Comparison of an EKF based Processing System with a Standard Hydrographic Software Tool using a Low Cost Bathymetric Multi Sensor Platform

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Key Words: Bathymetry Mapping, Low Cost, Kalman Filter, Hydrographic Data Processing

SUMMARY

Surveying in shallow waters play a crucial role in mapping harbour areas, coastal habitats and natural environments in coastal and inland waters. In order to enforce the market of survey systems a low cost Multi Sensor System has been developed and together with it the work flow of processing the Single Beam echosounder data that is recorded. The recorded data of the MSS was processed using an extended Kalman Filter and estimating the state of the system for each time epoch. In the light of multiple options of processing on the market available however, a second attempt to process the acquired MSS data was approached which is to store the hydrographic data as a generic sensor format and therefore be able to perform the necessary post processing steps via a commercially available hydrographic processing software. A comparison between the two methods of processing was therefore made and the results show a non-significant advantage in favour of the original post processing method with an extended Kalman Filter. It is assumed that due to the approach of integrating a sensor network into the processing steps the processing quality of the Kalman Filter tops those of a manual post processing activity after generating a generic sensor format file. However, lacks of continuous data sets and a rather unreliable method of determining a reference value to compare with lead to the conclusion that this subject is a matter of further investigation.

1. INTRODUCTION

Within the recent decades geodetic data has been increasingly published and visualised on open-source servers such as OpenStreetMap and it's marine pendent OpenSeaMap (Bärlocher 2012). Following this phenomenon, the importance of dealing with end-user generated geodetic datasets has risen accordingly. For hydrographic surveyors and other institutions in the environmental sector coastal water surveying and mapping play important roles in diverse applications ranging from environmental management to safety of navigation and basic research. The significance of user-generated data platforms, such as OpenStreetMap and OpenSeaMap, has underscored the need of harnessing community-driven information for mapping coastal and inland waters. Recognizing the potential of user-collected data in this context, the importance of validating and processing such data can't be neglected. This paper therefore deals with a comprehensive comparison between an Extended Kalman Filter (EKF) based processing system and a standard hydrographic software tool using a low-cost bathymetric Multi-Sensor Platform (MSS). Furthermore, a novel method of post-processing user-originated data is introduced—converting it to a generic sensor format and importing it into more user-friendly visualization and processing tools for bathymetric mapping.

In response to the growing need for cost-effective solutions to map shallow water areas, a low-cost MSS has been developed (Diederichs 2017). This MSS integrates an Inertial Measurement Unit (IMU), Global Navigation Satellite System (GNSS), and a Single Beam Echo Sounder (SBES) into a bathymetric survey platform that provides an affordable and accessible solution for acquiring bathymetry data in shallow water environments. By acquiring three-dimensional point data in a geodetic coordinate frame, the MSS expands the opportunities of bathymetric data on platforms like OpenSeaMap, empowering an additional possibility to gather geodetic data from underwater areas that can not only be used by surveyors but also sailors and skippers on leisure occasions.

Tests conducted in inland waters have already demonstrated the capability of low-cost survey systems to consistently acquire bathymetric datasets (Kraft 2019). These datasets now undergo two distinct post-processing methods. The first approach employs Extended Kalman Filtering (EKF), combining SBES, GNSS and IMU parameters to estimate state variables of the MSS. This integration enhances the precision of bathymetric data, minimizing inaccuracies induced by sensor outlier measurements during data collection. Notably, the EKF framework allows users to establish a case-sensitive system model, accommodating known inaccuracies set up by the user. During the workflow of post-processing the inaccuracies of each sensor need to be set by the user which yields to the problem that more than just superficial knowledge about the sensor platform is required by the user who – as assumed - does not have a geodetic surveyor's background.

The second post-processing method involves converting MSS results into a generic sensor file format and subsequently processing the data using QPS Qimera, a widely utilized software package in hydrographic surveying. This alternative streamlines the processing workflow, eliminating the need to establish a separate EKF. The dataset can be thoroughly analysed for each time step and exported into various formats, reducing the overall processing effort. This dual-method approach provides flexibility and serves users with varying preferences and expertise levels.

