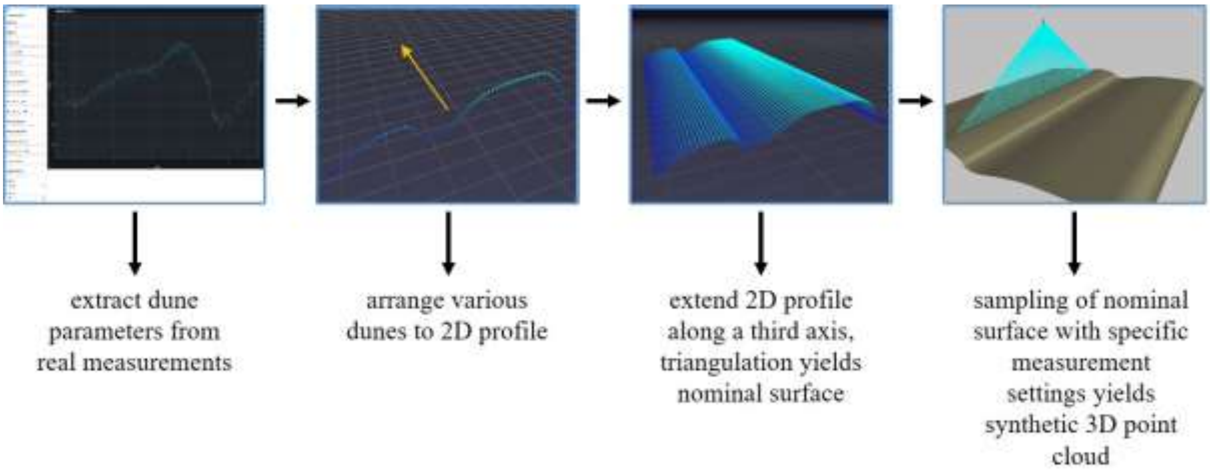

Figure 3. Procedure of dune simulation.

2.4 Determination of Measurement Settings

As bed forms are a dynamic component of the river bed, the geometric and morphodynamic situation at the observation area is unknown. The measurement settings have to be adapted to the current river bed situation. Thus, premeasurements are necessary in order to get an approximate overview of the situation concerning the river bed at that time. Several settings can be derived from premeasurements and are described in the following.

2.4.1 Measurement Line Direction

In order to minimize the required measurement time and possible inconsistencies of the merged 3D point cloud, the measurement lines should be aligned perpendicular to the average slip face orientation of the dunes.
Slip faces can be detected by computing normal vectors as described in (Zhou et al. 2018), whereby the neighborhood within a specified radius of each point is considered. The principal axis of these adjacent points is calculated with the use of covariance analysis. A locally dense accumulation of normal vectors with low inclination is an indicator for a slip face. Using a density-based spatial clustering algorithm, which is described in (Ester et al. 1996) and (Schubert et al. 2017), individual dunes can be distinguished.
Computing the mean orientation of normal vectors per dune yields the mean orientation of each dune. The measurement lines can then be planned perpendicular to the average dune orientation.

2.4.2 Point Distance Along Track

The velocity of the vessel combined with the sampling rate of the MBES affects the point distances on the river bed. Too high point distances on the river bed lead to a loss of detail in

representing the bed forms. Reducing the point distance means an effort. Either an MBES with a higher sampling rate is necessary (the entire multisensory system must be able to resolve this data rate), or the velocity of the vessel has to be reduced.
In order to determine an upper limit of the along track point distance, synthetic measurements with various point distances of the simulated dune field are conducted. The dune parameters, as described in Sect. 1, have to be adapted to typical dune geometries of the actual real measurements. Thus, the dune parameters can be extracted from the vertical sections of the premeasurement along the computed measurement lines, using the dune tracking tool developed in the MAhyD project as used in (Lorenz et al. 2021). The tool is based on the software RhenoBT (Frings et al. 2012) and BedformsATM (Gutierrez et al. 2018).
As the simulated dune field serves as a known reference, the difference of the actual dune volume to the nominal dune volume can be computed. The changes of volume difference due to a decreased point distance are related to the maximum change in volume difference. Starting from the smallest point distance, the point distance is selected after which the volume change exceeds the limit of 20 % for the first time.

