DOI: 10.23784/HN114-03

# Comparison of MEMS and FOG-based inertial navigation systems for hydrographic applications

*An article by CHRISTIAN JOHN VIETHEER*

**Accurate and reliable navigation is a major key for modern hydrographic surveying. Especially in conditioning environments, inertial navigation systems (INS) are indispensable to assure high-qualitative bathymetric data. This article aims to compare the rising technology of MEMS (microelectromechanical systems) with a high-end FOG (fibre-optic gyro) by evaluating data acquired simultaneously under equal, realistic conditions within hydrographic applications. Therefore, MacArtney Germany equipped two survey vessels with a complete multibeam echo sounder (MBES) survey configuration and conducted tests at the Port of Hamburg. Different INS data sets were merged with respective MBES soundings and transferred into interactive webmaps and statistical plots, providing a basis for a meaningful interpretation of the motion and positioning efficiency of the tested INS.**

INS – inertial navigation system | MEMS – microelectromechanical system | FOG – fibre-optic gyro

**Author**
Christian John Vietheer works as a hydrographer at GEO Group Offshore in Stralsund.

c.vietheer@geogroup.de

## Introduction

INS provide two key values for an accurate computation of underwater surfaces: motion and position. Swath systems require accurate motion data of a survey vessel when moving through water. Without any motion compensation a bathymetric surface would be fully distorted. A reliable computation of precise trajectories is necessary to localise acoustic footprints accurately, especially when GNSS systems fail e.g. in multipath environments or under bridges. Since INS can be cost-intensive investments for hydrographic vessels, hydrographers cannot simply base their decision for a certain product on manufacturer's data sheets but rather on information that refer to real case scenarios.

This research is inspired by a study of the UK Hydrographic office, conducted by David Parker and Duncan Mallace (2005), which focuses mainly on the comparison of motion sensors.

To make raw INS data comparable, it is essential to log data from each sensor simultaneously, whenever sensors experience the same movement. In contrast to artificial testing conditions, it was decided to acquire real world data within realistic scenarios like under-bridge surveys facing strong swells. Multibeam soundings were merged with different INS sensor data to compute various bathymetric surfaces, which differences only depend on the motion respectively positioning performance of a respective sensor, since all systems were aided by the same GNSS device and combined with the same multibeam echo sounder data set. Main aspects to be discussed are the quality of motion (roll, pitch, and heading) under dynamic conditions, the quality of the inertial position (and altitude) during GNSS outages respectively shadowing and the quality of bathymetric surfaces based on specific sensor data sets.

In this research, the MEMS-based sensors Apogee-E (high-end), Ekinox2-E (mid-range) and the Ellipse2-E (low-cost) from the manufacturer SBG Systems are compared to the fibre-optic sensor Phins III by IxBlue (fig. 1). All systems are strapdown inertial measurement units (IMU) consisting of three orthogonally mounted gyroscopes and accelerometers. Running internal Kalman filters to increase the performance parameters, they provide position, heading, attitude, speed and heave. All systems have to be aided by an additional GNSS system.

GNSS aiding for all systems was realised with the AstRx U-MARINE GNSS receiver. MBES data were


**Fig. 1:** Sensor layout

Source: IxBlue, SBG Systems, Septentrio, Teledyne acquired with the Reson Seabat T50-P, an ultra-high resolution portable sonar system.

Advantage of FOG-based systems is the non-existence of any movable parts due to the use of the Sagnac-effect of light waves in fibre-coils. Beside the obviously lower performance parameters, great advantages of MEMS are especially their low prices and sizes, making INS affordable even for »small« surveying companies. However, MEMS require a dual-antenna GNSS system to compute accurate heading data (due to comparably high drift rates and noise characteristics), while FOGs are capable of computing the heading without external aiding (Lu et. al 2015).

## Survey preparation

As for any mobilisation of hydrographic vessels, preparation steps consisting of a sensor-alignment survey, the installation (interfacing and configuration), and a proper calibration had to be conducted in advance. For this research, it was decided to build a new installation especially designed for sensor testing purposes (fig. 2). This kind of installation was a new attempt to design a mobile testing system, which can easily be transported to any place and mounted on different vessels without the necessity to repeat alignment surveys.