The Generic Sensor Format is a data format originally developed by the company Leidos and released in the year 1995 in order to provide an easy transfer-method for bathymetric data given the high amount of acquisition devices and their corresponding processing software packages (Leidos 2019). The format consists of a list of records which is filled for each ping with the data of the according sounding device. The advantage of parsing the survey data into the GSF is the high compatibility with numerous software packages on the market and it's fairly easily accessible data structure.

To validate the quality and compare the two post-processing methods, we analyse the GSF dataset and the EKF-calculated points statistically. A ground truth dataset has not been available underwater in the open field-testing area, emphasizing the significance of a robust comparison to ensure the reliability and consistency of the bathymetric data. However, first tests of the MSS of the former project in 2018 have been carried out in a swimming pool with pre-marked depths. This allowed the collected data to be compared and validated with independent ground-truth data, nevertheless dealing with moderate accuracy (Kraft, 2019).

The approach of utilizing a Multi-Sensor System for surveying shallow water areas provides an affordable and broadly applicable opportunity for surveyors, particularly those with limited budgets. The comparative analysis of post-processing methods aims to contribute valuable insights into enhancing the efficiency and reliability of bathymetric data, ultimately optimising the reliability of a user data-based mapping system for coastal areas.

2. MULTI SENSOR SYSTEM FOR BATHYMETRIC PURPOSE

A Multi Sensor System (MSS) is defined according to the unique information each type of sensor in the system is able to provide (Luo 1990). Due to the interest in underwater topography the planned and constructed MSS must include sonar, positional and inertial instruments in order to obtain exact points in a three-dimensional space.

1. Motivation

As part of an academic project dealing with shallow water investigations a Multi Sensor Platform has been developed at the HafenCity University in the year 2018. The bathymetry investigation in shallow water areas can be carried out using diverse land surveying tools as well as airborne remote sensing measurement practices, if water visibility allows as such. However, for shallow water areas without a stable access and very turbid waters a bathymetry sensor platform comes in most handy (Mandlburger 2021). For the sake of collecting a lot of data originating from non-commercial but leisure skippers and due to the reason of limited resources the project was taken on under the goal of cost efficiency.

2. Instruments used

2.1.Single Beam Echo Sounder (SBES)

A SBES is fixed below the hull of the platform, measuring the distance between the transducer head and the first threshold exceeding echo. Using the sound velocity of the water (previously derived taking temperature and salinity values from the water) the distance through the water column is determined by

$$d = \frac{1}{2}ct$$

with $t \coloneqq \text{two-way travel time}$ and $c \coloneqq \text{sound speed in water}$

The device used is a single beam from the company Airmar with a vertical resolution of 5 mm and an opening angle of 9 degrees (Airmar 2018).

2.2. Inertial Measurement Unit (IMU)

In order to obtain the platform’s/vessel’s orientation and therefore to correct the distance measurement into depth values an inertial measurement unit must be used on the platform. With the MPU 6050 from Invensense the orientation of the platform according to it’s 3 axes is determined by measuring the turn rate around them as well as the acceleration along them (InvenSense 2018). The IMU is built into the Data logger from OSM (OpenSeaMap 2018).

2.3. GNSS Receiver

For determining the position of the MSS an evaluation kit from Ublox has been chosen. The evaluation kit was as an upgrade to the previously used NEO-6 module and provided a better horizontal accuracy (uBlox 2017).

2.4. OSM Data Logger

The Data logger receives the echosounder data and converts it to NMEA messages. The logger itself is produced by OpenSeaMap and includes the gyroscope and accelerometer in the IMU 6050 from Invensense mentioned above.

3. DATA ACQUISITION

Figure 1: Multi Sensor System on swimming platform

For collecting test data two test runs have been carried out for the Multi Sensor Platform (Figure 1). The principal idea was to obtain one dataset from an area with known and foreseeable water depth and little to no variation in the bathymetry. Another dataset was to be acquired in open water meaning unknown bathymetry and possibly a variation on the sea floor. Both test runs were carried out on a small-scale area with survey lines no larger than 20 to 30 metres.