2.4.3 Measurement Line Length

In a first step, the measurement lines are limited to the bordering of the dune field, in order to not measure flat parts of the river bed.
The measurement lines can be shortened by considering the bed form migration rate. A second premeasurement having a certain time gap to the first premeasurement is necessary in order to estimate an approximate migration rate, which is typical for the actual morphodynamic situation. The cross-correlation function of vertical sections along the previously computed measurement lines measured at two different times yields an estimation of the migration rate. The measurement lines have to be shortened, so that the geometrical migration induced offset among neighboring stripes does not exceed a defined threshold. This threshold can be defined by considering the along track measurement uncertainty of the measured points.
This measurement uncertainty at the border of an echosounder fan is computed according to Sect. 2.2 for different depths underneath the echosounder and stored as a look up table.

3. Results

3.1 Measurement Line Direction

In Fig. 4, the colored slip faces of dunes are detected according to the method described in Sect. 2.4.1.

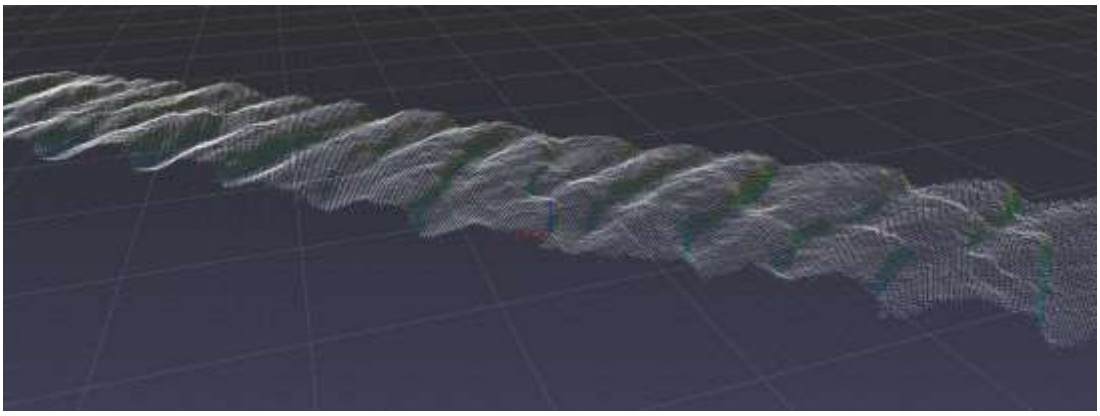

Figure 4. Detected slip faces of dunes in real measurement data.

Considering the bottom depth underneath the echosounder, the distance between two measurement lines is chosen, so that neighboring stripes have a certain overlap (~5 m is recommended to prevent holes in the point cloud, considering the maneuverability of the vessel). Applying this distance, the dune field (dune slip faces colored in green, measurement lines are black) is completely covered (see Fig. 5).