Previous to any data recording or calibration, all systems of the survey layout had to be interfaced using a local network (fig. 3), configured regarding in- and outputs, synchronised using pulse per second (PPS) and merged within one acquisition and logging software.

During all operations, RTK correction data were received via the NTRIP caster axio-net to provide cm-level accurate real-time GNSS positions. The GNSS receiver in these tests was operated as rover using GPS, GLONASS, Galileo and Beidou satellite positioning systems. To compute precise positions, the INS do not only require valid lever arms to the GNSS phase centre but also the selection of a proper motion profile to enhance their internal algorithms. For example: The marine operation mode does intelligently »know« that significant

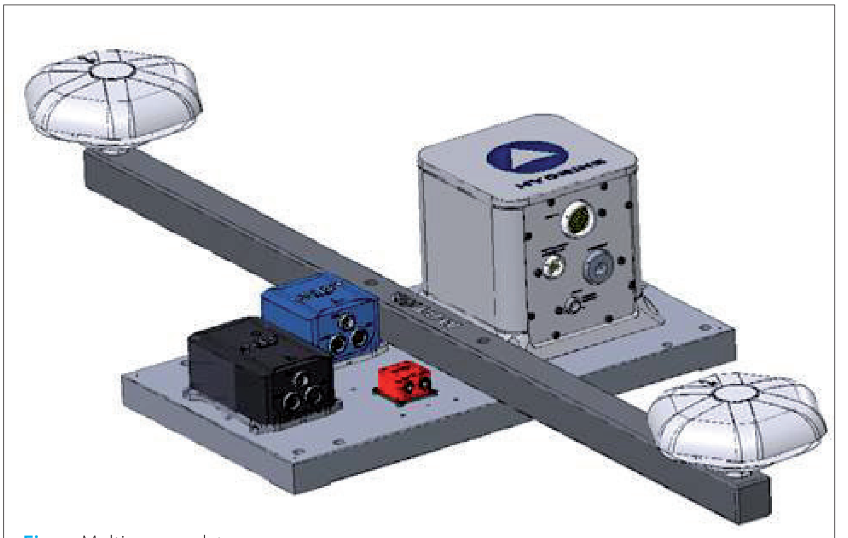

**Fig. 2:** Multi sensor plate

height jumps should be rejected, since a vessel moves over a more or less stable surface (apart from waves of course). The used hydrographic acquisition software was Teledyne PDS. All different sensors have been implied in PDS as various, possible data sources for bathymetric surface computations.

Since aim of this research is to focus on the effects of the INS performance on the bathymetric quality, it was highly relevant to minimise every error source due to proper system calibration. Attitude related errors (pitch and roll misalignments) can be reduced by conducting a so called patch test, while refraction errors can significantly be reduced by applying valid sound velocity profiles to introduce beam refraction correction.

## Execution

In order to investigate the sensor performances, several hydrographic (and automotive) survey scenarios were carried out with the effort to simulate typical river, harbour- and construction site surveys.

The inertial positioning performance has been tested in poor GNSS environments within under-