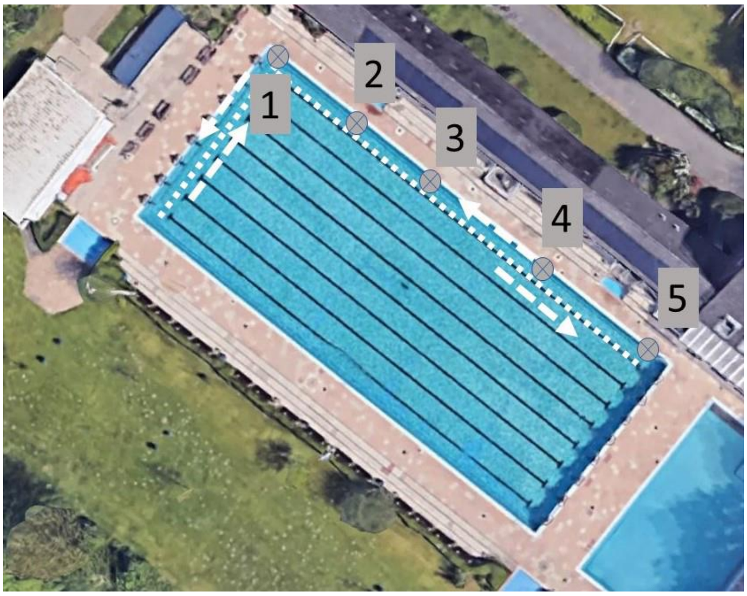

Figure 2: Overview of the test run area

The first test run which was supposed to happen in known waters took place at a swimming pool. With almost no variation on the ground and a comparably precise knowledge of the water depth the MSS measured the pool depth for several lines. The validation of those obtained water depths was examined by taking five points of the pool and take measurements of the depth using a measurement tape.

The second test run in unknown territory took place in a nearby river with the MSS being pulled from a canoe crossing the river three times. The river bed turned out to be substantially flat with less depth variations than expected. Still, the open water test run provided a capable dataset for analysing multiple ways of data processing. Also, after checking the depths obtained by the MSS from the pool in the test run before the system model for the extended Kalman filter could be optimised and applied on the second run.

4. DATA PROCESSING USING A SELF-DETERMINED EXTENDED KALMAN FILTER

Hydrographic data processing is a crucial step in analysing and interpreting data gathered from water bodies for scientific research. This process involves the systematic manipulation, transformation, and quality control of raw hydrographic data obtained through various instruments such as sonar, sensors, and water sampling devices. The primary objectives are to extract meaningful information, correct for errors or biases, and ultimately derive accurate and reliable insights about the studied aquatic environment (Lurton 2004).

Initially, raw data, which includes measurements of water depth, temperature, salinity, and other relevant parameters, undergoes pre-processing to address issues like outliers and sensor noise. Calibration procedures are implemented to ensure data accuracy and consistency. Spatial and temporal interpolation methods may be employed to fill gaps in the dataset and create a continuous representation of the water column (Bjørnø 2017).

a. Extended Kalman Filtering (EKF) in Hydrography

Extended Kalman Filtering (EKF) is a recursive data assimilation technique used for state estimation in dynamic systems. In the context of extracting water depths from sonar measurements, EKF proves valuable in mitigating uncertainties and inaccuracies inherent in underwater sensing (Scheider 2021).

Sonar systems emit sound waves and measure the time taken for the waves to return after bouncing off the seafloor. However, factors like acoustic signal distortion, sensor noise, and variations in water properties can introduce errors in depth estimation. EKF addresses these challenges by continuously updating and refining the estimated depth based on the incoming sonar measurements and a dynamic system model.

The EKF algorithm involves two main steps: prediction and update. The prediction step utilizes the system model to forecast the expected depth, incorporating the dynamics of the underwater environment. The update step then compares the predicted depth with the actual sonar measurement, adjusting the estimate based on the disparity between the two.

By iteratively repeating these steps with each new sonar measurement, EKF provides a real-time, accurate estimate of water depths, compensating for uncertainties and enhancing the reliability of underwater mapping and navigation systems. This application of EKF in sonar-based depth extraction is instrumental in improving the precision and robustness of underwater mapping and navigation technologies (Marchthaler 2017).

b. Dynamic System Model for Multi Sensor Platform

In order to create the system model for the EKF specified for the MSS the observations vector and the state vector needs to be defined. The observations vector as defined is shown below (Eq. 2) and includes all variables that are measured by the available sensors on board.