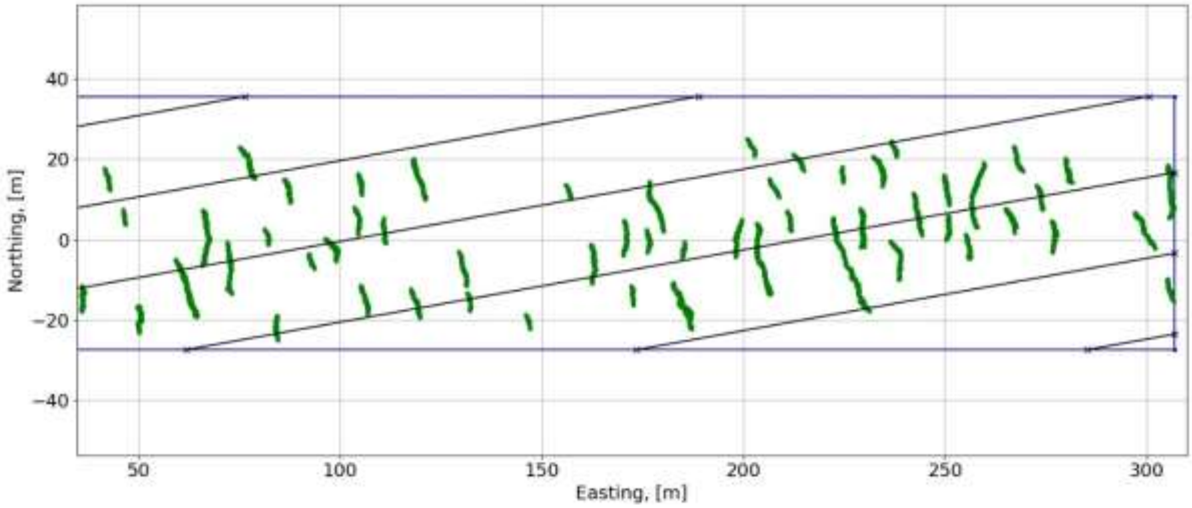

Figure 5. Measurement lines (black) orientated perpendicular to dune slip faces (green).

3.2 Point Distances Along Track

The changes of volume difference due to a decreased point distance related to the maximum change in volume difference (see Fig. 6) yield an upper limit of the along track point distance. In this case, a point distance of 0.06 m should not be exceeded.
Using this information, the velocity of the vessel has to be limited, considering the sampling rate of the MBES.

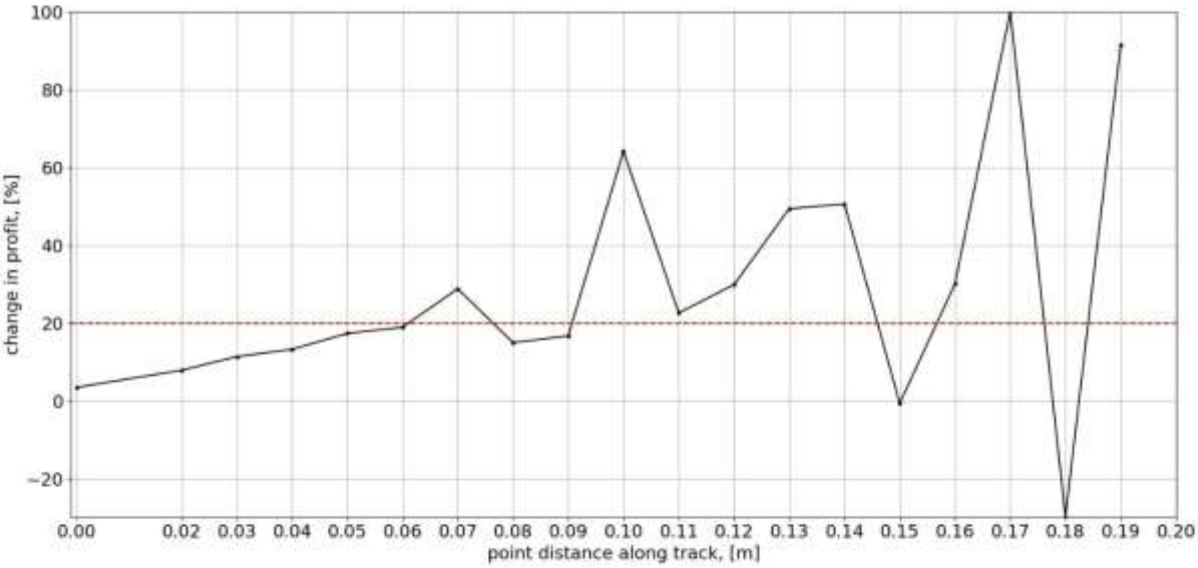

Figure 6. Change in profit due to variation of point distance along track with threshold in dashed red line.