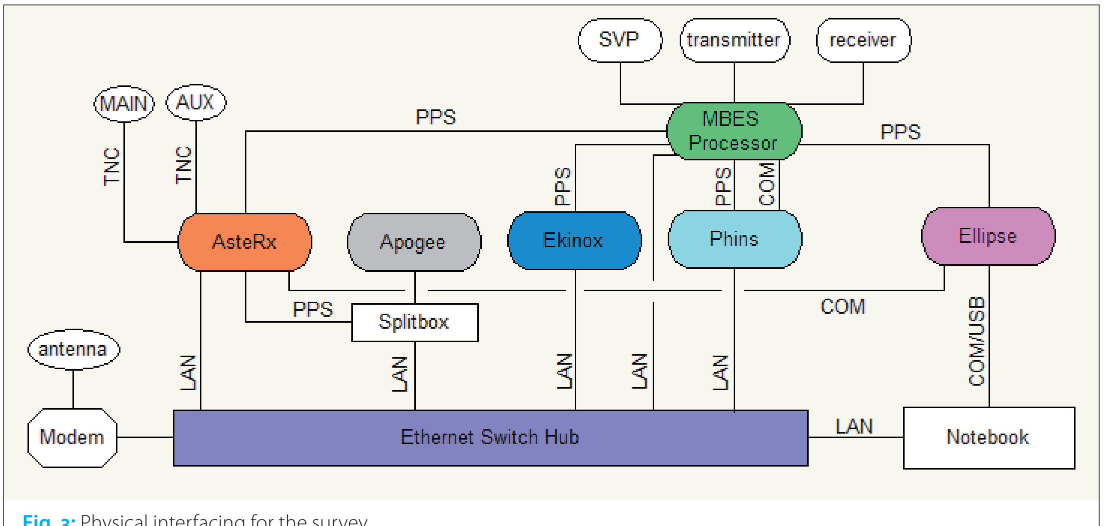


**Fig. 3:** Physical interfacing for the survey

bridge surveys and close to pillars under conditions of signal shadowing, GNSS dropouts and multipath effects. The attitude performance (roll, pitch) has been tested under open-sky conditions using the swell, induced by container ships and boats in the Hamburg port area when passing the survey vessel, to simulate erratic motion patterns as they could be faced under harsh weather conditions e.g. in coastal surveys.

Tests were conducted at five days of field work in Berlin and Hamburg. While water depths in Berlin (Verbindungskanal) are very low and thus suitable for positioning tests but not for motion tests, the motion performance was tested mainly on the Elbe in Hamburg due to water depths of more than 20 metres in some areas, which are (almost) comparable to average depths of the coastal regions of the North and Baltic Sea.

## Processing

Focus of this research is not only to investigate how efficient the sensors perform during real-time acquisition but also how strong artefacts or distortions, e.g. due to low performances during GNSS outages, could be improved due to post-processing of INS data and if e.g. bathymetric data, based on low-cost navigation solutions, could be almost as qualitative as computations based on high-end systems when importing post-processed-kinematic (PPK) INS data as basis for advanced underwater floor computations. Processing in this case means basically that a Kalman filter runs over the data in time-forward and -backward direction and then combines different solutions to minimise jumps and spikes that might occur e.g. when a valid GNSS position drops in again after signal loss under a bridge. For post-processing the manufacturer's own software products SBG Qinertia and IxBlue APPS were used. In this research, due to its broad and easy manageable opportunities, it was decided to process bathymetric point cloud data and export layers for the final evaluation within the additional cleaning software BeamworX AutoClean (fig. 4). Advantage of this software is that necessary configuration changes (e.g. selection of sensors) for these tests can easily be done previous to any raw INS data import and further that automatic filters treat each sensor data set equally.

## Evaluation

Different methods of presenting, visualising and comparing hydrographic survey results as well as raw position, altitude, motion and heave data have been chosen: Most meaningful are interactive webmaps that present bathymetries, computed on basis of the different inertial sensor data in real-time as well as after post-processing (loosely and tightly coupled filtering) of position and motion data. Beside a visual interpretation of the pure bathymetry, adequate spatial quality measures allow more detailed insight into the sensors qualitative performance in combination with multibeam echo sounders. These are the height of the 95 % confidence interval (vertical standard deviation of points per grid cell), the survey accuracy conformance (e.g. IHO special order) and the difference surface (deviations to a reference surface; here based on processed data of the Phins).

## Results related to positioning

All in all, from the huge amount of bathymetric data, selected areas and scenarios for investigating the positioning and motion efficiency of each INS have been chosen. Not all of the results that can be found under www.ins-test-macartney.de will be presented in this article but two exemplary scenarios will be demonstrated in the following to give brief insight into some meaningful analyses.

The example scenario focusing on the positioning performance of the INS is located right underneath the Elbbrücken in Hamburg (fig. 5). Due to the massive steel of two bridges that had to be passed, the INS had to compute positions during GNSS outages just based on their internal gyros, accelerometers and filters.