Equation State vector $\mathrm{x_k}$:

$$x_k = \left(X_k, Y_k, h_k, SOG_k, \mathrm{COG_k}, \Phi_\mathrm{k}, \Theta_\mathrm{k}, \dot{\phi}_\mathrm{k}, \dot{\theta}_\mathrm{k}, \dot{\psi}_\mathrm{k}, \mathrm{a_{x_k}}, \mathrm{a_{y_k}}, \mathrm{a_{z_k}}, \mathrm{d_k}\right)$$

Eq. 1: state vector x of EKF for the MSS

Observation vector z_k:

$$z_k = \left(X_k, \mathrm{Y_k}, \mathrm{h_k}, \mathrm{SOG_k}, \mathrm{COG_k}, \mathrm{p_k}, \mathrm{q_k}, \mathrm{r_k}, \mathrm{a_{x_k}}, \mathrm{a_{y_k}}, \mathrm{a_{z_k}}\right)$$

Eq. 2: observation vector z

With

$X :=$ GPS UTM x-value, Easting [m]

$Y :=$ GPS UTM Y-value, Northing [m]

$h :=$ GPS ellipsoidal height [m]

$SOG :=$ Speed over Ground determined by GPS [m/s]

$COG :=$ Course over Ground determined by GPS [degrees]

$\Phi :=$ Orientation around Y-axis of MSS (Roll)[deg]

$\Theta :=$ Orientation around X-axis of MSS (Pitch)[deg]

$\dot{\phi} :=$ Change of Roll-Angle [deg/s]

$\dot{\theta} :=$ Change of Pitch-Angle [deg/s]

$\dot{\psi} :=$ Change of Heading-Angle [deg/s]

$\mathrm{a_x} :=$ Acceleration along X-Axis of MSS [m/s^2]

$\mathrm{a_y} :=$ Acceleration along Y-Axis of MSS [m/s^2]

$\mathrm{a_z} :=$ Acceleration along Z-Axis of MSS [m/s^2]

$p :=$ turning rate around X-Axis of body-firm coordinate system [deg/s]

$q :=$ turning rate around Y-Axis of body-firm coordinate system [deg/s]

$r :=$ turning rate around Z-Axis of body-firm coordinate system $[\mathrm{deg}/s]$

The state vector meanwhile (Eq. 1) presents all variables describing the state of the MSS. It is important to point out that the values of the state vector do not align with those of the observation vector even though the variable is named equally.

After defining the state and observation vectors both functions are linearized so that the values can be iteratively estimated. While defining the error model the inaccuracies given by the sensors' manufacturers and the noise values are represented by matrices within the algorithm. Those values for the noise model are especially hard to define for the first time and after the test run in known waters these were adapted once more. A more detailed description of the system model and it's entries can be found in Kraft 2019.

5. DATA PROCESSING BY CONVERTING BATHYMETRIC DATA INTO GENERIC SENSOR FORMAT

The Generic Sensor Format (GSF), developed by the company Leidos, is a standardized file format designed for the efficient transfer of hydrographic survey data. GSF serves as a universal framework, encompassing diverse sensor data encountered in hydrographic surveys, including bathymetric, geophysical, and geospatial information. Its primary purpose is to facilitate seamless interoperability between different hydrographic survey systems, sensors, and software applications (Leidos 2019).

a. Advantages of Generic Sensor Format (GSF)

GSF offers several advantages, such as promoting data consistency, reducing the need for custom data converters, and enhancing collaboration within the hydrographic community. By encapsulating a comprehensive range of data types, including navigation details, sensor parameters, and geospatial references, GSF ensures a comprehensive representation of survey data. The most comfortable property of the Generic Sensor Format however is it's compatibility for most hydrographic post processing software currently on the market which presents the main reason for this choice.