Since the direction of vessel track is orientated perpendicular to the slip faces of the dunes, the point distances on the longitudinal section of a dune approximately correspond to the along track point distances. In this direction, the dune induced height variation is most distinct. Therefore, the along track point distance is more important to be controlled than the across track point distance, in order to adequately represent the bed forms.

3.3 Measurement Line Length

In order to reduce the migration rate induced horizontal offset between neighbored measurement stripes, the length of measurement lines should be limited by taking the migration rate related to the achievable along track TPU into account.
According to Fig. 1, possible migration rates – from $v_{mig} = 0.05, ..., 0.65$ m/h for Germany – are used to estimate the limitation of measurement line length. Given an average depth underneath the echosounder and a maximum beam angle of 70°, the along track TPU comes to $\sigma = 0.069$ m (68% confidence level). A typical speed over ground is assumed to be $v_{sog} = 1$ m/s (velocity during measurement) against and $v_{sogBack} = 4$ m/s with the flow. A turn of the vessel can be performed in the time $t_{turn} = 30$ s. Considering these settings, the length of the measurement line l should not exceed:

$$l = \frac{\frac{\sigma}{v_{mig}} - 2t_{turn}}{\frac{1}{v_{sog}} - \frac{1}{v_{sogBack}}}.$$

As presented in Fig. 7, the length of measurement line can vary in the range from approximately 5000 m to 257 m, applying the previously assumed measurement parameters.

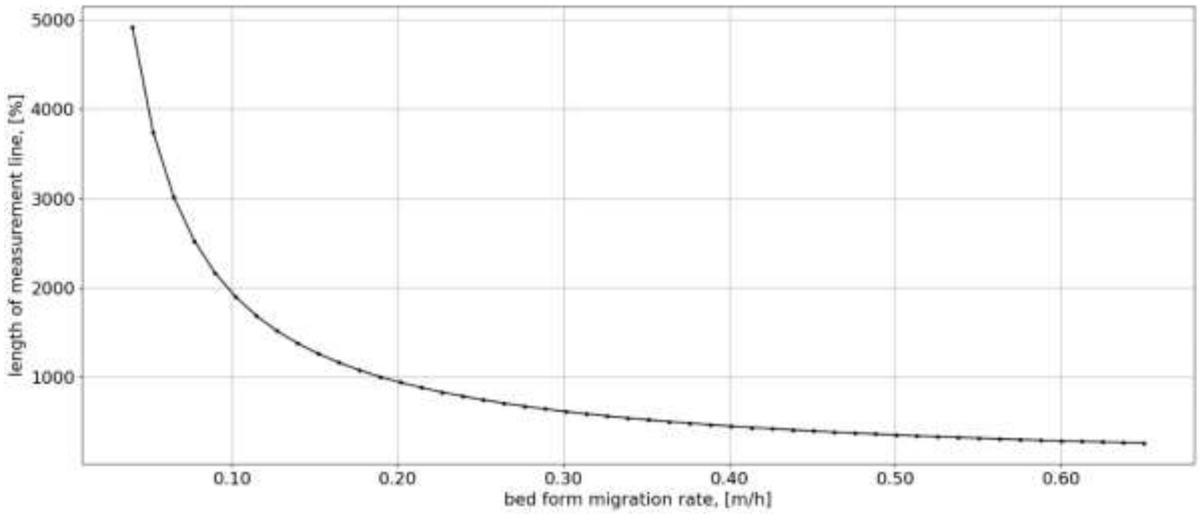

Figure 7. Migration rate induced limitation of measurement line length.