Inspecting the pure bathymetry, the fibre-optic system (Phins) provides trajectory data that lead to smooth and undistorted surfaces even without post-processing. Data of the high-end MEMS

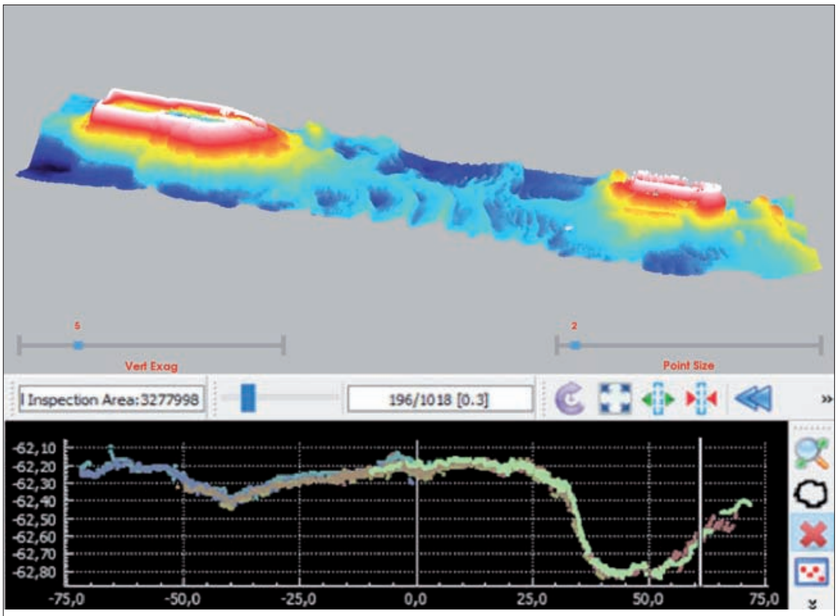


**Fig. 4:** Bathymetric point cleaning in AutoClean

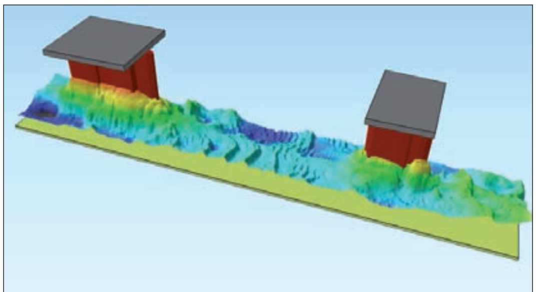

**Fig. 5:** 3D-model of bathymetry under a bridge

**References**

Parker, David; Duncan Mallace (2005): A Direct Comparison of the Motion Sensors' Performance from the 2005 Common Dataset; Shallow Survey 2005, 4th international conference; high resolution surveys in shallow water, Plymouth (UK), 18 pp.

Lu, Baofeng; Qiuying Wang; Chunmei Yu; Wei Gao (2015): Optimal Parameter Design of Coarse Alignment for Fiber Optic Gyro Inertial Navigation System; Sensors, Vol. 15, Nr. 7, pp. 15006–15032