To collect or transfer hydrographic data via a GSF file, survey systems with compatible sensors recorded measurements, and the acquired data is stored in the standardized GSF format. The process of storing GSF data does not necessarily happen online during the survey but can also be carried out offline by the processor himself which e.g. allows him to fit in the desired sonar information which was acquired by other instrument types. The GSF file can then be easily shared and utilized across various hydrographic software tools or systems that support this universal format.

However, potential obstacles may arise, including compatibility issues if survey equipment or software lacks GSF support, and variations in GSF versions that can pose challenges in data interpretation. Adherence to GSF standards and thorough metadata documentation are crucial to overcoming these challenges, ensuring efficient data exchange and collaboration within the hydrographic community.

b. Converting SBES Data to GSF-Data

In the conversion of Single Beam Echosounder (SBES) data into a Generic Sensor Format (GSF) file, the process involves populating different records within the GSF structure to encapsulate various sensor-specific information. GSF files are constructed by filling records for inertial movements, sonar measurements, geodetic parameters, potential time delay, time synchronization, position measurements, and more. Each record corresponds to the specific sensor used during hydrographic surveys, ensuring a comprehensive representation of the collected data (Leidos 2019).

In the case of Single Beam Echosounders, which provide depth measurements for a single point directly beneath the survey vessel, a dedicated record is created within the GSF file to accommodate the relevant data. This record captures raw measurements from the SBES, including depth soundings and associated parameters.

One of the strengths of the GSF format lies in its flexibility to accommodate data from various sensors on board a platform or within a multi sensor system. Whether it's data from a multibeam echo sounder, a Single Beam Echosounder, or other sensors, all raw measurements can be seamlessly integrated into the GSF file within their respective records.

To facilitate the parsing of raw information into the GSF file, a Python wrapper for a C# library is employed. This wrapper enables the opening of a GSF file and facilitates the systematic filling of records with the necessary information. This integration of programming languages ensures a robust and efficient conversion process, allowing researchers and hydrographers to integrate diverse sensor data into a standardized and versatile GSF file format (UK Hydrographic Office 2024).

During the process of parsing the recorded SBES data into the generic sensor format together with positional and orientation measurements the gsf records were filled with a python code using the discussed wrapper for the gsf library. Notably, the SBES Data is not represented by a single beam data record itself so a work-around needed to be implemented: the record for multibeam echosounders were reviewed instead by filling each ping with only one beam representing the single beam data record.

c. Software used for Hydrographic Processing

A widespread option of hydrographic processing and data validation software options are available on the market, providing solutions to diverse needs within the field. Notable among them are QPS Qinsy, HYPACK, and CARIS HIPS & SIPS. QPS Qinsy, in particular, stands out due to its extensive adoption in both academic research and commercial applications. Its widespread usage underscores its reliability and robust feature set (Kazimierski 2023).

Choosing commercial software like QPS Qinsy offers distinct advantages over self-made processing tools such as the Extended Kalman Filter written for the MSS in this project.

Commercial solutions provide a user-friendly interface, comprehensive support, and continuous updates, ensuring compatibility with evolving hydrographic standards. These features streamline workflows, enhance efficiency, and offer a level of reliability and validation crucial for accurate hydrographic data processing. In contrast, self-made tools may lack the sophistication and broad applicability found in established commercial software, potentially introducing complexities and limitations in the processing pipeline.

6. RESULTS

a. Ground-Truth measurements compared to EKF Post Processing and Dataset generated from GSF