Up to this point, the limitation of measurement line length is a theoretical approach. Under the action of low migration rates, this approach does not seem necessary. However, a data review of the performed measurements on the River Rhine has shown, that noticeable horizontal offsets occur after 1 km long measurement lines. The calculated TPU values are pessimistic, since systematic components of a relative consideration might still be included. Furthermore, the correlations among the individual components are not yet considered. Smaller TPU values would yield smaller limits of line length.

3.4 Workflow

The results presented above lead to a semi-automatic workflow for dune tracking surveys. First important characteristics can be derived from the first premeasurement. Thus, premeasurements are necessary in order to refine the measurement settings by considering these characteristics. A high point density is not important at this stage of survey. A section (max. ~ 750 m) of the river in the complete width should be observed with an increased velocity (max. ~ 3 m/s), stripe by stripe. The most important question is, if and where a dune field is existing. Observing the complete width of the river is time expansive. Due to the information given by the premeasurement, the measurement area can be limited to the boundary of the dune field. As depicted in Fig. 8, information concerning the upper limit of the along track point distance, affecting the velocity of the vessel, and the direction of measurement lines can be retrieved. A second premeasurement is necessary in order to compute the bed form migration rate, which is used to determine a limitation of measurement line length.

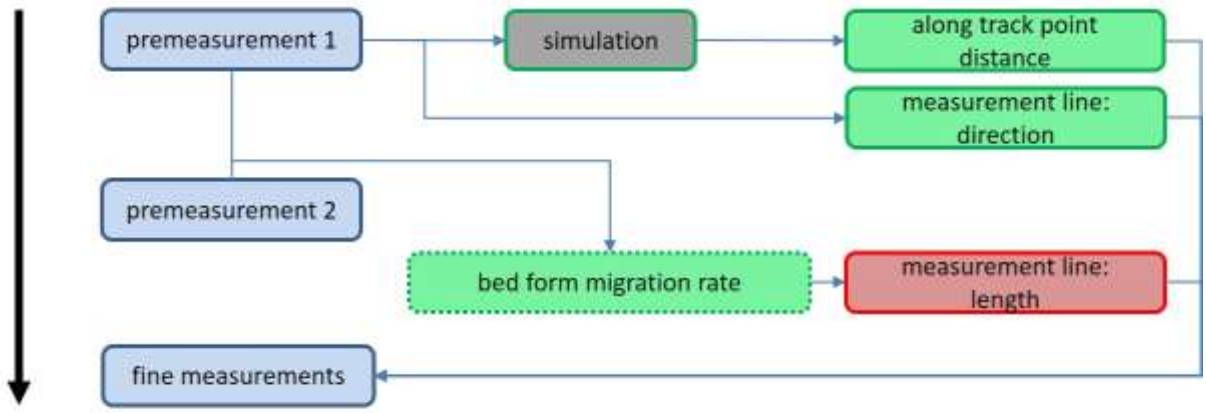

Figure 8. Semi-automatic workflow for dune tracking surveys.

Finally, all measurement settings, that contribute to the consistency and quality of river bed observation are derived and can be considered in further fine measurements. The retrieved 3D point clouds can be used to conduct dune tracking analysis or other morphodynamic analyses. As the limitation of measurement line length seems to be irrelevant, it is colored red. However, this has to be validated in the future. The dotted frame of the bed form migration rate indicates the use of migration rates of other rivers in the example concerning the limitation of line length.

4. Conclusions and Outlook

This paper presented a development of a measurement workflow for dune tracking purposes. Based on theoretical considerations and a simulation, this workflow enables the refinement of premeasurements in order to retrieve a consistent 3D point cloud representing bed form structures with fine measurements. It is possible to automatically determine the limitation of the along track point distance and the orientation of measurement line direction perpendicular to dune slip faces. Due to too pessimistic TPU values, an automatic limitation of measurement line length seems not necessary. A limitation of line length may become relevant again due to an improvement of the TPU approach in the future.

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BIOGRAPHICAL NOTES

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