**Further information**

www.ins-test-macartney.de

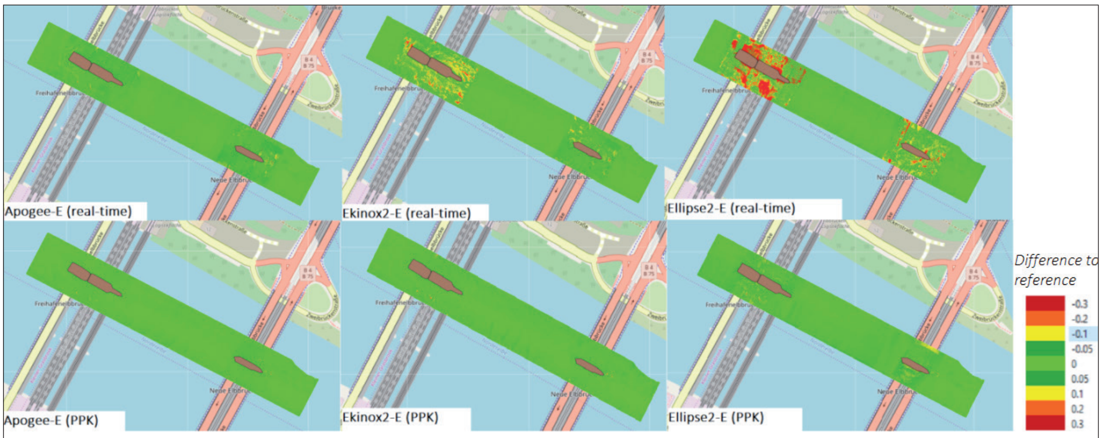


**Fig. 6:** Difference surfaces (Elbbrücken)

Apogee lead to very slight, negligible artefacts, while data of the mid-range MEMS Ekinox leave small shifts of the bathymetric computation under both bridges. Both latter surfaces appear to be completely smooth and improved after importing post-processed trajectory data as computation basis and are finally as qualitative as the Phins-based surface. While obvious distortions on the surface, based on the low-cost system Ellipse, can be significantly dampened due to INS post-processing, this sensor can still not reach results of comparable quality. An inspection of the 95 % confidence interval for each computation reflects these findings. For every computation, post-processing of trajectory data lowers the surface grid cell standard deviations (STD) to more precise values, most effectively for the MEMS sensors, since their real-time computations are of comparably lower precision. Besides the Ellipse, where some distortions still remain, post-processing of the upper-grade MEMS leads to FOG-comparable results. This fact demonstrates that lower-grade MEMS can still not reach the same quality as fibre-optic systems in real-time, though a simple and fast INS processing can almost compensate this disadvantage. When using the relatively strict HPA (Hamburg Port Authority) standard as accuracy norm, it is obvious that under the open sky all systems provide data that lead to 99 % accuracy conformance; even the low-cost system Ellipse. In the critical under-bridge areas, only the Apogee performs almost as satisfying as the Phins. Ekinox and Ellipse remain beyond those results in real-time, while post-processing increases their accuracy conformances for the complete area up to comparable values. Though the Ellipse, with 93 %, remains still below those qualities, the advance compared to a GNSS-only based positioning solution (approximately 72 %) is evident. The analysis of the difference surfaces underlines these statements and shows very low deviations under the bridges for the Apogee, stronger for Ekinox and obvious for Ellipse real-time solutions (fig. 6). These deviations almost disappear after the import of processed trajectories.

For inspecting the positioning performance of each sensor directly, an exemplary survey line, passing both bridges of the surveyed area and lasting for ca. 150 seconds in total, was chosen. Position differences of all sensors are related to positions of the post-processed Phins-trajectory (fig. 7).

As expected, most significant position differences appear for the Ellipse. Though drifts are recognised, all tested MEMS perform »below« respectively better than specified by their datasheets (see table).

| RTK outage | 1. dropout (30 s) | 2. dropout (25 s) | Specifications |
|---|---|---|---|
| Apogee | 37.8 cm | ~ 12.5 cm | 17 cm (10 s) |
| Ekinox | 131.4 cm | ~ 17.5 cm | 300 cm (30 s) |
| Ellipse | 742.15 cm | ~ 450 cm | 100 cm (10 s) |

| PPK outage | 1. dropout (30 s) | 2. dropout (25 s) | Specifications |
|---|---|---|---|
| Apogee | 2.21 cm | < 2 cm | 3 cm (10 s) |
| Ekinox | 2.54 cm | ~ 2 cm | 5 cm (10 s) |
| Ellipse | 17.64 cm | ~ 2.2 cm | 10 cm (10 s) |