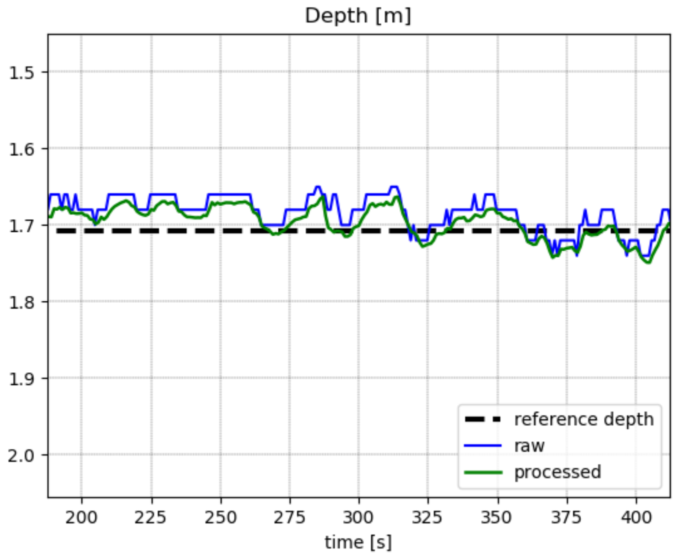

Figure 3: SBES Data raw vs EKF processed vs reference depth

After carrying out the test runs and determining the system model for the MSS's Kalman Filter the measured values of the MSS were filtered and compared to the reference depth of the pool of 1.707 m. This depth serves as a true value for all measurements discussed in this paper in order to validate the experiments and to quantify the accuracy of each processing method. In Figure 3 one of the survey lines' depth results can be seen together with the filtered values from the EKF. In Figure 4 the same survey line appears during the process of manually editing the points in QPS Qimera after the data has been parsed into a gsf file.

The survey line presented in those images shall serve as an example of this project's outcome. During the EKF processing the enhancement of all sensor's properties, inaccuracies and (mostly) raw measurements leads an estimation of the MSS's state which represents the corrected version of the sensors' measurements themselves. The processed values appear to smooth the raw data however not like a typical smoothing filter but with a tendency to include behaviour of the MSS which is not visible in the depth data only. For sure, the processed data displayed depends heavily on the noise matrix applied to the Kalman Filter and would look more different if it were for a less trusty MSS and a more trustful Filter.

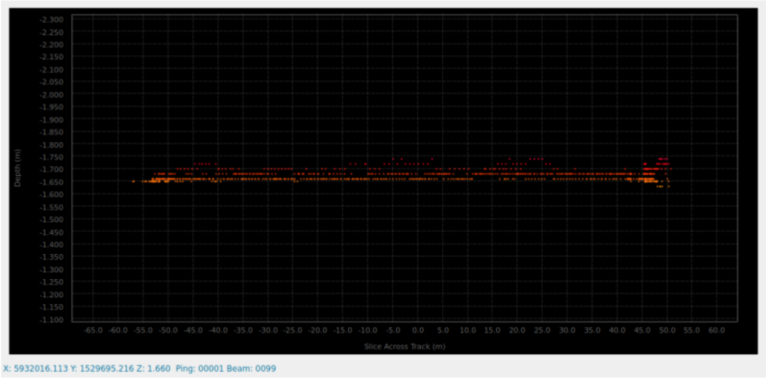

Figure 4: SBES Data parsed into GSF

The same dataset being parsed into gsf and processed with QPS Qimera appears rather chooppier than the EKF Dataset. Due to the low resolution of the Single Beam Echosounder of 0.5 cm the depth measurements are represented by multiple steps whereas the EKF data is represented by a smoother line due to it's representation focused on the whole sensor-set and the time scale which contains a higher resolution. In the GSF dataset point processing is very much intuitive but speculative as well since the outliers are easily detectable and deletable by hand. Other points however laying around the mean value, must be rejected or accepted in a highly speculative manner.

b. Differences of two Post Processing methods: Statistical Approach

This section delves into the comparative assessment of post-processing outcomes using the Extended Kalman Filter (EKF) and the Generic Sensor Format (GSF) method, considering a reference depth of 1.707 meters from the pool for validation.

The datasets from the other survey lines underwent the very same processing methods via EKF and GSF-parsing as described before. In total, four survey lines have been recorded with three along the pool length and one across.

With a measured referenced depth of 1.707 m, each processed survey data was analysed according to it's best fit to this ground truth value via

$$Acc = \frac{d_{ref}}{d_{ref} + \Delta d}$$

With Δd representing the absolute difference between the mean survey line value and d_{ref}.

Subsequently, a statistical analysis was conducted to determine the accuracies of these post-processed datasets. The results are presented in Table 1, highlighting the differences in accuracies between the two post-processing techniques.

Survey Line	EKF	GSF
Line 1	98,73 %	99,39 %
Line 2	99,23 %	99,03 %
Line 3	98,62 %	98,47 %
Crossline	98,55 %	95,27 %

Table 1: Accuracy Comparison between EKF and GSF Methods

The EKF-processed data displays slightly higher accuracy across all survey lines except Line 1. In general, the values for the accuracy do not differ for a significant amount. The very largest difference can be seen in the crossline in which the accuracy of the GSF parsed dataset ranges at 95.27 % whereas the EKF processed data receives an accuracy value of 98.55 %.

Notably, the vertical resolution achieved through EKF processing ranges far below that of the GSF method. The EKF's ability to provide a higher level of detail in the vertical domain contributes to the smoother representation of the dataset which is evidently visible in the results.

Additionally, it's important to highlight the process of point-erasing in QPS Qimera, which lacks statistical validation and is instead carried out manually by a human operator. This subjective approach introduces an element of speculation, as the human operator decides which points to retain or remove based on their judgment. In contrast, the EKF method offers a more automated and statistically grounded process.

While the accuracy difference between the EKF and GSF methods is marginal, it remains consistent across all surveyed lines. This consistency reinforces the subtle but persistent advantage of the EKF-processed data in accurately representing the underwater environment.

7. CONCLUSION

In this paper two post processing methods for a Single Beam Echosounder dataset have been presented and compared to each other in terms of processing quality. During the processing method of the EKF all sensors' properties and systematic inaccuracies are put together as well as the non-systematic errors evolving from white noise or inconsistent and wrongly applied methods during survey. In the end a "state" of the Multi Sensor Platform is estimated for each timepoint including the chosen state variables. Another post processing method is presented in which the echosounder data together with other sensor information is parsed into a file format that is easily importable into commonly used commercial hydrographic software. After following both workflows for the same datasets, the results show a slight advantage of the EKF processing method, however the significance of the differences can't be fully outlined. It is still to conclude that the EKF solution appears to be more reliable regarding the true state of the MSS. The reason of this is assumed in the nature of the Kalman Filter itself. While a conventional filtering method – as well as the method of the gsf parsed error erasing process –

uses mainly or only the data available from the sensor which is to be observed the Kalman Filter estimates a state of the whole system. While this can induce singular sensor observations to drift off for a short amount of time the estimated values of the system and the constantly updating Kalman Filter lead to a correction overall and therefore to a higher quality in each single observation as well. The counterpart of including all parameters is then the observation and analysis of a sensor, in this case the Single Beam Echo Sounder, without taking other observations into account. Rejected measurement points are more likely to be falsely rejected as well as accepted points are likely to be falsely accepted.
While these conclusions are not significantly justified by the observations from the processing methods and their comparison it is also fair to say that the meaningfulness of this test in particular has it’s limits especially regarding the data size and the accuracy of the ground truth data itself. The reference depth was measured with a measurement rod from the side of the swimming pool which leads to the assumption that human errors could be involved in the determination of the ground truth data. The standard deviation of the five measurements on a pool that is supposed to contain equal depths at each point is listed at 1.67 cm with the highest and lowest values ranging 5 cm apart, this makes it easy to suspect an unreliable reference to be compared with. Reaching further, a dataset to process depends largely on the quality of the data acquisition which also was at a pioneer state for this project’s MSS.

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BIOGRAPHICAL NOTES

M.Sc. Markus Kraft is a research associate at the HafenCity University Hamburg. He has a background in Oceanography and Hydrography. Since 2019, he is a member of the Hydrography and Geodesy group as well as DHyG (German Hydrographic Society). His current research topics are the integration and analysis of multibeam echo data on an autonomous underwater vehicle.

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Prof. Dr.-Ing. Harald Sternberg is professor for Hydrography and Geodesy at the HafenCity University Hamburg since 2017, before that he was professor for Engineering Geodesy and Geodetic Metrology since 2001. Beside his research activities in the area of hydrography, indoor navigation and data-driven analysis, he was the vice president for teaching and studies at the HCU for 13 years. He is a member of the DVW (in the past he has chaired the Multi-Sensor-Systems working unit) and of the DHyG, and was delegated to the IBSC (FIG/IHO/ICA international board on standards of competence for hydrographic surveyors and nautical cartographers) by the FIG.

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