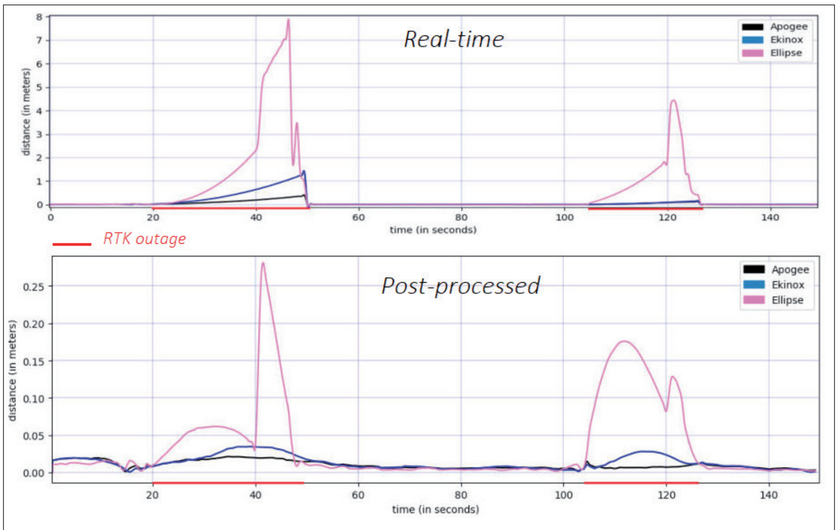


**Fig. 7:** Real-time and post-processed position differences

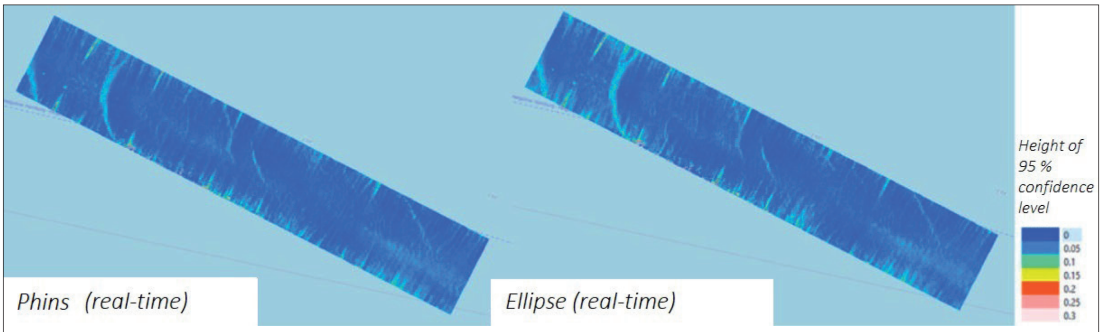


**Fig. 8:** 95 % confidence layers (Blankenese)

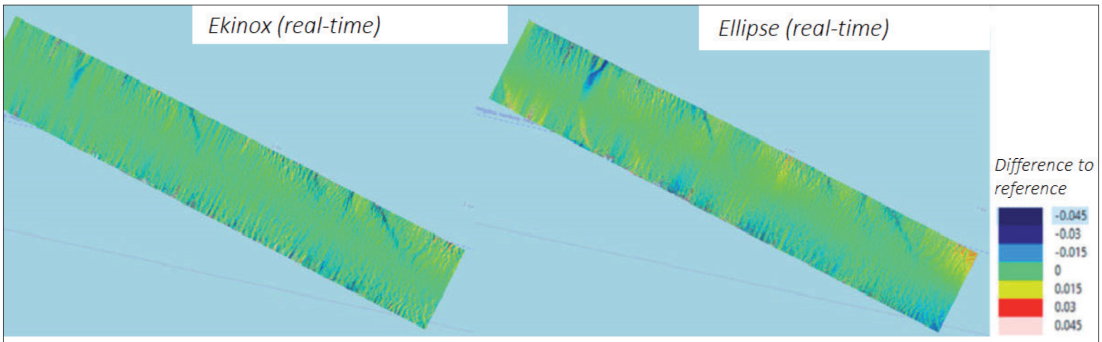


**Fig. 9:** Difference surfaces (Blankenese)

**Project partners**
This project was realised by MacArtney Germany in cooperation with Nicola Engineering and WSA Berlin, who provided survey vessels and skippers for the tests. Engineers of SBG Systems supported regarding sensor configuration and post-processing issues. The project was part of the Master's thesis »Comparison of MEMS and FOG based Inertial Navigation Systems for Hydrographic Applications: Inspection and Improvement of Bathymetric Data Sets Quality« at the Hamburg HafenCity University and was supervised by Prof. Dr. Harald Sternberg.

Though smoothing the trajectory, some of the noises, as measured in real-time, can still be detected after post-processing but are greatly enhanced. Since the drift during the first, almost similar lasting dropout appears to be much stronger for every MEMS, it can be derived that an initial impulse during dropouts, due to induced movements of the vessel (e.g. caused by waves), might be the reason for the strength of a drift.

## Results related to motion

Every surface computation of the following test example (field near Blankenese) is based on the same positioning source (Phins; real-time) in order to focus on the effects of the sensors motion performances on bathymetric quality only. Within these kinds of shallow water and open sky surveys, none of all computations show any artefacts or obvious differences. In the pure bathymetric analyses, even the Ellipse produces reliable data and satisfying high quality. Highest precision is still achieved with the Phins. However, grid cell standard deviations of every lower priced MEMS are only about 1 to 2 mm above. Since real-time qualities are high, it is clear that motion post-processing is not necessarily required and increases the quality only very slightly. Post-processing would be only recommended if distinct errors are recognised. Hence, it can be stated that all tested motion sensors deliver similar precision and quality in bathymetric computations in this specific scenario (even the low-cost sensor). Other factors like the nature of the environment, the refraction in water and the multibeam system itself appear to affect the achieved surface precision more distinctly. Looking at the 95 % confidence layers (fig. 8), it is hard to differentiate between Ellipse and Phins based surfaces (easier detectable when switching directly in the interactive webmap). Both mentioned computations provide average grid cell standard deviations below 2.5 cm (fig. 8).

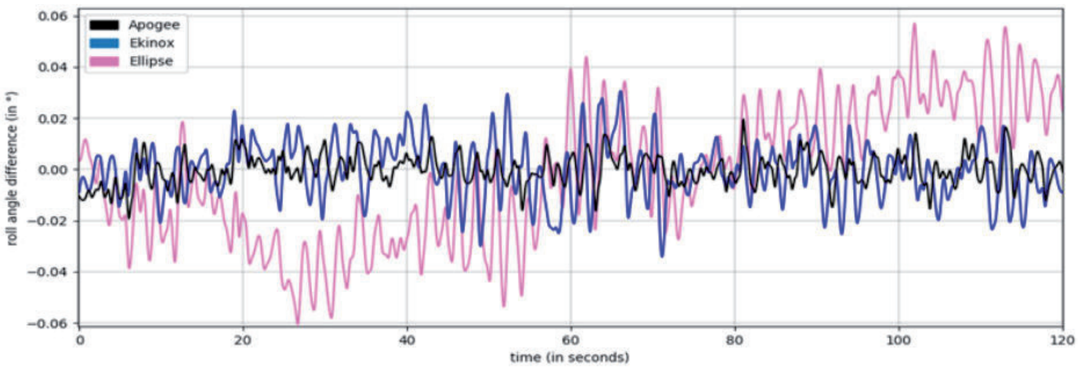


**Fig. 10:** Real-time roll differences of the MEMS to the FOG

Values for the derived survey accuracy conformances state the same: Very high accuracy conformance for the Phins with 99.6 % and in no way inferior results for each MEMS-based computation (above 99.5 % each). This fact is also underlined by the difference surfaces (very low differences of 1 cm up to 1.5 cm). When analysing difference surfaces visually (fig. 9), it has to be clarified what patterns signify: stripes on the image refer to short-time deviations to the reference motion while blur and extensive patterns refer to »longer« lasting drifts.

These kinds of drifts are slightly recognised only for the Ellipse when looking at a series of angle value differences between the Phins and all MEMS (see fig. 10). While all MEMS show low noises around the »true« value (assumption), the Ellipse (magenta line) also drifts slightly. Though these drifts do not affect these shallow water computations, they might be a critical point if this sensor is operated within deep water surveys.

## Conclusion

Within the inspection of the bathymetric results in the webmaps, it is obvious that the inertial positioning performance of the INS is the critical point rather than their motion performance. The low-cost system could not manage longer GNSS-outages as efficient as its superior competitors. Under the open sky and during good GNSS reception, all INS appear to archive similar, qualitative results. An investigation of raw data logs proofs all MEMS to drift less in position and altitude than maximally specified by their manufacturers. From the previously presented results it can be derived that especially low-cost and mid-range MEMS require post-processing of raw data in order to archive high quality results (comparable to those of a FOG) in under-bridge surveys. Whenever the GNSS signal reception is valid, e.g. in off-shore surveys without any shadowing of signals, post-processing can be skipped. When observing pure bathymetries and changes, only related to INS motion data sources, no distinct differences can be detected, even under conditions of strong dynamics. In fact, noises and drifts have been identified but they are still in ranges that do not distinctly decrease the bathymetric data sets quality. This experience leads to the assumption that very precise motion sensing might be required in deep water surveys or e.g. in land applications, when acquiring point data with mobile laser scanners, rather than in these shallow water surveys. The determination of accurate positions is the more demanding part for harbour surveys and the key aspect to be improved, especially considering future advances in MEMS technology. //